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A late-Holocene palaeoecological record from Ambra Crater in the highlands of Papua New Guinea and implications for agricultural history

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Abstract: A series of monoliths collected from Ambra Crater in the Upper Wahgi valley, Papua New Guinea have been subject to multiproxy (pollen, microcharcoal and diatom) palaeoecological investigation. The palaeoecological record enables a relatively high-resolution reconstruction from *c.* 4000–500 cal. BP. Throughout the sequence, the valley floor and crater area were continuously deforested and carpeted with a grassland-disturbance taxa mosaic. Vegetation communities in the valley were largely unaffected by successive tephra deposition events, although some muted effects occurred. Tephra deposition did have considerable local effects on soil water conditions and hydrology in the base of the crater. The Ambra Crater record is consistent with longer chronologies from wetlands in the Upper Wahgi valley, which document extensive disturbance to dryland forests and their replacement with grasses and other disturbance taxa from the mid Holocene. The Ambra Crater record, taken in conjunction with previously published multisite data, enables critique and discrimination of different interpretations of agricultural history in the highlands during the late Holocene.

Key words: Pollen, diatoms, tephra, vegetation history, agriculture, Papua New Guinea, tropical highlands, late Holocene, Ambra Crater.

Introduction

Recent multidisciplinary investigations have built on previous research to clarify the history of agriculture and associated palaeoecological change in the Upper Wahgi valley in the highlands of Papua New Guinea (Powell *et al.*, 1975; Golson, 1977; Golson and Gardner, 1990; Denham *et al.*, 2003, 2004; Denham and Haberle, 2008). A major analytical focus of renewed investigations in the region has been the emergence of agriculture from *c.* 7000–6500 cal. BP at Kuk Swamp. Multiproxy palaeoecological investigations have since been undertaken at an adjacent site, Ambra Crater in the Upper Wahgi valley (Figure 1), in order to generate a relatively high-resolution land-use and vegetation history for the vicinity during the late Holocene.

Ambra Crater was selected for intensive study because it provides a complement to Holocene palaeoecological records at three open wetlands in the vicinity: Kuk Swamp (within Kuk Research Station; Denham *et al.*, 2004); Ambra Lake (Powell, 1982) and Warrawau Plantation (Powell, 1970). These previous wetland palynological records contain detrital materials from catchments of variable size and 'old' reworked pollen resulting from on-site drainage and cultivation, eg, at Kuk (Denham *et al.*, 2009); consequently, the disentangling of dryland and wetland components within the pollen spectra can be problematic, particularly for grasses and other non-forest taxa that occur in both dryland and wetland environments. In contrast, the Ambra Crater record is derived from a small volcanic crater subject to gradual accretion through time, with limited evidence for disturbance (Blong, 1982), excepting current planting with coffee (*Coffea* sp.). The record is of high resolution, relative to previous work for the time period in the region, and enables continuous reconstruction of vegetation history. The catchment of Ambra Crater is smaller than the main wetlands of the floor of the Upper Wahgi valley, which have provided palaeoecological records. Consequently, the crater contains relatively fewer detrital materials, which are primarily of local origin from the interior rim of the crater; although, the crater has been subject to extra-local aeolian deposition. Several tephra layers at Ambra Crater provide good chronostratigraphic control and correlate, albeit variably, with similar tephra sequences at other archaeological and palaeoecological sites across the highlands (Blong, 1982; Coulter, 2007).

In the New Guinea highlands during the mid and late Holocene, successive technological innovations in, as well as the relative

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importance of, dryland and wetland forms of agriculture have been variably interpreted as adaptive responses to progressive deterioration of forest and soil resources (Golson, 1977, 1982), as socially mediated responses to changes in production needs (Golson and Gardner, 1990; Bayliss-Smith and Golson, 1992), and as climatically induced (Haberle and David, 2004), as well as in more contingent terms (Denham and Haberle, 2008). These interpretations have been based on archaeological evidence from the wetlands (Golson, 1977; Bayliss-Smith *et al*., 2005), increases in inorganic sediment fluxes to lakes (Oldfield *et al*., 1980, 1985), and palynological evidence for progressive deforestation and extension of anthropogenic grasslands (Haberle, 1998, 2003) during the late Holocene. The timing of initial deforestation, evidenced in the form of grass- and fern-dominated pollen assemblages and microcharcoal peaks, is observed at Kuk Swamp by *c*. 7000–6500 cal. BP (Denham *et al*., 2004). The pollen record from Ambra Crater is removed from the main cultivated wetlands, such as Kuk and Warrawau, and should therefore shed light on whether the Upper Wahgi valley was uniformly and permanently deforested since this time.

Tephra deposition, associated with eruptions off the north coast of New Guinea, has occurred in the highlands repeatedly during the Holocene (Blong, 1982). The impact of tephras on highland landscapes and society is uncertain. Blong (1982) collated evidence from oral history and sedimentological studies indicating that deposition of the Tibito tephra (305–270 cal. BP, following Haberle, 1998), while spatially variable, was a widespread event that had major impacts on landscapes, rivers, animals and vegetation, as well as people. While the aftermath of the event is remembered in oral histories as a time of hunger, the beneficial effects on soil fertility and crop yields are also reported. The correspondence between the timing of Tibito tephra deposition and variable evidence for increased soil erosion led Haberle (1998) to suggest that increased yields after tephra fertilization (Blong, 1982; Wood, 1987) encouraged more intensive cropping, which in turn led to increased rates of soil degradation. Interpretation of patterns of human landscape exploitation in the few centuries following Tibito deposition is complicated by uncertainty over the timing of the introduction of sweet potato (*Ipomoea batatas*), which, through its greater productivity in formerly marginal soils and habitats, is credited with encouraging greater soil degradation. Haberle (1998) also speculated that a similar pattern of agricultural intensification and soil loss occurred in response to the earlier, Olgaboli tephra (1190–970 cal. BP). Older tephra falls may have similarly encouraged brief episodes of land-use intensification and land degradation, which might be visible in the vegetation history from Ambra Crater.

