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A late Quaternary record of environmental change and human impact from New Caledonia

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Abstract

A late Quaternary vegetation record is presented from a lowland site on the leeward southwest coast of New Caledonia. Plum Swamp is a backswamp on the Plum River at around 10 m a.s.l., just within the ultramafic terrain that dominates the southern third of New Caledonia. Pollen analysis, charcoal analysis, radiocarbon dating and stratigraphic analysis are employed to reconstruct the vegetation and sedimentary history of the valley. The vegetation record commences at around 20,000 yr BP and shows that from this time up until the late Holocene the valley was forested. The greater representation of taxa more prevalent at higher altitudes during the late glacial suggests a response to cooling and an enrichment of the lowland forest with more montane elements. The late glacial transition between 14,000 and 9000 yr BP is a period of instability within the valley when vegetation is disturbed by fire. Forest recovers after this and there is increasing stability until the arrival of people in the late Holocene at around 3000 yr BP. The initial colonisers of New Caledonia had a profound effect upon the vegetation of the valley, converting the lowland forest to a stunted and species poor maquis on the ultramafic sediments and *Melaleuca* woodland on the non-ultramafic substrates. However, sedimentary processes are relatively unchanged during this time. Dramatic geomorphic change does occur in the catchment though, during the latter part of the 20th Century as a consequence of mining. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

The late Pleistocene and early Holocene environmental history of tropical south Pacific islands is known from only a few sites. In the tropical southwest Pacific there are two islands with records that extend back into the Pleistocene: the main island of New Caledonia (Hope and Pask, 1998) and Taveuni, Fiji (Southern, 1986). The only other Pleistocene records from between 0 and 30°S are from the southeastern Pacific; the Galapagos Islands (Colinvaux, 1972) and Easter Island (Flenley and King, 1984). All of these sites record some vegetation change during the last glacial maximum (LGM; around 18,000 ^{14}C years before present). Of these sites, Easter Island is the only one known to record vegetation change in response to the LGM as well as human impact in the late Holocene.

While there are only a few long palaeoenvironmental records from the tropical south Pacific there

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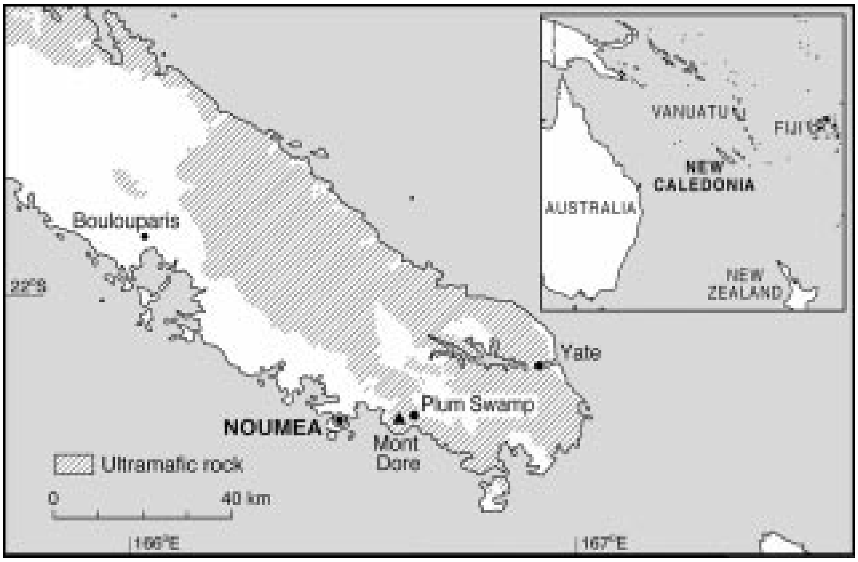

Fig. 1. Southern section of New Caledonia showing the location of the study site and distribution of ultramafic terrain.

are many more Holocene records (Hope et al., 1999). In general these studies have focussed on the issue of whether vegetation disturbance in the late Holocene can be used as a proxy of human impact and as a consequence, in situations where the archaeological record remains enigmatic, be a marker of initial colonisation (Flenley et al. 1991; Kirch and Ellison, 1994; Parkes, 1997; Dodson and Intoh, 1999). This is made possible by the late colonisation of these islands during a period of relative climatic stability. Although humans were in the Bismarck Archipelago and in the northern end of the Solomon Islands chain during the late Pleistocene (Allen and Gosden, 1988, 1991; Wickler and Spriggs, 1988) people only began to move into the islands east of the Solomons from around 3200 yr BP (Spriggs and Anderson, 1993; Sand, 1996; Spriggs, 1997).

This paper investigates the causes of lowland vegetation change in New Caledonia since the LGM. An understanding of the vegetation response to long term climate is important for establishing how we might separate natural from anthropogenic induced changes to the landscape in the fossil record and whether records of vegetation change are admissible as proxy records of colonisation in Pacific islands. An aim of the study, which investigated several sites on New Caledonia, was to establish if evidence of human impact could be detected in lowland pollen records and whether this is in accordance with the archaeological record for the island and the region. It is reasonable to expect that human impact will be more pronounced in the lowlands of Pacific islands given the density of coastal archaeological sites. This paper presents an analysis of one these sites, Plum Swamp, a backswamp in the Plum River valley on the southwest coast of New Caledonia.

2. Environmental setting

The Plum River valley is located approximately 18 km due east of Noumea on the eastern side of Mont Dore (Fig. 1). Plum Swamp (22° 16′S, 166° 37′E) is a backswamp on the Plum River at an elevation of around 10 m a.s.l. Steep slopes rising to around 400 m surround the river valley except for the southern end, which empties into the Baie de Mouéa. The valley lies just within the ultramafic terrain that dominates the southeast corner of the main island of New Caledonia (Fig. 1). The ultramafics form a highly selective substrate, being deficient in aluminium and the plant nutrients potassium, phosphorus and calcium while having excesses of magnesium, chromium and nickel (Brooks, 1987). Most of this terrain is characterised by a very distinct vegetation type called maquis (an evergreen, sclerophyllous, bushy formation);

Plate 1. Plum swamp looking west from road above swamp. *Melaleuca quinquenervia* woodland to south of swamp. Stunted maquis in foreground.

however, rainforest is also found on this substrate. A nickel mine has operated at various times since 1936 on Mont Dore (Fig. 1). While the mine is no longer in operation, tailings fans, gully erosion and landslips as a result of mining are widespread.

New Caledonia has a tropical to subtropical climate influenced by the prevailing southeast trade winds. The trade winds and the presence of a central mountain chain result in the great majority of New Caledonia's precipitation falling on the east coast producing a marked dry zone on the leeward west coast. The east coast routinely receives rainfall in excess of 4000 mm/yr, whereas the west coast may receive less than 1000 mm/yr (Section d'Hydrologie, 1981). The average annual rainfall for Plum is between 1300 and 1500 mm/yr, with the warmest and wettest months being from December to April (Section d'Hydrologie, 1981). Mean annual temperature at the site is around 24°C, with a seasonal range of 2–4°C. Annual rainfall is highly variable and years of rainfall shortage are linked to the El Niño-Southern Oscillation (ENSO) phenomenon (Morliere and Rebert, 1986). The effect of ENSO is most pronounced on the leeward west coast.

The slopes of the Plum River valley are primarily covered by ligno-herbaceous maquis with patches of bushy maquis. The ligno-herbaceous maquis (cyperaceous maquis) is a formation that is essentially Cyperaceae interspersed with a discontinuous cover of shrubs. This is considered to be a secondary formation, although on the human timescale it seems relatively stable (Jaffré, 1995). A *Melaleuca quinquenervia* woodland with an understorey of grass occurs on the southern side of Plum Swamp on soils not derived from the ultramafic rock (Plate 1). A depauperate maquis dominated by *Casuarina equisetifolia* is found to the north of the swamp (Fig. 2). There are several small pockets of lowland rainforest to the southeast. The swamp surface itself is dominated by *Carex* sp. (Cyperaceae) with scattered juveniles of *M. quinquenervia*.

3. Methods

3.1. Sediment analysis

A reconnaissance survey of the main river valley was used to describe bank exposures along the main channel and tributary (Fig. 2). Descriptions were carried out in the field and samples were taken for radiocarbon dating and X-ray diffraction (XRD) analysis. A near north–south and east–west survey along the main axes of the backswamp was conducted

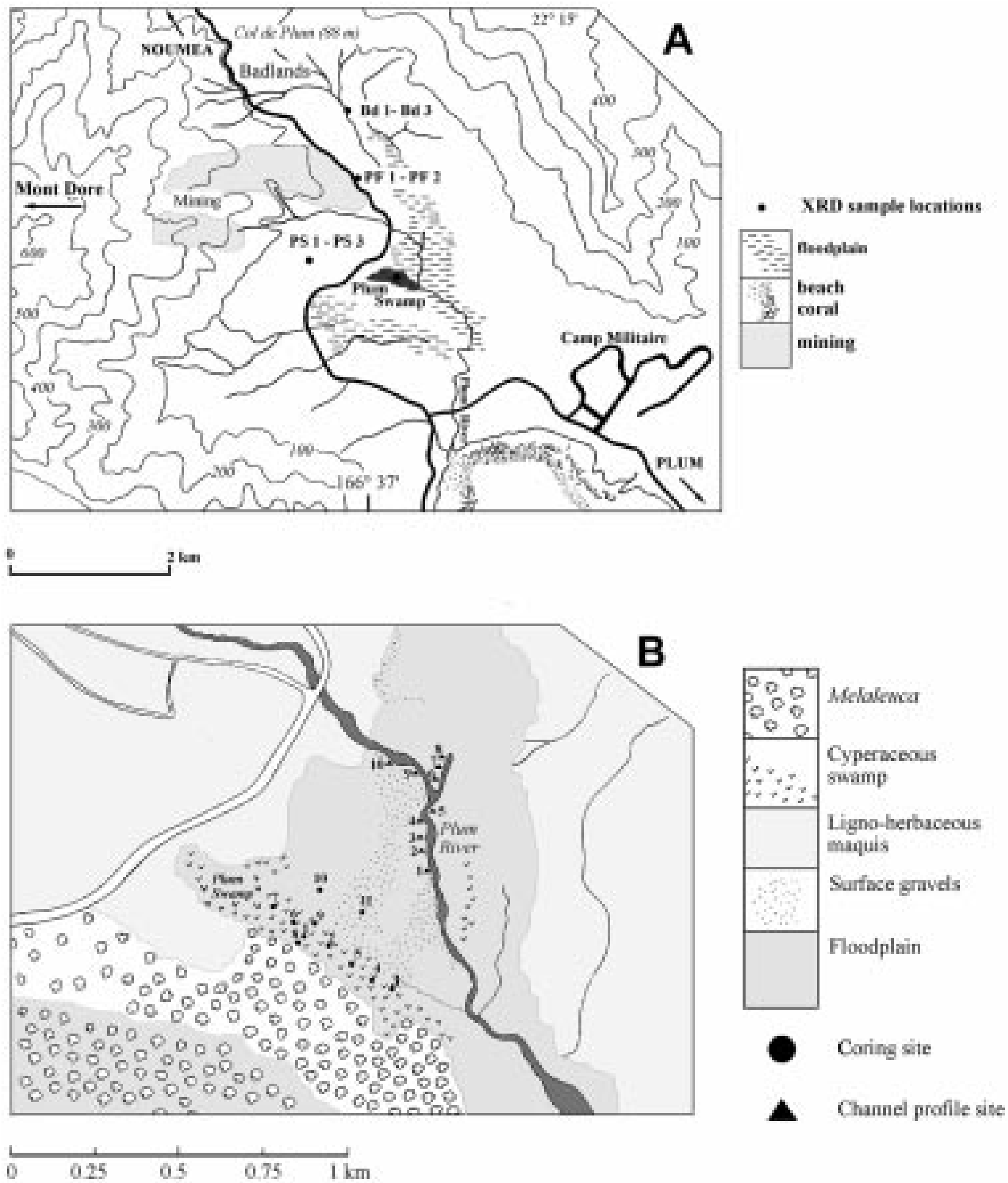

Fig. 2. (A) Map of the Plum River valley. (B) Site map for Plum Swamp showing the location of pollen cores, stratigraphy coring sites and channel profiles. Pollen cores: Plum Edge = core 1; and Plum Centre = core 2.

using a D-section corer (Fig. 2). With the exception of the two cores used for pollen analysis, cores were logged on site. The two cores used for pollen analysis were described in the laboratory and samples taken for pollen analysis, radiocarbon dating, loss-on ignition and XRD analysis.

