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Extended vegetation histories from ultramafic karst depressions

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Abstract. Solutional landforms (karst) can form on old surfaces on ultramafic rocks in the tropics because of the solubility of some magnesium-rich minerals under warmth and high CO_2. The radiocarbon dating of organic pond deposits in several tropical ultramafic karst hollows demonstrates that very slow sediment accumulation has occurred, relative to other tropical shallow lakes. Some sites have gaps in their records, whereas others appear continuous. Sections of organic lake muds from the Indonesian sites Wanda and Hordorli provide sequences of ages from modern back to >35 000 years ago at depths of 3–4 m. In New Caledonia, no Holocene record has been obtained, and dates of 17 000–30 000 years ago are found near the top of deep organic layers that, in some cases, are buried by inorganic muds derived from an erosion event. These ages, pollen analyses and the increasingly compressed organic sediments with depth mean that deeper levels should be well beyond radiocarbon dating limits. Only at one New Caledonian lake were deeper sediments beyond detectable ^{14}C measurement. Other sites returned finite dates at all levels tested, suggesting that some mechanism is moving small amounts of younger organics down profile. The slow sediment-accumulation rates provide an explanation why high concentrations of pollen relative to tropical peats and limnic sediments derived from high nutrition substrates are preserved in the sediments. This makes them attractive targets for studying the palaeoecology and forest stability of the surrounding vegetation. The sites are sensitive to disturbance because the poor nutrition impedes successional recovery after disturbances such as fire and landslips.

Additional keywords: climate change, palaeoecology, radiocarbon dating, tropical lake sediments, vegetation histories.

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Introduction

Ultramafic karst landforms in the tropical South-west Pacific

The movement of the Australian plate northward since the late Mesozoic has up-thrust deep-ocean rocks in many locations, from the Philippines and Indonesia eastward to New Caledonia. Ultramafics, including volcanic peridotite, lherzolite, harzburgite and dunite, and metamorphic serpentinite, are magnesium- and iron-rich rocks with virtually no free silica. They have been derived from the uplift of subocean crust, which has usually re-melted and intruded continental crust. Intrusions of basic igneous rocks such as gabbro and basalts are often associated with ultramafic regions. Magnesium silicate minerals such as olivine are prominent in ultramafic rocks and, in tropical climates in the presence of carbon dioxide, they are relatively soluble and weather rapidly. In moist tropical conditions, up to 98% of the original volume of dunites are lost (Loffler 1978), the remnants being enriched in iron, aluminium and sometimes rarer minerals of nickel, cobalt and chromium.

Ultramafic areas are often mountainous but their landforms are usually rounded and well weathered, with a relative lack of surface streams. Some areas in an ultramafic province may have internal drainage with solutional (karst) landforms such as blind valleys (polje) and isolated dolines (sink holes) on a similar scale to those in neighbouring limestone (Wirthmann 1970, 2000; Loffler 1978; Latham 1986). However, pseudo-karst processes may also be involved, because very deep weathering mantles can form in the tropics, sometimes containing layers of tough ferruginous crust. The ultramafic regolith, comprising up to 60% iron oxide, typically goethite, and clays can be eluviated from below such crusts, a process termed subcutaneous weathering by Loffler (1977). Substantial underground stream ways can form, followed by collapse and the formation of closed depressions that may contain shallow lakes or swamps.

The balance between solutional processes and the eluviation of fine particles in creating karstic landforms has not been studied. However, both Loffler and Latham considered solution to be very important in preserving relictual plateau surfaces from valley erosion. These plateaux are sometimes marked by karstic depressions and shallow lakes and these closed basins have been reported across the wet tropics, including Cuba (Pacheco *et al*. 2003), South-east Asia and the Pacific. They are not generally noted in temperate regions, although karst landforms are described from ultramafic rocks on Lesbos Island in the Mediterranean (Riedl and Papadopoulu-Vrynioti 2001).

Tropical karst infills

In the tropics, many lowland swamps and lakes record a rapid rate of production of organic debris. Sequences of peats or organic mud built-up in such sites rarely cover a long-time span. Walker and Chen (1987) reviewed tropical sedimentary records and it is clear that accumulation rates of 80–100 mm 100 year^{-1} are the norm. In areas with new volcanic soils, such as the Dieng Plateau, central Java, a rate of infill of small lakes of up to 80 mm per 100 years has been noted (Pudjoarinto and Cushing 2001), and some swamps have similar infill rates (Osborne *et al*. 1993). With rare exceptions, lower-altitude tropical sites have yielded detailed but chronologically limited vegetation histories, often hindered by an extreme dilution of pollen by other organic debris. By contrast, karst lakes developed in ultramafic rocks have very limited nutrients and possible toxic effects from nickel and other metals that inhibit plankton and algal growth. This creates the potential for very slow organic sedimentation, with the possibility of very long records before a site is infilled by organic debris. This might also result in a relatively high concentration of pollen arriving from the surrounding vegetation. However, only a few such basins seem to have been investigated and dated (Hope *et al*. 1988; Stevenson and Hope 2005).

Forest on nutrient-poor substrates may be sensitive to minor disturbance and may take a very long time to recover from changes that remove the nutrient capital. In this sense, ultramafic substrates act to amplify ecological disturbance. Because long records in the tropics are rather rare and often difficult to interpret because of the high local floristic diversity, a sensitive record can provide new insights into the ‘natural’ stability of closed forests and the influences of climatic change or low levels of human interference.

The present paper reports on the dating of organic sediments recovered from very similar shallow lakes in five ultramafic surfaces in the islands of Sulawesi, Maluku, New Guinea and New Caledonia (Fig. 1). These sites are providing important results in assessing environmental change, but accurate dating has been problematical in some cases.

Materials and methods

Shallow ponds or swamps were located from air photographs, maps or from local knowledge, many requiring lengthy journeys to reach. They were cored with a D Section auger either by standing in shallow water or from a boat or raft anchored by lengths of water pipe. Most of the radiocarbon dates were obtained from 5–15-cm sections of core. The sections consist of algal gyttya (nekron mud) with some horizontal banding, and often contain leaf and twig fragments. The sediments are mostly highly organic (>70%), with neutral pH of 6–7.5. Material for dating was taken from cores in the field and stored in plastic bags. In most cases, any coarse, fibrous material was wet sieved from the gyttya, and only the fines (<250 microns) were dated. There are also some wood dates based on single logs. All samples were pre-treated with an