In sum, the Ambra Crater record addresses two inter-related research themes. First, how uniform and persistent was human management of the Upper Wahgi landscape – especially the dryland component away from major wetlands – during the Holocene? Second, what were the effects of successive tephra events on land-use and vegetation history?

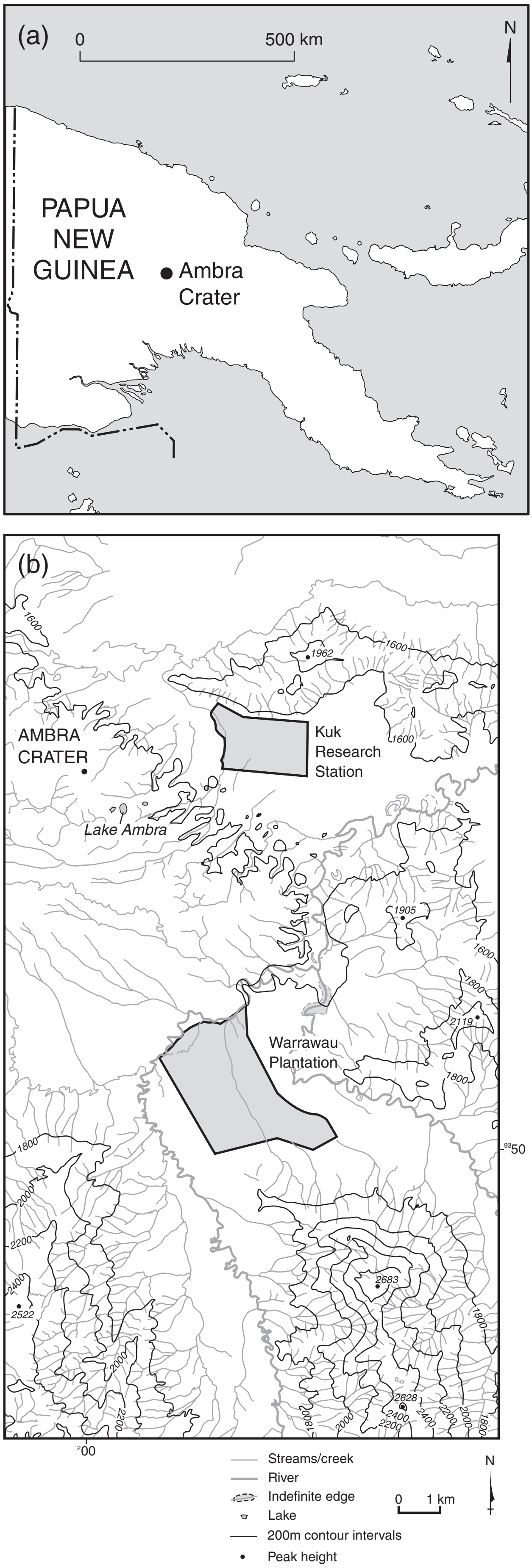

Figure 1 Location of Ambra Crater in Papua New Guinea and in the Upper Wahgi valley

Site location

Ambra Crater (5°47′S, 144°17′E) is located approximately 10 km northeast of Mount Hagen town and 3.5 km west of Kuk (Figure 1). The small volcanic cone marks a side vent of the main Mount Hagen volcano. The base of the crater is at an altitude of *c*. 1680 m and rises approximately 80 m higher; the interior crater floor is at an altitude of *c*. 1760 m and measures less than 100 m in diameter. The crater is overlain by Tomba Tephra (Blong, 1982), which dates to at least 50 000 years ago (Pain and Blong, 1976), and was formed during an earlier, poorly dated phase of volcanic activity