3.2. Pollen analysis

The two cores collected for pollen analysis are cores 1 and 2 on Fig. 2. They are referred to as Plum Edge and Plum Centre, respectively. Plum Centre has the longest record in terms of depth and

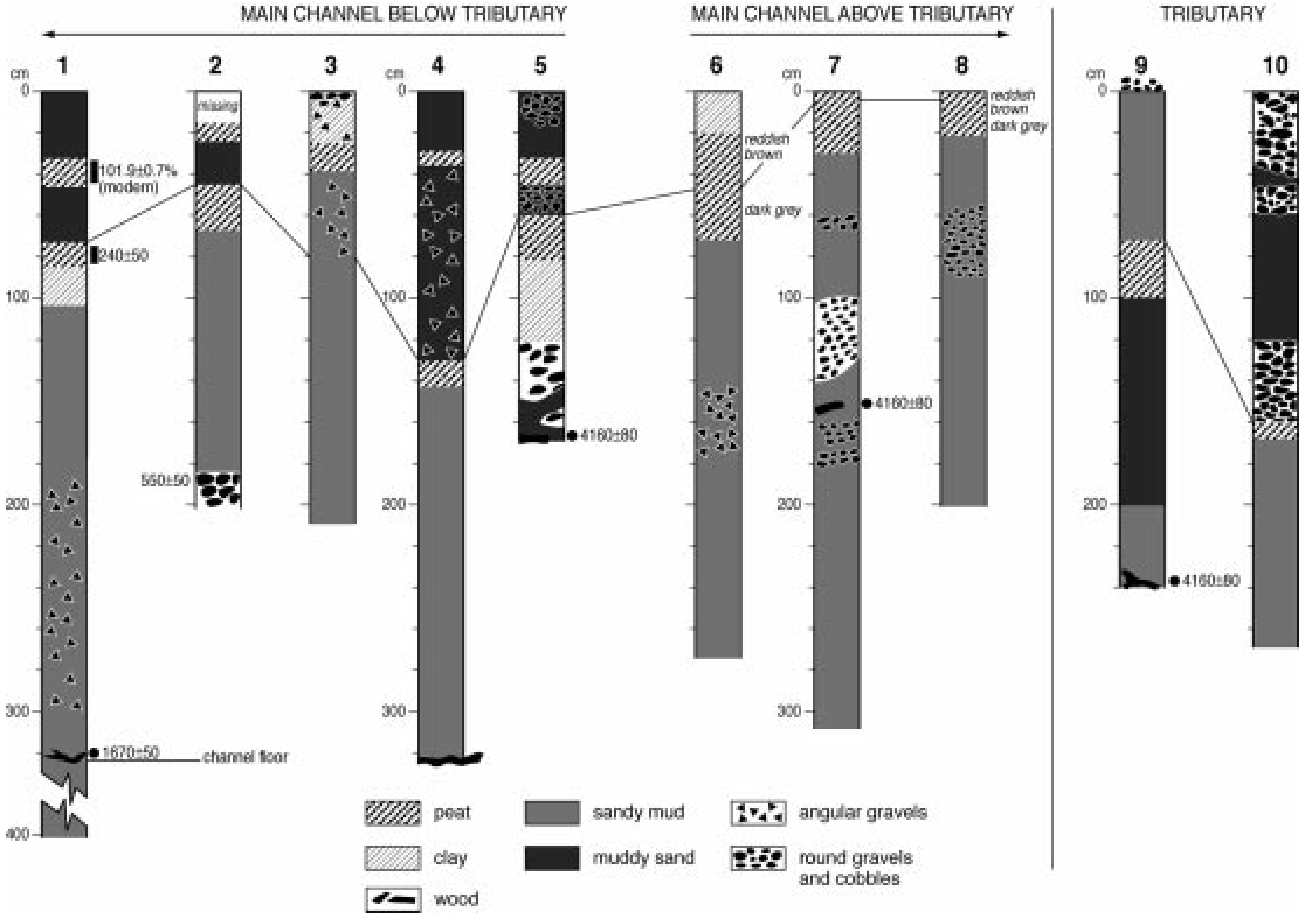

Fig. 3. Channel stratigraphy of Plum River and main tributary. Radiocarbon ages are shown. See Fig. 2 for profile locations.

time and is the main focus of the pollen analysis. The Plum Edge core provides a much shorter record and is used to assess whether there is spatial variation in the backswamp fossil pollen. Processing of the samples followed the standard acetolysis method described by Moore et al. (1991). Cyperaceae pollen and fern spores were counted outside the terrestrial pollen sum, and because *Pandanus* pollen overwhelmed the lower samples, at least 100 terrestrial pollen grains were counted for these levels in addition to the *Pandanus* pollen. A decision was made to include *Melaleuca* and *Pandanus* pollen in the terrestrial pollen sum for the following reasons. Very few individuals of *Melaleuca* are found on the surface of the swamp due to its ultramafic nature. By far the majority of these trees are found on higher ground to the south of the swamp (refer to Plate 1). Similarly, while *Pandanus* is found throughout the ultramafic terrain, it is also most prevalent on dryer ground adjacent to water bodies. Carbonised particle counting was based on the point count method (Clark 1982).

In addition to pollen and fern spores, the zygospores of filamentous green algae were also counted. These grow in shallow water or along the littoral zone of lakes and often form associations with certain plants (Hoshaw and McCourt, 1988). Three types of spore were routinely encountered, *Pseudoschizea circula*, *Debarya* and *Zygnema* (Hoshaw and McCourt, 1988; Kuhry, 1988; van Geel and Grenfell, 1996).

3.3. Numerical analyses

The fossil pollen diagrams are percentage diagrams plotted using the program PSIMPOLL (Bennett, 1997). A summary pollen diagram is shown for each core based on the terrestrial pollen sum. The individual pollen curves for each core are also based on this pollen sum.

All analyses were carried out within PSIMPOLL. Numerical zonation of the pollen data used optimal splitting by sum of squares analysis. Palynological richness provides a comparative estimate of the expected number of taxa in each sample and is determined by rarefraction analysis (Birks and Line, 1992). This subroutine within PSIMPOLL takes a standardised count (which must be less than the actual count) and compares the richness between samples. Principal components analysis (PCA) was used to reduce the pollen diagrams to bi-plots of the relationship between samples and the taxa contributing most to the analysis (Birks and Gordon, 1985).

4. Results

4.1. Channel stratigraphy and chronology

There are three principal sediment types found in the bank exposures of the main channel and the Mont Dore mine tributary. A basal unit of dark brown to brown sandy mud (silt and clay), a middle unit of reddish brown to black peat, and an upper unit of reddish brown muddy sand, sometimes with gravels and cobbles (Fig. 3).

All exposures have a 2–3 m deep unit of brown sandy mud (Fig. 3). Coring beneath the channel bed at the base of profile 1 revealed that this unit extends for at least another metre in depth. There is a gradual change to the overlying fibrous peat unit which is commonly 20–40 cm thick. A sharp boundary to the topmost unit of reddish brown sandy mud exists in all profiles except 7 and 8, where the peat unit is at the surface (Fig. 3). The unconformity between the middle unit of black peat and the topmost unit of muddy sand can be traced throughout the system and is represented by the solid line in Fig. 3. This uppermost unit of muddy sand coarsens upstream to sand, gravels and cobbles. The sands in the lower reaches are weakly horizontally bedded, while in the upper reaches of the tributary the gravels and cobbles are strongly bedded and well-sorted. There is a weak band of peat, 5–10 cm thick, in the downstream profiles (profiles 1–5) midway through this topmost unit. The 160 cm of cobbles, gravels, sands and clays in the bank exposure at profile 10 are part of the gravel splay.

The channel in the lower part of the main valley is a deep gully with bank heights of 2–4 m. The main tributary on the western side of the valley originates from the Mont Dore mine (Fig. 2). Between the tributary channel and the backswamp is a splay of coarse material such as gravels and cobbles through which the tributary channel is incised by 3 m. The incision of the tributary and main channel must postdate the mining operations on Mont Dore as flows through

Table 1
Radiocarbon ages and calibrated ages for Plum River profiles

Profile number and depth	Lab number	^{14}C Age years BP[a]	Calibrated age yr BP (range) 2 sigma[b]	Sample type
1 (40–46 cm)	Beta-52263	101.9 ± 0.7% (modern)		Peat; between two mineral layers.
1 (74–80 cm)	Beta-52264	240 ± 50	290 (500–0[c])	Peat; at top of valley fill.
2 (160 cm)	Beta-52266	550 ± 50	540 (670–430)	Root from insitu *Araucaria* stump at base of valley fill.
7 (157 cm)	Beta-52268	690 ± 50	655 (780–520)	Wood in middle of valley fill. Has been transported.
1 (320 cm)	Beta-52265	1670 ± 50	1545 (1820–1340)	Root from insitu *Araucaria* stump at base of section.
9 (250 cm)	Beta-52269	4150 ± 70	4640 (5030–4280)	Wood. Burnt. Insitu stump at base of profile 9.
5 (250 cm)	Beta-52267	4160 ± 80	4690 (5210–4230)	Wood from top of insitu stump; creek bed adjacent to profile 5.

[a] 1955 denotes influence of bomb ^{14}C.
[b] Calibrated using Stuvier and Reimer (1993).
[c] 0 represents a "negative" age BP.

these channels would not be capable of lifting cobbles and gravels overbank and onto the floodplain. Above the tributary junction in the main valley the gravels and reddish brown sediments characteristic of the mining spoil are absent. Instead the valley floor is peat covered with some areas of channel scour. The headwaters of the main valley channel are characterised by a distinctive badland. The pale creamy colour of the badland soils sets this area apart from the dominant iron rich ultramafic soils on the surrounding slopes.

Seven radiocarbon dates were obtained on peat and wood within the channel to establish a chronology for the sediments (Table 1) and appear also on Fig. 3. From profile 1 the two peat layers and an in-situ *Araucaria* tree root from the base of the exposure, just above the channel bed, were dated. The weak layer of peat found within the topmost unit of muddy sand is modern (Table 1; Beta-52263) and the lower unit of black peat gave an age of 240 ± 50 yr BP. The sample of tree root from the base of profile 1 gave an age of 1670 ± 50 yr BP, while a tree root sample from the base of profile 2 returned an age of 550 yr BP. Two other wood samples taken from a stump in the main channel bed opposite profile 5 and from the base of profile 9 gave ages of around 4150 yr BP. Both stumps were in growth position. It is important to note that the latter two samples are tree trunk material and not tree root. It is estimated that root material from these stumps is probably a metre or so below the channel bed and as such the results do not reflect inconsistencies in the dates between profiles 1, 2, 5 and 9. A wood sample taken from within the sandy mud unit of profile 7 gives an age of around 700 yr BP, but as the wood shows signs of being transported this is the maximum age of the deposit.

There are insufficient radiocarbon dates to draw firm conclusions about changing rates of sedimentation, however, the dates are internally consistent. Importantly the ^{14}C dates show that the main layer of peat accumulated in the valley up until modern times, and that the uppermost unit is associated with mining. The hiatus in the accumulation of the topmost unit of reddish brown muddy sand and the return to peat accumulation is consistent with a break in mining operations for 16 years between 1947 and 1963. The uppermost very coarse sediments of the gravel splay and the subsequent channel incision is thus probably associated with the more intense mining after 1963.

4.2. Plum swamp stratigraphy and chronology

The locations of the core sites are shown in Fig. 2, and the stratigraphy is illustrated in Figs. 4 and 5. Core

