Contiguous Multi-Proxy Analyses (X-Radiography, Diatom, Pollen, and Microcharcoal) of Holocene Archaeological Features at Kuk Swamp, Upper Wahgi Valley, Papua New Guinea

Tim Denham,[1,]* Kale Sniderman,[1] Krystyna M. Saunders,[1] Barbara Winsborough,[2] and Alain Pierret[3]

[1]*School of Geography and Environmental Science, Building 11, Monash University, Clayton Campus, VIC 3800, Australia*
[2]*Winsborough Consulting, 23606 Round Mountain Circle, Leander, Texas 78641*
[3]*IRD-IWMI-NAFRI, UMR 211-Biogeochemistry and Ecology of Continental Environments, BP 06, Vientiane, Laos PDR*

Contiguous multi-proxy analyses (X-radiography, diatom, pollen, and microcharcoal) have been conducted on the fills of early, mid-, and mid-late Holocene features at Kuk Swamp, Upper Wahgi Valley, Papua New Guinea. The features are associated with key periods of archaeological interest: plant exploitation (ca. 10,000 cal yr B.P.), earliest cultivation (6950–6440 cal yr B.P.), and earliest ditches (ca. 4000 cal yr B.P.). The analyses are designed to clarify uncertainties regarding the reliability and association of different samples within feature fills for the interpretation of human activities on the wetland in the past. Methodologically, these investigations have clarified site formation processes, including pedogenesis within feature fills, which enable a better determination of archaeological associations for different samples within those fills. Substantively, the results provide higher resolution interpretations of paleoenvironments and past human activities on the wetland margin. © 2009 Wiley Periodicals, Inc.

INTRODUCTION

Kuk Swamp in the Upper Wahgi Valley, Western Highlands Province, Papua New Guinea (Figure 1) is an important archaeological and paleoecological site for understanding the emergence and transformation of agriculture on the island of New Guinea (Golson, 1977, 2007; Golson & Hughes, 1980; Bayliss-Smith & Golson, 1992; Denham et al., 2003; Denham, Haberle, & Lentfer, 2004; Bayliss-Smith et al., 2005; Denham, 2007; Denham & Haberle, 2008). Pioneering multidisciplinary investigations were undertaken at the site in the 1970s and 1980s by Jack Golson (Golson, 2007). Renewed multidisciplinary investigations were conducted by Tim Denham from the late 1990s (Denham, 2003; Denham, Golson, & Hughes,

*Corresponding author; E-mail: Tim.Denham@arts.monash.edu.au.

Geoarchaeology: An International Journal, Vol. 24, No. 6, 715–742 (2009)

Published online in Wiley Interscience (www.interscience.wiley.com). DOI:10.1002/gea.20283

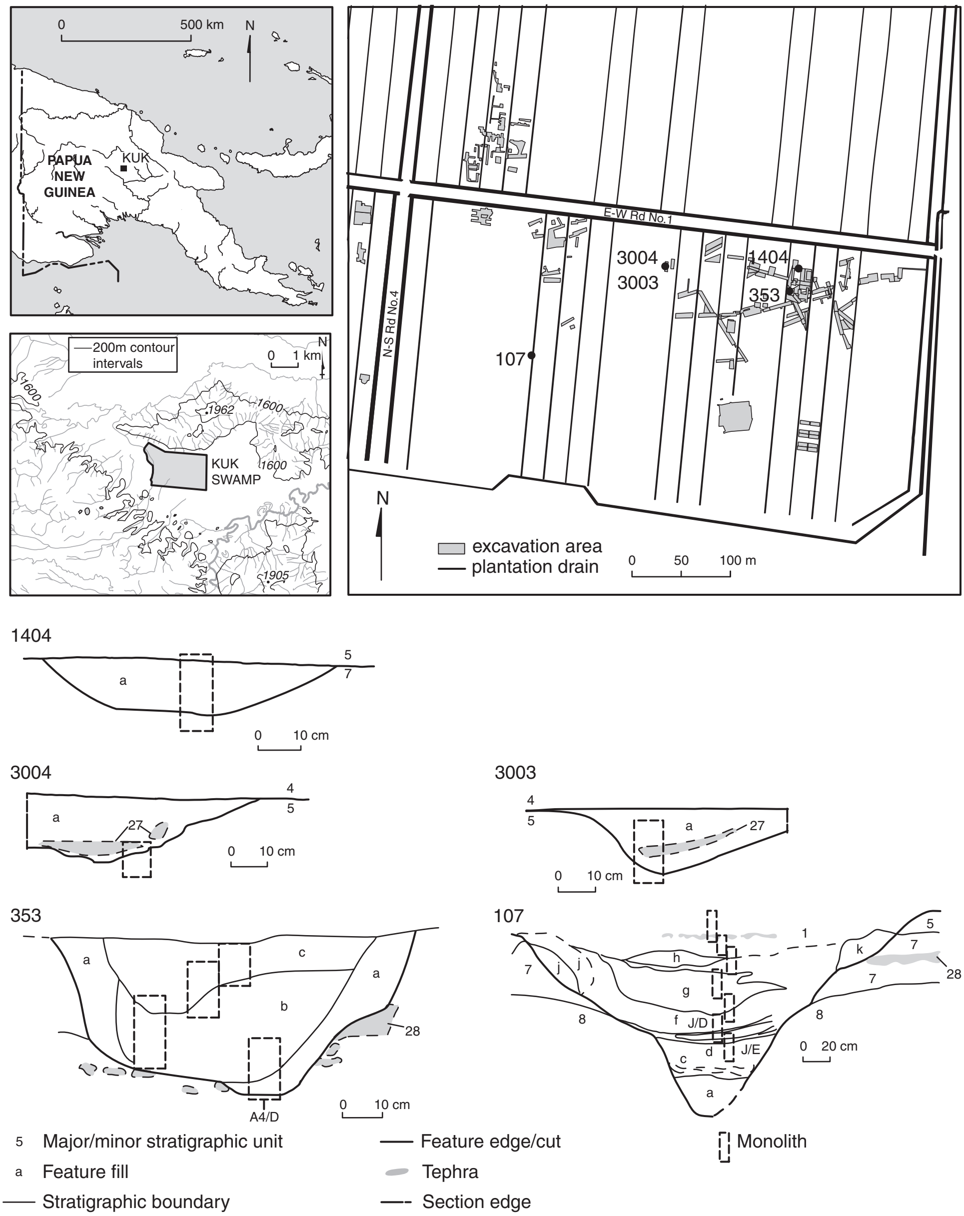


Figure 1. Location maps of: (upper left) Kuk in Papua New Guinea; (lower left) Kuk in the Upper Wahgi Valley; and (right) sample locations from excavations at Kuk, including (bottom) associated sections. Note that alphabetical suffixes are added to feature numbers to denote feature fills.

2004). These studies indicate that agriculture was practiced on the island of New Guinea by at least 6950–6440 cal yr B.P. (Denham et al., 2003) and potentially by ca. 10,000 cal yr B.P. (Golson, 2007; cf. Denham, Golson, & Hughes, 2004).

Sampling conducted as part of renewed investigations included relatively (for the region) high-resolution sampling of archaeological and stratigraphic contexts for multi-proxy paleoecological analyses (pollen, microcharcoal, phytolith, and diatom) and mixed-method stratigraphic analyses (including X-radiography and thin-section descriptions) (Denham, 2003; Denham et al., 2003; Denham, Haberle, & Lentfer, 2004). Detailed stratigraphic analyses of varying resolution enabled the provenance of samples used for paleoecological analysis and dating to be determined with precision. The archaeological and stratigraphic associations of individual samples were inferred with a high degree of accuracy, and taphonomic processes were evaluated. Although the analytical component of the renewed research was intensive, uncertainties have since emerged over how feature fills formed, as well as regarding the reliability of samples from different levels within those fills (usually upper, middle, and lower) to represent the agricultural activities with which they have been associated (Denham, Haberle, & Pierret, 2009). Consequently, contiguous multi-proxy analyses were necessary to verify previous results and interpretations of agricultural emergence and transformation.

In this paper, the results of multi-proxy analyses (X-radiography, diatom, pollen, and microcharcoal) to address issues of feature fill formation and sample association are presented. These samples were taken directly from sediment slices of monoliths used for X-ray analysis, collected through feature fills. The features are associated with key periods of archaeological interest: plant exploitation (ca. 10,000 cal yr B.P.), earliest cultivation (6950–6440 cal yr B.P.), and the earliest ditches (conservatively from ca. 4000 cal yr B.P.). Consequently, analytical results can be directly related to pedofeatures and soil structures within the stratigraphy. The contiguous sampling of feature fills enables more precise interpretations of archaeological remains at Kuk and sheds light on processes associated with plant exploitation, early agriculture, and agricultural transformation during the early, mid-, and mid-late Holocene, respectively.

GEOGRAPHICAL, ARCHAEOLOGICAL, AND PALAEOECOLOGICAL CONTEXTS

Kuk Swamp (5°47′S, 144°20′E) is located at ca.1560 m altitude on the floor of the Upper Wahgi Valley (Figure 1), one of the largest intermontane valleys along the highland spine of New Guinea. The wetland at Kuk is a relatively minor branch of the much more extensive North Wahgi Swamp. The Kuk Swamp catchment comprises heavily weathered tephra-mantled lahar deposits, primarily of Pleistocene age (Pain et al., 1987).

The Upper Wahgi Valley has a lower montane humid climate, an average annual temperature of 19°C, and annual rainfall of ca. 2700 mm (Hughes, Sullivan, & Yok, 1991). The climate is moderately aseasonal and dominated by local orographic effects (Powell et al., 1975). Seasonal variations in mean monthly rainfall, temperature, and humidity are moderate, slight, and slight, respectively (McAlpine, Keig, & Falls, 1983), with very low variability in annual rainfall (McAlpine, Keig, & Falls, 1983). A slight dry season occurs between May and June, although soil water content does not usually limit plant growth (McAlpine, Keig, & Falls, 1983).

Kuk is the type-site for the investigation of early agriculture in the highlands of New Guinea (Golson, 1977; Denham, 2007). Archaeological excavations at Kuk have identified multiple periods of human manipulation and drainage for cultivation dating from ca. 10,000 cal yr B.P. (Golson & Hughes, 1980) to the recent past (Bayliss-Smith et al., 2005). The chronology of archaeological remains has been reconstructed using radiocarbon dating, tephrochronology (cf. Coulter et al., in press), and stratigraphic associations (Denham, Golson, & Hughes, 2004).

The earliest activities date to ca. 10,000 cal yr B.P. (Denham et al., 2003:Tables S1, S2). Some researchers consider them to represent nascent agricultural activities (Golson & Hughes, 1980; Golson, 1991, 2007), whereas others consider them to represent broad-spectrum plant exploitation (Denham, 2003, 2004, 2007; Fullagar et al., 2006).

Palynological evidence indicates localized forest disturbance in the Kuk catchment during the terminal Pleistocene (Powell, 1982). From the beginning of the Holocene, anthropic disturbance increased (Denham & Haberle, 2008). During the early Holocene, the primary forest signal in pollen spectra declines and a *Pandanus* swamp forest became established on the wetland. Increased erosion rates within the catchment, represented by the deposition of an alluvial fan comprised of "gray clay" on the wetland margin between ca. 10,000 and 7000 cal yr B.P., have been associated with forest clearance for cultivation from the beginning of the Holocene (Golson & Hughes, 1980; Hughes, Sullivan, & Yok, 1991). Within this gray clay deposit, intact chains of banana (*Musa* sp.) phytoliths (Denham, Haberle, & Lentfer, 2004) and starch residues of tuberous plants on stone tools (Fullagar et al., 2006) are suggestive of continuity with earlier plant exploitation and later cultivation practices documented in archaeological excavations.