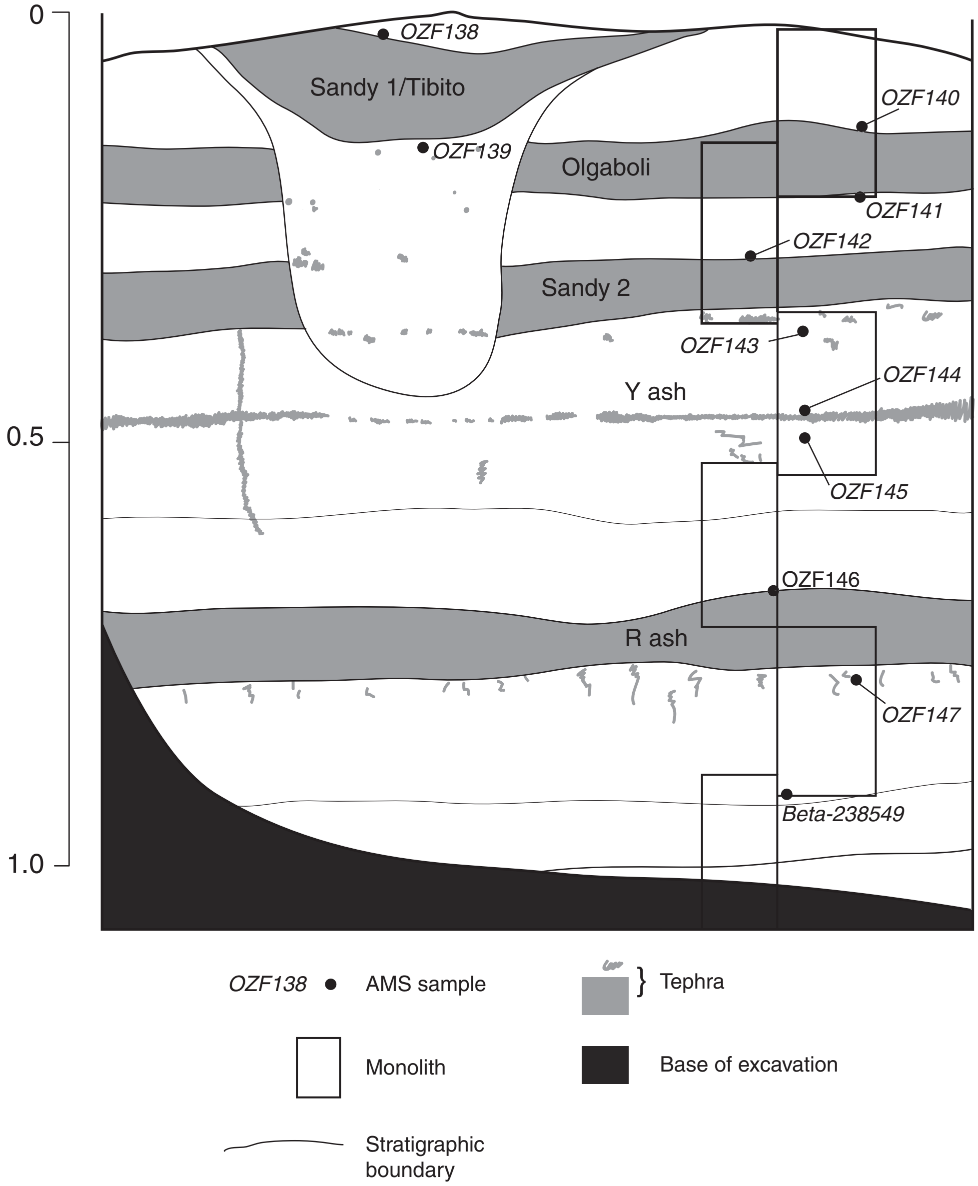

Figure 2 Stratigraphy of the test trench showing sample locations

in the valley (Pain *et al*., 1987). The interior of the crater has been artificially drained, both for the present-day cultivation of coffee and in the past.

The lower montane humid climate of the Upper Wahgi valley is slightly seasonal and dominated by local orographic effects. Average annual temperature is 19°C and annual rainfall is *c*. 2700 mm (Hughes *et al*., 1991). Soil water content is typically sufficient for plant growth throughout the year (McAlpine *et al*., 1983).

Vegetation communities in the Mount Hagen region are well-studied for the present and the past (eg, Powell, 1970, 1982; Powell *et al*., 1975; Denham *et al*., 2004; Denham and Haberle, 2008). Undisturbed primary forests, ie, primarily without human disturbance, in the Upper Wahgi valley during the Holocene would be anticipated to have comprised mixed lower montane rain forest (predominantly represented palynologically by *Castanopsis-Lithocarpus*) on the valley floor, with an increasing dominance of upper montane forest (predominantly represented palynologically by *Nothofagus*) on the upper slopes of the valley walls. Secondary forest taxa, mainly light-demanding species that colonize disturbed patches within primary forest, include species within the genera *Acalypha, Dodonaea*, *Macaranga* and *Trema*. Tracts of grassland on the valley floor are usually inferred to result from human activities, primarily agriculture, although once established they are maintained by periodic burning. Although a feature of the valley's flora throughout the Holocene, increasing frequencies of *Casuarina* pollen after *c*. 1200 cal. BP are inferred to represent the innovation and adoption of tree-fallowing (Haberle, 2007).

Field methods

In 1999, a 100 cm × 60 cm test trench was excavated into the floor of Ambra Crater. The unit was excavated to a depth of approximately 100 cm (Figure 2), below which excavation was impractical given the need to preserve existing crop cover. The upper few centimetres of topsoil, with high organic litter and root contents, and associated with recent and ongoing cultivation, were removed prior to stratigraphic recording in the field and monolith sampling.

A series of overlapping monoliths were collected in split, 8 cm wide sections of zinc piping that were pushed into the cleaned wall of the test trench, while the lowest pipe section was pushed into the base of the test trench. Each monolith was then cut out of the trench wall, wrapped in foil and clean film, labelled and bagged. Monoliths were stored under refrigeration in an approved Australian Quarantine and Immigration Service (AQIS) facility at the School of Archaeology and Anthropology, Faculty of Arts, Australian National University.

Laboratory methods

Stratigraphy was described in the field and laboratory. Samples for dating, diatom and pollen analyses were taken from cleaned monoliths in the laboratory.

Ten samples, comprising up to 5 cm^3 of bulk sediment, were extracted from below and above each tephra and submitted to the Australian Nuclear Science and Technology Organisation (ANSTO) for AMS radiocarbon dating. An additional two samples