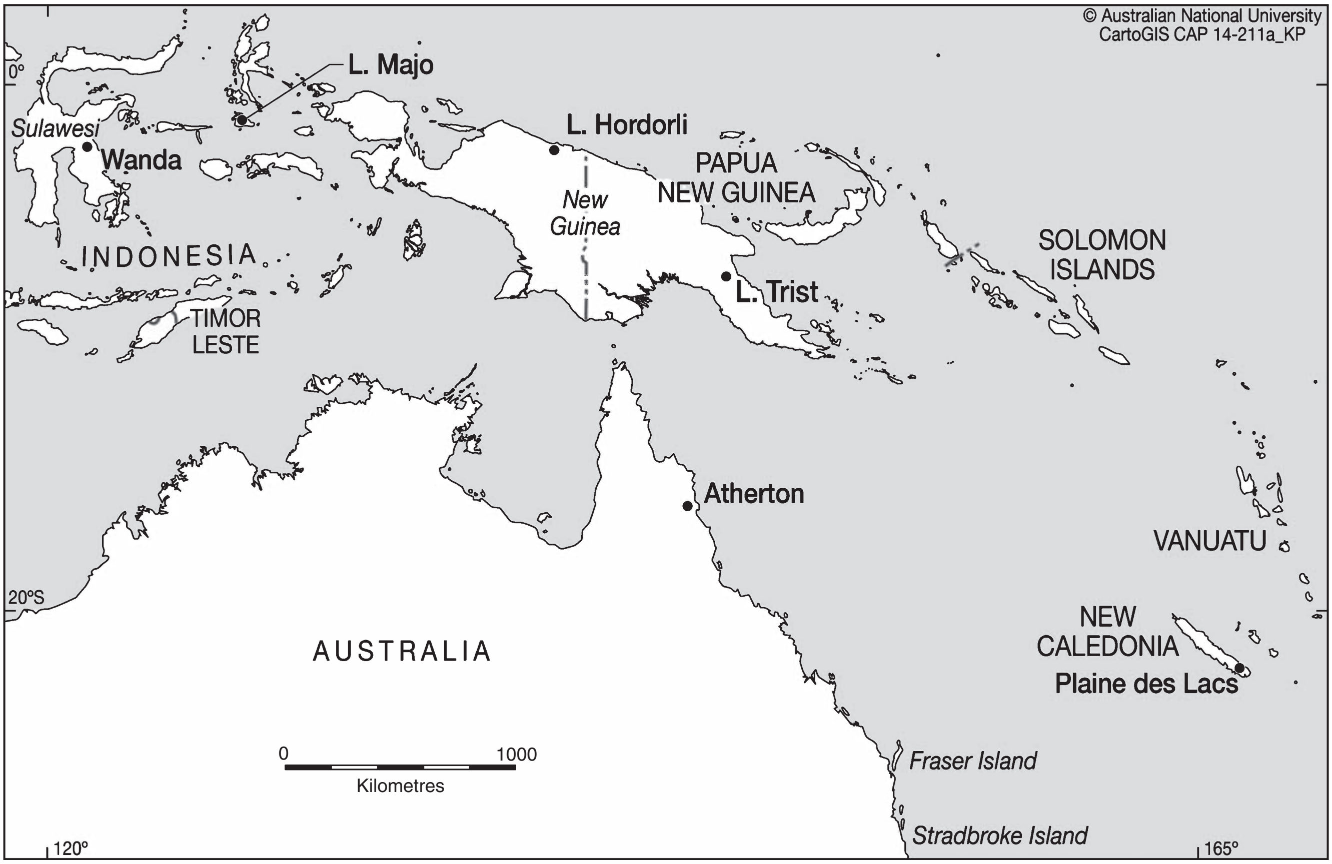

Fig. 1. Location of sites mentioned in the text.

acid–hot alkali–acid wash before rinsing with distilled water. Wood dates are based on cellulose, with lignin being removed by sodium hypochlorite (Gupta and Polach 1985). Most of the samples are conventional radiometric determinations, counted as benzene samples in a liquid scintillometer; however, some accelerator mass spectrometry (AMS) dates are also included, based on 1-cm sediment slices. The results (Appendix 1) are reported as calibrated ages (calibrated years before present, cal y B.P.) based on OxCal 4.2.3 (Bronk Ramsey and Lee 2013), utilising the SH13 calibration model.

Results – the coring sites

Site climates

The sites are described from west to east. All except one are lower-montane (altitude 170–800 m) and occur in high-rainfall areas with precipitation greater than 2500 mm year^{-1} and subdued seasonality. Mean annual temperatures vary from 20°C to 25°C, with low diurnal and seasonal variability, except for the New Caledonian sites which experience winter minima down to 10°C and tropical storms that are absent from the more equatorial sites. All are subject to inter-decadal dry phases associated with the ENSO phenomenon. Altitudes given here are derived from recent DEM data and may differ from those given in original publications.

Lake Wanda, South Sulawesi, Indonesia, 2°32.66′S, 121°23.27′E, 534-m altitude

In the north-east of the Indonesian province of South Sulawesi, several large and old lakes occur as a result of major faulting and tectonic depression in the late Cenozoic. They are largely surrounded by ultramafic rocks (Soeria Atmadja *et al*. 1974), although some Miocene limestones and other sediments outcrop in the catchment. Small areas rich in closed depressions are apparently distributed along minor fault lines. One such area near a nickel mine at Soroako has several closed depressions with shallow lakes or swamps (INCO 1972), and one of these was chosen for coring after testing of several others. Lake Wanda is a swamp ~4 ha in area and is usually covered by water ~50 cm deep, with no evidence that it dries out.

The region is mountainous and supports a dense rainforest with rather low stature on the deep regolith formed on ultramafic rocks. The forest canopy is ~20 m in height and formed by Myrtaceae (*Xanthostemon confertiflorum*, *Kjellbergiodendron*, *Eugenia* and *Tristania*) species, Lauraceae, including *Cinnamomum*, Anacardiaceae (*Gluta papuana*), Rubiaceae (*Timonius*, *Canthium* and *Gardenia*), Sapotaceae, Clusiaceae and Burseraceae. *Gymnostoma sumatrana* (Casuarinaceae), and Euphorbiaceae such as *Homalanthus*, occur on disturbed areas. (Balgooy and Tantra 1986). At Lake Wanda, the vegetation consists of sparse sedges, scattered pitcher plants (*Nepenthes*) and *Eriocaulon*, except for some isolated bushes of *Metrosideros petiolata* near the centre. Little human impact seemed to have taken place at the time of coring, other than small fish traps placed in the water (Hope 2001). The area has since been disrupted by mining and the dumping of overburden and flotation waste.