The earliest generally acknowledged evidence of agriculture at Kuk comprises the bases of former mounds—a form of raised bed used for cultivation—preserved on the wetland margin and dated to 6950–6440 cal yr B.P. (Kuk Phase 2; Golson, 1977; Denham et al., 2003). Although only a few stone tools have been found in association with these mounds, they indicate the exploitation of a tuberous plant (Fullagar et al., 2006). Importantly, elevated frequencies of banana (*Musa* sp.) phytoliths found within the fills of features associated with mounds are interpreted to represent the cultivation of bananas, most probably in multi-cropped plots, along the wetland margin (Denham et al., 2003; Denham, Haberle, & Lentfer, 2004).

At 6950–6440 cal yr B.P., the paleoecology of the catchment undergoes a profound change. Forests decline dramatically and grassland becomes dominant, a transformation associated with the expansion of agricultural activities across the valley floor (Denham & Haberle, 2008). Grasslands were maintained by periodic burning and persisted on much of the valley floor, with some localized forest recovery (Powell, 1970), until the arrival of Australian gold prospectors in 1933 (Denham, Haberle, & Lentfer, 2004; Denham & Haberle, 2008; Sniderman, Finn, & Denham, 2009).

Over the last 4000 years (Kuk Phases 3–6), the wetland has been repeatedly drained using ditches dug to form interconnected networks. Ditch networks have changed through time; earlier networks were rectilinear, trellis, and dendritic (Denham, 2005a), whereas later networks (after ca. 2000 years ago) were gridded to delineate plots of varying size and alignment (Bayliss-Smith et al., 2005). Multi-proxy investigations of ditched agriculture have been limited in comparison to earlier periods. However, early ditches at Kuk indicate cultivation occurred in a predominantly grass landscape.

RESEARCH RATIONALE

During previous investigations, macrofossil and microfossil assemblages within the fills of archaeological features were used to reconstruct past human activities and paleoenvironments on the wetland margin and within the catchment (Denham, 2003; Denham et al., 2003; Denham, Haberle, & Lentfer, 2004). The basal portion of often relatively homogeneous primary fills was usually assumed to be most representative of past plant exploitation and cultivation. However, various hypothetical interpretations cast doubt on the assumed reliability of using the basal portion of a fill to represent human activities associated with the past use of a feature (Figure 2; Denham, Haberle, & Pierret, 2009). For example, does the basal portion of the fill represent deposition shortly after a feature was dug (i.e., composed primarily of inwashed or slumped residual materials) or deposition of materials that accumulated on adjacent surfaces or mounds during use (i.e., composed primarily of soils and materials associated with plant exploitation or cultivation, respectively)? Highly divergent impressions of paleoenvironments and past human activities are obtained, depending on the derivation and formation of each sample of fill analyzed. Such uncertainties may be exacerbated in deeper features (i.e., ditches and paleochannels). According to different formation scenarios, different levels within the fill of features—and the plant macrofossil and microfossil assemblages contained therein—could be representative of, and associated with, past human activities documented archaeologically (Figure 2). Robust interpretations of past human activities at Kuk, as elsewhere, are dependent on establishing association between analytical data and archaeological contexts. In part, these issues have been addressed by relating multi-proxy sampling to detailed stratigraphic investigations of poorly differentiated fills, including X-radiography and thin-section description (Denham, 2003). However, an element of uncertainty remains that can only be addressed through renewed contiguous multi-proxy analysis (Denham, Haberle, & Pierret, 2009).

METHODS

In this study, five key archaeological features were targeted for contiguous, mixed method, and multi-proxy analyses. Feature 1404 is part of a paleosurface associated with plant exploitation at ca. 10,000 cal yr B.P. Although the exact function of this paleosurface and its constituent features are open to debate (Denham, Golson, & Hughes, 2004), this type of feature is considered to have been dug for the growing

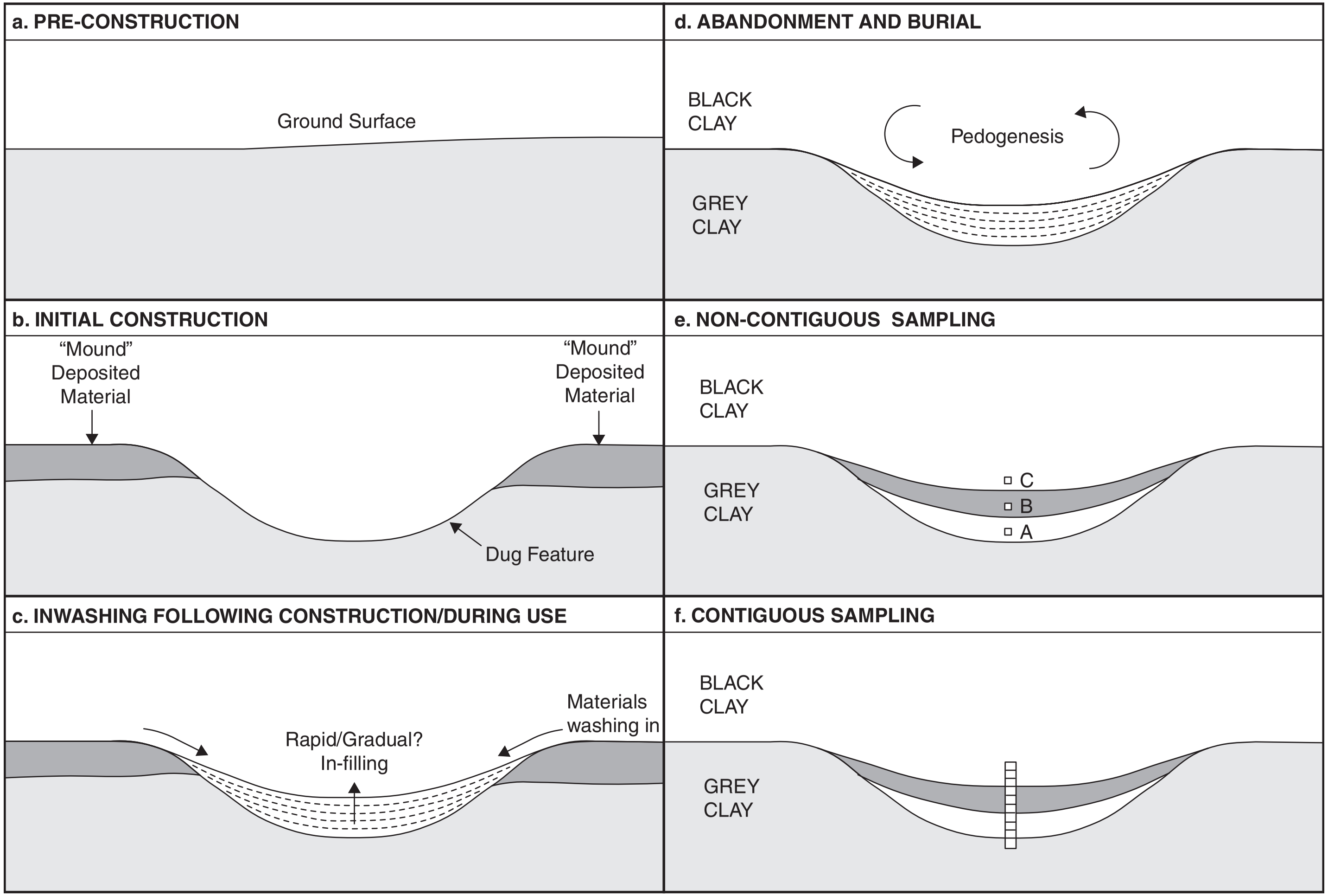


Figure 2. Schematic representation of former land surface (a) subject to mound construction (b); slopewash following construction and during use (c); abandonment, burial, and pedogenesis (d); archaeological excavation and original spot sampling (e); and subsequent contiguous sampling (f) (modified version of Denham, Haberle, & Pierret, 2009). Note how the archaeological associations of samples A, B, and C within different portions of the feature fill in (e) are unclear and partially determined by the nature and rate of infilling (c) and subsequent post-depositional alteration (d). Contiguous sampling and resultant multi-proxy analysis through the feature fill (f) are designed to identify that portion containing materials associated with former cultivation on adjacent mounds.

or gathering of taro (*Colocasia esculenta*) and other water-tolerant plants. Features 3003 (runnel) and 3004 (basin) form part of a paleosurface associated with mounded cultivation at 6950–6440 cal yr B.P. (Denham et al., 2003; Denham, Golson, & Hughes 2004). The features were dug to define—and to enhance microtopographical drainage around—mounds used for cultivation along the wetland margin (see Figure 2). The basal fills of a palaeochannel (107) and a ditch (353) were targeted to investigate the earliest ditch networks at Kuk, dated to ca. 4000 cal yr B.P. (Denham et al., 2003: Table S2; Denham, 2005a).

Contiguous sampling was undertaken to clarify the association between different parts of a fill, which had accumulated within an archaeological feature, and the human activities on the wetland margin, which had produced the archaeological feature, as well as associated environmental changes. The suite of multi-proxy techniques generates complementary information on local environments: pollen and microcharcoal provide local and extra-local environmental data; diatoms provide highly localized data on water and soil moisture conditions; and X-radiography provides medium-resolution information on depositional environments, post-depositional modifications, and sample integrity.

X-Radiography

In the field, intact monoliths were collected through the fills of archaeological features using sections of zinc piping. The location of each monolith was marked directly on excavation plans and stratigraphic profiles (Figure 1). A 1-cm-thick slice cut vertically down the monolith was X-radiographed and targeted segments were contiguously sampled for paired paleoecological analyses. The location of each sample was plotted directly on the X-radiograph.

X-radiography is a comparatively underutilized technique in archaeological contexts (see Barham, 1995, for discussion), although it offers a meso-scale level of investigation for soils, sediments, and fills often missing in archaeological studies (Gilbertson, 1995) and can link macro-level field descriptions to micromorphological description. At Kuk, a mixed-method approach was used to investigate stratigraphy and archaeological fills (after Canti, 1995; Denham, 2003). X-radiography can identify complex primary structures within "thick bedded" or "massive" sedimentary deposits, otherwise invisible or poorly expressed (Krinitszky, 1970).

A 1-cm-thick vertical slice was cut from each monolith and mounted on a Perspex base for X-radiography. Analysis was undertaken at CSIRO-Canberra using an Oxford XTG tube and phase contrast imaging system utilizing phosphor storage image plates (see Moran, Pierret, & Stevenson, 2000). X-ray absorption and phase contrast imaging enables greater differentiation of material types within samples compared to standard film radiography because the image represents refractive indices as well as X-ray absorption. During the current study, images are evaluated in terms of degrees of contrast that represent differential X-ray absorption. Optimal image contrast was obtained at 60 kV, 0.3 mA, and 30-second exposure. Terminology used follows Bullock et al. (1995), who propose generic descriptive terminology for stratigraphic descriptions at multiple scales.

Diatoms

Comparatively few archaeological studies have utilized diatoms (e.g., Denham et al., 1999; Trombold & Israde-Alcantara, 2005), despite high potential (Battarbee, 1988) and their widespread use in paleoecological studies (Smol, 2008). Diatoms are unicellular algae with a siliceous cell wall that preserves well in most sedimentary environments (Battarbee et al., 2001). They occur in all types of aquatic habitats and are highly sensitive environmental indicators of nutrient concentrations, salinity, pH, temperature, and light availability (Stoemer & Smol, 1999).