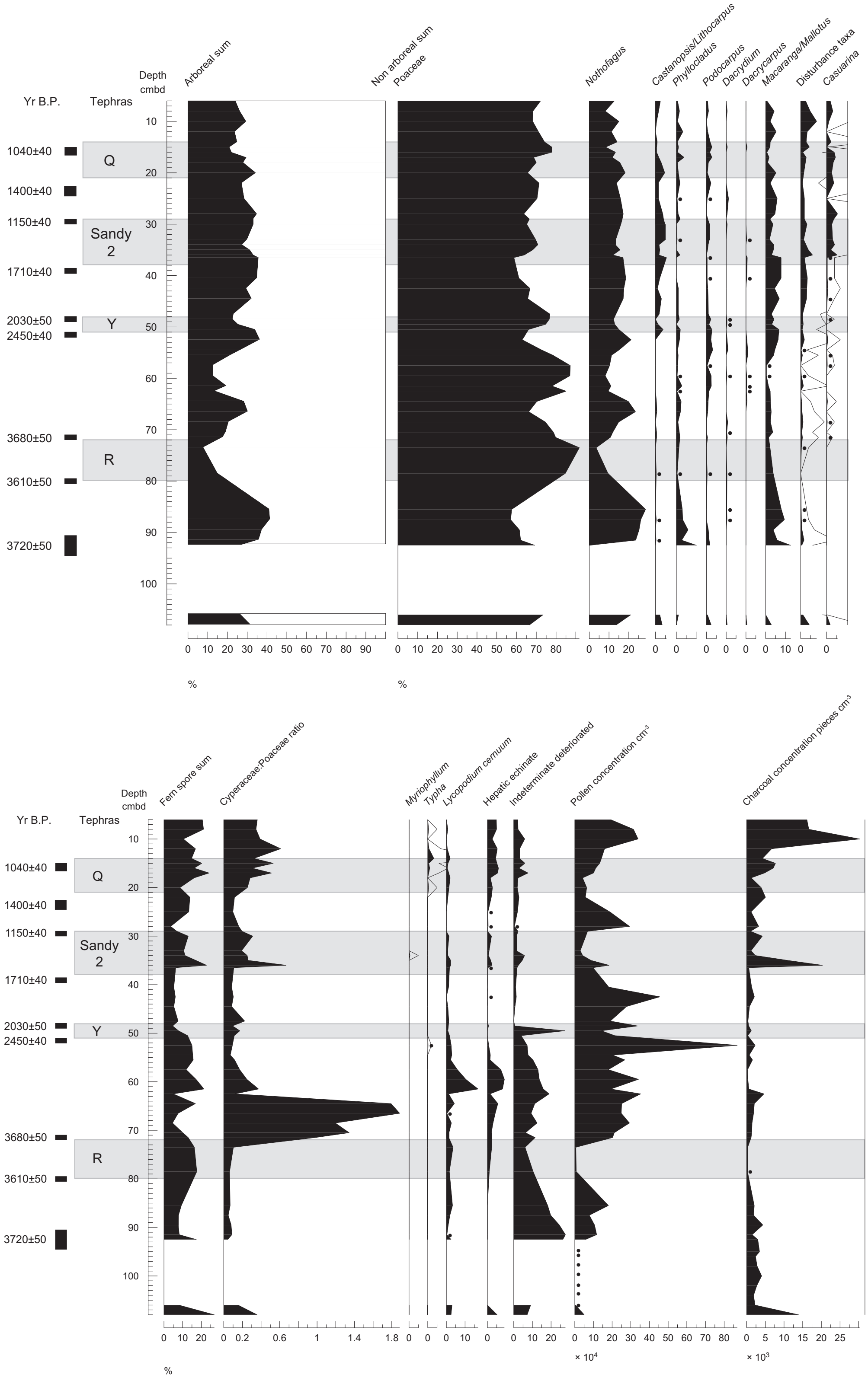

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Figure 3 (continued)

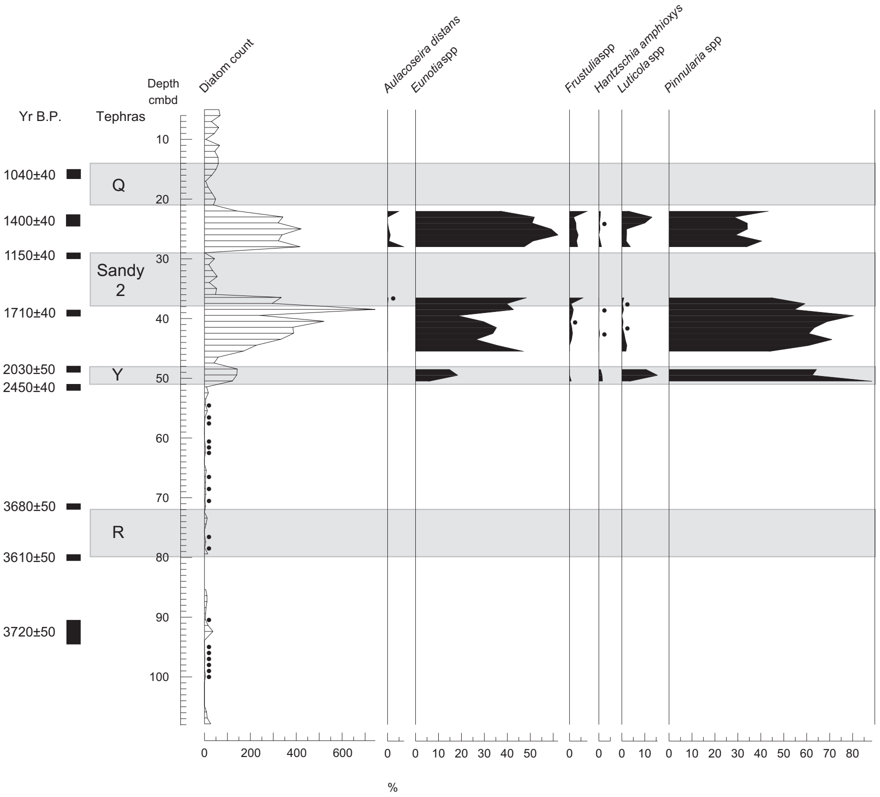

Figure 3 Palaeoecological summary diagram of pollen, microcharcoal and diatom analyses

of at least 10 cm^3 of sediment were subject to a pollen preparation, omitting acetolysis and ethanol dehydration steps to avoid contamination with modern carbon (Brown *et al.*, 1989), and submitted to Beta Analytic, Inc. for AMS radiocarbon dating. These latter two samples were designed to date the base of the sequence beneath the lowest tephra. Unfortunately, the lowest sample yielded insufficient carbon for AMS dating and no other suitable material for dating was present.