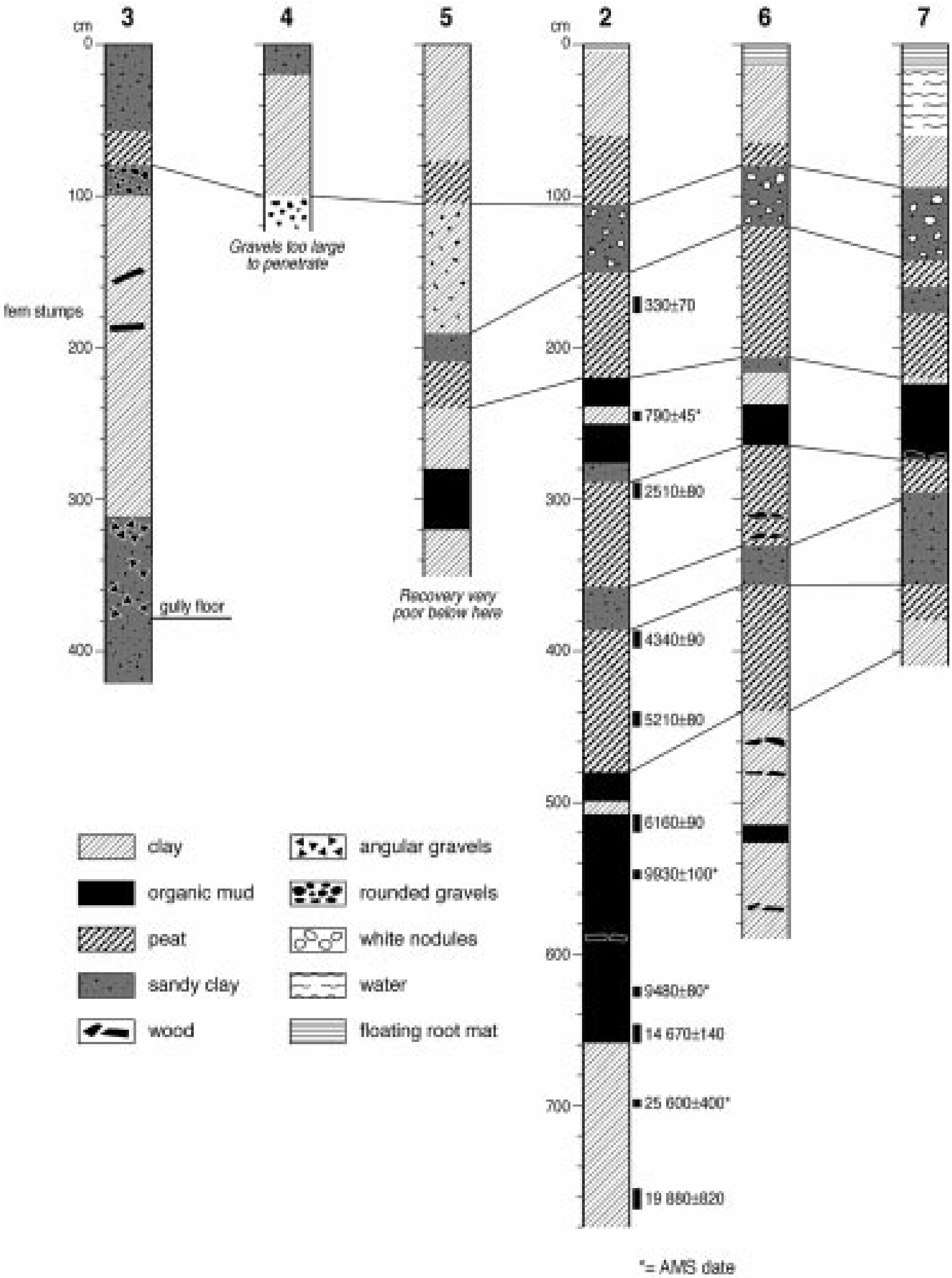

Fig. 4. Plum Swamp stratigraphy. East–west transect. Radiocarbon ages are shown. See Fig. 2 for core locations.

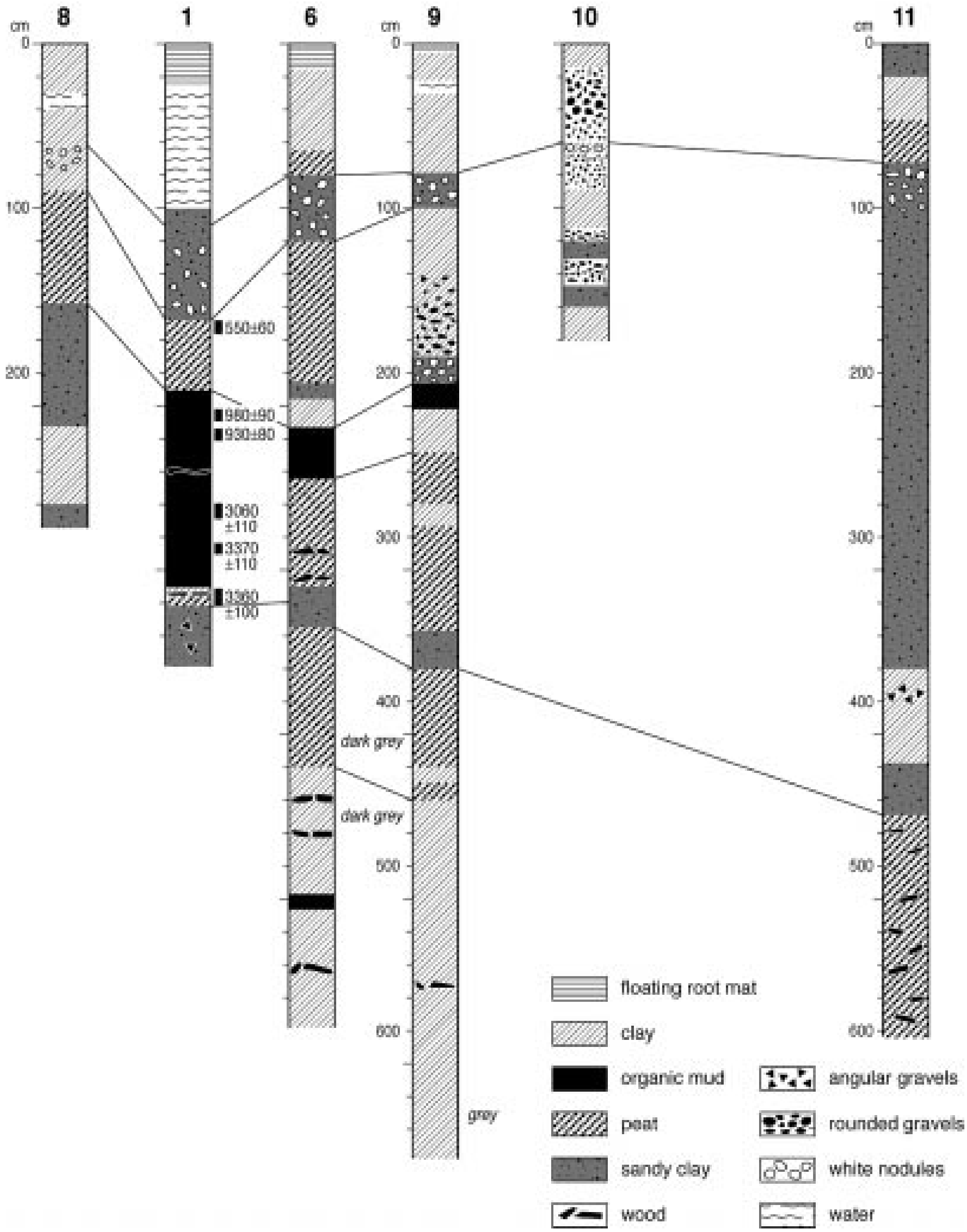

Fig. 5. Plum Swamp stratigraphy. North–south transect. Radiocarbon ages are shown. See Fig. 2 for core locations.

Table 2
Radiocarbon ages from Plum Swamp

Plum centre (Core 2) depth in cm	Lab number	^{14}C Age yr BP[a]	Calibrated age yr BP (range) 2 sigma[b]	Bulk sample type
166–176	Beta-53530	330 ± 70	390 (510–0[c])	Peat
242–247	OZA-957	790 ± 45[d]	690 (780–660)	Slightly organic clay
286–296	Beta-53531	2510 ± 80	2570 (2760–2340)	Peat
342–350	Beta-76835	3510 ± 70	3760 (3930–3620)	Peat
387–397	Beta-53532	4340 ± 90	4870 (5260–4650)	Peat
440–450	Beta-52262	5210 ± 80	5940 (6180–5850)	Peat
508–518	Beta-70396	6160 ± 90	7020 (7220–6850)	Organic mud
545–550	OZA-958	9930 ± 100[d]	11010 (11880–10960)	Organic mud
623–628	OZA-959	9480 ± 80[d]	10520 (10910–10230)	Organic mud
648–658	Beta-70397	14670 ± 140	17560 (17910–17200)	Organic mud
696–700	OZA-960	25600 ± 400[d]		Slightly organic clay
757–767	Beta-70398	19880 ± 820		Slightly organic clay
Plum edge (Core 1) depth in cm				
168–176	Beta-43682	550 ± 60	542 (650–500)	Peat
223–231	Beta-43683	980 ± 90	920 (1062–690)	Organic mud
232–240	Beta-438684	930 ± 80	830 (970–670)	Organic mud
280–288	Beta-43685	3060 ± 110	3260 (3470–2940)	Organic mud
305–310	Beta-43686	3370 ± 110	3620 (3880–3360)	Organic mud
330–340	Beta-43687	3360 ± 100	3610 (3840–3370)	Slightly organic clay

[a] 1955 denotes influence of bomb ^{14}C.
[b] Calibrated using Stuvier and Reimer (1993).
[c] 0 represents a “negative” age BP.
[d] AMS date.

1 was collected in 1991 as part of reconnaissance fieldwork and at the time there was approximately 50 cm of water overlying the Core 1 site. The remaining descriptions are from the 1993 fieldwork season when the surface of the swamp was largely dry.

All of the swamp cores, with the exception of cores 3 and 4, follow the same general pattern and alternate between periods of clay, organic mud and peat accumulation (Figs. 4 and 5). White nodules less than 2 mm in diameter are found in all swamp cores except 3, 4 and 5. XRD analysis revealed that these are siderite, an iron carbonate that precipitates in a reducing environment with a pH above 8 (Drever, 1988). In general the backswamp sequence fines away from the main channel and organic input increases with distance from the channel. The sediments are finer at the base of the deepest sediments, increasing in coarseness toward the surface.

Quite different stratigraphic profiles were observed in cores 3 and 4 (Fig. 4). The record from core 4 is truncated as the gravels at 100 cm were too coarse to penetrate with a D-Section corer and too loose for recovery with an auger. Profile 3 is the head wall of a tributary gully at the eastern end of the swamp. The sandy clays and peat layers common to the top 100 cm of the swamp cores are found here and are underlain by small rounded gravels 3–4 mm in diameter in a sandy clay matrix, similar to those in core 5. From 100 to 300 cm there is a fine organic clay. Below 300 cm the sediment resembles the bottom sandy mud unit of the main channel exposures. The sediment at this end of the swamp clearly suggests that it is transitional between the main channel exposures and the western end of the swamp.

Cores 10 and 11 are on the gravel splay between the swamp and the mine tributary (Fig. 5). The siderite nodules found in the swamp cores are found in both these profiles within the top metre. Core 10 has much more sand and gravel than the swamp cores, and could not be cored past 180 cm depth. Core 11 is finer textured

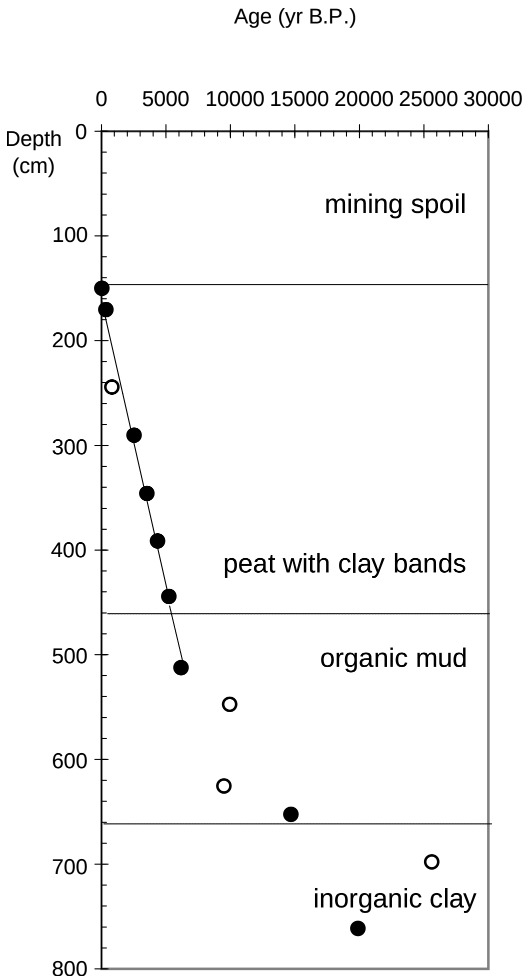

Fig. 6. Age depth relationship for Plum Centre. Hollow symbols equal AMS dates.

than 10. Below 100 cm it is composed primarily of a sandy clay. Being closer to the main channel the topmost units contain more sand. Peat with a large amount of wood was recovered from 470 to 600 cm and coring was not possible beyond 600 cm because of wood. The 360 cm of olive brown sandy clay beneath the siderite nodules appears similar to the bottom sandy mud unit in the river channel exposures, and the peat unit may be related to the lowest peat unit in the backswamp between 4 and 5 m depth.

4.3. Chronology

Samples for radiocarbon dating were taken from the two pollen cores, Plum Centre (core 2) and Plum Edge (core 1). Eight conventional radiocarbon dates were obtained from Plum Centre with 4 additional AMS dates from the less organic sediments. Six conventional radiocarbon dates were obtained for Plum Edge. The results of the dating are shown in Table 2 as conventional ages in years BP, along with their calibrated age estimates. An age model for the sediments above 450 cm has been estimated by a straight line of best fit (Fig. 6). Below 450 cm estimates of sediment age are more difficult to infer as there are several age reversals. The conventional date at 760 cm required extended counting due to the low carbon content of the sample which may explain its young age relative to the AMS date at 700 cm. However, these inorganic clays in the base of the core are at least LGM in age or older. Some consideration should also be given to the possibility that a hiatus in sedimentation took place between this unit and the overlying organic mud. Perhaps by coincidence the straight line of best fit from the upper age model intersects with the youngest date from the organic mud unit at 510 cm (Fig. 6). The two AMS dates from this section are also reversed, although all the dates from this unit suggest that it is younger than LGM in age.