Samples for diatom analysis were prepared using standard methods (Battarbee, 1986). Samples were cleaned of all organic material and acid-soluble minerals by boiling in hydrogen peroxide and nitric acid. Samples were rinsed 4–5 times until a pH of 6–7 was reached, air-dried onto coverslips (22 × 22 mm) and mounted on glass slides using Naphrax. Five hundred diatoms were counted where possible; two slides per sample were counted in their entirety when fewer than 500 diatoms were present. Analysis occurred using an Olympus BH2 with oil immersion at 1500×. The relative abundance of all species (including unidentified forms) was recorded as a percentage of the total number of frustules counted for each sample (Battarbee et al., 2001). Taxonomy was based on Vyverman (1991, 1992); additional taxonomic and ecological references include Hustedt (1938, 1959), Patrick and Reimer (1966), Florin (1970), Lowe (1974), Krammer and Lange-Bertalot (1986, 1988, 1991a, 1991b), Krammer (1992, 2000), Vyverman et al. (1995), Cameron et al. (1999), and Lange-Bertalot (2001).

Pollen and Microcharcoal

Samples for pollen and microcharcoal analyses were processed by adapting standard palynological techniques (Moore, Webb, & Collinson, 1991). Samples from features 1404, 3003, 3004, and 107 were dispersed in warm sodium pyrophosphate, spiked with exotic *Lycopodium* spores (tablet form from Lund University, Sweden), then treated with KOH, concentrated HF, and acetolysis, followed by ethanol dehydration before mounting in glycerol on glass slides. Samples from 107 were generally difficult to disperse, which was probably due to allophane/organic complexes (Wood, 1987), and required a second HF treatment following acetolysis. In response to difficulties experienced in processing pollen samples from 107 and elsewhere in the Wahgi Valley (Sniderman, Finn, & Denham, 2009), samples from 353 were treated with a weak Schulz solution (1:10 w/v 35% HNO_3:$KClO_3$), before concentrating the organic residue with sodium polytungstate (Munsterman & Kerstholt, 1996), then treating with HF to remove residual amorphous silica.

To facilitate comparison among all features, despite differences in pollen diversity, diagrams are presented as summaries of major vegetation types and important taxa. These types include: primary forest (e.g., *Nothofagus*, Podocarpaceae, *Castanoposis*/*Lithocarpus*, and a range of other angiosperms, but excluding *Pandanus*), with *Nothofagus* and *Pandanus* depicted separately; secondary forest (i.e., woody, early seral taxa characteristic of forest regrowth, including Moraceae/Urticaceae, *Dodonaea*, *Celtis*, *Acalypha*, *Schefflera*, *Casuarina*, *Trema*, and *Psychotria*); herbs (predominantly Poaceae); Cyperaceae; aquatics (predominantly *Typha* and Melastomataceae); and Pteridophytes. Microscopic charcoal was counted as all black, angular, opaque particles $> 10\ \mu$m, and calculated as particles cm^{-3} (Patterson, Edwards, & Maguire, 1987).

Diatom, pollen, and microcharcoal figures were developed in the software program C2 version 1.4 (Juggins, 2003). Diatom and pollen data were $\log(x + 1)$ transformed for statistical analyses. Detrended correspondence analysis (DCA) was used to explore patterns of species compositional change between samples (Bradshaw, Rasmussen, & Odgaard, 2005). DCA is a powerful tool for summarizing multi-proxy sediment records and ecosystem dynamics (Birks & Birks, 2001). DCA, with detrending by segments, rescaling of axes, and downweighting of rare species, was performed on the diatom and pollen data using the software program R version 2.4 (R Development Core Team, 2006).

RESULTS

A composite stratigraphy for Kuk is presented to facilitate interpretation, including context numbers (Figure 3; note that context numbers are given in square brackets). Dating results for individual features and archaeological associations are published and discussed elsewhere (Denham, 2003; Denham et al., 2003; Denham, Golson, & Hughes, 2004). Monoliths were collected and radiographs taken of the lowest consolidated fills within each feature and underlying material, where possible. An exception was channel 107, because the basal fill was unconsolidated wet sediment.

A total of 55 samples were counted for diatoms and 76 species were identified. Of these, 51 occurred with a maximum relative abundance $\geq 1\%$. Diatom preservation was variable and particularly poor in the gray clay zones. Thirty-eight of the 55 samples had diatom counts > 100 and were used for interpretation. The diatom assemblages were characterized by three genera: *Aulacoseira*, *Luticola*, and *Synedra*, and to a lesser extent by the genera *Hantzschia*, *Eunotia*, and *Orthosira*. These genera indicate a wide range of habitat types and reflect both standing water and saturated and exposed soil conditions.

A total of 76 samples were counted for pollen and charcoal. Pollen proportions were calculated relative to a sum of dryland types. Dryland sums generally exceeded 200 (mean value 236), although only smaller sums of 150–200 could be achieved in eight pollen-poor samples (two within channel 107, and the six lowermost samples below and within feature 1404). Features 107 (111 pollen types observed) and 353 (73 types) were far more diverse and exhibited better pollen preservation than features 1404 (50 types), 3004 (44 types), and 3003 (41 types), which were older. Of note, *Pandanus* spp. are prominent in gray clay–derived fills, but a very minor component of 353 and 107. *Pandanus* spp. grains are unlikely to be preferentially preserved in oxidized gray clay–like sediments due to their thin walls. This suggests that differences in pollen diversity are not solely an artifact of differential preservation between aerobic and anaerobic contexts.

FIELD NAME	DESCRIPTION	INTERPRETATION	TEPHRA (symbol) [context number]
Topsoil [1]	Very dark brown silty clay	Topsoil associated with contemporary cultivation	Tibito (Z) [20}
Crumby black [3]	Black silty clay	Buried cumulative A horizon	Olgaboli (Q) [22]
			Baglaga (Y) [24]
Black clay [4]	Black clay	Buried cumulative A horizon	Kim (R) [26]
Grey clay [5]	Grey-brown clay	Buried B horizon reflecting oxic and anoxic environments	
Black organic clay [6+7]	Black organic-rich clay	Buried, immature A/C horizon (limited pedogenesis): upper mixed clay horizon [6] over a more organic clay [7]	Ep [28] Rom [29]
Peat [8]	Dark reddish brown peat with clay laminae, logs and tephra	Peat (autogenic), alluvium (detrital) and tephra (aeolian) sediments	

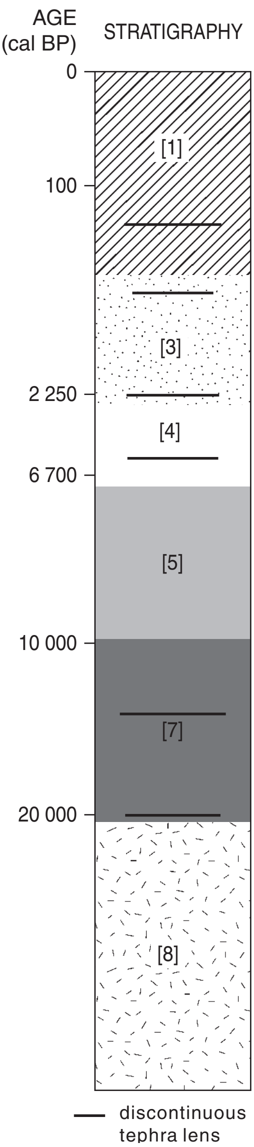


Figure 3. Stratigraphic summary of the site (modified version of Coulter et al., in press:Figure 4). Only the most significant tephrochronological markers are included and marked. Context numbers are given in square brackets and are applied to minor and major stratigraphic units, as well as to the cut and fills of features (Denham, 2003). R + W [27] is not displayed because it is a phytolith-rich deposit and not a tephra.

Plant Exploitation, ca. 10,000 cal yr B.P.

A monolith was collected from the fill of a feature [context 1404; Figures 1 and 3] to investigate the paleosurface, which was dated to ca. 10,000 cal yr B.P. (Denham, 2003; Denham et al., 2003, Denham, Golson, & Hughes, 2004; Denham, Haberle, & Lentfer, 2004). Visually, the upper portion of the monolith is massively structured gray clay [5], which is slightly marbled with black clay [4]. The portion of this deposit within the cut of the feature is considered a fill [1404a]. The lower portion of the underlying black organic clay [7], which in turn is marbled with gray clay [5], is also massively structured except for an Ep ash lens [28]. The basal 8 cm of the radiograph slice were subject to contiguous sampling for multi-proxy analyses: the gray clay–type fill [1404a] (samples 1–3 cm), namely a feature fill that is visually indistinguishable from gray clay [5], and underlying black organic clay [7] of Pleistocene age (samples 4–8 cm).

Within the radiograph (Figure 4a), there is a clear disjuncture between the upper, denser, massively structured, and relatively inorganic feature fill [1404a] and the lower, less dense, subangular, blocky to granular structured black organic clay. Both units have very few, filled and unfilled, medium and coarse macrochannels. These relatively recent macrochannels probably represent roots (confirmed by visual

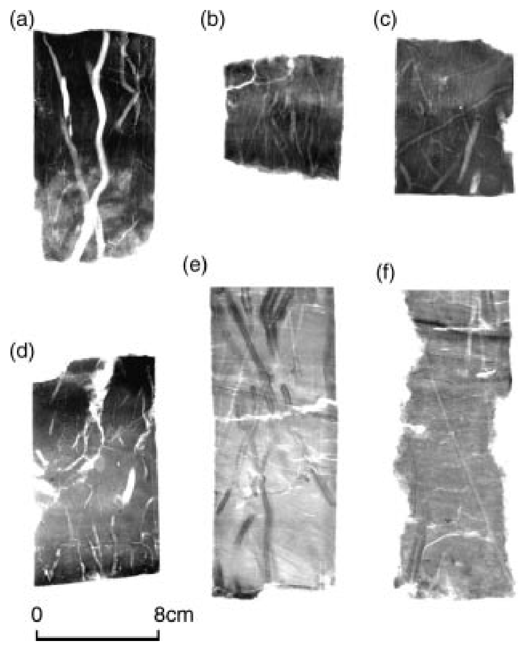


Figure 4. X-radiographs of monoliths from features at Kuk: (a) feature 1404; (b) feature 3004; (c) feature 3003; (d) ditch 353 (A4/A); (e) channel 107 (J/D); and (f) channel 107 (J/E). *Note:* Darker areas on the images represent denser material and lighter areas represent less dense material.

inspection showing root tissues) and faunal burrows (based on uniform widths, sinuosity, and lack of distributaries). The boundary between fill [1404a] and underlying black organic clay is abrupt and broken. The darker areas within the lighter fabric seemingly represent voids within the black organic clay infilled by gray clay. The lower portion of this X-radiograph suggests that the upper boundary of black organic clay may have been at or near a paleosurface subject to limited soil formation, which was subsequently buried underneath a gray clay–type fill. The infilled structural voids exhibit a subangular, blocky to granular structure characteristic of immature soil development.