An 8-m core (SKW86) was collected and five dates were obtained from algal gyttya. The sediments are highly organic throughout and were sloppy in the top metre but became very firm and could not be recovered below 8 m. The results of dating indicated that there is a halt in sedimentation at ~345-cm depth, covering the period from 15 000 to 7000 years ago. A second core (SKW90) was taken ~15 m from the earlier core, closer to the margin. Results from SKW90 indicated that overlapping dates of 2700 years ago for the SKW86 samples at 332 and 350 cm may be too young, because the palynology of the SKW90 core, which is well controlled as 5000 to 4000 years ago, fits well with matching levels of the 1986 core. If so, then the upper 2000–3000 years of both cores is missing.

The presence of significant levels of *Castanopsis*–*Lithocarpus* pollen below 360 cm (Hope 2001) suggests that SKW86 is Pleistocene below the hiatus at 350 cm. The section from 492 to 617 cm has a net sediment accumulation rate of only 5.6 mm 100 year^{-1} (Fig. 2). The section below 550 cm has a notional infill about twice that rate; however, the very old dates are very imprecise. This raises the possibility that some contamination of deeper levels by younger carbon may be occurring. Extrapolation of the more reliable rate suggests a possible age of ~72 000 years at 8-m depth.

The pollen diagram from Lake Wanda showed that forest has been present around the site throughout, whereas a phase of increased grass and charcoal that occurred from ~35 000 to ~15 000 years ago possibly reflects a phase of more open vegetation. This may have been caused by drier conditions that slowed or stopped sedimentation at times; however, the dating is not sufficiently detailed to demonstrate this.

Located nearby on the same relict surface as Lake Wanda, Lake Towuti (320-m altitude) is a large deep lake that is fed by waters from a predominately ultramafic catchment and is ‘ultra-oligotrophic’ (Russell *et al*. 2014). Although this is a system very different from the shallow karstic basins, a 12-m core taken from the lake is thought to span 65 000 years (Russell *et al*. 2014). The mean sediment accumulation rate (based on 22 AMS dates) above 641 cm of 19.4 mm 100 year^{-1} is relatively constant (Fig. 2). This is a very slow rate, although it is more than twice the net sediment build up in the older levels at Wanda site. Isotopic studies on leaf waxes in the core suggested that a dry phase occurred from 33 000 to 16 000 years ago; however, this caused little change to the rate of sediment accumulation in the lake. As expected, the small karst basins are more responsive to environmental changes than is the large system.

Lake Majo, Obi Island, Maluku Province, Indonesia, 1°28.22′S, 127°29.64′E, 172-m altitude

The north-west of Obi Island, ~250 km north of the provincial capital, Ambon, is predominantly made up of ultramafic rocks. A closed depression contains several lakes, including the largest, Lake Buaya (Crocodile), which is ~5 km long and of unknown depth. At the eastern end of the same basin, there are at least three lakes ~200 m across, the eastern-most of which, Lake Majo, was chosen for coring.

The main vegetation on ultrabasic slopes facing the sea is a woodland of *Leptospermum flavescens*, with scattered *Casuarina equisetifolia.* Disturbed areas have a dense mat of *Gleichenia bolanica* and *Pteridium* ferns, with some *Melastoma* and pitcher plants (*Nepenthes*) tangled through. Small patches of

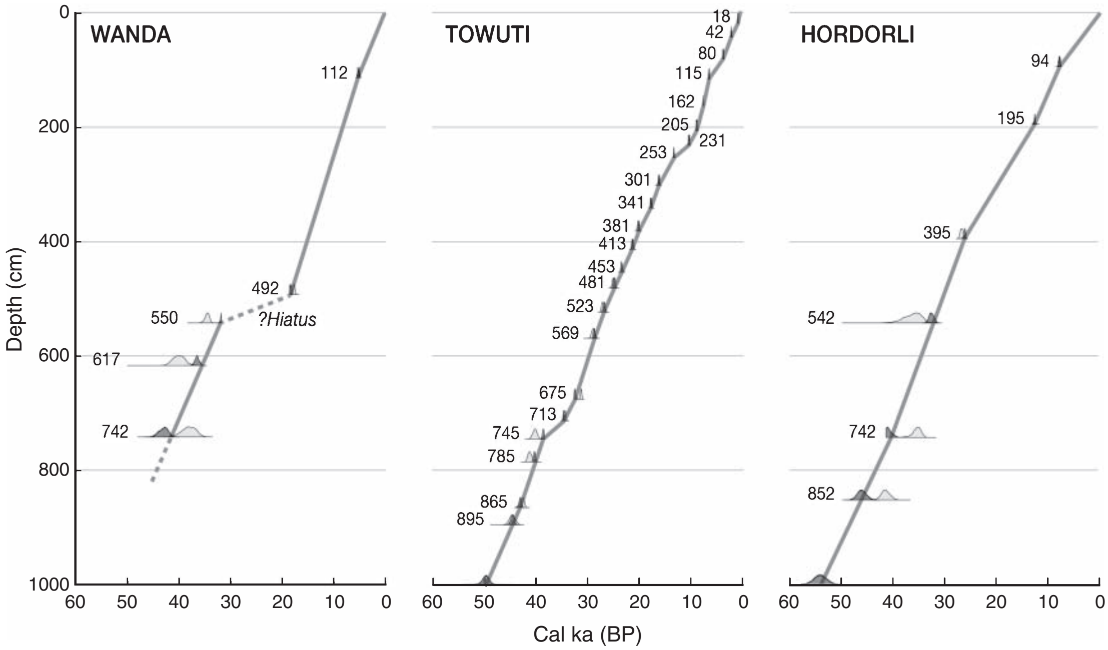

Fig. 2. Age–depth model for the Pleistocene section of Lake Wanda, Sulawesi, and for a 10-m core from Lake Hordorli, Papua Province. The age–depth model of Russell *et al*. (2014) from the upper 8 m of Lake Towuti is shown for comparison.

rainforest became more common on the ridges at 275-m altitude. The forest is short statured (20–25 m) but diverse, dominated by Myrtaceae (*Syzygium*, *Xanthostemon*), *Calophyllum*, *Elaeocarpus* spp, Lauraceae, Rubiaceae, Moraceae, *Podocarpus* and other lowland taxa and is relatively poor in aroids, palms and other climbers, although *Pandanus* sp. is common. On waterlogged areas, the forest is more simple and open with *Calophyllum* sp., two species of palms, an orbicular-leafed *Syzygium*, Sapindaceae, a *Castanopsis* sp. and a remarkable stilt-rooted casuarina, possibly *C. sumatranum*. The floor of the forest resembles a mangrove area, with a tangle of hoop roots that emanate from the *Syzygium.* The casuarina, shrub *Pandanus* sp., and an araliad (possibly *Polyscias* sp.), a large terrestrial orchid and sedges form an open shrubland close to the edge of water bodies, grading into a sedgeland of *Machaerina* and *Rynchospora* with tufts of a grass (probably *Leersia hexandra*), *Eriocaulon* sp. and *Utricularia* sp. living in pools. Water marks show that this vegetation is often inundated up to a depth of ~80 cm.