Contiguous and paired *c.* 1 cm^3 samples of moist sediment were extracted for pollen and diatom analyses. Samples were not collected from 80.5–82.5 cm below datum (cmbd) because of severe disturbance within stored monoliths. All pollen samples were spiked with exotic *Lycopodium* marker grains (available in tablet form from Lund University, Sweden), and processed for pollen analysis using standard methods involving dispersal in Na-pyrophosphate, then treatment with 10% KOH, weak Schulz solution (1:10 w/v solution of 35% HNO_3:$KClO_3$), acetolysis, and concentrated HF (Moore *et al.*, 1991). Samples were subsequently dehydrated in ethanol and mounted in glycerine on glass slides.

Pollen was counted using a Zeiss Axiolab compound microscope fitted with E-Pl 10x/20 objectives, at 400× and 1000×, along transects. Identifications were made by comparisons with regional pollen floras and taxon-specific treatments (Powell, 1970; Garrett-Jones, 1979; Haberle 1995), and with the pollen reference collection held in the Centre for Palynology and Palaeoecology, Monash University. Pollen percentages were calculated relative to a pollen sum, composed of dryland taxa, varying between 94 and 429 depending on pollen concentrations. Cyperaceae, other aquatics, ferns and unidentified types were excluded from the dryland pollen sum, and their percentages were calculated relative to a sum of dryland+aquatic and fern taxa. A pollen and diatom diagram was produced using Psimpoll version 4.26 (available from Keith Bennett at http://www.chrono.qub.ac.uk/psimpoll/psimpoll.html). In total, 60 pollen samples were examined, though six samples between 95 cmbd and 104 cmbd were devoid of pollen, which is partly attributable to processing difficulties associated with allophane clay/organic complexes (Wood, 1987). Microcharcoal was counted on all slides at 200× magnification, as opaque, angular objects >10 μm long, and calculated as particles/cm^3.

A total of 77 pollen types were identified, and are summarized in the pollen diagram (Figure 3) as 13 indicative ecological types plus an arboreal/non arboreal sum, a sum of woody disturbance taxa (Moraceae/Urticaceae, *Celtis*, *Acalypha*, *Pandanus* spp., *Pandanus antaresensis* type, *Psychotria*, *Schefflera* type, and *Trema*), a fern spore sum, and a Cyperaceae: Poaceae ratio (SOM Figure S1, available online, for the complete pollen diagram). Deteriorated indeterminate types, and pollen and charcoal concentrations are also depicted. Owing to the considerable influence of tephra layers on pollen composition, the diagram has been left unzoned. The diagram is discussed chronologically in terms of successive tephra layers and intervening organic-rich sediments.

The basic diatom preparation method of Renberg (1990) was followed for qualitative analysis, with the exception that the oxidation (H_2O_2) step was repeated to destroy persistent organic matter. Diatoms were identified at 1000× magnification, using a Zeiss Axioscope with differential interference contrast optics, with reference to published floras (Reichardt, 1988; Vyverman, 1991;

Table 1 Stratigraphic descriptions for Ambra Crater (from monolith sequence and depths may vary slightly along section)

Depth (cmbd)	Colour	Texture	Description	Lithostratigraphy
3.5–17.5	10YR 2/1 Black	Silty clay loam	Angular blocky structure, weak, slightly sticky and slightly plastic; note: few flecks (10YR 2/2)	Allophanic-organic soil? (detrital and *in situ*)
17.5–23.5	10YR 3/2 Very dark greyish brown	Silt loam	Single grain, no ped formation, slightly sticky and slightly plastic	Holocene tephra: Olgaboli (Q)
23.5–31.5	10YR 2/1 Black	Organic silt	Spheroidal structure (soft), moderate, slightly sticky and slightly plastic, few fine rootlets	Organic soil (*in situ* and detrital)
31.5–36.5	10YR 4/3 Brown	Loamy sand	Structureless (single grain), non-sticky and non-plastic; note: (i) penetrated with vertical black-filled voids; (ii) minor ferric mottling (10YR 4/6)	Holocene tephra: Kuning (Sandy 2) (slightly weathered and root-penetrated from overlying palaeosol)
36.5–47.5	10YR 2/1 Black	Clay to silty clay	Structureless (massive), sticky and plastic; note: few flecks of tephra (loamy sand, 10YR 4/4, dark yellowish brown) in upper 2–3 cm	Allophanic-organic soil? (detrital and *in situ*)
47.5–49.5	10YR 5/3 Brown	Silty clay loam	Band of tephra, weathered and partially homogenized; note: minor ferric oxidation (7.5YR 3/4, dark brown)	Holocene tephra: Baglaga (Y ash)
49.5–74	10YR 2/1 Black	Clay to silty clay	Structureless (massive), sticky and plastic; note: no sign of transition to slightly lighter variant in stored samples, although basal 10 cm more coherent/stronger (probably more clay-rich)	Allophanic-organic soil? (detrital and *in situ*)
74–83	10YR 7/6 Yellow	Sandy silt loam	Structureless (single grain), moderate, non-sticky and non-plastic; note: (i) many ferric mottles throughout (7.5YR 5/6, strong brown); (ii) few mottles (10YR 7/3, very pale brown); (iii) in-filled vertical voids (10YR 4/2, dark greyish brown)	Holocene tephra: Kim (R ash) (slightly weathered and root-penetrated from overlying palaeosol)
83–91	10YR 2/1 Black	Clay loam	Structureless (massive), hard, very sticky and plastic, few fine rootlets; note: few ferric mottles (10YR 2/2, very dark brown)	Allophanic-organic soil? (detrital and *in situ*)
91–110.5	10YR 4/2 to 4/3 Dark greyish brown to brown	Clay	Structureless (massive), hard, very sticky and very plastic; note: common ferric mottles throughout (7.5YR 3/3, dark brown)	Detrital soil (heavily weathered clay)
Ditch (upper fill)	2.5Y 5/3 (to 5/4) Light olive brown	Silt loam	Spheroidal to single grain structure, weak, slightly sticky and slightly plastic, few rootlets; note: common ferric oxidation mottles along base (7.5YR 4/4)	Holocene tephra: Kenta (Sandy 1) or Tibito (Z) (very slightly weathered)
Ditch (lower fill)	10YR 3/1 Very dark grey	Silty (clay) loam	Weak spheroidal structure, slightly sticky and slightly plastic	Allophanic-organic soil? (detrital and *in situ*)

Krammer and Lange-Bertalot, 1999a, b, 2000, 2004). All slides were counted along 15 traverses, with broken and dissolute diatoms included, consistent with the method described by Battarbee *et al.* (2001). Of the 111 samples analysed, only 22 had a count greater than 100. For these, proportions were calculated relative to a sum of all diatom types.