Diatom preservation within the gray clay–type fill [1404a] was too poor for interpretation (Figure 5a). Consequently, the interpretation of diatom composition is restricted to underlying Pleistocene strata. From 4 cm and below, diatom composition is dominated by three aquatic taxa: *Aulacoseira italica* (Ehrenberg) Simonsen, *Aulacoseira* sp. 1 (currently undescribed), and to a lesser extent by *Eunotia praerupta* Ehrenberg. The base of the sequence is dominated by *A. italica*, benthic in eutrophic lakes, and *Synedra ulna* (Nitzsch) Ehrenberg, tolerant of high nutrient conditions. Additional species include *Luticola goeppertiana* (Bleisch) Mann, which is tolerant of pollution, and *Hantzschia amphioxys* (Ehrenberg) Grunow, which can occur in turbid environments (Vyverman, 1991). The decline in *A. italica* and *E. praerupta* upward from the base to 4 cm suggests lower nutrient concentrations. In addition, the increasing proportion of *Orthosira epidendron* (Ehrenberg) Crawford to a maximum of 6% relative abundance by 4 cm suggests an increasing presence of bryophytes (Vyverman, 1991), which occurred when the top of the organic-rich clay was exposed at the surface and subject to pedogenesis. Although the diatoms within black organic clay overwhelmingly indicate permanently wet conditions, aerophilous taxa *H. amphioxys*, *Pinnularia borealis* Ehrenberg var. *rectangularis* Carison, *L. goeppertiana*, and *O. epidendron* increased slightly. This general trend may suggest either deposition of soil washed in from the catchment or limited soil formation.

Pollen and microcharcoal values are variable throughout the sequence (Figure 5a). At the base of the diagram, primary forest taxa and *Pandanus* spp. exhibit low values, while herbs (dominated by Poaceae) and Cyperaceae dominate the dryland sum. The importance of grasses and sedges in Pleistocene levels probably reflects local conditions on the wetland, rather than vegetation communities on the valley floor and walls, which were forested (Denham, Haberle, & Lentfer, 2004; Denham & Haberle, 2008). Charcoal is present in relatively low and variable concentrations. Against a backdrop of variability, general trends indicate decreasing herb and primary forest, and increasing *Pandanus* spp. values up the profile; these changes are clearest in the upper 3 cm of the record and follow or are associated with charcoal peaks at 2–3 cm. The Pleistocene environment is clearly represented at 8 cm, while samples at 1–2 cm represent the fossil content of the gray clay–derived feature fill. The intervening samples from 4–7 cm probably represent decreasing amounts of intermixing with gray clay and pedogenesis at the top of the organic-rich clay.

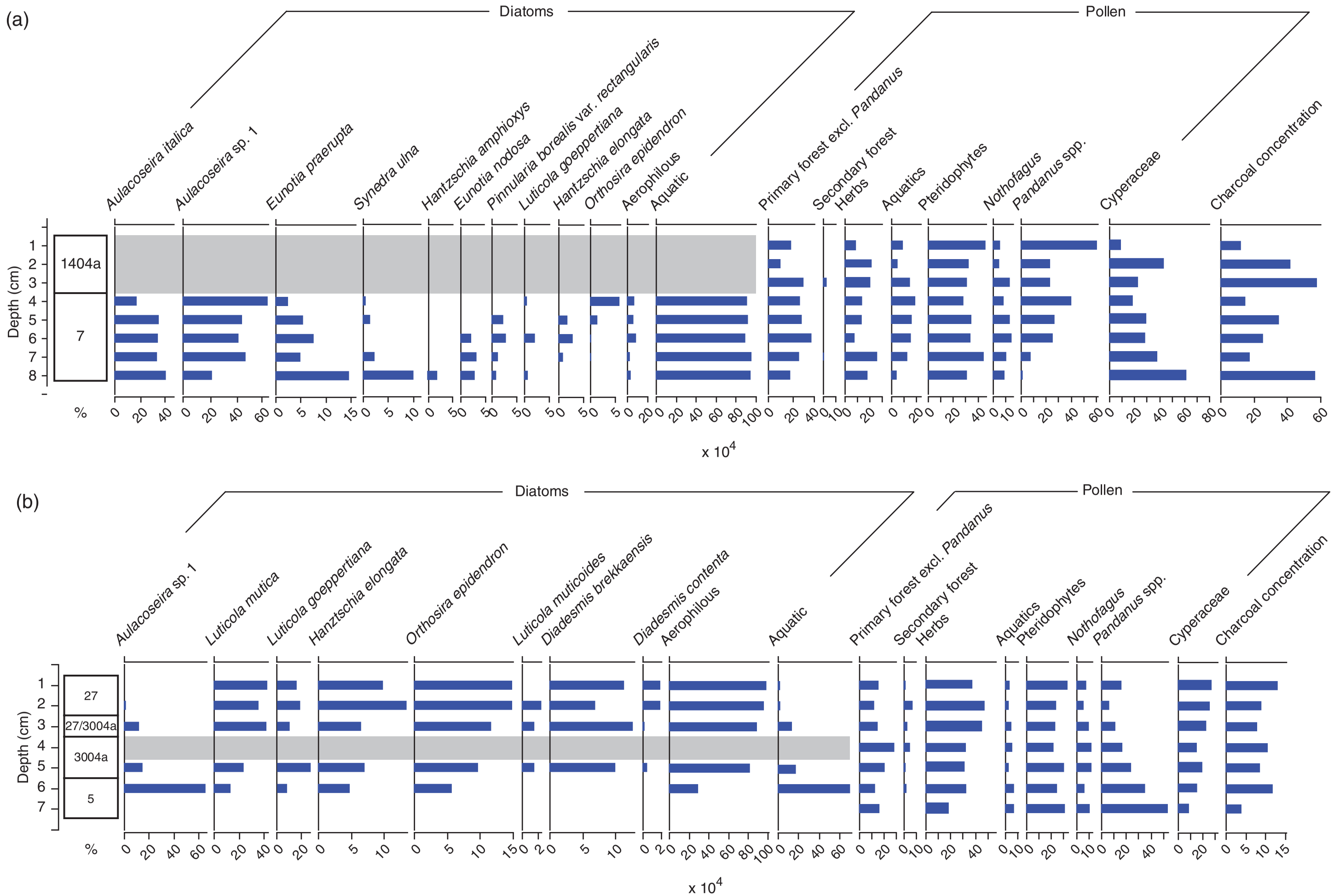
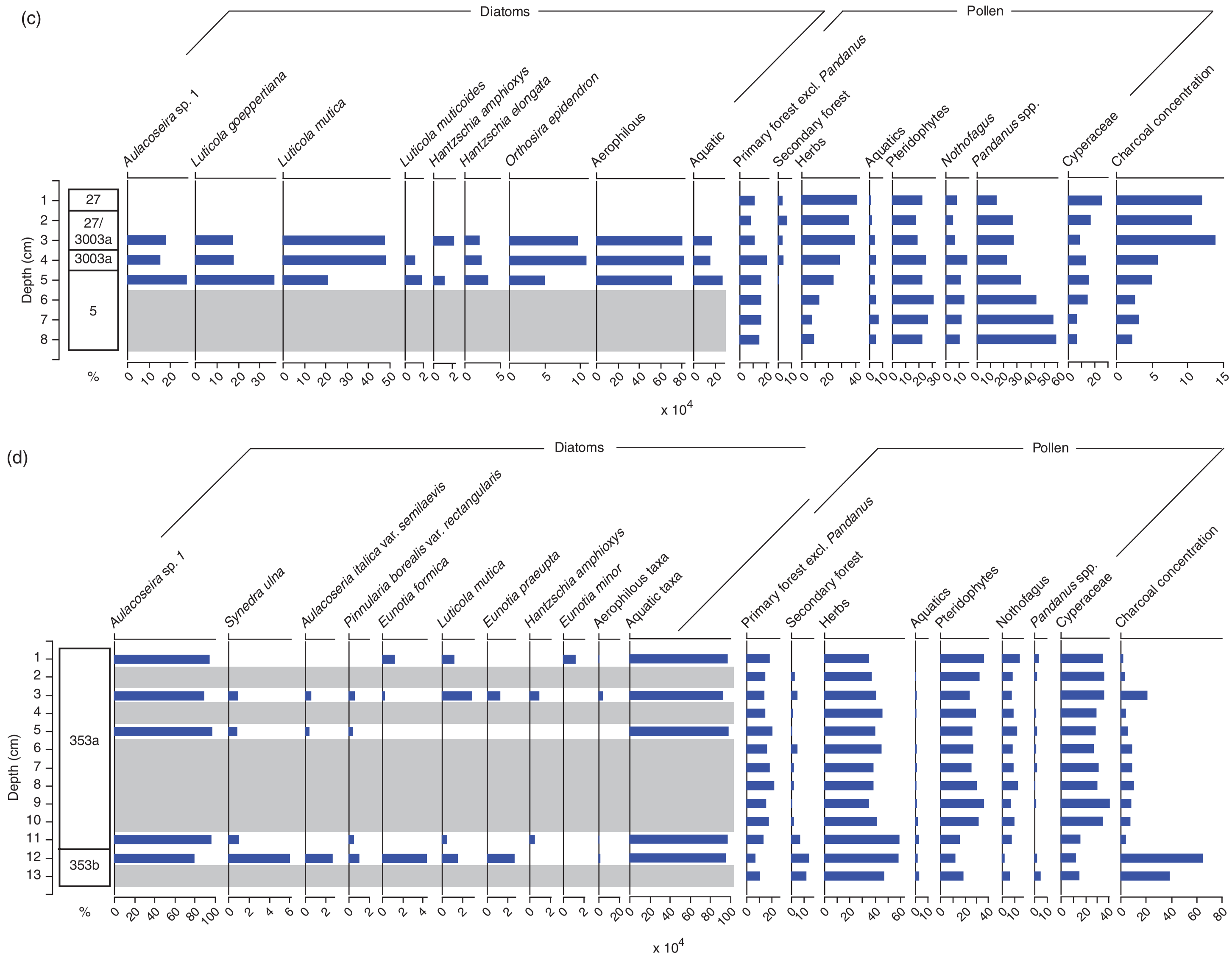


Figure 5. (*Continued*)


(c)
Diatoms
Pollen
Aulacoseira sp. 1
Luticola goeppertiana
Luticola mutica
Luticola muticoides
Hantzschia amphioxys
Hantzschia elongata
Orthosira epidendron
Aerophilous
Aquatic
Primary forest excl. Pandanus
Secondary forest
Herbs
Aquatics
Pteridophytes
Nothofagus
Pandanus spp.
Cyperaceae
Charcoal concentration
Depth (cm)
27
27/
3003a
3003a
5
%
x 10^4
(d)
Diatoms
Pollen
Aulacoseira sp. 1
Synedra ulna
Aulacoseria italica var. semilaevis
Pinnularia borealis var. rectangularis
Eunotia formica
Luticola mutica
Eunotia praeupta
Hantzschia amphioxys
Eunotia minor
Aerophilous taxa
Aquatic taxa
Primary forest excl. Pandanus
Secondary forest
Herbs
Aquatics
Pteridophytes
Nothofagus
Pandanus spp.
Cyperaceae
Charcoal concentration
Depth (cm)
353a
353b
%
x 10^4