The sandy clay unit with the creamy white nodules found within the top 150 cm of most cores is a clear stratigraphic marker and the two dates from the peat layer below this unit suggest that it is probably modern. This is in keeping with the age of the lower peat layer in the channel exposures, which was found to be around 240 yr BP. Like the river channel exposures, there is a return to peat accumulation within the upper inorganic layers. Mining has led to the deposition of sand, gravels and clays along the river channel and across the floodplain, with only the clays reaching the back of the swamp. Within the swamp 1–2 m of sediment has been deposited since 1936, at an average of 25 mm/yr. This is markedly different from the pre-mining environment where on average 0.6 mm was being deposited per year.

4.4. XRD analysis

XRD analyses were carried out on sediments from the backswamp and surrounding valley to broadly

Table 3
Selected XRD results for bulk mineral analysis ***** dominant (>60%). **** abundant (40–60%). *** moderate (20–40%). ** small (5–20%). * trace (<5%).

Sample							
Location	Sample Description	Quartz	Goethite	Haematite	Siderite	Kaolinite	Smectite
Core 2 125 cm	White Nodules	**			*****		
Core 2 37–40 cm	Sediment	***	****		**		
Core 2 130–132 cm	Sediment	****	**		***		
Core 2 247–250 cm	Sediment	****				***	**
Core 2 282–285 cm	Sediment	****	****			*	
Core 2 372–375 cm	Sediment	***	***		***		
Core 2 552–555 cm	Sediment	***				*	****
Core 2 718–720 cm	Sediment	*****				*	**
Fan deposit 250 cm depth	C horizon sediment	****	***			**	
Fan deposit 250 cm depth	Weathered stone	*****		**			
Slope deposit	Pisolitic upper soil	**	*****				
Slope deposit	Earth above bedrock		*****			*	
Badland 1	Remnant of A2 horizon	**					****
Badland 2	B horizon	**					****
Badland 3	Sediment coming out of badland	***					****

investigate the major sources of sediment to the backswamp over time. Identifiable sources seemed possible given the quite different geologic nature of the badland area in the headwaters of the valley. Sediment samples were analysed from the badlands area, from two slope deposits and from core 2.

Goethite, smectite and siderite dominate the secondary minerals in the bulk sediment analysis. Smectite is the defining mineral for the badlands area and mineralogically sets these deposits apart from the slope deposits (Table 3). Three of the core samples also have abundant smectite 718–720, 552–555 and 247–250 cm, and lack the iron rich minerals of the slope deposits. Goethite is the defining mineral of the slope deposits, and the remaining core samples are mineralogically more like the samples taken from the slopes and fans.

It would appear that the inorganic fraction of the basal sediments in the Plum Centre core and the organic mud originates from the badlands in the headwaters. The origin of clay layers after 5000 yr BP is predominantly from the slopes and fans. The 247–250 cm clay band is within the human occupation period and is dominated by smectite suggesting the material is largely from the headwaters. An AMS date from the clay gave an age of 790 yr BP. This is the first time clays of largely smectite composition have been deposited since the mid-Holocene. The iron carbonate siderite, which is most visible as the creamy white nodules in the upper 1.5 m of the swamp, is also found in a sample from 372 to 375 cm. The sample from 282 to 285 cm contained goethite only.

4.5. Pollen and charcoal analysis

Zonation of the Plum pollen data set resulted in two significant zones, labelled PC-A and PC-B for Plum Centre and PE-A and PE-B for Plum Edge. The pollen and spore percentages, palynological richness, carbonised particle concentration and loss-on ignition are shown for each core. While 135 pollen types were identified from the Plum sediments, some remain unidentified and have been assigned a type number. Defining a specific lifeform category for many of the pollen types was also difficult as many lowland genera and families exist as trees or shrubs and also comprise quite different vegetation types, such as rainforest and maquis. The somewhat ambiguous category of trees and shrubs therefore dominates the summary pollen diagram. In general, only taxa with values of 5% or more in at least one sample are shown as individual curves. Taxa with values of less than 5% in all samples have been grouped under other pollen types. This category, for most of the record, is 10%

or less of the pollen sum. The full range of taxa identified is shown in Appendix A.

4.6. Plum centre

Zone PC-A(>21,000–2200 yr BP) is dominated by the pollen of trees and shrubs from lowland forest, in particular *Pandanus*. There is a significant change in pollen coincident with a charcoal peak from 660 to 610 cm (Fig. 7). Relative to Zone PC-B the percentage of fern spores and Cyperaceae pollen is extremely low. Zone PC-A has been further subdivided subjectively to aid description on the basis of significant changes in the stratigraphy into Zones PC-A1, PC-A2 and PC-A3. The pollen taxa in Fig. 7 have been arranged from left to right, by the taxa that define zone PC-A, followed by the taxa that define zone PC-B.

Sub-zone PC-A1(> 21,000 yr BP to around 14,000 yr BP). The highest percentages of tree pollen occur in this zone at around 70%, declining to 40% by the top of the zone. A majority of the tree pollen (20–50%) is *Pandanus krauelianis* sim. (Fig. 7). It should be noted that there is no comprehensive *Pandanus* reference collection for New Caledonia and this species is not found in the territory. The identification is based on a collection of New Guinea highland species held by the department of Archaeology and Natural History. *Apodytes clusiifolia* and *Nothofagus* are also important tree pollen taxa. *A. clusiifolia* is an endemic rainforest species found on a variety of substrates from 0 to 1000 m a.s.l and is noted as being one of the principal species of rainforest above 750 m altitude where the mean annual temperature is around 18°C (Villiers, 1980; Cherrier, 1982). *Nothofagus*, while found close to sea level, is also more prevalent at altitude (Read and Hope, 1996). *Macaranga alchorneoides* is a principal species of lowland rainforest found in the valleys of the ultramafic terrain (Cherrier, 1982). This pollen type increases in the upper part of zone PC-A1. *Rauvolfia* pollen is also present in small amounts in these basal sediments. *Rauvolfia* can be a tree or shrub of primary or secondary forest, but prefers constantly damp soil and is often found along river banks and in open places. Fern spores are low to absent throughout this zone and palynological richness varies from 12 to 25 taxa (Fig. 7).

This zone has a unique stratigraphy relative to the rest of the core; a dark grey silty clay, which becomes increasingly silty with depth. There is an abrupt boundary between this unit and the overlying organic sediment. Charcoal fragments are found in this zone, and although their concentration is extremely low, they are an indication that fire was not entirely absent from the environment (Fig. 7). The sediments are probably older than 18,000 radiocarbon years.

Sub-zone PC-A2(14,000 yr BP to around 6000 yr BP). This zone encompasses the late glacial transition; however, once again the actual chronology is not well defined. It coincides with a shift to organic mud accumulation and begins with a significant increase in charcoal concentration and a corresponding vegetation change (Fig. 7). The highest values of Cyperaceae pollen in this zone coincide with the peak in charcoal values at 640 cm and sedge fibres in the stratigraphy between 624 and 640 cm suggest that Cyperaceae was growing on the surface of the site. Some of the largest percentages of pollen types that could not be formally identified occur during this period in zone PC-A2. Percentages of indeterminate taxa are also high. Palynological richness estimates for the period of disturbance are between 25 and 30 taxa. Values for the rest of the sub-zone are much lower, between 10 and 20 taxa.

The major tree pollen taxa that decrease with the charcoal peak are *Apodytes*, *Macaranga* and *Pandanus*, while the tree and shrub taxa that increase significantly during this period are *Ascarina*, Casuarinaceae, Cunoniaceae, *Melaleuca* and the Myrtaceae in general. There are only two species of *Ascarina* on New Caledonia. Both are found as either shrubs or small trees on a variety of terrain in wet evergreen forest or maquis, and usually between 150 and 1500 m a.s.l. Very small amounts of Poaceae (grass), and the highest percentages of Asteraceae and *Trema* pollen also occur. All three are indicators of disturbance and more open habitats.

Following the charcoal peak, *Pandanus* pollen increases and remains at around 20–30% for the rest of the sub-zone. The other dominant tree and shrub pollen are *Macaranga* and Casuarinaceae. Notably, the curves of these two taxa are the inverse of each other. Results from the modern pollen rain study (Stevenson, 1998) suggest that the levels of

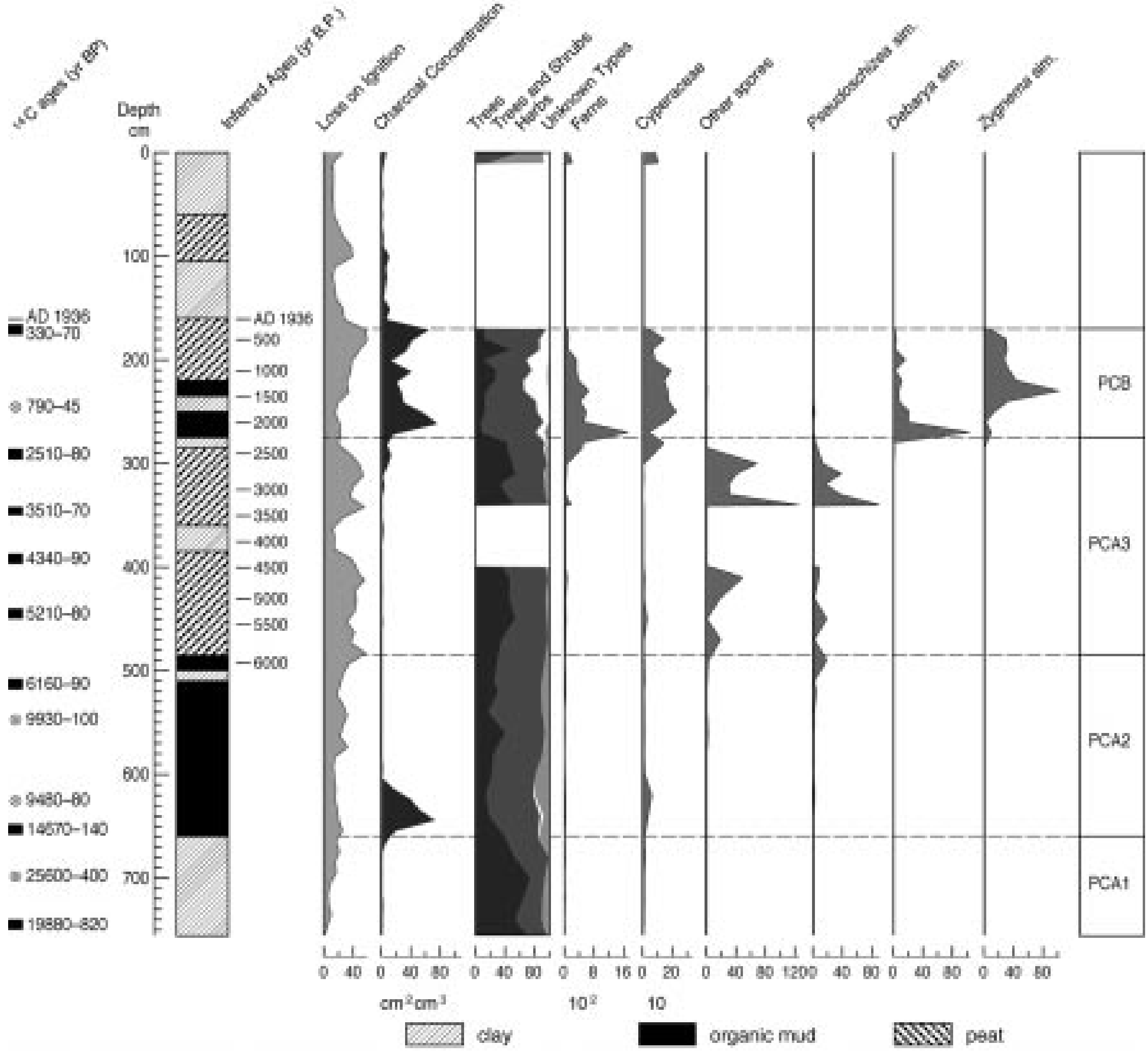

Fig. 7. Plum Centre pollen diagram. The summary diagram is based on the terrestrial pollen sum. Fern spores, Cyperaceae and Zygnemataceae are percentages of the terrestrial pollen sum. Selected taxa are shown as individual pollen curves. In general these are taxa that have a value of 5% in at least one sample. Dots indicate presence of taxon at a value of <1%. The diagram also includes loss-on-ignition, charcoal concentration and estimates of palynological richness.

Casuarinaceae pollen recorded throughout zone PC-A2 are most likely from a regional or extra-local source. *Rauvolfia* pollen reappears in the upper part of this zone.