Very few diatoms were observed in samples below 51 cmbd and all samples containing diatoms showed high degrees of dissolution and fragmentation. A total of 32 diatom taxa were observed and grouped into six indicative, ecological types in the diagram (Figure 3; SOM Figure S2, available online, for diatom percentage diagram incorporating all samples with counts >100, and Table S1, available online, for habitat preferences of diatom taxa). Noted on the diatom slides, but not counted, were testate amoebae plates, sponge spicules, chrysophycean stomatocysts and phytoliths.

Results

The stratigraphy exposed in the excavation at Ambra Crater comprised a series of late-Holocene tephras separated by predominantly black or dark coloured deposits, primarily allophanic-organic complexes or organic soils (Table 1; Figure 2). The series of tephras at Ambra Crater was identified in the field as corresponding to a well-established tephra sequence at Kuk Swamp, which is also variably present at other archaeological and palaeoecological sites in the highlands (Golson, 1982; Haberle, 1998). However, the widespread practice of using the physical characteristics, whether determined in the field or the laboratory, to identify tephras at highlands' sites has now been geochemically tested (Coulter, 2007). Although not directly relevant to this palaeoecological study, geochemical results cast doubt on the reliability of some, predominantly field-based, tephrochronological interpretations of late-Holocene strata at archaeological and palaeoecological sites in the highlands.

The series of AMS dates obtained on bulk organic samples at Ambra Crater exhibit generally good chronostratigraphic integrity; namely, they generally get older down the profile (Table 2; Figure 2). There are three chronological reversals, one associated with the ditch at the top of the section (OZF138 and OZF139), another near the top of the main sequence (OZF141 and OZF142) and a very slight reversal lower down the section (OZF146 and OZF147). Such reversals can be anticipated when dating bulk organic samples in deposits subject to soil formation in the present or the past (Matthews, 1985; Scharpenseel and Becker-Heidmann, 1992). In each case, a reversal may reflect either the incorporation of residual, or older, organic material into the upper sample, or the contamination of the lower sample by younger organic material, eg, decomposed root material. Two reversals at Ambra Crater are relatively minor, whereas the third, the uppermost, is more severe. Given that Tibito (Q tephra) and Kenta (Sandy 1 tephra) were both deposited within the last *c*. 500 years (Jack Golson and Russell Blong, personal communication, 2000 in Denham, 2003), the first reversal represents the incorporation of older carbon into the upper dated sample (OZF138). Older carbon was incorporated as a result of local reworking during a period of cultivation and drainage,

Table 2 AMS radiocarbon dates for Ambra Crater

Sample number	Context	Material	Depth (cmbd)	Radiocarbon age (BP)	Calibrated age (cal. BP)	Probability
Stratigraphy						
OZF140	Above Q	Bulk organic sample	15–16.5	1040±40	890–800	0.512
					960–900	0.488
OZF141	Below Q	Bulk organic sample	22.5–24.5	1400±40	1330–1180	1.000
OZF142	Above Sandy 2	Bulk organic sample	29–30	1150±40	1080–930	0.996
					1120–1110	0.004
OZF143	Below Sandy 2	Bulk organic sample	38.5–39.5	1710±40	1470–1420	0.143
					1630–1480	0.768
					1690–1650	0.089
OZF144	Above Y	Bulk organic sample	48–49	2030±50	2060–1820	0.989
					2110–2090	0.011
OZF145	Below Y	Bulk organic sample	51–52	2450±40	2540–2340	0.816
					2620–2590	0.041
					2700–2640	0.143
OZF146	Above R	Bulk organic sample	71–72	3680±50	3740–3730	0.008
					3790–3770	0.014
					4090–3830	0.970
					4140–4130	0.007
OZF147	Below R	Bulk organic sample	79.5–80.5	3610±50	3980–3690	1.000
Beta-238549	Near the base of the sequence	pollen	90.5–94.5	3720±50	4100–3850	0.940
					4150–4110	0.060
Ditch						
OZF138	Above tephra	Bulk organic sample	Ditch fill	750±40	600–560	0.277
					720–630	0.723
OZF139	Below tephra	Bulk organic sample	Ditch fill	560±40	560–500	0.942
					630–610	0.058

All dates calibrated using CALIB 5.0.2 (Stuiver and Reimer, 1993; Stuiver *et al*., 2005) and SHCAL04 calibration data set (McCormac *et al*., 2004).

which is represented by the ditch. Based on the known age of Olgaboli (Q tephra) at 1190–970 cal. BP (Haberle, 1998), the second reversal represents the incorporation of younger carbon into the lower dated sample (OZF142). The third reversal is extremely slight, the age ranges for the two dates overlap considerably (OZF146 and OZF147), and solely reflects the relatively instantaneous deposition of R tephra.

The multiproxy results are discussed from the base of the stratigraphy upward (Figures 2 and 3). The basal portion of the analysed stratigraphy is undated, but the lowest date of 4150–3850 cal. BP corresponds to 90.5–94.5 cmbd. However, the site is considerably older; a basal peat has been dated to at least 32 000 years old (ANU 1466; Blong, 1982).