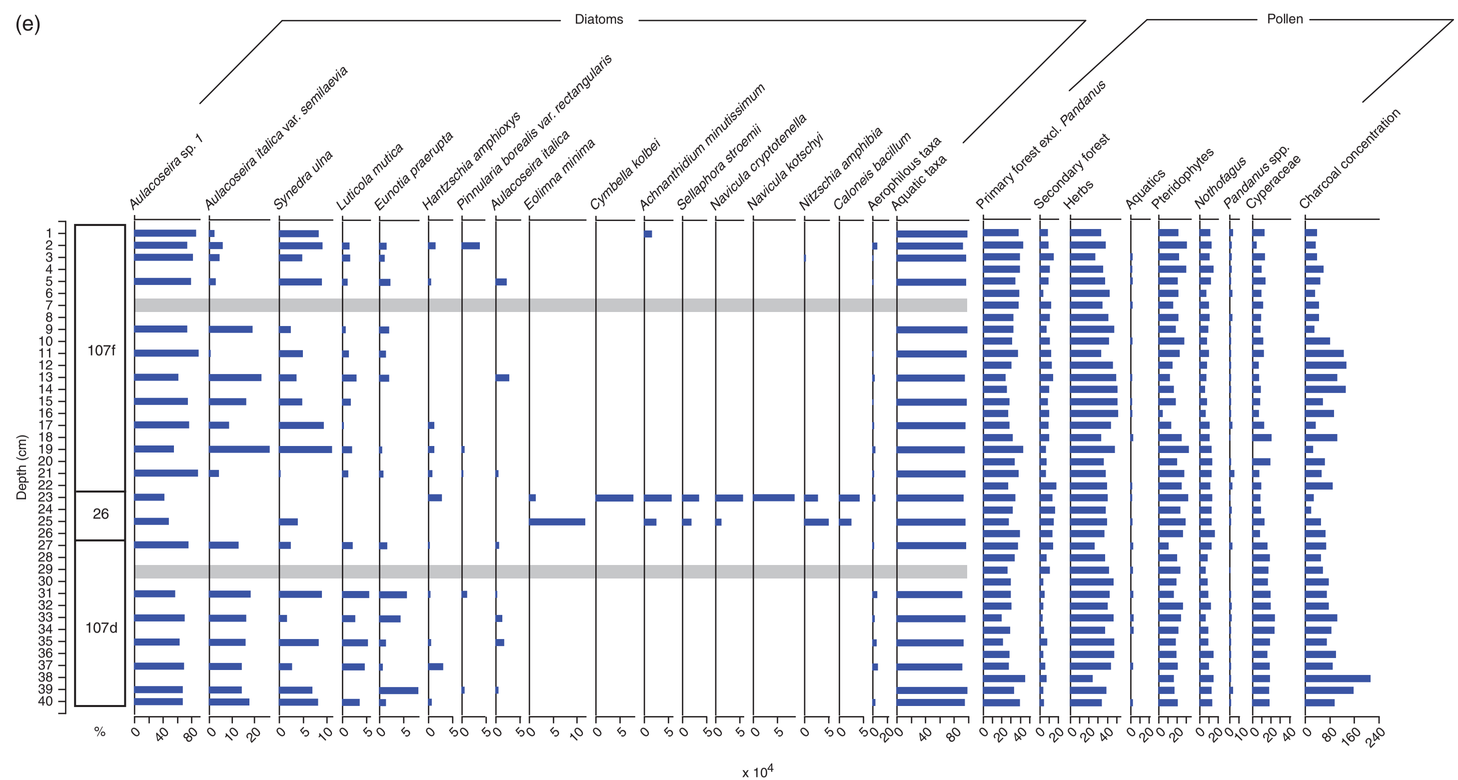


Figure 5. Diatom, pollen, and charcoal summary diagrams for (a) feature 1404, (b) feature 3004, (c) feature 3003, (d) ditch 353, and (e) channel 107. Refer to Figures 1 and 2 for the associated sections and stratigraphy, which are indicated by context numbers in the left-hand column. Gray boxes indicate samples containing <100 diatoms. Each taxon has also been classified as aerophilous or aquatic, for which summary percentages are depicted.

Mound Cultivation, 6950–6440 cal yr B.P.

Two features associated with mounded cultivation (dating to 6950–6440 cal yr B.P.; Denham, Golson, & Hughes, 2004) were sampled and contained similar stratigraphy (Figure 1): an upper lens of "R + W" [27], a black clay fill, and the underlying gray clay [5] into which the feature was cut. "R + W" is a phytolith-rich deposit dating to 6440–5990 cal yr B.P. (Denham et al., 2003:Table S2), which was formerly considered to be a tephra (Denham, Golson, & Hughes, 2004). In both monoliths, the lower boundary of R + W is diffuse, representing some intermixing with black clay fills. The underlying gray clay is marbled with black clay, suggesting the downward movement of black clay into voids within the gray clay.

A monolith collected through the fill of a deeper "basin" feature [3004] comprised: R + W (1–2 cm), a mixed R + W and black clay fill (3 cm), black clay fill (4–5 cm), and gray clay (6–7 cm) (Figure 4b). Another monolith collected through the fill of a shallower "runnel" [3003] composed of: R + W (1 cm), a mixed R + W and black clay fill (2–3 cm), black clay fill (4 cm), and gray clay (5–8 cm) (Figure 4c). Two units are clearly contrasted on both X-radiographs. The upper unit is lighter, with a greater density of predominantly vertically oriented, fine macrochannels; it corresponds to the black clay fills [3003a and 3004a] and R + W. The lower unit is darker, has fewer vertically oriented, fine macrochannels, and corresponds to gray clay. The macrochannels visible on the radiographs are probably roots, which are more frequent above gray clay, but still relatively abundant through gray clay. Very few filled, medium to coarse macrochannels with external ferric iron hypocoatings are present in both units. The R + W and black clay fills [3003a and 3004a] are lighter and less dense than underlying gray clay. Of significance, the lower boundary of the lighter zone in both radiographs is irregular and is suggestive of some form of disturbance or cut.

The diatom compositions of both contiguously sampled monoliths reflect a transition from wetter to drier conditions (Figures 5b, 5c). The lowest sample (6 cm) within gray clay below feature 3004 is dominated by *Aulacoseira* sp. 1, with *Luticola mutica* (Kützing) Mann and *Luticola goeppertiana* as minor components (Figure 5b). Upward through the black clay fill [3004a] and R + W lens above gray clay, aerophilous taxa become dominant through increases in *L. mutica*, *L. goeppertiana*, and *Orthosira epidendron*. The increasing proportion of *Diadesmis contenta* (Grunow ex van Heurck) Mann, absent from older sediments at Kuk, suggests drier conditions, shallowing, and perhaps shading by vegetation, because optimal conditions are at the air–water interface (Vyverman, 1991).

The gray clay below feature 3003 is characterized by poor diatom preservation (Figure 5c). However, from 5 to 3 cm, the diatom assemblage is dominated initially by *A.* sp. 1, *L. goeppertiana*, and to a lesser extent *L. mutica*, before becoming dominated by *L. mutica*. Both *L. goeppertiana* and *L. mutica* are tolerant of organic pollution (Salomoni et al., 2006). Although *A.* sp. 1 is an aquatic taxon and the assemblages are predominantly aerophilous, there are slightly drier conditions above 5 cm.

Significantly, one sample (6 cm) below feature 3004 is the only sample within gray clay with sufficient diatoms for interpretation. It suggests much wetter conditions, probably standing water, which contrasts with the moist and drier conditions within the fills of both features [3003a and 3004b], and plausibly all cut features around mounds during cultivation on the wetland margin. In comparison to the terminal Pleistocene/early Holocene period represented by feature 1404, the diatom records for features 3003 and 3004 indicate a shift from predominantly standing water below gray clay, to an exposed but damp soil environment above gray clay.

The pollen signal in both features is similar (Figures 5b, 5c): gray clay samples are relatively rich in *Pandanus* spp. and primary forest taxa, while feature fills are dominated by herbs with some secondary forest taxa. Charcoal concentrations are higher within feature fills, particularly in 3003. However, there are transitions in pollen and charcoal frequencies that suggest sediment mixing and/or pollen translocation across the boundary near the base of each feature. For feature 3003, the transition is reflected in increasing Poaceae and decreasing *Pandanus* spp. values from 7 cm to 3 or 4 cm. For feature 3004, admixing along the boundary may be greater than for 3003 and is reflected in intermediate Poaceae and charcoal values, as well as gradually decreasing *Pandanus* spp. values from 6 to 4 cm.

Early Ditch Networks, ca. 4000 cal yr B.P.

Two features, a palaeochannel (107) and a ditch (353), associated with the earliest artificial drainage networks at Kuk (Denham, 2005a), were selected for investigation (Figure 1). Both features are relatively well dated: channel 107 to ca. 4260–3830 cal yr B.P. (Denham et al., 2003:Table S2) and ditch 353 to 4350–3980 cal yr B.P. (Denham et al., 2003:Table S1). Previous multi-proxy analyses within these features were comparatively limited (Denham, 2003).

Ditch 353

A series of monoliths were collected through the fills of ditch 353, but only the lowest monolith (A4/D) was analyzed as part of this study. Visual inspection shows an upper, root-penetrated "new gray clay fill" [353b, 1–11 cm], which is a discontinuous deposit at Kuk (Denham, Golson, & Hughes, 2004:289), with some black marbling. There is an abrupt lower boundary between 11 and 12 cm to black clay fill [353a, 12–13 cm]. A lighter band hinders demarcation of the boundary between upper and lower fills within the radiograph (Figure 4d). The upper, homogenous and dense, dark area within the radiograph is penetrated by an unfilled, slightly off-vertical, fine megachannel and very few, partially filled, vertically oriented, medium macrochannels. Several coarse macrochannels are present within the lighter band, with a continuation of some of the finer macrochannels. Toward the base of the lighter band, several coarse macrochannels with ferric iron hypocoatings can be seen (length < 3 cm), which predominantly represent roots or faunal burrows.

The basal fills of ditch 353 are characterized by poor diatom preservation; only 5 out of 13 samples were sufficient for interpretation (Figure 5d). These samples are dominated by *Aulacoseira* sp. 1, an aquatic taxon. Poor diatom preservation, particularly in the upper fill, may be a result of rapid, mid-late Holocene deposition of clay-rich sediment, visually comparable to the early Holocene gray clay [5], following a new episode of erosion within the catchment (Denham, 2003). If the ditch had filled gradually, like many others at Kuk, it would be anticipated to contain relatively rich assemblages of diatoms with preferences for aquatic and moist conditions.

The pollen assemblage within ditch 353 is more floristically diverse than within features 1404, 3003, and 3004 (Figure 5d). There is a discontinuity centred on 10–11 cm that reflects the boundary between the two fills. The lower fill [353a] is relatively rich in herbs, secondary forest taxa, and charcoal, whereas the upper fill [353b] is characterized by higher primary forest, Cyperaceae, ferns, and *Nothofagus* values, and lower herb and charcoal values. These changes, dominated by fluctuations in Poaceae, Cyperaceae, and ferns, may reflect in part changing hydrological conditions within the fill in response to changing deposition rates, and in part admixture with locally reworked Late Pleistocene material, which is *Nothofagus*-dominated, into Holocene post-clearance sediments. Valley-wide changes in vegetation are a less plausible explanation, since primary forest and *Nothofagus* were not extensive in the vicinity at this time; *Nothofagus* grew at higher altitudes, or had a minor presence at Kuk, during the Holocene (Denham, Haberle, & Lentfer, 2004; Denham & Haberle, 2008; Sniderman, Finn, & Denham, 2009).

Channel 107

A series of monoliths were collected through the fills of channel 107. The basal fill was unconsolidated and could not be sampled as a monolith. The lowest two monoliths (J/D and J/E) were analyzed in order to shed light on paleoenvironments associated with and following the abandonment of early ditch networks, which articulated with channel 107.

The radiograph (Figure 4e) of monolith J/D shows fine laminae of well-preserved, predominantly organic-rich sediments throughout the main unit [107f], with occasional fine laminae of mineral rich material (which appear darker in the radiograph). The laminae appear contiguous and are slightly inclined. Several laminae of very fine (silt-sized or less) tephra, identified as R ash [26] and dated to 3980–3630 cal yr B.P. (Denham et al., 2003:Table S2), slope diagonally across the center of the slice. The frequency of macrochannels decreases with depth; only very few medium macrochannels continue to the base. These macrochannels are filled and have weak to moderately impregnated ferric iron hypocoatings. The thickness of hypocoatings varies in the radiograph, although this may be an artifact of the potentially variable thickness of the slice.