Sub-zone PC-A3 (6000 yr BP to 2200 yr BP. In this upper part of the core the chronology is much more robust (Fig. 6). The percentages of *Pandanus* pollen increase in the lower part of sub-zone PC-A3 as do *Araucaria* and Cunoniaceae. At the same time the percentages of Casuarinaceae pollen decrease dramatically. The values of *Macaranga* pollen on average remain the same as zone PC-A2. There are four species of *Araucaria* that occur in lowland rainforest and the conifers in general are found in very wet conditions (Jaffré, 1995).

PC-A3 contains a clay band between 360 and 385 cm.

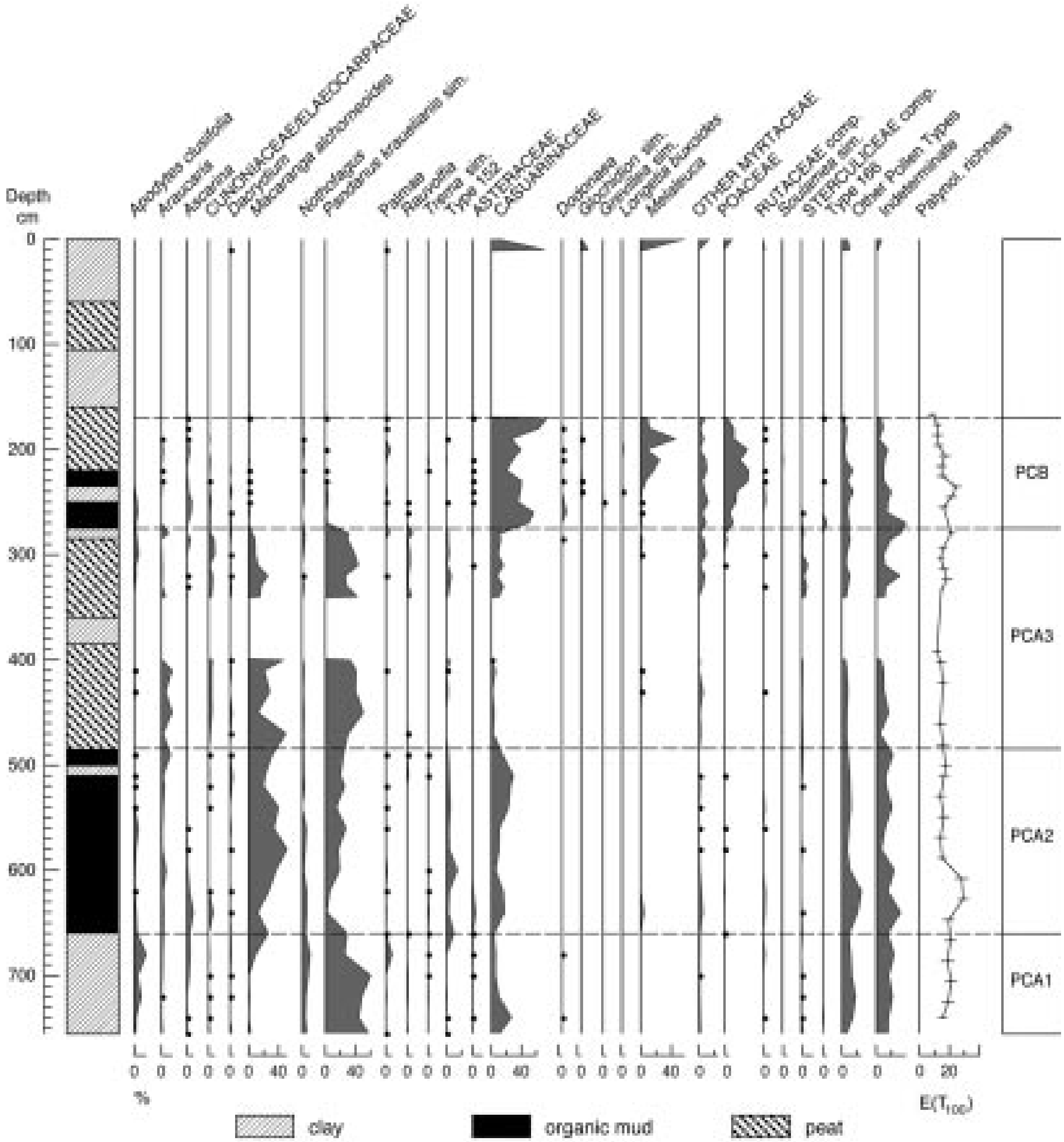

Fig. 7. (*continued*)

These sediments and those either side of the band contain only poorly preserved pollen and spores. There is also a bias toward the partial preservation of robust pollen types, such as Casuarinaceae and trilete fern spores, with a further bias introduced by these grains being easily distinguished even when poorly preserved. Therefore the results from this section of the core are not included in the palaeovegetation analysis.

Following the clay layer there are increased values of *Apodytes* pollen and a decrease in *Araucaria* pollen (Fig. 7). *Pandanus* percentages remain high while *Macaranga* pollen decreases. Of the tree and shrub taxa Casuarinaceae pollen increases and there are significant amounts of Myrtaceae pollen, other than *Melaleuca,* in the upper part of the zone. The highest values of *Rauvolfia* pollen are found in the upper part of zone PC-A3 and *Ascarina*, which was largely absent from the record, reappears after 550 cm (Fig. 7).

In Fig. 7 the 'other spores' category refers to a small, round, highly ornate spore. It is likely to be from a plant growing on the surface of the site. Of the filamentous green algae, *Pseudoschizea circula* (Zygnemataceae) is the only one significantly present in zone PC-A3. There is a lack of ecological information regarding the Zygnemataceae especially for tropical regions. However, they are a good indicator of shallow water and changing trophic conditions.

Charcoal is low to absent throughout sub-zone PC-A3, but begins to rise towards the top at around 300 cm (2700 yr B.P). This coincides with an increase in fern spore percentages (Fig. 7). These changes are not reflected in the terrestrial pollen sum and the individual pollen curves show that on the whole, pollen deposition from terrestrial tree and shrub taxa is relatively unchanged at this point. The highly ornate spore thought to be associated with peat accumulation is very high after the clay layer, but decreases to zero with the increase in charcoal, fern spores, and Cyperaceae pollen. Similarly, the green algae *Debarya* and *Zygnema* spores are seen in small amounts at the very top of the zone PC-A3 in association with these other changes (Fig. 7). All of these factors taken together suggest that the site surface was undergoing change at this time, either hydrological or trophic.

Zone PC-B (2200–300 yr BP) begins with a sharp rise in charcoal and dramatic changes in the pollen and spore ratios (Fig. 7). The charcoal concentration remains high up to the present surface. Significant changes in individual pollen types that occur across the PC-A and PC-B boundary include an abrupt decline in *Pandanus* and abrupt increases in Casuarinaceae and Poaceae (grass) pollen (Fig. 7). The highest values of grass occur in this zone.

Other changes in zone PC-B include the disappearance of *Apodytes* pollen by 1500 yr BP and a significant increase in *Melaleuca* after this time (Fig. 7). The Myrtaceae pollen values from the upper part of zone PC-A3 are maintained in zone PC-B. *Nothofagus* pollen percentages do not change from those recorded for PC-A3. *Dacrydium* pollen is found throughout the record in very low percentages, but disappears entirely at around 1200 yr BP. Of interest is the small but continued input of *Araucaria* pollen up until around 700 yr BP, remembering that there is evidence of *Araucaria* tree stumps buried in the main valley channel. A number of the rarer pollen types are found exclusively in zone PC-B and are indicative of an open shrubby environment, in particular *Longetia buxoides*, *Soulamea*, *Glochidion* and *Grevillea*.

Palynological richness values of between 15 and 30 taxa, following the first major charcoal peak, are the same as those estimated for the disturbance period in zone PC-A2. By 700 yr BP palynological richness is between 5 and 15 taxa as the terrestrial pollen record is dominated by *Melaleuca* and Casuarinaceae pollen. *Melaleuca* grows along the southern margin of the swamp on the less ultramafic soils, whereas *Casuarina equisetifolia* is a dominant shrub in the stunted maquis to the north of the site.

Overall the record in zone PC-B is characterised by large quantities of Cyperaceae pollen and fern spores (Fig. 7). *Debarya* and *Zygnema* dominate the green algae of zone PC-B, *Zygnema* outnumbering *Debarya* after 1400 yr BP.

The sediments above 150 cm were interpreted as mining spoil deposited from the Mont Dore mine tributary after 1936 AD. While the charcoal concentration is low, the rate of deposition is so high in this upper part of the core that it cannot be sensibly compared with the previous levels and does not necessarily indicate less fire in the environment. The two uppermost pollen samples are surface samples collected from the edge of the swamp and formed part of the modern pollen rain study. The relative values of the dominant taxa resemble those of around 300 yr BP, suggesting that the vegetation of the river valley has changed little since that time.

4.7. Plum edge

The Plum Edge core is a much shorter core spanning only the last 3300 yr. Pollen preservation is quite poor for many of the samples and several samples, although counted, have not been included in the analysis. The general patterns seen in the pollen diagrams of Plum Centre are also seen here for the same age range. Zone PE-A, 340–265 cm, and zone PE-B, 265 to 180 cm (Fig. 8).

Charcoal is present in low concentrations in the bottom section of zone PE-A, increasing significantly

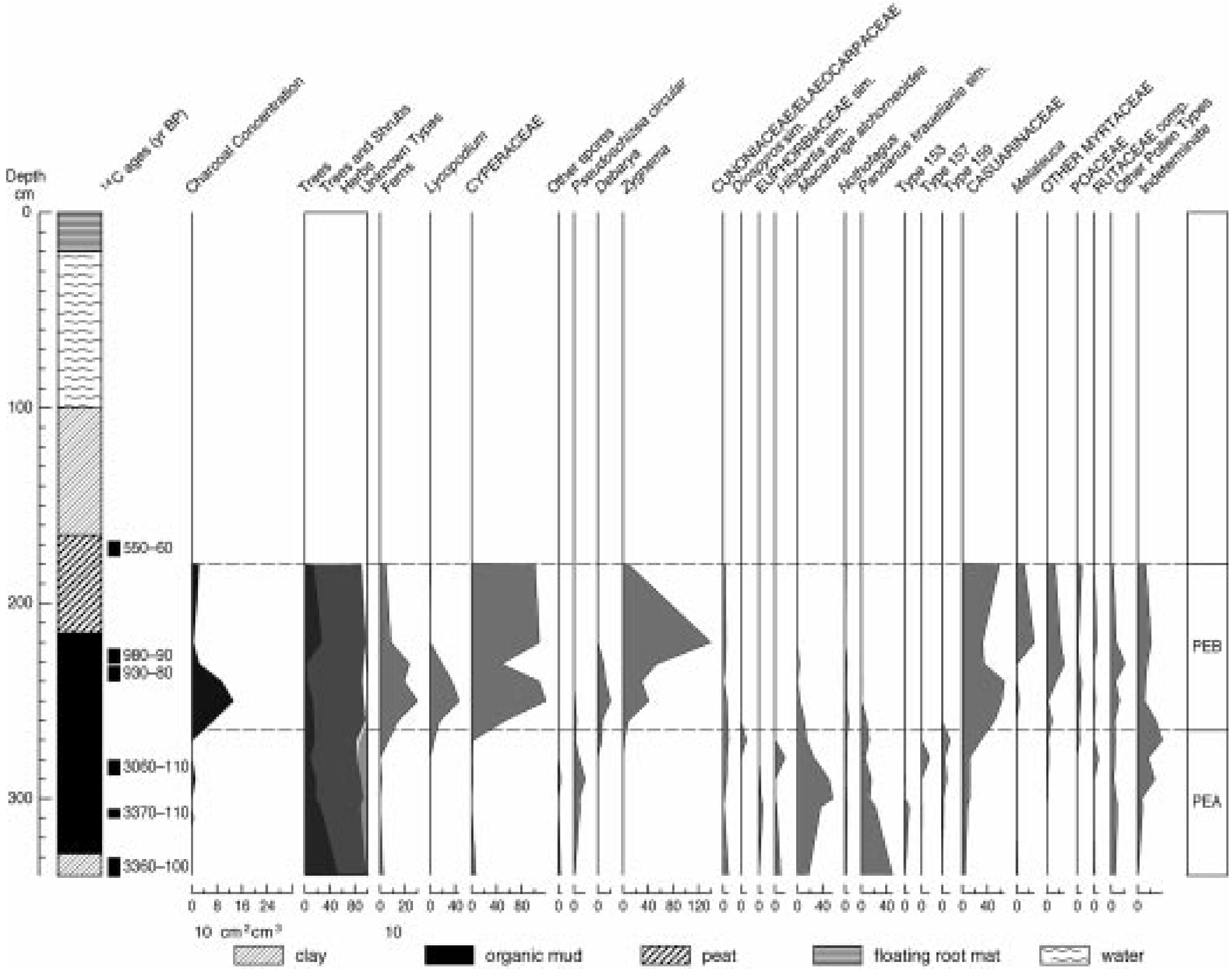

Fig. 8. Plum Edge pollen diagram. The summary diagram is based on the terrestrial pollen sum. Fern spores, Cyperaceae and Zygnemataceae are percentages of the terrestrial pollen sum. Selected taxa are shown as individual pollen curves. In general these are taxa that have a value of 5% in at least one sample. Dots indicate presence of taxon at a value of <1%. The diagram also includes loss-on-ignition, charcoal concentration and estimates of palynological richness.

just before zone PE-B (Fig. 8). This is in keeping with the changes in charcoal seen for this time period in Plum Centre. The broad changes in pollen composition seen across the PC-A and PC-B boundary in Plum Centre are also seen here. *Pandanus krauelianis* sim. and *Macaranga alchorneoides* pollen dominate zone PE-A and disappear in zone PE-B. Casuarinaceae, *Melaleuca* and other Myrtaceae pollen dominate zone PE-B. Poaceae pollen values in the Plum Edge core never approach the values found in the Plum Centre core, but nevertheless grass pollen is most abundant in zone PE-B. A significant number of pollen types are only found in zone PE-A, but the pollen counts are too low for palynological richness to be estimated.