A core was taken down to 650 cm on the south-eastern margin of the lake, to the limit of the available rods. The top metre could not be sampled because of the watery nature of the sediment, although hand samples of the reed mat were taken. The core consisted of 110 cm of fibrous sedge peat over gyttya down to 380 cm, overlying peaty clays to the base. An age model based on three dates indicated rapid sedimentation that averages 105.7 mm 100 year^{-1}, although this includes a substantial influx of clay (Fig. 3).

The rate of accumulation of Lake Majo is matched by that in the mid-Holocene section from Lake Wanda (111.4 mm 100 year^{-1}) and is typical of high-nutrient tropical peatlands (Dommain *et al*. 2014). The possible cause of rapid accumulation phases is unknown, but may reflect nutrient inputs from non-ultramafic sources such as fire-induced erosion. Charcoal occurred in both cores, indicating catchment burning. Pollen found in the Lake Majo core contains a substantial proportion of grass throughout and a rising input from *Casuarina*, raising the possibility that a hydric succession incorporating a nitrogen fixer allowed high productivity.

Lake Hordorli, Papua, Indonesia, 2°32.48′S, 140°35.3′E, 798-m altitude

The Cyclops Mountains of north-eastern Papua are largely ultramafic and reach a height of 2160 m (Baker 1955). Lake Hordorli is a swampy basin ~400 m in diameter, with an area of 8 ha, set into a bench at 800-m altitude on the southern slopes of the range, although there are scattered ponds in the area at higher elevations. The site lies above the daily cloud-lie altitude and experiences mists and fog drip in addition to high rainfall. The lower montane forest has a dense canopy that is overtopped by scattered *Araucaria cunninghamii* (van Royen 1965). It is a very mixed forest that includes other gymnosperms such as *Papuacedrus papuana*, *Phyllocladus hypophyllus* and *Podocarpus* spp. Microphyll-leafed angiosperm taxa dominate, such as *Cryptocarya*, *Litsea*, *Dysoxylum*, *Galbulimima belgraveana*, *Garcinia graminea*, *Planchonella cyclopensis*, *Timonius*, *Ardisia* and *Stenocarpus moorei.* Dipterocarps such as *Hopea* sp. and the oaks, for example, *Lithocarpus molluccana*, occur occasionally, together with a wide array of Moraceae and Myrtaceae. The surface vegetation on the lake consists of an open sedgeland ~40 cm in height, which is often flooded for short periods (Fig. 4).

Cored down to 10 m, the sediment throughout is a uniform brown algal mud that becomes increasingly stiff with depth (Hope and Tulip 1994). Leaves and fragments of wood occur throughout, usually bedded, although obvious laminations are

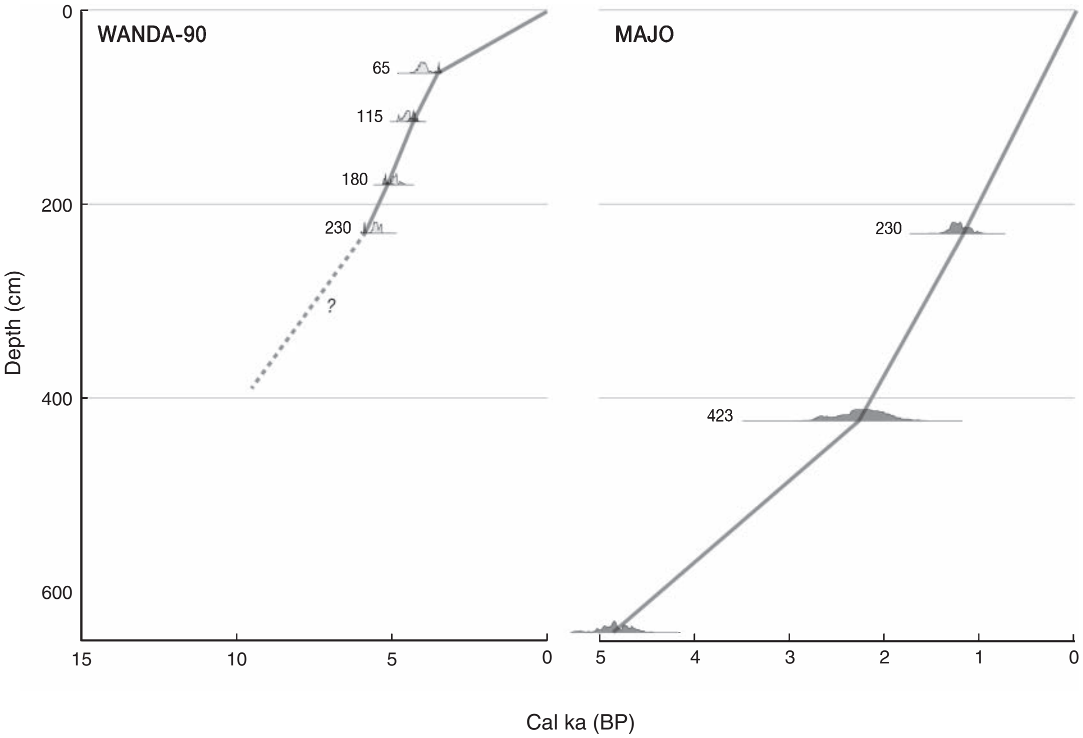

Fig. 3. Age–depth model for the Holocene section of Lake Wanda, Sulawesi, and for the 6.5-m core from Lake Majo, Maluku Province, Indonesia.

Fig. 4. Infilled karst hollow (termed telaga mati or dead lake), Lake Hordorli, Cyclops Mountains, Papua Province, Indonesia.

absent. The upper four dates (Fig. 2) indicate an average sedimentation rate of 14.4 ± 1.5 mm 100 year^{-1}, although there is an apparent slowing towards the surface. The levels below 600 cm are probably beyond dating limit; however, because levels at 742.5, 852 and 920 cm returned finite ages, it seems that some contamination by a younger organic component is occurring. An extrapolation of the sedimentation rate indicates an age of ~68 000 years for the base of the core at 1000 cm, if the age of ~37 000 years at 542.5 cm is accepted.

Analysis of magnetic properties and nutrients (Hope *et al.* 1988) showed very little change down the core, suggesting a stable environment. Pollen analyses (Hope and Tulip 1994) showed that the lake has never dried out, although at times the water depth has apparently been greater than it is at present. Changes in the pollen spectra seem tuned to a glacial or sea-level signal, with a transition from *Nothofagus* forest to the present mixed lower montane forest occurring at 12 000 years ago. The site is unusual in recording no fires over the 50 000-year period before this transition. Forest has surrounded the site continuously, although an increase of carbonised particles and the pollen of disturbance trees in samples from the top metre may reflect some human interference in the catchment.