On visual inspection, monolith J/E is highly heterogeneous, with speckles of distinctly contrasted material throughout (Figure 4f). These speckles are not depicted in the radiograph, which shows stratified organic-rich deposits [107d, f] with some laminae of fine inorganic material. The main dark band near the top of the slice is a lens of R ash [26], with several very fine lenses of the same tephra 1–2 cm below the main band. The frequency of macrochannels continues to decrease with depth and is inversely related to the degree of preservation of inherited stratification. The organic-rich nature of these basal sediments and their fine laminae suggest that they are not associated with fluvial deposition within the paleochannel. Rather, they are more consistent with gradual colluvial and autochthonous accumulation within an abandoned reach. Inorganic material was washed in from adjacent land surfaces and peat accumulated *in situ* under waterlogged conditions.

The deposition of R ash within the fills of channel 107 is clear in the stratigraphy; lenses of R ash bifurcate and interleave with sediments. The main occurrence (23–26 cm) is plausibly associated with primary eolian deposition of the tephras, whereas the upper lenses derive from secondary alluvial and colluvial redeposition. Interleaved material between fine ash lenses represents the accumulation of slope-washed or detrital, organic and mineral material. These sediments represent a relatively short period, probably weeks or months, and accumulated after the channel had been abandoned. Consequently, the channel 107 fills analyzed here probably accumulated over decades rather than centuries.

Diatom assemblages within channel 107 are relatively well preserved and constant (Figure 5e). Only two samples (7 and 29 cm) contained insufficient diatoms for interpretation. Nearly all samples were dominated by aquatic taxa *Aulacoseira* sp. 1 and *Aulacoseira italica* var. *semilaevis* (Grunow) Valeva & Temniskova-Topalova. Aquatic-dominated assemblages are anticipated within an aggrading, and abandoned channel, which is likely to have contained standing or slow-moving water. There was a sudden change in conditions at 25 and 23 cm, corresponding to the main R ash lens, where the diatoms previously present dramatically decreased, or disappeared, and new species appeared that were previously absent from the record. These diatoms are suggestive of standing water and altered water chemistry, as indicated by *Eolimna minima* (Grunow) Lange-Bertalot, *Cymbella kolbei* Hustedt, *Achnanthidium minutissimum* (Kutzing) Czarnecki, *Sellaphora stroemii* (Hustedt) Kobayasi, *Navicula cryptotenella* Lange-Bertalot, *Navicula kotschyi* Grunow, *Nitzschia amphibia* Grunow, and *Caloneis bacillum* (Grunow) Cleve, which are aquatic taxa (Vyverman, 1991).

Pollen assemblages within channel 107 are relatively uniform and charcoal values fluctuate gradually (Figure 5e). There is a slight increase in secondary forest taxa and a slight decrease in Cyperaceae above 27–30 cm, which corresponds to the deposition of the main R ash lens. Otherwise the record presents a picture of continuous local importance of herbaceous taxa and pteridophytes, with substantial values of primary and secondary forest, which are interpreted as background signals, based on evidence for extensive deforestation of the valley at this time (Denham & Haberle, 2008). Values for primary forest are higher (mean value = 33%) in this feature than in others (mean values = 15–24%), primarily because of the greater contribution (6–20% of the dryland sum) of *Castanopsis*/*Lithocarpus*. The increase in *Castanopsis*/*Lithocarpus* is locally derived and suggestive of either forest recovery or managed stands within the catchment.

DISCUSSION

The contiguous multi-proxy analyses at Kuk have substantive and methodological significance. Substantively, the findings provide high-resolution paleoenvironmental information to augment previous analyses and archaeological interpretations. Methodologically, the findings demonstrate the importance of contiguous sampling, rather than spot sampling, to understand site formation processes and to correlate samples with past human activities and archaeological remains.

Palaeoenvironments and Taphonomy

The analyses expand previous interpretations of local and extra-local paleoenvironments at Kuk associated with early and later agricultural activities. X-radiographs of feature fills and diatom assemblages largely reflect highly localized environments within or adjacent to a feature. Pollen and microcharcoal analyses provide complementary information on local environments and shed light on vegetation history and human activities within the catchment.

The diatom assemblages show substantial changes, particularly in response to a change from open water in the terminal Pleistocene to saturated and exposed soil conditions by the mid-Holocene (compare Figure 5a to Figures 5b, 5c). A short-lived drying event at c. 10,000 cal yr B.P. was associated with formation of an immature soil profile during human use of the wetland margin. The most apparent transition occurs at the time of mounded cultivation at 6950–6440 cal yr B.P., when aerophilous diatoms dominate. Drier conditions were prolonged; gray clay and black clay are both homogenized deposits that lack well-preserved stratification, except for lenses of R + W in feature fills and depressions, as well as discontinuous lenses of R ash within feature fills and occasionally within the black clay unit.

Although mid-late Holocene assemblages (Figures 5d, 5e) are dominated by aquatic taxa, the assemblages are distinct from those of the terminal Pleistocene, when Kuk was an open water environment. Although high proportions of *Aulacoseira* sp. 1, and to a lesser extent *Synedra ulna* and *Eunotia praerupta*, are common to both periods, overall diatom compositions vary. The variations do not solely reflect those between an open water system (terminal Pleistocene) and standing water environments within abandoned paleochannels and ditches (mid-late Holocene). Specifically, the lower abundance of species tolerant of high nutrients, pollution, and turbidity in the mid-late Holocene suggests better water quality within the abandoned waterways. The retention of fine stratification within the fills of channel 107 indicates prolonged sediment anoxia, whereas the fills of ditch 353 are shallower below ground surface, drier, and more homogenous.

Pollen and microcharcoal results provide greater interpretive resolution for understanding the environmental context of early plant exploitation and agricultural activities at Kuk, as well as how these activities in turn changed the environment. Stepped changes in vegetation history are clearest when evaluated against the microcharcoal record. Microcharcoal frequencies are lowest during the terminal Pleistocene, with a slight peak associated with drier conditions locally at ca. 10,000 cal yr B.P., which is contemporary with human use of the wetland margin. Herbaceous taxa dominate the record locally, but forests were extensive on the valley floor and walls during the terminal Pleistocene. Forests were subject to increasing levels of disturbance during the early Holocene.

During the period of gray clay deposition, between 10,000 and 7000 cal yr B.P., Kuk reverted to wetter conditions. The dominance of *Pandanus* spp. within gray clay, accounting for up to 60% of the dryland pollen, supports previous inferences of a *Pandanus* swamp forest at Kuk during this period (Denham, Haberle, & Lentfer, 2004). Dominance of *Pandanus* spp. pollen is generally associated with lower microcharcoal levels, whereas more recent contexts characteristically have higher herbaceous pollen and higher microcharcoal levels.

The advent of locally drier conditions, associated with the mounded cultivation at 6950–6440 cal yr B.P., coincides with higher levels of burning, dramatic falls in *Pandanus* and other forest species, and dramatic increases in herbs, predominantly grasses. These general patterns were documented during previous work (Denham et al., 2003; Denham, Haberle, & Lentfer, 2004). Of interest to the current study, however, are the admixed pollen and microcharcoal signals within the primary fills of features associated with mounded cultivation. The admixed record most plausibly results from the slopewashing of gray clay–derived material into the feature shortly after construction and during cultivation.

Except for the reworked fill (353b) within ditch 353, mid-late Holocene microcharcoal records are much higher than those recorded in the terminal Pleistocene to mid-Holocene sections. The differences may partially be accounted for by preservation, but may also reflect the periodic burning of grasslands on the valley floor. The high forest pollen values for channel 107 samples are seemingly anomalous for Holocene samples at Kuk (Denham et al., 2003) and a comparably aged record from Ambra Crater (Sniderman, Finn, & Denham, 2009). However, the channel 107 record is consistent with forest recovery noted at Warrawau (Powell, 1970) and may suggest a spatially restricted expansion of *Castanopsis*/*Lithocarpus* on the floor and lower slopes of the Upper Wahgi Valley at ca. 4000 cal yr B.P.

Analyses of DCA Axis 1 sample scores of diatom and pollen data can provide a summary of compositional change, which can be useful for interpreting major shifts and patterns in species data (Bradshaw, Rasmussen, & Odgaard, 2005). Surprisingly, the greatest compositional change in both the diatom and pollen data occurred between the mid- (features 3003 and 3004) and mid-late Holocene (channel 107 and ditch 353), while little compositional change occurred between the terminal Pleistocene and early and mid-Holocene (Figures 6a, 6b). For diatoms, this finding primarily reflects differences in local environments of deposition, especially local hydrology, between paleosurface features (1404, 3003, 3004) and waterways (107, 353). Abrupt compositional change in the diatom flora also marks the deposition of R ash at 23–25 cm within channel 107 (mid-late Holocene). For pollen, the finding is more surprising because both mid- and mid-late Holocene environments are considered to reflect grasslands maintained by burning (Denham & Haberle, 2008). As detailed above, the compositional change may reflect taphonomic processes rather than paleoenvironmental change.

Past Practices and Multi-Proxy Interpretation

Contiguous multi-proxy analysis through the fills of archaeological features at Kuk was considered necessary to address outstanding issues of feature fill formation and sample representativeness. Our interpretations show the value of using contiguous samples, as well as the importance of a multi-proxy approach.