Like Plum Centre, fern spores increase significantly with the first large peak of charcoal at the top of zone PE-A (Fig. 8). The highest values of damaged and crumpled grains also appear in this sample, suggestive of some reworking, although there is no suggestion in the stratigraphy of any dramatic change in sediment type. Zygospores of the Zygnemataceae follow the same pattern as the Plum Centre core, with *Pseudoschizea* most abundant in zone PE-A and *Debarya* and *Zygnema* most abundant in zone PE-B (Fig. 8). *Zygnema* dominates the uppermost samples.

4.8. PCA analysis

Fig. 9 shows the results of the PCA performed on the terrestrial pollen data, excluding ferns, from the Plum Centre core. Pollen taxa accounting for sample variance are displayed as a bi-plot. The first component (axis 1) explains 51% of the variance and is defined by high positive loadings for *Macaranga* and *Pandanus*, and high negative loadings for Casuarinaceae, Poaceae and *Melaleuca*, reflecting the difference between forested and non-forested conditions. The second component (axis 2), explains a further 10% of the variance and is defined by high positive loadings for *Macaranga* and high negative loadings for *Pandanus*, reflecting the significant changes in local forest composition. It is noteworthy that the three sub-zones of zone PC-A, defined by stratigraphic changes, plot out as three distinct groups.

5. Discussion

5.1. Environmental reconstruction

From around 20,000 yr BP until the arrival of people in the late Holocene, Plum Swamp was surrounded by littoral forest and lowland rainforest. Thereafter, human impact had a profound effect upon the vegetation within the Plum River valley, transforming it to a stunted and species poor open maquis on the ultramafic substrates and a *Melaleuca* woodland on the non-ultramafic soils. At 20,000 yr BP littoral forest around the site was dominated by *Pandanus*. Taxa that are more common at higher altitudes, such as *Apodytes clusiifolia* and *Nothofagus*, suggest the enrichment of the lowland forest with more montane taxa as reported from tropical lowland sites with late glacial records, such as Lake Hordorli, Irian Jaya (Hope and Tulip, 1994), Lake Tagimaucia, Fiji (Southern, 1986) or Lake Pata from lowland Amazonia (Colinvaux et al., 1996). The increase in *Macaranga alchorneoides* and the decrease in *Pandanus* around the site from 20,000 yr BP may reflect an expansion of lowland rainforest and the contraction of littoral forest in response to a drying of the valley bottom. XRD analysis suggests that at this time sediment was derived primarily from the badland terrain in the headwaters of the valley. That such a small area can dominate as the sediment source suggests geomorphic stability and low erosion rates under the lowland rainforest at that time.

A dramatic vegetation change in association with fire occurs after 14,000 yr BP, suggesting environmental instability during the glacial to interglacial transition. The vegetation change was to a disturbed lowland rainforest, which is recorded as an increase in diversity, but with the local loss of *Pandanus* and *Macaranga*. The site itself became more open and water depths may have become shallower enabling Cyperaceae to grow near the margins. In the absence of fire, forest re-established around the site with *Pandanus* and *Macaranga* once again locally dominant. While assigning ages to this period is difficult, a more stable environment was probably in place by around 9000 yr BP. There is no stratigraphic evidence suggesting that erosion from the surrounding slopes increased during this period.

The sediments change from organic mud to peat at

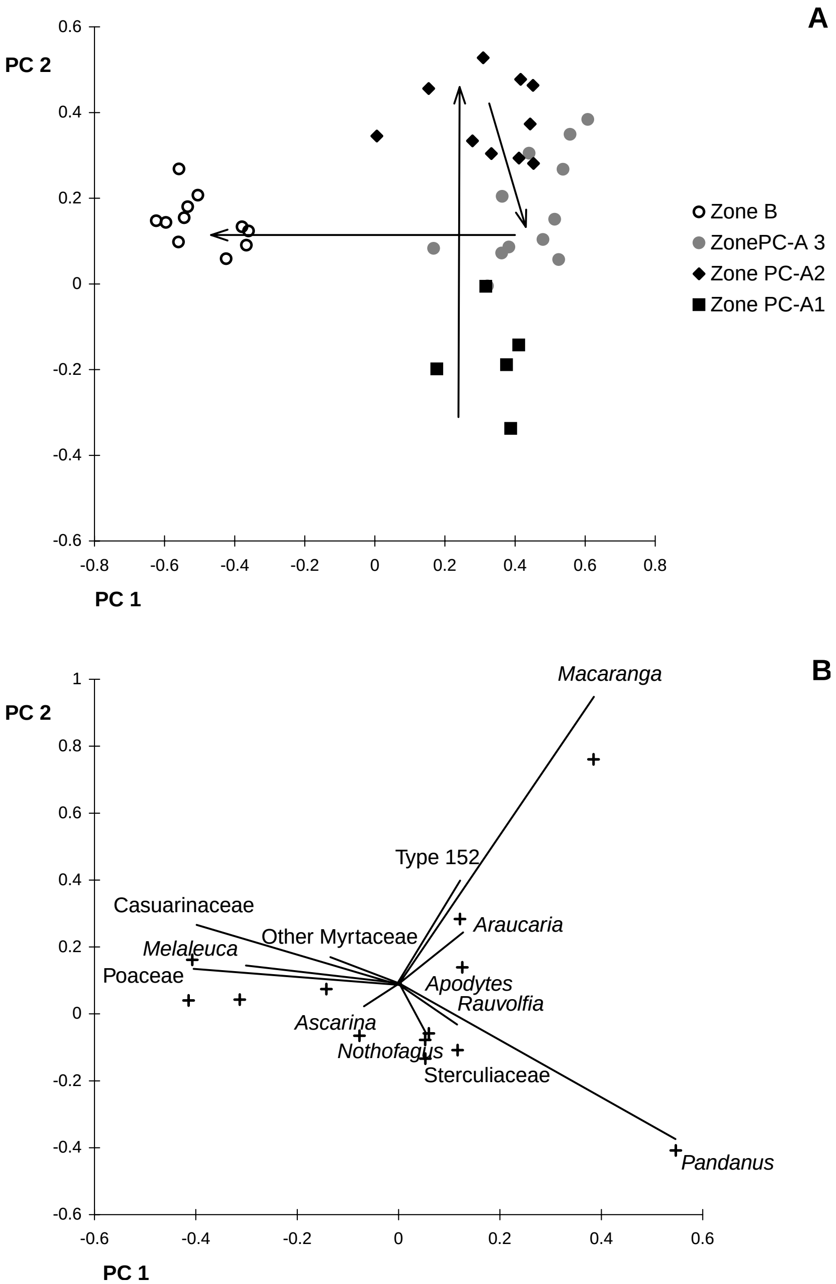

Fig. 9. Principal components analysis (PCA) bi-plots for pollen percentage data from Plum Centre. (A) Pollen samples are identified according to their respective zones and the midpoint of each zone is connected by an arrow in stratigraphic order. (B) Pollen taxa that determine the distribution of the samples.

around 6000 yr BP, revealing that accumulation processes at the site underwent a fundamental change. The peat at 470 cm depth in Core 11, beyond the current limits of the swamp, is indicative that the swamp area was once more extensive. From around 6000 to 4000 yr BP, percentages of *Araucaria* pollen increase significantly while Casuarinaceae pollen decreases. Conifers in New Caledonia are not found in regions where the mean annual rainfall is below 1300 mm and the Araucariaceae family form a stable component of many dense rainforests (Jaffré, 1995). In combination with the constantly increasing *Pandanus* values this may indicate that the forest was more closed and that the climate was wetter. The water environment at the site was suitable for the growth of filamentous green algae, suggesting that water conditions were shallow, rich in oxygen and stagnant or slow flowing.

The 25 cm band of sandy clay dated to around 4000 yr BP in the Plum Centre core is found in all swamp cores of this depth and the absence of well preserved pollen suggests that it was probably deposited quite rapidly. However, the clay band is not associated with a change in charcoal concentration. It is assumed that an extreme event, such as a cyclone, led to the deposition of this sandy clay across the floodplain and into the swamp. The goethite content suggests that the source of the material is the neighbouring slopes and not the badland in the headwaters and as such this may have been a local disturbance rather than catchment wide devastation. The vegetation composition of the valley following this event was largely unchanged, although relative percentages change. The decrease in *Araucaria* and *Macaranga* pollen and increase in Casuarinaceae pollen may reflect the colonisation of a local landslip by *Casuarina*. The increase in *Rauvolfia* is some indication that the area around the site, while permanently wet, was more open.

The boundary between zone A and zone B, based on the terrestrial pollen sum, is at around 2200 yr BP and is almost certainly the result of human activity. However, the impact of people on the landscape may have begun somewhat earlier, at around 2700 yr BP. This is suggested by three lines of evidence: the increase in charcoal concentration, an increase in fern spores and Cyperaceae pollen, and the sandy clay layer. After 2200 yr BP the landscape around the site changes from lowland rainforest locally dominated by *Pandanus* and *Macaranga* to an open landscape where *Casuarina*, ferns and grass dominate. The site itself opens up and Cyperaceae begins to grow on the swamp surface. The establishment of *Melaleuca*, presumably growing in its present day location on the less ultramafic soils, appears to have taken longer. Its dominance in the lower reaches of the valley after 1500 yr BP is probably related to a much altered fire regime promoting the expansion of this vegetation type. More frequent burning leads overall to a vegetation of less taxonomic diversity.

The vegetation of the site itself undergoes a significant change as a result of this impact. The expansion of Cyperaceae, the elimination of the swamp plant that produced the ornate spore, plus the replacement of *Psuedoschizea circular* by *Debarya* and eventually its replacement by *Zygnema*. However, without ecological information on the extant species of freshwater green algae from New Caledonia little can be said about the environmental implications of these changes.

5.2. Climate change and vegetation response in the tropical pacific

There are three factors at the LGM to which tropical lowland vegetation may have responded; cooler temperatures, lower CO_2 levels and in some regions changes to precipitation. There is a growing body of independent geochemical evidence from corals and ground water that suggests a significant cooling of tropical sea surface temperatures (SSTs) during the LGM (Guilderson et al., 1994; Stute et al., 1995; Beck et al., 1997; McCulloch et al., 1999). These studies place the cooling of tropical oceans to between 6 and 8°C, significantly cooler than the CLIMAP (1976, 1981) estimates of no change to 2°C cooler than present. However a recent re-evaluation of the CLIMAP data for the Australasia region confirms that there were minimal SST changes in the tropics at the LGM (www.rses.anu.edu.au/envgeo/AQUADATA/quataust.html). In addition to the proxy data, a simulation has been run using an atmospheric general circulation model with insolation and CO_2 levels appropriate for the LGM, plus the maintenance of near modern ocean heat transport (Webb et al., 1997). The model was able to produce 5–6°C cooling in tropical SSTs with reduced evaporation for the subtropics.

While the degree of cooling during the LGM in the tropics is still a debated issue, the greater representation of higher altitude rainforest taxa during this period in the fossil record at Plum suggests that temperatures were cooler. However, the degree of temperature depression relative to present is still uncertain. Lowland rainforests on the west coast of New Caledonia are, under present climatic conditions, maintained by precipitation and the exclusion of fire (Sarlin, 1954; Mueller-Dombois and Fosberg, 1998). In general they exist where the yearly precipitation averages are between 1500 and 3500 mm (Sarlin, 1954; Section d'Hydrologie, 1981; Mueller-Dumbois and Fosberg, 1998). The upper altitudinal limit of lowland rainforest is approximately 1000 m a.s.l, where the mean annual temperature is around 17°C. Given that the mean annual temperature at Plum is around 24°C, the greater abundance of pollen from species more prevalent at altitudes where the mean annual temperature is around 6°C cooler lends some weight to significantly reduced temperatures during the LGM in New Caledonia. In the Plaine des Lacs region east of Plum, two sites, Lake Suprin and Lake Emeric, were studied by Hope and Pask (1998). In many ways the stratigraphy of these sites are similar to Plum. They have a basal mineral sediment unit that is not seen in the overlying sediment units, with the younger sedimentary units alternating between organic and inorganic deposition. From the chronology obtained so far, the sediments appear to be much older than those at Plum and the records remain somewhat enigmatic as they are reported as not retaining Holocene sediments. However, from the present day distribution of *Nothofagus* in the Plaine des Lacs region and the prevalence of *Nothofagus* forest at around 30,000 yr BP in the Lake Suprin record, Hope and Pask (1998) suggest that temperatures may have been cooler by as little as 1°C to as much as 5°C. Narrower estimates of temperature change are not possible from either the Plum or Plaine des Lacs data sets.