Lake Trist plateau doline, Morobe Province, Papua New Guinea, 7°29.25′S, 146°59.52′E, 2054-m altitude

Loffler (1977, p. 133, 1978) reported closed depressions and dolines on a high plateau of dunite east of Lake Trist, a tectonic lake in the Bowutu Mountains ~80 km south of Lae, Papua New Guinea. The plateau is completely covered by upper montane rainforest that includes *Nothofagus* and *Podocarpus*. An active doline, 2.7 km east of the lake, is ~3.2 ha in extent and is occupied by grasses and sedges. The site is sometimes dry but subject to frequent flooding, with the water draining down tunnels close to the western margin. Gullying has exposed two metres of bedded silts and clays interlayered with organic material, especially wood, on the floor of the doline. Four well preserved logs between 67 and 185 cm down section were cleaned and treated with hot 10% HCl and hot dilute NaOH solutions before combustion and benzene counting (Loffler 1978).

Three of the four dates are much older than expected, ranging from 35 700 years to 40 800 years old. One wood sample at 140 cm was only 10 000 years old and can be disregarded in the overall interpretation of the site. The other three ^{14}C ages are not significantly different from each other, given the large errors associated with them. Loffler (1978) suggested that the logs are evidence of former forest growing on the floor of the doline, which would reflect more efficient subsurface drainage at that time. It is possible that most of the deposit is old and that little sediment has been preserved over most of the history of the site. Pollen analyses of the sediment showed that the surrounding forest was dominated by *Nothofagus*, indicating high rainfall. This record does not help calculate sedimentation rates, but demonstrates the great antiquity of materials held in these systems.

Plaine des Lacs, New Caledonia, 22°17′S, 166°59′E, 210–280-m altitude

New Caledonia has a series of dissected plateaux formed from ultramafic rocks, and Latham (1986, p. 191) described dolines containing organic-rich sediments in the north-west. In this seasonal climate, extensive ironstone laterites have formed within a very deep regolith of ferrolitic soils. After erosion, the ironstones form a tough surface called cuirasse. In the south-east of the island, the plateau of the Plaine des Lacs features hundreds of small shallow lakes that occupy steep-sided dolines (Fig. 5). There are also dry dolines and extensive blind valleys draining through sinkholes. The lakes vary from ephemeral to permanent. Some larger lakes to the west of the Plateau (Lac en Huit, Grand Lac) appear to be recently formed by Holocene fan building. A few kilometres to the east, a deep doline called La Trou can rapidly fill to a depth of 15 m and then empty in a few days, leaving no deposits (Bernard Suprin, pers. comm.). Some of the lakes such as Lac Emeric dry

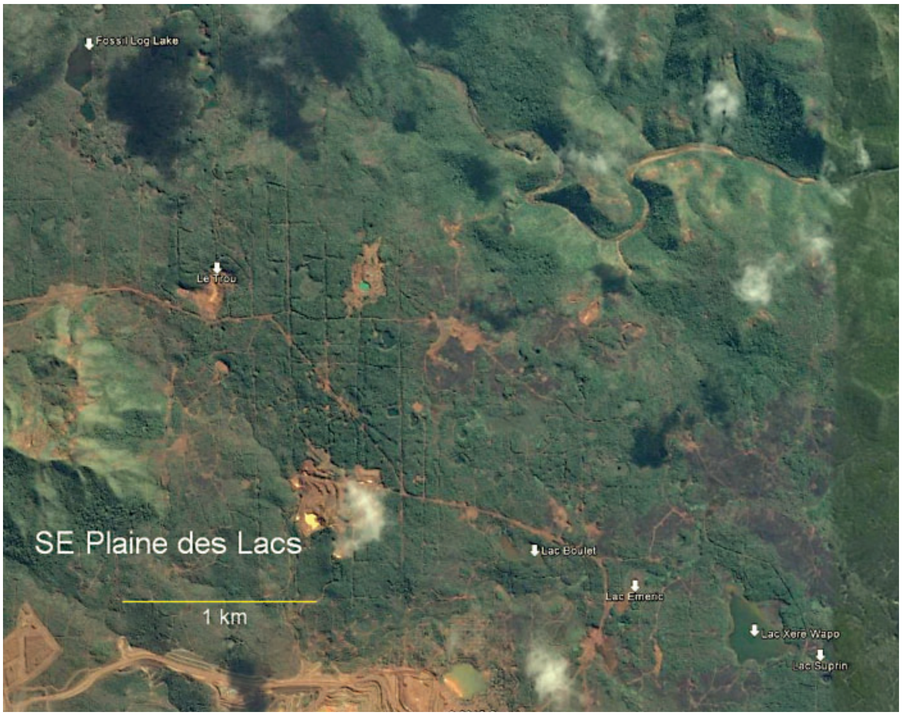

Fig. 5. The south-eastern section of the Plaine des Lacs, Grande Terre, New Caledonia.

completely after a few weeks with little rain, whereas other basins such as Lac Xere Wapo dry only during exceptional droughts.

Five lakes have been shown to have infills of dateable organic sediments, including buried wood. These lakes lie within 5 km of each other, in similar internally drained depressions. Their margins are vegetated by sparse sedges in water depths of 0.5–1.5 m. In two cases, 2–3 m of orange silty iron oxide has washed into the basin, whereas another two lakes have a topmost horizon of logs, including tree stumps in position of growth, above algal gyttya (Hope and Pask 1998).

Fossil Log Lake, 22°15.456′S, 166°57.151′E, 295-m altitude

This small elongate lake of ~5 ha lies ~3.5 km east of Grand Lac, and is up to 5 m deep, with both muddy and rocky shorelines. Surrounding the lake is a low forest of bushy maquis (Jaffre *et al*. 2004; McCoy *et al*. 1999), with *Dacrydium araucarioides* and *Gymnostoma deplancheanum* present in a scrub of *Tristaniopsis* and other Myrtaceae. *Gymnostoma* maquis is a secondary formation resulting from fire. Bernard Suprin recovered a log, four metres in length and 30 cm in diameter, which was sticking up from near-surface organic-rich sediments exposed by extreme low water levels. The log was identified as *Neocallitropsis pancheri*, a rare and fire-sensitive gymnosperm that is absent from the area today (Suprin and Hope 2001).