Below the basal tephra, which was identified as R tephra and previously dated to 3980–3630 cal. BP (Denham *et al*., 2003), Poaceae, representing *c*. 60% of the dryland sum, and *Nothofagus*, generally representing *c*. 20% of the sum, dominate. Both forest (summarized here by *Castanopsis*/*Lithocarpus* and Podocarpaceae) and disturbance-indicating (Moraceae/Urticaceae, *Celtis*, *Acalypha*, *Pandanus* spp., *Psychotria*, *Schefflera* and *Trema*) woody taxa are present in low quantities. Diatoms, Cyperaceae and other aquatics are sparse. Large numbers of deteriorated pollen grains are encountered, and pollen and charcoal concentrations are relatively low. Pollen concentrations drop to very low levels within the R tephra, with higher proportions of Poaceae and fern spores and lower values of *Nothofagus*.

During the *c*. 1200 years between R and Y tephra deposition, the arboreal:non-aboreal ratio fluctuates moderately without changing the strong dominance of Poaceae, and other woody taxa retain values similar to below R tephra. An exception is *Casuarina*, absent immediately below R tephra, but which is consistently present, albeit initially as a trace, above. Immediately above R tephra, the Cyperaceae:Poaceae ratio increases to high values. This probably represents impeding of local drainage associated with tephra deposition, as similar, but muted Cyperaceae responses are associated with the Y, Sandy 2 and Q tephras. Fern spores, numbers of deteriorated grains and charcoal concentration remain similar to values seen beneath the R tephra, while pollen concentration increases. *Lycopodium cernuum* and Hepatics increase and the abundance of diatoms is low during this period.

Y tephra has been poorly dated to 2650–1950 cal. BP (Denham *et al*., 2003) and the dates presented here also yield a broad potential age range (Table 2). From the base of Y tephra to the base of Sandy 2 tephra, arboreal:non-arboreal proportions remain relatively constant, with the exception of a short-lived Poaceae peak within Y tephra. *Castanopsis*/*Lithocarpus* increase from the base of Y tephra upward, as do disturbance taxa. Just below and within the base of the Sandy 2 tephra, *Macaranga*/*Mallotus* values are the highest in the diagram. Trace *Casuarina* values are consistent with those achieved earlier. Diatom abundance increases initially within Y tephra and are greatest between Y tephra and Sandy 2 tephra; they are dominated by epiphytic or metaphytic, shallow water taxa, particularly species of *Eunotia* and *Pinnularia*. Fern and other spores, Cyperaceae and other aquatics are low. Spores of *Lycopodium cernuum* and Hepatics, and deteriorated pollen grains occur in low frequencies above Y tephra. Pollen concentrations remain generally high, except for low values within Y tephra.

Sandy 2 tephra deposition is poorly dated at Ambra Crater (Table 2) and at other sites in the highlands. There is little indication of any change in arboreal taxa within, or above the Sandy 2 tephra, as Poaceae, *Nothofagus*, other forest taxa and disturbance indicators all maintain consistent values throughout. However, *Casuarina* values abruptly increase near the base of Sandy 2 tephra and maintain these values throughout the remainder of the record. The abundance of diatoms decreases dramatically within the tephra, but dramatically and immediately increases above the tephra. In the organic-rich sediments between Sandy 2 and Q tephras, shallow-water diatoms are consistently prominent, although there are two, single-sample peaks of *Aulacoseira distans*, although only representing *c*. 5% of total count, that indicate more persistent waterlogging on the floor of the crater. Fern spores, Cyperaceae and *Myriophyllum* increase within, and decrease above, the tephra. Coincident with the increase in *Casuarina* values, charcoal concentrations increase abruptly within Sandy 2 tephra and fluctuate around relatively low-to-moderate levels in the sediments below the Q tephra.

Arboreal pollen proportions are generally consistently low, at 30% or less of the total sum, below, within and above Q tephra, which is relatively well-dated to 1190–970 cal. BP (Haberle, 1998). Exceptions include disturbance taxa, which increase slightly above the tephra and *Casuarina*, which decreases slightly immediately above the tephra. The abundance of diatoms is low within the tephra, and counts are too small to represent percentage data. Diatoms within and above the tephra are predominantly shallow water *Eunotia* spp., *Luticola mutica*, and *Pinnularia* fragments. Fern spores, Cyperaceae and *Typha*, and Hepatics increase within the tephra and maintain relatively high values above. Pollen concentrations increase following the relatively low levels within Q tephra, with elevated charcoal concentrations above the tephra.

A ditch containing a tephra, either Tibito or Sandy 1, dates to the last 500 years (Figure 2, Table 2). Imprecision results from the effects of old carbon in the fills of the ditch. The ditch was dug to drain the crater for cultivation, as witnessed at wetlands across the region for the same time period (Golson, 1982; Bayliss-Smith *et al*., 2005). The ditch cut postdates the top of the stratigraphic column analysed. Consequently, levels within the stratigraphic column postdating *c*. 500 years ago have been incorporated into the topsoil, presumably during prehistoric and modern cultivation.

Interpretations

The pollen, microcharcoal and diatom records exhibit four major features. First, the record is dominated throughout by herbaceous taxa, principally Poaceae. Poaceae account for at least 55% of the dryland pollen sum and arboreal taxa remain relatively low throughout. In combination with three other pollen diagrams from wetlands in the Upper Wahgi valley (Denham *et al*., 2004; Denham and Haberle, 2008), the Ambra Crater record indicates the dryland slopes of the valley floor were extensively deforested and disturbed continuously since at least 4000 cal. BP.

Second, there is a major separation above and below the base of the Y tephra. Below, samples have relatively few diatoms, high numbers of deteriorated pollen grains, and large values of *Lycopodium cernuum* and Hepatics, which may be suggestive of aeration and imply that the site was only intermittently waterlogged. Alternatively, poor diatom preservation may also result from dissolution in interstitial waters of wetlands (Bennett *et al*., 1994). Above this, particularly to the base of Q tephra, deteriorated grains, *Lycopodium cernuum* and Hepatics have lower frequencies and the abundance of diatoms is much higher. Collectively, these features suggest the site was waterlogged, most probably under shallow water throughout this period.