Of greater consequence is that the survival of rainforest at Plum is dependent more on the availability of adequate moisture. Plum currently receives around 1300–1500 mm of precipitation per annum. Therefore the continued presence of littoral and lowland rainforest during the LGM at Plum suggests that water availability was not significantly different from present. In regions of New Caledonia where annual rainfall is around 1000 mm or less, sclerophyll forest and grassland are found in non-ultramafic terrain and ligno-herbaceous maquis (which is dominated by ferns) on the ultramafics. There is no indication of a shift to either vegetation type in the record. In the Plaine des Lacs region rainfall is much higher at around 3000 mm/yr. While there is no direct evidence for a drier environment in the pollen record, Hope and Pask (1998) interpret an increase in mineral sediment as slope instability resulting from drier conditions at around the LGM. LGM changes in humidity were interpreted as accounting for some of the vegetation change seen in the ocean cores taken from the Loyalty Basin, between Grande Terre and the Loyalty Islands (Méon and Pannetier, 1994). Latham (1986) also interpreted drier conditions leading up to the LGM from calcrete in a river terrace dated to 26,000 yr BP. Although there is no clear evidence in the Plum record for a response to reduced precipitation, cooler temperatures may have reduced evaporation, offsetting any precipitation reduction, as was found by the model of Webb et al. (1997).

The contribution of lower CO_2 concentrations at the LGM to vegetation change is still hard to evaluate in fossil pollen records. For Plum, some of the compositional change in the glacial record may be in response to lower CO_2, however there is little evidence for a shift to vegetation attempting to cope with CO_2 induced stress. This may be further evidence that the humidity at Plum remained high.

In general the most significant vegetation changes throughout the record have been in association with fire. Fires lit either intentionally or inadvertently in New Caledonia can burn rainforest up to 600 m altitude (sometimes higher), where average rainfall is greater than 3000 mm/yr (Mueller-Dumbois and Fosberg, 1998). The conditions required for the ignition of rainforest can be difficult to assess given the predominance of human activities in the current landscape. However, we know from anecdotal evidence that fires in rainforest usually occur during very dry times, such as extreme El Niño years, where there is on average a 22% decrease in mean monthly rainfall for the year (Morliere and Rebert, 1986). Charcoal particles are found throughout the Plum record as

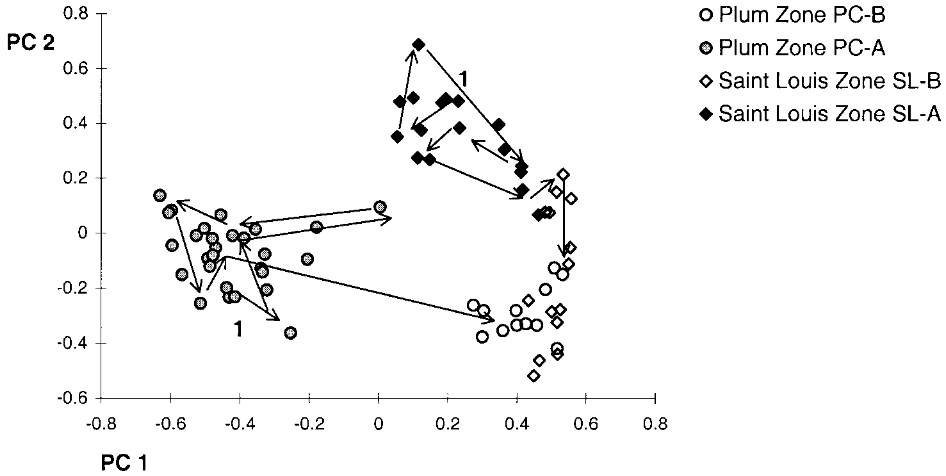

Fig. 10. Principal components analysis (PCA) bi-plot for Plum Swamp and Saint Louis Lake pollen percentage data. Solid symbols represent samples from the pre-colonisation period (Plum Zone PC-A; Saint Louis Zone SL-A) and hollow symbols represent the samples interpreted as recording human impact (Plum Zone PC-B; Saint Louis Zone SL-B). Arrows show the direction of vegetation change at each site. **1** denotes the basal sample at each site.

well as the two Pleistocene records from the Plaine des Lacs (Hope and Pask, 1998). These three records taken together suggest that fire has a long history in the New Caledonian environment and that it has played an important role in the disturbance ecology of the forests. Charcoal in the glacial record may stem from drier conditions leading to increased fuel loads, while charcoal in the late Holocene record may result solely from the actions of people, or may be a combination of both people and climate. As yet the record is not of the appropriate resolution for disentangling these two factors.

Whether the instability at Plum between 14,000 and 9000 yr BP reflects a response to wholesale precipitation depression or increased seasonality is unknown. However, it does bear some similarity to other tropical records from the southwest Pacific. It is during this period that some of the most rapid changes occur to vegetation in tropical Australasia. Conditions on the Atherton Tableland (Kershaw, 1995) appear to be more arid during this period, while on Taveuni, Fiji (Southern, 1986), conditions are interpreted as more seasonal. Tree lines in New Guinea rise rapidly between 13,000 and 10,000 yr BP (Hope, 1976; Walker and Flenley, 1979). Haberle (1998) reports a period of increased disturbance in montane New Guinea from 14,000 to 12,000 yr BP, which he suggests may be the result of periods of increased drought. The view for Australia and New Guinea generally, is that the increase in aridity during the late glacial arose from rapid temperature increase offsetting any precipitation increase (McGlone et al., 1996). It seems fair to assume, however, that the extremes of the last glacial were over by 9000 yr BP and that most tropical islands in this region had climates that approximated the present day. This is an important assumption for the detection of human impact in the record.

5.3. Human impact

Unlike other parts of the world, positive evidence of human presence in the landscape through the detection of pollen from domesticated plants is extremely difficult as agriculture is centred round the tubers of yam, taro and sweet potato. These plants rarely get to flowering stage and have poorly dispersed pollen grains. Therefore the interpretation of human impact is usually based on a sudden shift in the rate of vegetation change (usually in association with fire) which is coincident with human arrival and unparalleled in earlier parts of the record (Haberle, 1994; Walker and Singh, 1993). On some islands late Holocene sedimentation in coastal valley bottoms following colonisation is also viewed as anthropogenic. Some research has concluded that there was massive erosion from the hillslopes associated with initial agriculture practices (Kirch, 1983; Spriggs, 1986; Lepofsky, 1996). Nunn (1992) feels that the impact of settlement on Pacific island environments has been overstated.

The dramatic change to the landscape in the late Holocene at Plum is well within the time period covered by the archaeological record for New Caledonia. It is known that people were within the vicinity of the Plum River Valley from a coastal pottery find, even though dates associated with this particular style of pottery are usually from the period between 1800 and 1300 yr BP. The vegetation change after 2700 yr BP is more dramatic than that which occurred during the late glacial and is supported by other lines of evidence. This is further illustrated by a PCA of the Plum data set along with a nearby Holocene record that explores human impact from Saint Louis Lake (Stevenson and Dodson, 1995; Stevenson, 1999) on the northwestern side of Mont Dore (Fig. 10). The two sites had quite different vegetation communities surrounding them prior to human arrival, but converge to similar vegetation types dominated by *Melaleuca*, *Casuarina*, and grass after 3000 yr BP. Both became environments of less taxonomic diversity. It would seem that the coastal savanna which dominates the west coast of New Caledonia today was created by the initial colonisers and then greatly extended after European settlement.

The impact of New Caledonia's first inhabitants on geomorphic processes at Plum was not significant. No sediment unit in the swamp, apart from the mining spoil, is unique to the human period. In addition, the rates of accumulation up to European colonisation appear to change little, with the radiocarbon ages falling along a straight line. There is also a trend in the valley of increasing stability as the valley bottom became peat covered in the last few hundred years leading up to European arrival. While there is no evidence for catastrophic changes to erosion and sedimentation rates during the pre-European period, the channel profiles and swamp cores reflect major stratigraphic change in relation to mining activity on Mont Dore.

6. Conclusions

This study has revealed the potential that palynological studies have for examining environmental change in the southwest Pacific, including vegetation response to large-scale climate changes and the impact of people on tropical island landscapes. The tropical southwest Pacific is relatively untouched when it comes to long records of vegetation change, even more so when lowland records are considered. The study has utilised fossil pollen and microscopic charcoal, stratigraphical analysis and XRD analysis of lowland deposits dating from around 20,000 yr BP and has reached three major conclusions.

1. Lowland vegetation on the leeward coast of New Caledonia did not undergo significant change at the LGM. Although lowland forest during the LGM at Plum appears to be enriched with taxa more prevalent at higher altitudes, suggestive of cooler conditions, the vegetation does not record responses that can be linked to a significant precipitation depression.
2. Between 14,000 and 10,000 yr BP vegetation disturbance associated with fire is evident, suggesting a period of environmental instability. There are no significant vegetation changes during the early to mid Holocene however, and the Plum valley appears to have become moister and more stable.
3. Vegetation change following the arrival of people at around 3000 yr BP is profound and unprecedented in the earlier part of the record. Through sustained burning, a forested landscape is converted to an open landscape with a lowered taxonomic diversity in the late Holocene.

New Caledonia is a key location for further work into environmental change in the Pacific during the late Quaternary, particularly for understanding the response of lowland vegetation to LGM climate on islands of the tropical Pacific. Ongoing research will establish whether Plum is locally anomalous in New Caledonia or whether the retention of lowland rainforest during the last glacial maximum was indeed widespread. The study has contributed significantly to our understanding of the landscape changes brought about by people in New Caledonia and increases our confidence in such records being reliable indicators of human impact in Pacific islands where the archaeological record remains enigmatic.

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Appendix A

A list of all taxa identified in samples from Plum Swamp. Some genera have been lumped into their respective families for the pollen diagrams and for statistical analyses. Taxa with >1% in at least one sample are included in the statistical analyses and are marked by an *.

Gymnosperms

Agathis[Araucariaceae]*
Araucaria [Araucariaceae]*
Dacrydium[Podocarpaceae]*
Neocallitropsis[Podocarpaceae]*
Podocarpus[Podocarpaceae]*

Dicots

Acanthaceae
Alyxia sim. [Apocynaceae]
Amaranthaceae*
Antidesma sim. [Euphorbiaceae]
Apocynaceae *
Apodytes clussifolia [Icacinaceae]*
Araliaceae*
Argophyllum sim. [Grossulariaceae]
Ascarina[Chloranthaceae]*
Asteraceae*
Austrobuxus [Euphorbiaceae]
Barringtonia [Barringtoniaceae]*
Beauprea sim. [Proteaceae]
Casuarinaceae*
Celtis[Ulmaceae]*
Cerberiopsis [Apocynaceae]*
Citronella sim. [Icacinaceae]*
Codia[Cunoniaceae]*
Corynocarpus [Corynocarpaceae]
Cunoniaceae/Elaeocarpaceae*
Cupaniopsis sim. [Sapindaceae]
Desmodium sim. [Leguminosae]*
Dilleniaceae*
Dodonaea sim. [Sapindaceae]*
Epacridaceae
Escallionaceae
Euroshinus sim. [Anacardiaceae]
Ficus [Moraceae]*
Flacourtiaceae*
Garcinia [CLUSIACEAE]
*Geniostoma*sim. [Loganiaceae]*
Gesneriaceae
Glochidion [Euphorbiaceae]*
Goodeniaceae*
Grevillea sim. [Proteaceae]
Hedycarya sim. [Monimiaceae]*
Hibbertia sim. [Dilleniaceae]*
Homalanthus sim. [Euphorbiaceae]
Ilex[Aquilifoliaceae]
Kermadecia/Stenocarpus [Proteaceae]
Labiatae comp.
Longetia buxoides [Euphorbiaceae]*
Loranthaceae comp.
Macaranga alchorneoides [Euphorbiaceae]*
Malpighiaceae
Melaleuca [Myrtaceae]*
Melastoma [Melastomataceae]*
Meliaceae
Meryta [Sapindaceae]
Myrtaceae*
Nothofagus [Fagaceae]*
Phyllanthus [Euphorbiaceae]
Piperaceae comp.*
Pittosporum sim. [Pittosporaceae]