The log was sectioned ~20 cm above its base to give a slab 25 cm across and 3 cm in thickness. The inner and outer 25 rings were dated separately and the tree rings from three sections gave an average count of 255 ± 8 rings. It is possible that the rings are annual because the mean radiocarbon ages of the inner and outer groups of rings differ by 515 ± 220 years. The tree died at 13 520 ± 235 calibrated years before present. The rate of sedimentation cannot be calculated and the deposit is probably relictual; however, the fresh nature of the wood, which retained its characteristic aromatic oils, demonstrates excellent preservation.

Lake Emeric, 22°17.038′S, 166°58.900′E, 228-m altitude

This depression is often dry and covers ~2 ha. Coring revealed 5 m of sediments consisting of 288 cm of orange limonite silts overlying black gyttya containing two thin layers of white silt-clay. The lower sediments contain abundant wood, including stumps, apparently in position of growth. Organic-rich horizons from within the upper orange silts gave an inverted pair of dates, suggesting that older organic materials may have been reworked into the silts during major catchment erosion. A modern date (Emeric A 263) on wood is obviously intrusive, indicating the incorporation of bomb-produced radiocarbon. Given anomalous dates in the upper 270 cm, no credence can be placed on ages in this section.

Immediately below the orange limonites, a gyttya date of 30 000 years (Emeric A 292) is taken as the maximum time of commencement of the phase of slope erosion and as a minimum date for the cessation of organic accumulation at this site (Fig. 6). The lower dates in both cores are all finite and again indicate that some younger organic component may be moving down profile. If the sedimentation rate of 6.4 mm 100 year^{-1} between Emeric A 292 and A 366 is extrapolated, the inferred ages of Emeric A 420 and A448 become 45 500 years and 50 000 years, respectively. Emeric A292 comprises well stratified laminated gyttya that had been sealed in by a thin band of kaolinitic clay that extended across the whole lake basin and, hence, is unlikely to have been disturbed. However, given similar dates at greater depths, there is a possibility that all the dates in this section have been affected by younger contamination and that all understate the

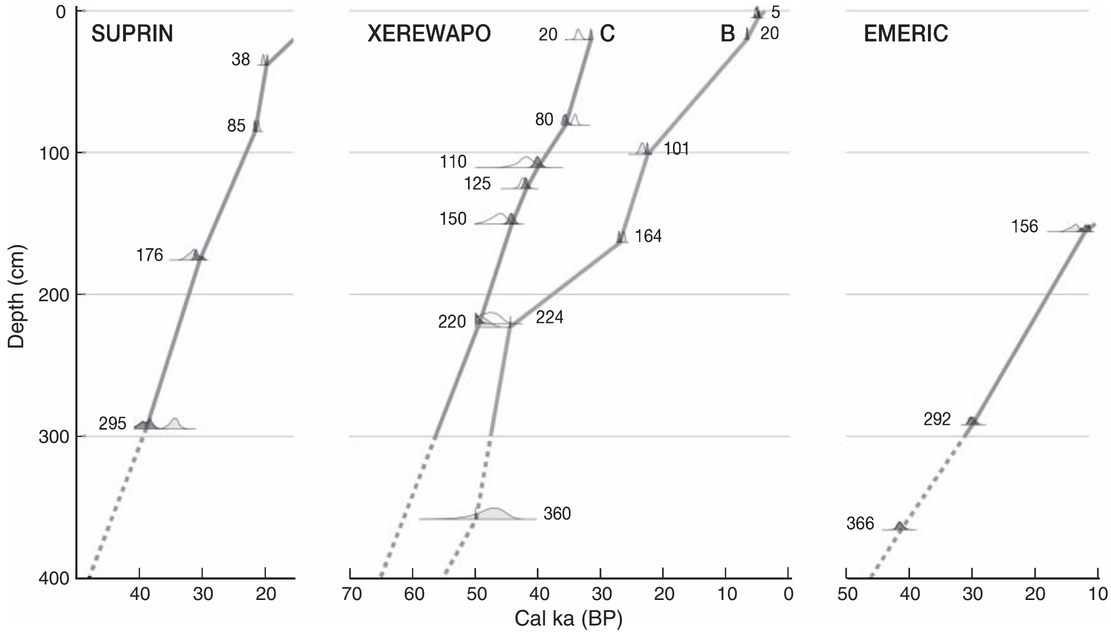

Fig. 6. Age–depth models for Plaine des Lacs sites Lake Emeric (Core A), Lake Xere Wapo (Cores B and C) and Lake Suprin.

true age of the sediment. The dated wood (Emeric A448) comes from a very woody layer that may indicate shallow conditions and a swamp forest on site.

Lake Suprin, 22°17.247′S, 166°59.504′E, 238-m altitude

Three kilometres east of Lake Emeric with slightly greater water depths, the central basin of this 1-ha doline drains northward through cracks in the cuirasse. There are numerous stumps near the surface set in 50 cm of organic muds. At least some of these trees were *Retrophyllum minor*, a podocarp that can grow in water because it has air-conducting roots similar to those found on swamp cypress (*Taxodium distichum*) and some mangroves. Below this is 250 cm of brown ferrilitic clays, overlying more than 200 cm of black organic gyttya and silt horizons. The dates come from the base of the uppermost organics, two distinct organic bands in the inorganic layer and from the top of the organic fill in the lake. The dates of 20 000–21 000 years ago from the top 100 cm imply that the surface sediments are Pleistocene and that any more recent sediment has been lost down to the level of the interlocking trees. Such scouring may be the result of cyclonic rain washing out the shallowest sediments periodically. Given the problem of mixing found at Lake Emeric, a date of 31 000 years ago from 176 cm must be regarded as possibly incorporating older organics. However, the considerable thickness of organics near the surface makes significant contamination unlikely. The date of 34 600 years ago (Suprin 295) is a maximum age for the onset of erosion, but has no confirmation from deeper horizons.

Lake Xere Wapo, 22°17.191′S, 166°59.280′E, 233-m altitude

This is the largest lake (~80 ha) in the area and it drains eastward through a sink in the surrounding cuirasse. Around the margin, there is a layer of wood, including stumps, near the surface. The sediment around the stumps is very soft gyttya. A date (Xere Wapo A 119) on wood in limonitic clays 10 m from the margin suggests that the surface sediments on the edge of the lakes are very old, perhaps 25 000 years old. In the centre of the lake (~1.5-m water depth), Xere Wapo B consists of 1240 cm of organic sediments, with only minor horizons of silt and clay (Stevenson and Hope 2005), whereas Xere Wapo C is a 250-cm core taken from the same general area, to check the dating using AMS on specific fractions (Stevenson *et al*. 2010). Dating of surface oozes (XWB-5, XWC-10, 20) indicates that older sediment may be being mixed into modern materials. In XWC, there is an inversion ~85–87 cm and potentially both young and old sediment may have been mixed and incorporated, possibly as a result of the development of a *Retrophyllum*–Myrtaceae swamp forest at this level. Dates below this level are Pleistocene but differ between the cores, although both have a date of ~47 000–49 000 years ago at 220 cm that indicates that deeper levels are beyond the limit for radiocarbon dating. The dating is too variable to derive likely sedimentation rates, but rates seem to be slow and subject to disturbance and possible gaps in the record.