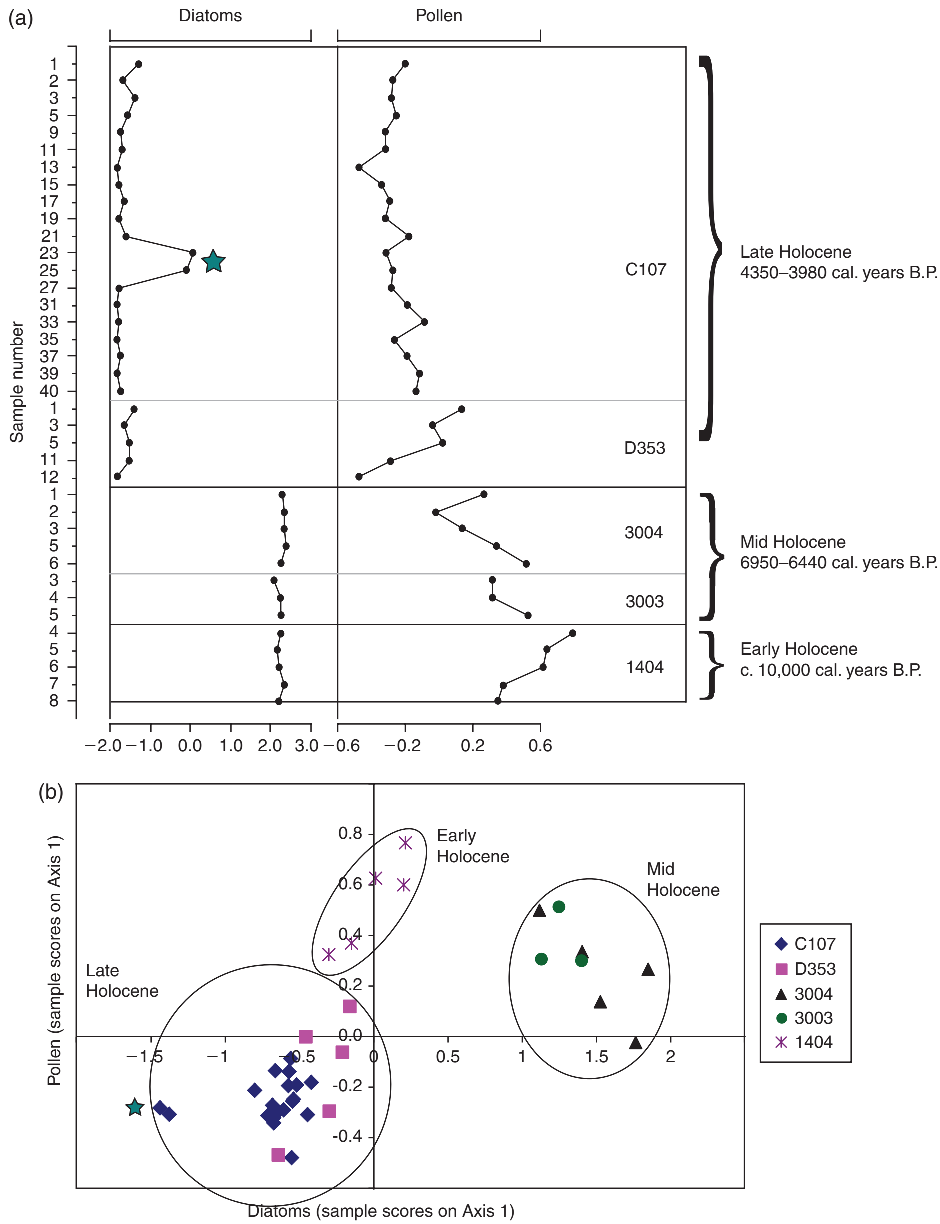


Figure 6. Detrended correspondence analysis for the diatom and pollen data in the different sections, demonstrating compositional change between samples and sections. Only those samples with both diatom and pollen data are illustrated. (a) Chronological depiction of DCA Axis 1 sample scores for the three distinct time periods and five sections. Each sample is represented by a dot. *Note:* The degree of variation in the diatom data is much greater than in the pollen data (as indicated by the scale on the x-axis). The gray star signifies an R ash lens dated to ca. 3980–3630 cal yr B.P. (b) Plot of diatom sample scores and pollen sample scores (Axis 1 only), showing a clear distinction between the early and mid-Holocene compared to the mid-late Holocene samples. The star highlights the outliers in both figures.

The investigation of feature 1404 enables high-resolution interpretation of site-formation processes at 10,000 cal yr B.P. Of note, the X-radiograph shows limited soil formation at the top of the black organic clay, which was exposed at the surface when the feature was dug. Pedogenic intermixing of this unit with gray clay–derived fill, visible as marbling, is reflected in transitional pollen assemblages (samples 4–7 cm). The uppermost and lowest samples (1 cm and 8 cm) are characteristic of gray clay and black organic clay (respectively) and post-date and pre-date the earliest plant exploitation at ca. 10,000 cal yr B.P. (Denham, 2005b; Golson, 2007). The basal fill samples (2–3 cm) are considered most representative of the paleoenvironments at the time that the land surface was used; they are associated with increased burning and slightly higher herb values, but otherwise do not indicate large-scale environmental change. Wholesale environmental transformation is not anticipated to accompany plant exploitation within a small patch or plot on the wetland margin. Although diatoms are poorly preserved in the fill, a slightly drier local environment is indicated within black organic clay that was exposed at the surface at the base of the feature. In sum, the local drying of the environment (diatoms) enabled human manipulation and use of a portion of the wetland (archaeology), which included burning and limited transformation of the vegetation (microcharcoal and pollen) and was short-lived (immature soil development in X-radiograph).

The multi-proxy analyses of features 3003 and 3004 provide relatively clear impressions of site formation and human activities associated with mounded cultivation at 6950–6440 cal yr B.P. The most dramatic trends are the reduction in *Pandanus* spp. and increases in burning and herbaceous taxa from gray clay to black clay fill. Diatom assemblages record a shift from aquatic to aerophilous local environments across this boundary. In sum, several major transformations to the local and extra-local environment occurred at 6950–6440 cal yr B.P.: the drier, but still damp, soil environment (diatoms) enabled, and was enhanced by, mound construction (archaeology); and human use of the wetland transformed the environment to grassland maintained by periodic burning (pollen and macrocharcoal). These multi-proxy results are consistent with interpretations of mounded cultivation on the wetland margin.

The multi-proxy analyses for mid-late Holocene features associated with early ditch networks are less conclusive. The basal fill of ditch 353 (353a) indicates high burning, high herb, and low forest values, whereas the new gray clay fill (353b) indicates low burning, slightly lower herbaceous, and slightly higher forest taxa. The lowest two samples are considered most representative of the environment when the first ditches were constructed at Kuk, whereas the new gray fill is considered to represent the relatively rapid deposition of reworked material, including Pleistocene-aged *Nothofagus* pollen, from the catchment. The latter interpretation is corroborated by the paucity of diatoms within fill 353b. By contrast, the fills of channel 107 exhibit good diatom, pollen, and microcharcoal preservation, and retain stratification associated with original deposition. The paleoecological assemblages within channel 107 are almost uniform down the profile, which is expected, given that it probably formed over several decades. The only deviation occurs within an R ash lens and comprises a different composition of aquatic diatom taxa; this is not clearly registered in the pollen assemblages. Primarily, the fills of channel 107 reflect an open, herbaceous-dominated environment with some local recovery (compared to features 3003 and 3004) of *Castanopsis/Lithocarpus*, which may be attributable to managed groves.

The multi-proxy analyses have verified and augmented previous interpretations of human activities on the wetland margin at Kuk during the early, mid-, and mid-late Holocene. The analyses provide methodological rigor previously unachieved at Kuk, or at any other site in the region. Additionally, they enable a degree of interpretive detail and chronological resolution that grounds, but was missing from, previous investigations (Denham et al., 2003; Denham, Haberle, & Lentfer, 2004). The results of multi-proxy analyses remove any doubts regarding site formation processes within these contexts and provide a more reliable basis for reconstructing the emergence and transformation of agricultural activities at Kuk.

CONCLUSIONS

Contiguous multi-proxy analyses (X-radiography, diatom, pollen, and microcharcoal) have been conducted through the fills of early, mid-, and mid-late Holocene features at Kuk. The analyses were prompted by uncertainties regarding the reliability and association of different samples within features for the interpretation of plant exploitation and agricultural activities in the past. Methodologically, these investigations enable: higher-resolution interpretation of the paleoenvironments at the time of human activities on the wetland margin; the characterization of site formation processes, particularly pedogenesis; and the determination of samples most representative of past activities on the wetland margin.

Most importantly, the adoption of multi-proxy analyses permits more precise interpretations of key archaeological remains associated with plant exploitation and early agricultural practices at Kuk in the highlands of Papua New Guinea. A relatively short-lived period of plant exploitation occurred on the wetland margin at ca. 10,000 cal yr B.P. and local characterizations suggest drier conditions, limited soil formation, disturbance by burning, and resultant opening up of the landscape. Mounded cultivation was practiced at 6950–6440 cal yr B.P. and is associated with marked paleoenvironmental transformations including drier, but still damp, conditions on the wetland margin, together with increased microcharcoal levels and herbaceous taxa representing the establishment of grassland maintained by periodic burning. By contrast, the earliest ditch networks, dating to ca. 4000 cal yr B.P., provide less conclusive reconstructions, largely due to the presence of locally reworked sediment in some ditch fills; however, open grassland environments are indicated, with potentially some managed groves. The methodological rigor and substantive contributions of these multi-proxy analyses not only augment the precision of geoarchaeological reconstructions at Kuk Swamp; they also provide a "best practice" guide for future work in the region.

Denham conducted the fieldwork at Kuk (1998–1999), directed the laboratory investigations, and is primarily responsible for the interpretation of results. Sniderman undertook the pollen and microcharcoal analyses. Winsborough undertook the diatom counts, and Saunders interpreted the results as well as assisting with overall site interpretation. Pierret undertook the X-ray image analysis at Land and Water, CSIRO-Canberra. The fieldwork was supported by the Australian National University while Denham was a PhD student. The analytical research was supported by Flinders University (small grant 250-1251), a Monash Research Fellowship, and an ARC Discovery postdoctoral research fellowship. We thank Mac Kirby (Land and Water, CSIRO-Canberra) for facilitating the X-ray image analysis, as well as Gary Huckleberry and two anonymous reviewers for constructive comments on an earlier version of this manuscript.

REFERENCES

Barham, A.J. (1995). Methodological approaches to archaeological context recording: X-radiography as an example of a supportive recording, assessment and interpretative technique. In A.J. Barham & R.I. MacPhail (Eds.), Archaeological sediments and soils: Analysis, interpretation and management (pp. 145–182). London: Institute of Archaeology, UCL.

Battarbee, R.W. (1986). Diatom analysis. In B.E. Berglund (Ed.), Handbook of Holocene palaeoecology and palaeohydrology (pp. 527–570). Chichester: John Wiley & Sons.

Battarbee R.W. (1988). The use of diatom analysis in archaeology: A review. Journal of Archaeological Science, 15, 621–644.

Battarbee, R., Carvalho, L., Jones, V., Flower, J., Cameron, N., Bennion, H., & Juggins, S. (2001). Diatoms. In J. Smol, H. Birks, & W. Last (Eds.), Tracking environmental change using lake sediments, Vol. 3: Terrestrial, algal and siliceous indicators (pp. 155–202). Dordrecht: Kluwer Academic Publishers.

Bayliss-Smith, T., & Golson, J. (1992). A Colocasian revolution in the New Guinea highlands? Insights from Phase 4 at Kuk. Archaeology in Oceania, 27, 1–21.

Bayliss-Smith, T.P., Golson, J., Hughes, P., Blong, R., & Ambrose, W. (2005). Archaeological evidence for the Ipomoean Revolution at Kuk Swamp, upper Wahgi valley, Papua New Guinea. In C. Ballard, P. Brown, R.M. Bourke, & T. Harwood (Eds.), The sweet potato in Oceania: A reappraisal (pp. 109–120). Sydney: Ethnology Monograph 19, Department of Anthropology, University of Pittsburgh, and Oceania Monograph 56, University of Sydney.

Birks, H.H., & Birks, H.J.B. (2001). Recent ecosystem dynamics in nine North African lakes in the CASSARINA Project. Aquatic Ecology, 35, 461–478.

Bradshaw, E.G., Rasmussen P., & Odgaard B.V. (2005). Mid- to late-Holocene land-use change and lake development at Dallund So, Denmark: Synthesis of multiproxy data, linking land and lake. The Holocene, 15, 1152–1162.

Bullock, P., Federoff, N., Jongerius, A., Stoops, G.J., & Tursina, T. (1985). Handbook for soil thin section description. Wolverhampton: Waine Research Publications.

Cameron, N.G., Birks, H.J.B., Jones, V.J., Berge, F., Catalan, J., Flower, R.J., Garcia, J., Kawecka, B., Koinig, K.A., Marchetto, A., Sánchez-Castillo, P., Schmidt, R., Šisko, M., Solovieva, N., Štefková, E., & Toro, M. (1999). Surface-sediment and epipelic diatom pH calibration sets for remote European mountain lakes (AL:PE Project) and their comparison with the surface waters acidification programme (SWAP) calibration set. Journal of Paleolimnology, 22, 291–317.

Canti, M. (1995). A mixed-method approach to geoarchaeological analysis. In A.J. Barham & R.I. MacPhail (Eds.), Archaeological sediments and soils: Analysis, interpretation and management (pp. 183–190). London: Institute of Archaeology, UCL.

Coulter, S.E., Denham, T., Turney, C.S.M., & Hall, V.A. (in press). The geochemical characterization and correlation of locally distributed Late Holocene tephra layers at Ambra Crater and Kuk Swamp, Papua New Guinea. Geological Journal, 44.