Third, successive tephra layers have a consistent influence on pollen and diatom assemblages. Within tephras, Poaceae values increase and *Nothofagus* values decrease slightly; while other arboreal taxa show little response. The effect is muted, but clearly apparent within each tephra. Taken at face value, the Poaceae peaks associated with successive periods of tephra deposition may reflect vegetation change, although taphonomic processes (ie, suppression of *Nothofagus* pollen dispersal and production with each tephra event) should not be excluded. *Nothofagus* is assumed to be an extra-local component throughout the Ambra Crater record, as discussed for other sites (eg, Denham *et al*., 2004). A similar Poaceae peak between *c*. 55–64 cmbd does not appear to be associated with a tephra. However, this peak could plausibly represent the NP tephra, which is present at Kuk in a chronostratigraphic position between R and Y tephras (Tim Denham, field observations in 1998 and 1999). At Ambra Crater, pedogenic processes may have reworked NP tephra into the soil during this drier period.

Telford *et al*. (2004) found that diatom concentrations in Mexican lakes typically increased abruptly in response to late-Quaternary tephra deposition, probably largely in response to silica fertilization. However, at Ambra Crater relationships between diatom abundance and tephra deposition are inconsistent. The lack of a diatom response immediately above R tephra is probably an artefact of dissolution. By comparison, above Y tephra diatom abundance increases steadily, is interrupted by deposition of Sandy 2 tephra, then rises to high levels again above Sandy 2 tephra. These may represent silica fertilization responses, but deposition of Q tephra engendered little or no change in diatom abundance. The lack of a response to Q tephra may reflect progressive shallowing of the basin, as the generally aerophilous habitat preferences of most of the diatoms indicate shallow and fluctuating water levels. A relationship between tephra deposition and changing water levels is corroborated by Cyperaceae and other aquatic taxa, which increase within or above tephras. Elsewhere in the Southern Hemisphere, increased fern spores are a conspicuous response to tephra deposition (Haberle and Bennett, 2000), but here this effect is not clear, since a sharp fern spike at 36 cm, coinciding with a charcoal peak and increased Casuarina, may instead be a product of human activity.

Finally, the increase in woody disturbance taxa, *Casuarina*, fern spores and Cyperaceae near the base of Sandy 2 tephra at 36 cm may reflect increased intensity of human use in the immediate vicinity around Ambra Crater, from about 1690–1420 cal. BP. This is broadly consistent with, but earlier than, an increase of *Casuarina* pollen in widespread highlands' sites from around 1200 cal. BP, which is thought to reflect the initiation of *Casuarina* silviculture and tree-fallowing (Haberle, 2007).

Conclusions and implications for understanding agricultural history

Pollen records within Kuk Swamp suggest that the Upper Wahgi valley was a deforested, agricultural landscape by 7000–6500 cal. BP (Denham *et al*., 2003). Two other wetland sites in the vicinity show comparable, albeit later and variable levels of disturbance from the mid Holocene (Denham *et al*., 2004; Denham and Haberle, 2008). From beyond the swamp margins, the Ambra Crater record is consistent with and confirms evidence from wetland sites of extensive disturbance to dryland forests and their replacement by grasses and other disturbance taxa from at least 4000 cal. BP. In contrast to other records from the vicinity, the Ambra Crater record is of relatively high resolution, ie, 60 pollen samples within a *c*. 3500 year period (*c*. 4000–500 cal. BP) and indicates that no major changes to land management practices occurred in the vicinity during this period.

The Ambra Crater evidence of slightly increased secondary forest from *c*. 2000 cal. BP and of *Casuarina* silviculture sometime between 1700 and 1100 cal. BP, is consistent with the signals of a cultivated landscape and land-use intensification previously established for highland valleys (Haberle, 1998). In terms of the original research questions, however, the broader picture is one of a continuously deforested, managed landscape largely unaffected by successive tephra deposition events, which might be expected to have had more dramatic, if brief, impacts on the landscape and people inhabiting it (Blong, 1982). Perhaps sampling resolution (*c*. 40 yr/1 cm sample) is insufficient to record short-term impacts. Similarly the absence of evidence of late-Holocene climatic changes, which have been suggested as potential drivers of agricultural innovation in the highlands (Haberle and David, 2004), may reflect an insensitivity resulting from chronological resolution of the record, as well as the masking effects of more dominant signals derived from human activities and tephra deposition.

Significantly, the Ambra Crater findings call into question a series of related models of agricultural development in the highlands that have invoked causal relationships between dryland and wetland spheres of agricultural activity (from Golson, 1977 to Bayliss-Smith and Golson, 1992). In general terms, these neo-Boserupian (Boserup, 1965) models have tended to assume continual population growth and pressure on the land, as well as land degradation, that were relieved and eventually recreated through innovations in the dryland sphere, eg, tillage and *Casuarina* silviculture, and through drainage and cultivation of valley floor swamps. In one cycle, maximizing existing technological exploitation of the dryland slopes results in decreased returns through land degradation and an impetus for people to drain the wetlands. Once the cultivation of drylands and wetlands was maximized using existing technology, there was an impetus for people to innovate in order to increase yields and sustainability of cultivation on the dryland slopes, and the more energy-intensive cultivation of wetlands was abandoned. If such cycles pertained during the late Holocene, as suggested based on archaeological evidence from Kuk Swamp (see Golson, 1977, 1982), some variation in land use and vegetation of the dryland sphere – represented by forest recovery or decrease in the Ambra Crater record – would be anticipated. None is present; an alternative, interpretative framework is thus more likely where cultivation occurred continuously, but spatially variably, on dryland slopes and in the wetlands since at least the mid Holocene (see Denham and Haberle, 2008).

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