Pollen and charcoal analysis showed fluctuations in fire, with a significant change towards more disturbance, which may suggest the onset of drier fire-prone climates ~40 000 years ago (340 cm) (Stevenson and Hope 2005). The absence of wood and a clear pollen zonation suggest that mixing is less likely in the deeper sediments.

Lake Boulet, 22°16.973′S, 166°58.587′E, 222-m altitude

This small, sheltered lake has a recently burnt forest of *Retrophyllum minor* above 3 m of soupy organic ooze and stiffer algal sediments to more than 650 cm. Only one date of 33 400 years ago, from gyttya at 590-cm depth, has so far been obtained from Lake Boulet, so it is impossible to estimate the age of the surface there, although a similar age to the erosional surfaces of Emeric and Suprin is feasible. These single dates cannot be assessed for potential contamination, and may in fact be older.

Pollen diagrams (Hope and Pask 1998; Stevenson and Hope 2005) from Emeric, Suprin and Xere Wapo show that large fluctuations in cover by *Nothofagus* and *Gymnostoma* occur throughout the history of each of the sites. Charcoal is evident at all levels, but varies in importance, although fire may have been instrumental in exposing soils with consequent increased silt loads in the lakes. These sites, thus, may also have some derived organic materials from soils that have been almost completely eroded from the area. At times, the floors of the lakes have supported swamp forest of *Retrophyllum*, which marks phases of relatively low water levels for extended periods.

These New Caledonian sites seem not to be able to accumulate organic matter at present and show much greater dynamism than do more equatorial sites. This must reflect a greater tendency to dry out and to be affected by fire and other disturbances, such as tropical storms. They also appear to have supported swamp forest in the past.

Discussion

Chronology of ultramafic karst deposits

Organic material, including leaves, fruits and wood, is well preserved in these sites. However, the transport of young carbon through the system seems to be occurring, owing to the internal drainage of these sites, also described by Head *et al*. (1989) in loessic palaeosol sections. Longmore (1997) discovered a similar phenomenon in partially permeable quartz sands in closed dune lakes on Fraser Island, Queensland. In this case, the organic component is quite acid and is strongly complexed with aluminium and iron. Similar organo-metal compounds may also provide the mechanism for complexation in the ultramafic sites. By contrast, several groundwater swamps in leached silica from the Cooloola–Stradbroke Island area have compressed age depth profiles, and have little sign of contamination down core (Moss *et al.* 2013).

Of the sites studied so far, Lake Hordorli has the most reliable dates from upper levels, allowing an estimate of organic contamination to be made. Gupta and Polach (1985, p. 131) showed that <1% of modern contamination would account for real ages of >55 000 years being counted in the range 32 000–35 000 before present. Higher levels of contamination, perhaps 2–4%, would be needed if organic compounds from all levels contributed to the material being translocated downward. If such contamination occurred generally in ultramafic karst, then any dates >28 000 years would need to be regarded as potentially beyond limit.

The inferred contamination of deeper horizons by young carbon appears to affect wood as well as bulk organic gyttya. Latham (1986, p. 163) analysed soil organic matter from a seasonally dry site in northern New Caledonia and found that it contained 15% fulvic acids and 10% humic acids at the end of the summer wet season. By the end of the dry season, the fulvics had dropped down to 11.4% and the humic acids had risen up to 13%, indicating a rapid rate of alteration, especially with some drying out of the profile. Both these acids can be mobile in soil, and can be immobilised by metal-complexing mechanisms. Pre-treatment of wood from Lake Xere Wapo to obtain the cellulose fraction did not resolve the dating problems there (Stevenson *et al*. 2010). In addition to translocation downward, inputs of eroded organic soils, mixing of older organics and disruption by roots have to be considered. However, the anoxic muds are not likely to have been bio-turbated.

AMS dating of individual wood or leaf samples on the basis of fractions produced from serial heating may solve the problem of the source of contamination, as shown by Turney *et al*. (2001) at Lynches Crater, Atherton, northern Queensland. An alternative dating method would be desirable, and these tropical sites could provide useful test opportunities for amino acid racemisation assays and possibly uranium-series dating, as reported by Longmore (1997). However, the open nature here postulated for the ultramafic karst systems, and their very low environmental radioactivity, may present problems. The quartz-free sediments prevent the application of optically stimulated luminescence (OSL) dating, although careful examination for aeolian dust and tephra fractions might prove them to be datable markers in some sites.

Ultramafic karst deposits as a palaeoecological resource

Small basins that reflect the immediate surroundings have been shown to be of most relevance in understanding the ecological dynamics of source vegetation (Higuera 2005). In spite of the possible problems in dating old sediments outlined above, pollen analyses have provided high-quality records of vegetation change that illuminate the stability of vegetation on ultramafic soils. Results have shown that vegetation in Sulawesi responded to drier conditions during Marine isotope stage 2 (MIS 2) (~30 000 to 10 000 years ago), but do show similarities between the Holocene and MIS 3 (55 000 to 32 000 years ago) floristic make up. At Lake Hordorli, MIS 2 was well marked by increased higher-altitude forest elements, but the Holocene vegetation had a higher proportion of secondary tree taxa represented than in MIS 3. In New Caledonia (which had no human population before 3000 years ago), the analyses established that there had been widespread landscape instability, probably associated with MIS 2 cooling and aridity. However, the relationship of fire with shrubby maquis vegetation extended well before this time, as did a decline in araucarians.

These long-scale results could be considerably improved with higher resolution and additional proxies such as macrofossil analyses, phytoliths and biomarkers. Scanning cores at 1-mm scale with Itrax X-ray fluorescence could map erosion inputs that might be reflected by responses by the local vegetation. It might also discover inputs from atmospheric dust and tephra that are otherwise undetectable (Roberts *et al*. 2011). Thus, the infills in ultramafic karst hollows have great potential to provide information on the long-term stability of vegetation and the time taken for response to disturbance events.