Planchonella [Sapotaceae]
Proteaceae*
Psidium guava [Myrtaceae]
Psychotria [Rubiaceae]*
Rauvolfia [Apocynaceae]*
Rubiaceae
Rutaceae comp.*
Sapindaceae*
Sapotaceae*
Sloanea *[Elaeocarpaceae]*
Smilax comp. [Smilacaeae]*
Solanaceae
Soulamea sim. [Simaroubaceae]
Spathodea sim. [Bignoniaceae]
Sterculiaceae*
*Tapeinosperma*sim. [Myrsinaceae]
*Trema*sim. [Ulmaceae]*
Urticaceae*
Verbenaceae

Monocots

Cyperaceae
Flagellaria [Flagellariaceae]*
Joinvillea[Flagellariaceae]
Palmae*
Freycinetia[Pandanaceae]
Pandanus krauelianis id. [Pandanaceae]*
Pandanus tectorius *[Pandanaceae]**
POACEAE*

Spores

Lycopodium[Lycopodiaceae]
Selaginella[Lycopodiaceae]
Psilate monolete fern spores
Polypodiaceae
Pteridium esculentum [Dennstaedtiaceae]
Cyathaceae
*Sphenomeris*sim. [Dennstaedtiaceae]
Trilete Type A
Psilate trilete fern spores

Unknown types

Type 19
Type 49
Type 63
Type 65*
Type 66*
Type 77
Type 84*
Type 89
Type 151*
Type 152*
Type 153*
Type 157*
Type 158*
Type 159*
Type 160*
Type 161*
Type 164*
Type 165*
Type 166*
Type 167*
Type 168*
Type 171*

Aquatics

Myriophyllum [Haloragaceae]
Nepenthes [Nepenthaceae]
Typha [Typhaceae]
Round ornate spore
Debarya [Zygnemataceae]
Zygnema [Zygnemataceae]
Pseudoschizea [Zygnemataceae]

References

Allen, J., Gosden, C. (Eds.), 1991 report of the Lapita homeland project. Occasional Papers in Prehistory No. 20, Department of Prehistory Australian National University, Canberra.

Allen, J., Gosden, C., Jones, R., White, J.P., 1988. Pleistocene dates for the human occupation of New Ireland, northern Melanesia. Nature 331, 707–709.

Beck, J.W., Récy, J., Taylor, F., Edwards, R.L., Cabioch, G., 1997. Abrupt changes in early Holocene tropcial sea surface temperature derived from coral records. Nature 385, 705.

Bennett, K.D., 1997. Documentation for PSIMPOLL 2.3 and PSCOMB 1.02: C programs for plotting pollen diagrams and analysing pollen data. Department of Plant Sciences, University of Cambridge, Cambridge.

Birks, H.J.B., Gordon, A.D., 1985. Numerical Methods in Quaternary Pollen Analysis. Academic Press, London (317 pp.).

Birks, H.J.B., Line, J.M., 1992. The use of rarefraction analysis for estimating palynological richness from Quaternary pollen-analytical data. The Holocene 2, 1–10.

Brooks, R.R., 1987. New Caledonia. In: Brooks, R.R. (Ed.), Serpentine and its Vegetation: A Multidisciplinary Approach. Croom Helm, London.

Cherrier, J.F., 1982. Les conditions d'existence de la foret dense humide en Nouvelle Caledonie: donnees ecologiques.C.T.F.T, Noumea.

Clark, R.L., 1982. Point count estimation of charcoal in pollen preparations and thin sections of sediment. Pollen Spores 24, 523–535.

CLIMAP Project Members, 1981. Seasonal reconstruction of the earth's surface at the last glacial maximum. Geological Society of America Map and Chart Series, MC-36.

CLIMAP Project Members, 1985. The surface of ice age earth. Science 191, 1131–1137.

Colinvaux, P.A., 1972. Climate and the Galapagos Islands. Nature 240, 17–20.

Colinvaux, P.A., Lui, K.-B., De Oliveira, P., Bush, M.B., Miller, M.C., Kannan, M.S., 1996. Temperature depression in the lowland tropics in Glacial times. Climate Change 32, 19–33.

Drever, J.I., 1988. The Geochemistry of Natural Waters. Prentice Hall, New Jersey.

Dodson, J.R., Intoh, M., 1999. Prehistory and palaeoecology of Yap, federated states of Micronesia. Quaternary International 59, 17–26.

Flenley, J.R., King, S.M., 1984. Late Quaternary pollen records from Easter Island. Nature 307, 47–50.

Flenley, J.R., King, S.M., Jackson, J., Chew, C., Teller, J.T., Prentice, M.E., 1991. The Late Quaternary vegetational and climatic history of Easter Island. Journal of Quaternary Science 6, 85–115.

van Geel, B., Grenfell, H.R., 1996. Spores of Zygnemataceae. In: Jansonius, J., McGregor, D.C. (Eds.), Palynology: Principles and Applications. American Association of Stratigraphic Palynologists, pp. 173–179.

Guilderson, T.P., Fairbanks, R.G., Rubenstone, J.L., 1994. Tropical temperature variations since 20,000 years ago: modulating interhemispheric climate change. Science 263, 663–665.

Haberle, S., 1998. Late Quaternary vegetation change in the Tari Basin, Papua New Guinea. Palaeogeography Palaeoclimatology Palaeoecology 137, 1–24.

Haberle, S.G., 1994. Anthropogenic indicators in pollen diagrams: problems and prospects for late Quaternary palynology in New Guinea. In: Hather, J.G. (Ed.), Tropical Archaeobotany: Applications and New Developments. Routledge, London, pp. 172–201.

Hope, G.S., 1976. The vegetational history of Mt. Wilhelm, Papua New Guinea. Journal of Ecology 64, 627–664.

Hope, G.S., O'Dea, D., Southern, W., 1999. Holocene vegetation histories in the Western Pacific — alternative records of human impact. In: Galipaud, J.-C., Spriggs, M., Lilley, I. (Eds.), The South Pacific, 5000 to 2000 BP: Colonisations and Transformations. ORSTOM, Noumea, New Caledonia.

Hope, G.S., Pask, J., 1998. Tropical vegetational change in the late Pleistocene of New Caledonia. Palaeogeography Palaeoclimatology Palaeoecology.

Hope, G.S., Tulip, J., 1994. A long vegetation history form lowland Irian Jaya, Indonesia. Palaeogeography Palaeoclimatology Palaeoecology 109, 385–398.

Hoshaw, R.W., McCourt, R.M., 1988. The Zygnemataceae (Chlorophyta): a twenty-year update of research. Phycologia 27, 511–548.

Jaffré, T., 1995. Distribution and ecology of the conifers of New Caledonia. In: Enright, N.J., Hill, R.S. (Eds.), Ecology of the Southern Conifers. Melbourne University Press, Melbourne, pp. 171–196.

Kershaw, A.P., 1995. Environmental change in Greater Australia. Antiquity 69, 656–675.

Kirch, P.V., 1983. Man's role in modifying tropical and subtropical Polynesian ecosystems. Archaeology in Oceania 18, 26–31.

Kirch, P.V., Ellison, J.C., 1994. Palaeoenvironmental evidence for human colonization of remote Oceanic islands. Antiquity 68, 310–321.

Kuhry, P., 1988. Palaeobotanical–Palaeoecological studies of tropical high Andean peatbog sections (Cordillera Oriental, Colombia). J. Cramer, Berlim Stuttgart.

Latham, M., 1986. Altération et pédogenèse sur roches ultrabasiques en Nouvelle-Calédonie: genèse et évolution des accumulations de fer et de silice en relation avec la formation du modelé. Éditions de l'ORSTOM; Études et Thèses, Paris.

Lepofsky, D., Kirch, P.V., Lertzman, K.P., 1996. Stratigraphic and Paleobotanical evidence for prehistoric human-induced environmental disturbance on Mo'orea, French Polynesia. Pacific Science 50, 253–273.

McCulloch, M.T., Tudhope, A.W., Esat, T.M., Mortimer, G.E., Chappell, J., Pillans, B., Chivas, A.R., Omura, A., 1999. Coral record of equatorial sea-surface temperatures during the penultimate deglaciation at Huon Peninsula. Science 283, 202–204.

McGlone, M.S., Hope, G., Chappell, J., Barrett, P., 1996. Past climate change in Oceania and Antarctica. In: Veroni, M. (Ed.), Greenhouse: Coping with Climate Change. CSIRO Publishing, Collingwood, Australia.

Méon, H., Pannetier, W., 1994. Palynological study of the late Quaternary of Loyalty Basin (SW Pacific). Palaeogeography Palaeoclimatology Palaeoecology 111, 135–147.

Moore, P.D., Webb, M.E., Collinson, M.E., 1991. Pollen Analysis. . 2nd ed.Blackwell Scientific Publications, Oxford.

Morliere, A., Rebert, J.P., 1986. Rainfall shortage and El Niño-Southern Oscillation in New Caledonia, Southwestern Pacific. Monthly Weather Review 114, 1131–1137.

Mueller-Dumbois, D., Fosberg, F.R., 1998. Vegetation of the Tropical Pacific Islands. Springer, New York.

Nunn, P.D., 1992. Keimami sa vakila na liga ni Kalou (Feeling the hand of God): Human and Nonhuman Imacts on Pacific Island Environments.East–West Center, Honolulu, Hawaii.

Parkes, A., 1997. Environmental change and the impact of Polynesian colonization: sedimentry record from Central Polynesia. In: Kirch, P., Hunt, T.L. (Eds.), Historical Ecology in the Pacific Islands. Yale University Press, New haven, pp. 166–199.

Read, J., Hope, G.S., 1996. Ecology of Nothofagus Forests of New Guinea and New Caledonia. In: Veblen, T.B., Hill, R.S., Read, J. (Eds.), The Ecology and Biogeography of Nothofagus Forest. Yale University, pp. 200–256.

Sand, C., 1996. Recent developments in the study of New Caledonia's prehistory. Archaeology in Oceania 31, 45–71.

Sarlin, P., 1954. Bois et Forêts de la Nouvelle–Calédonie.Centre Technique Forestier Tropical, Nogent-Sur-Marne, France.

Section d'Hydrologie de l'ORSTOM-Noumea, Service Territorial de la Météorologie-Noumea, 1981. Éléments Généraux du Climat. In: Atlas de Nouvelle Calédonie et depéndances. Éditions de l'ORSTOM, Paris.

Southern, W., 1986. The late Quaternary environmental history of Fiji. Unpublished PhD thesis, Australian National University.

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

Spriggs, M., 1986. Landscape, land use, and political transformation in southern Melanesia. In: Kirch, P.V. (Ed.), Island Socities: Archaeological Approaches to Evolution and Transformation. Cambridge University Press, Cambridge, pp. 6–19.

Spriggs, M., Anderson, A., 1993. Late colonization of East Polynesia. Antiquity 67, 200–217.

Stevenson, J., 1999. Human impact from the palaeoenvironmental record on New Caledonia. In: Galipaud, J.-C., Spriggs, M., Lilley, I. (Eds.), The South Pacific, 5000 to 2000 BP: Colonisations and Transformations. ORSTOM, Noumea, New Caledonia.

Stevenson, J., 1998. Late Quaternary Environmental Change and the Impact of Melanesian Colonisation in New Caledonia. Unpublished PhD thesis, University of New South Wales, Kensington.

Stevenson, J., Dodson, J.R., 1995. Palaeoenvironmental evidence for human settlement of New Caledonia. Archaeology in Oceania 30, 36–41.

Stute, M., Forster, M., Frischkorn, H., Serejo, A., Clark, J.F.S.P.B.W.S., Bonani, G., 1995. Cooling of tropical Brazil (5°C) during the last glacial maximum. Science 269, 379–383.

Villiers, J.-F., 1980. Icacinaceaes, Corynocarpaceaes, Olacaceaes. In: Aubréville, A., Leroy, J.-F. (Ed.), Flore de Nouvelle Calédonie et Dépendances. Muséum National D'Histoire Naturelle, Paris,

Walker, D., Flenley, J.R., 1979. Late Quaternary vegetational history of the Enga Province of upland New Guinea. Philosophical Transactions of the Royal Society, London; Series B 286, 265–344.

Walker, D., Singh, G., 1993. Earliest palynological records of human impact on the world's vegetation. In: Chambers, F.M. (Ed.), Climate Changes and Human Impact on the Landscape: Studies in Palaeoecology and Environmental Archaeology. Chapman and Hall, London, pp. 101–108.

Webb, R.S., Rind, D.H., Lehman, S.J., Healy, R.J., Sigman, D., 1997. Influence of ocean heat transport on the climate of the Last Glacial Maximum. Nature 385, 695–699.

Wickler, S., Spriggs, M., 1988. Pleistocene human occupation of the Solomon Islands, Melanesia. Antiquity 62, 703–706.