Denham, T.P. (2003). The Kuk morass: Multi-disciplinary investigations of early to mid-Holocene plant exploitation at Kuk Swamp, Wahgi Valley, Papua New Guinea. Unpublished doctoral dissertation, Australian National University, Canberra.

Denham, T.P. (2004). Early agriculture in the highlands of New Guinea: An assessment of Phase 1 at Kuk Swamp. In V. Attenbrow & R. Fullagar (Eds.), A Pacific odyssey: Archaeology and anthropology in the western Pacific. Papers in honour of Jim Specht. Records of the Australian Museum, Supplement 29, 47–57.

Denham, T.P. (2005a). Agricultural origins and the emergence of rectilinear ditch networks in the highlands of New Guinea. In A. Pawley, R. Attenborough, J. Golson, & R. Hide (Eds.), Papuan pasts: Cultural, linguistic and biological histories of Papuan-speaking peoples (pp. 329–362). Pacific Linguistics 572. Canberra: Australian National University.

Denham, T.P. (2005b). Envisaging early agriculture in the highlands of New Guinea: Landscapes, plants and practices. World Archaeology, 37, 290–306.

Denham, T.P. (2007). Thinking about plant exploitation in New Guinea: Towards a contingent interpretation of agriculture. In T.P. Denham, J. Iriarte, & L. Vrydaghs (Eds.), Rethinking agriculture: Archaeological and ethnoarchaeological perspectives (pp. 78–108). Walnut Creek, CA: Left Coast Press.

Denham, T.P., & Haberle, S.G. (2008). Agricultural emergence and transformation in the Upper Wahgi valley during the Holocene: theory, method and practice. The Holocene, 18, 481–496.

Denham, T.P., Eblé, F., Winsborough, B., & Ward, J.V. (1999). Archaeological and palaeoenvironmental investigations at `Ohi-apilo Pond, Kalama`ula Ahupua`a, island of Moloka`i, Hawai`i. Hawaiian Archaeology, 7, 35–60.

Denham, T.P., Golson, J., & Hughes, P.J. (2004). Reading early agriculture at Kuk (Phases 1–3), Wahgi Valley, Papua New Guinea: The wetland archaeological features. Proceedings of the Prehistoric Society, 70, 259–298.

Denham, T.P., Haberle, S.G., & Lentfer, C. (2004). New evidence and revised interpretations of early agriculture in highland New Guinea. Antiquity, 78, 839–857.

Denham, T.P., Haberle, S.G., & Pierret, A. (2009). A multi-disciplinary method for the investigation of early agriculture: learning lessons from Kuk. In A. Fairbairn, S. O'Connor, & B. Marwick (Eds.), New directions in archaeological science (pp. 139–154). Terra Australis 28. Canberra: ANU E Press.

Denham, T.P., Haberle, S.G., Lentfer, C., Fullagar, R., Field, J., Therin, M., Porch, N., & Winsborough, B. (2003). Origins of agriculture at Kuk Swamp in the highlands of New Guinea. Science, 301, 189–193.

Florin, M.B. (1970). Late Glacial diatoms of Kirchner Marsh. In S.C. Minn., J. Gerloff, & B.J. Cholnoky (Eds.), Diatomaceae II (pp. 667–756). Berlin: J. Cramer.

Fullagar, R., Field, J., Denham, T.P., & Lentfer, C. (2006). Early and mid-Holocene processing of taro (Colocasia esculenta) and yam (Dioscorea sp.) at Kuk Swamp in the highlands of Papua New Guinea. Journal of Archaeological Science, 33, 595–614.

Gilbertson, D. (1995). Studies of lithostratigraphy and lithofacies: A selective review of research developments in the last decade and their applications in geoarchaeology. In A.J. Barham & R.I. MacPhail (Eds.), Archaeological sediments and soils: Analysis, interpretation and management (pp. 99–144). London: Institute of Archaeology, UCL.

Golson, J. (1977). No room at the top: Agricultural intensification in the New Guinea highlands. In J. Allen, J. Golson, & R. Jones (Eds.), Sunda and Sahul: Prehistoric studies in southeast Asia, Melanesia and Australia (pp. 601–638). London: Duckworth.

Golson, J. (1991). Bulmer Phase II: Early agriculture in the New Guinea highlands. In A. Pawley (Ed.), Man and a half: Essays in Pacific anthropology and ethnobiology in honour of Ralph Bulmer (pp. 484–491). Auckland: The Polynesian Society.

Golson, J. (2007). Unravelling the story of early plant exploitation in highland Papua New Guinea. In T.P. Denham, J. Iriarte, & L. Vrydaghs (Eds.), Rethinking agriculture: Archaeological and ethnoarchaeological perspectives (pp. 109–125). Walnut Creek, CA: Left Coast Press.

Golson, J., & Hughes, P.J. (1980). The appearance of plant and animal domestication in New Guinea. Journal de la Société des Océanistes, 36, 294–303.

Hughes, P.J., Sullivan, M.E., & Yok, D. (1991). Human induced erosion in a highlands catchment in Papua New Guinea: The prehistoric and contemporary records. Zeitschrift für Geomorphologie Supplementbände, 83, 227–239.

Hustedt, F. (1938). Systematische und ökologische Untersuchungen über die Diatomeen-Flora von Java, Bali und Sumatra nach dem Material der Deutschen Limnologischen Sunda-Expedition. Systematischer Teil 1. Archive für Hydrobiologie Supplement, 15 (pp. 1–790). Reprinted 1980 by Otto Koeltz Scientific Books, Koenigstein.

Hustedt, F. (1959). The pennate diatoms. Die Kieselalgen, Vol. 2 (Trans. Norman Jensen, 1985). Königstein, Germany: Koeltz Scientific Books.

Juggins, S. (2003). C2 user guide: Software for ecological and palaeoecological data analysis and visualisation. Newcastle upon Tyne: University of Newcastle.

Krammer, K. (1992). Pinnularia. Bibliotheca Diatomologica, Vol. 26. Berlin: J. Cramer.

Krammer, K. (2000). Diatoms of Europe, Vol. 1: The genus Pinnularia. Ruggell: A.R.G. Gantner Verlag K.G.

Krammer, K., & Lange-Bertalot, H. (1986). Susswasserflora von Mitteleuropa, Bacillariophyceae, Vol. 1: Naviculaceae. Jena: Gustav Fischer Verlag.

Krammer, K., & Lange-Bertalot, H. (1988). Susswasserflora von Mitteleuropa, Bacillariophyceae, Vol. 2: Bacillariaceae, Epithemiaceae, Surirellaceae. Jena: Gustav Fischer Verlag.

Krammer, K., & Lange-Bertalot, H. (1991a). Susswasserflora von Mitteleuropa, Bacillariophyceae, Vol. 3: Centrales, Fragilariaceae, Eunotiaceae. Jena: Gustav Fischer Verlag, Jena.

Krammer, K., & Lange-Bertalot, H. (1991b). Susswasserflora von Mitteleuropa, Bacillariophyceae, Vol. 4: Achnanthaceae Kritische Ergänzungen zu Navicula (Lineolatae) und Gomphonema Gesamtliteraturverzeichnis Teil 1–4. Jena: Gustav Fischer Verlag.

Krinitzsky, E.L. (1970). Radiography in the earth sciences and soil mechanics. New York: Plenum Press.

Lange-Bertalot, H. (2001). Diatoms of Europe, Vol. 2: Navicula sensu stricto: 10 genera separated from Navicula sensu lato, Frustulia. Ruggell: A.R.G. Gantner Verlag K.G.

Lowe, R. (1974). Environmental requirements and pollution tolerance of freshwater diatoms. Document No. EPA-670/4-005. Cincinnati, OH: U.S. Environmental Protection Agency.

McAlpine, J.R., Keig, G., & Falls, R. (1983). Climate of Papua New Guinea. Canberra: CSIRO and ANU Press.

Moore, P.D., Webb, J.A., & Collinson, M.E. (1991). Pollen analysis. Oxford: Blackwell Scientific Publications.

Moran, C.J., Pierret, A., & Stevenson, A.W. (2000). X-ray absorption and phase contrast imaging to study the interplay between plant roots and soil structure. Plant and Soil, 223, 90–115.

Munsterman, D., & Kerstholt, S. (1996). Sodium polytungstate, a new non-toxic alternative to bromoform in heavy liquid separation. Review of Palaeobotany and Palynology, 91, 417–422.

Pain, C.F., Pigram, C.J., Blong, R.J., & Arnold, G.O. (1987). Cainozoic geology and geomorphology of the Wahgi Valley, central highlands of Papua New Guinea. BMR Journal of Australian Geology and Geophysics, 10, 267–275.

Patrick, R., & Reimer, C.W. (1966). The diatoms of the United States. Monograph No. 13. Philadelphia: Academy of Natural Sciences.

Patterson, W.A.I., Edwards, K.J., & Maguire, D.J. (1987). Microscopic charcoal as a fossil indicator of fire. Quaternary Science Reviews, 6, 3–23.

Powell, J.M. (1970). The impact of man on the vegetation of the Mt Hagen region, New Guinea. Unpublished doctoral dissertation, Australian National University, Canberra.

Powell, J.M. (1982). The history of plant use and man's impact on the vegetation. In J.L. Gressitt (Ed.), Biogeography and ecology of New Guinea, Vol. 1 (pp. 207–227). The Hague: Junk The Hague.

Powell, J.M., Kulunga, A., Moge, R., Pono, C., Zimike, F., & Golson, J. (1975). Agricultural traditions in the Mount Hagen area. Occasional Paper No. 12. Port Moresby: Department of Geography, UPNG.

R Development Core Team (2006). R: A language and environment for statistical computing. Vienna: R Foundation for Statistical Computing (available from http://www.R-project.org).

Salomoni, S.E., Rocha, O., Callegaro, V.L., & Lobo, E.A. (2006). Epilithic diatoms as indicators of water quality in the Gravataí river, Rio Grande do Sul, Brazil. Hydrobiologia, 559, 233–246.

Smol, J.P. (2008). Pollution of lakes and rivers: A paleoenvironmental perspective, 2nd ed. Oxford: Blackwell Publishing.

Sniderman, J.M.K., Finn, J., & Denham, T.P. (2009). A late-Holocene palaeoecological record from Ambra Crater in the highlands of Papua New Guinea and implications for agricultural history. The Holocene 19, 443–452.

Stoemer, E.F., & Smol, J.P. (1999). The diatoms: Applications for the environmental and earth sciences. Cambridge: Cambridge University Press.

Trombold, C.D., & Israde-Alcantara, I. (2005). Paleoenvironment and plant cultivation on terraces at La Quemada, Zacatecas, Mexico: The pollen, phytolith and diatom evidence. Journal of Archaeological Science, 32, 341–353.

Vyverman, W. (1991). Diatoms from Papua New Guinea. Bibliotheca Diatomologica, Vol. 22. Berlin: J. Cramer.

Vyverman, W. (1992). Multivariate analysis of periphytic and benthic diatom assemblages from Papua New Guinea. Hydrobiologica, 234, 175–193.

Vyverman, W, Vyverman, R., Hodgson, D., & Tyler, P. (1995). Diatoms from Tasmanian mountain lakes: A reference data-set (TASDIAT) for environmental reconstruction and a systematic and autecological study. Bibliotheca Diatomologica, Vol. 33. Berlin: J. Cramer.

Wood, A.W. (1987). The humic brown soils of the Papua New Guinea highlands: A reinterpretation. Mountain Research and Development, 7, 145–156.

Received 23 June 2009
Accepted for publication 2 July 2009
Scientific editing by Jeff Blackford