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Appendix 1. Table of available dates from ultramafic karst basins

Cal y BP, calibrated, years before present; M, modern (post 1950AD); NDFB, not distinguishable from background

Sample, depth (cm)	Youngest (years)	Cal y BP	Oldest (years)	Radiocarbon age (years)	Laboratory no.
Lake Wanda, South Sulawesi, Indonesia, 2°32.66′S, 121°23.27′E, 534-m altitude					
Wanda86, 112.5	5045	5313	5581	4610 ± 80	ANU 5340
Wanda86, 332.5	2435	2678	2920	2610 ± 80	ANU 5341
Wanda86, 350.5	2358	2657	2955	2610 ± 120	OZD 406
Wanda86, 492.5	17 410	17 731	18 051	14 560 ± 130	ANU 5342
Wanda86, 550.5	33 720	34 617	35 513	30 500 ± 500	OZD 407
Wanda86, 617.5	37 508	39 955	42 402	35 370 +1390 –1180	ANU 5343
Wanda86, 742.5	35 594	38 241	40 888	33 640 +1330 –1140	ANU 5344
Wanda90, 65	3723	4005	4287	610 ± 80	ANU 5342
Wanda90, 115	4257	4539	4821	1390 ± 80	ANU 5343
Wanda90, 180	4622	4950	5278	2611 ± 120	OZD 407
Wanda90, 230	5310	5486	5661	15 560 ± 130	ANU 5343
Lake Majo, Obi Island, Maluku Province, Indonesia, 1°28.22′S, 127°29.64′E, 172-m altitude					
Lake Majo (Obi), 230	997	1373	1749	610 ± 80	ANU 5342
Lake Majo (Obi), 423	1813	2742	3671	1390 ± 80	ANU 5343
Lake Majo (Obi), 641	4528	5260	5992	2611 ± 120	OZD 407
Lake Hordorli, West Papua, Indonesia, 2°32.48′S, 140°35.3′E, 798-m altitude					
Hordorli, 94	7699	7944	8189	7140 ± 120	ANU 4859
Hordorli, 195	12 415	12 667	12 919	10 750 ± 120	ANU 4104
Hordorli, 395	26 217	26 776	27 334	22 500 ± 240	ANU 4105
Hordorli, 542.5	33 431	36 760	40 088	31 700 + 1750 – 1450	ANU 4858
Hordorli, 742.5	33 991	35 688	37 385	31 400 ± 750	ANU 4106
Hordorli, 852	39 706	41 555	43 403	37 150 + 1200 – 1050	ANU 4857
Hordorli, 920	36 470	38 785	41 099	34 300 ± 980	ANU 4856
Lake Trist plateau doline, Morobe Province, Papua New Guinea, 7°29.25′S, 146°59.52′E, 2054-m altitude					
Lake Trist sink 67.5	27 988	35 711	43 433	32 000 ± 7800	GX 3594
Lake Trist sink 102.5	36 589	40 764	44 939	37 000 ± 4400	GX 3593
Lake Trist sink 140	9521	10 036	10 550	8900 ± 215	GX 3592
Lake Trist sink 185	31 422	37 764	44 105	31 800 + 4000–2500	GX 3591
Plaine des Lacs, New Caledonia 22°17′S, 166°59′E, 210–280-m altitude					
Fossil wood Lake 50i	13 875	14 030	14 195	12 030 ± 90	ANU10169
Fossil wood Lake 50o	13 282	13 517	13 752	11 670 ± 120	ANU10170
Emeric A 156	12 689	14 090	15 491	11 760 ± 540	ANU 8351
Emeric A 263	0	M	ANU 8352		
Emeric A 292	29 051	29 925	30 798	25 730 ± 390	ANU 8000
Emeric A 366	40 571	41 494	42 416	37 040 ± 550	ANU 7998
Emeric A 420	32 854	33 848	34 842	29 760 ± 510	ANU 8353
Emeric A 448.5	33 611	34 498	35 385	30 360 ± 500	ANU 7999
Emeric B 140.5	27 406	29 120	30 834	24 640 ± 910	ANU 8417
Emeric B 219	34 000	35 172	36 343	31 120 ± 610	ANU 8418
Suprin 38.5	20 012	20 321	20 630	16 850 ± 120	ANU 8414
Suprin 85	20 836	21 181	21 526	17 520 ± 110	ANU 8413
Suprin 176	30 835	31 978	33 120	27 670 ± 560	ANU 8415
Suprin 295	32 984	34 578	36 172	30 360 ± 780	ANU 8416
Xere Wapo A 119	35 945	36 965	37 985	32 470 ± 670	ANU-8420
Xere Wapo B 5	4583	5025	5466	4400 ± 150	ANU9797
Xere Wapo B 20	6407	6592	6776	5780 ± 80	ANU9793
Xere Wapo B 84	28 838	29 306	29 773	25 250 ± 180	OZF755
Xere Wapo B 101.5	22 645	23 361	24 077	19 400 ± 300	ANU9794
Xere Wapo B 164	26 017	26 408	26 799	22 150 ± 140	OZF756
Xere Wapo B 224	47 240	49 554	51 867	46 050 ± 1350	OZF 757
Xere Wapo B 360	43 562	48 352	53 142	>47 000	OZE-449
Xere Wapo B 475	NDFB	OZE-448			
Xere Wapo C 10.25	9605	9877	10 149	8792 ± 53	Wk-18065
Xere Wapo C 20.25	32 017	33 173	34 329	29 237 ± 490	Wk-18066
Xere Wapo C 35.25	33 098	34 135	35 172	30 031 ± 542	Wk-18067

(*continued next page*)

Appendix 1. (*continued*)

Sample, depth (cm)	Youngest (years)	Cal y BP	Oldest (years)	Radiocarbon age (years)	Laboratory no.
Xere Wapo C 48.5	31 952	32 864	33 776	28 880 ± 340	OZJ-295
Xere Wapo C 80.5	33 497	34 135	34 772	29 990 ± 380	OZJ-296
Xere Wapo C 85.5	10 738	10 952	11 165	9590 ± 60	OZL-481
Xere Wapo C 86.5	20 511	20 823	21 134	17 250 ± 110	SANU-8316
Xere Wapo C 105.5	41 995	43 263	44 530	39 140 ± 800	OZJ-297
Xere Wapo C 110.5	39 398	42 118	44 838	37 478 ± 1426	Wk-17760
Xere Wapo C 115.5	41 035	42 023	43 010	37 670 ± 660	OZJ-291
Xere Wapo C 119.5	38 716	39 220	39 723	34 700 ± 190	SANU-8317
Xere Wapo C 120.5	33 817	34 289	34 761	30 240 ± 280	OZL-482
Xere Wapo C 125.5	41 548	42 474	43 399	38 270 ± 640	OZJ-292
Xere Wapo C 150.5	44 281	46 722	49 163	42 800 ± 1200	OZJ-298
Xere Wapo C 219.5	37 096	37 786	38 476	33 500 ± 190	SANU-8318
Xere Wapo C 220.5	45 707	47 883	50 058	44 300 ± 1700	OZL-483
Lac Boulet 590	32 467	33 447	34 426	29 370 ± 440	ANU 8419