

# **QEMSCAN® analysis of clay-rich stratigraphy associated with early agricultural contexts at Kuk Swamp, Papua New Guinea**

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## **Key Words**

Microstratigraphic analysis, QEM-EDS, mineral mapping, elemental distributions, pedogenesis, cultivation practices

## **Abstract**

Quantitative Evaluation of Minerals by Scanning Electron Microscope (QEMSCAN®) provides a diagnostic analytical tool to investigate clay-rich stratigraphy in early agricultural contexts at Kuk Swamp, Papua New Guinea. Previous *in situ* microstratigraphic analyses at Kuk, comprising thin section description and X-radiography, have been unable to differentiate and characterise clay mineralogy in the archaeological stratigraphy. Although prior X-ray diffraction provided compositional information on clay mineralogy for bulk samples, QEMSCAN® elemental and mineral analyses enable *in situ* identification and mapping of clay mineral occurrences and relationships. The results of the QEMSCAN® analyses permit reconstruction of the origin and post-depositional transformation of geogenic and biogenic sediments in clay-rich feature fills associated with former plant exploitation and cultivation. QEMSCAN® mineral analyses identify a positive association between smectite-rich contexts and biogenic silica (diatoms and phytoliths) and a negative association between kaolinite-rich contexts and biogenic silica. QEMSCAN® elemental analyses provide valuable information on neoformed minerals, which can be difficult to characterise optically within stratigraphy. These results show the value of QEMSCAN®, especially in combination with thin section micromorphology, to understand the origin and post-depositional formation of clay minerals at archaeological sites in the wet tropics, as well as in other environmental contexts.

## **Introduction**

Kuk Swamp in the Upper Wahgi Valley is a wetland archaeological site key to the investigation of early agriculture in the highlands of Papua New Guinea (Fig. 1; Golson 1977, 1982; Golson and Hughes 1980; Denham et al. 2003; Golson et al. 2017; Denham 2018). The

archaeological stratigraphy at Kuk preserves multidisciplinary evidence for repeated periods of wetland manipulation for plant exploitation and cultivation dating from c. 10,000 cal BP to the present. While prior field and stratigraphic analyses have established a robust chronology for the emergence and development of agricultural practices through time, an elusive feature of the investigations at Kuk is the nature of the clay-rich stratigraphy.

The Holocene stratigraphy at Kuk is dominated by clays, which often represent a problem for multiscalar analyses. Bulk techniques such as X-Ray Diffraction (XRD) are suitable for identifying clays but result in the homogenisation of the sample and thus the obliteration of microstratigraphic and contextual associations. In contrast, *in situ* contextual methods performed on stratigraphic blocks or thin sections derived from blocks, such as thin section description and X-radiography, preserve the contextual arrangement of sediments but are unable to resolve and differentiate clay minerals (Denham 2003a; Denham et al. 2009a; Denham and Grono 2017; Hughes et al. 2017). Here, a novel use of automated Quantitative Evaluation of Minerals using Energy Dispersive Spectroscopy (QEM-EDS), employing Quantitative Evaluation of Minerals by Scanning Electron Microscope (QEMSCAN<sup>®</sup>) technology, is applied to key early and middle Holocene contexts at Kuk in order to overcome limitations associated with the characterisation of clays encountered during prior X-radiographic and thin section investigations. QEMSCAN<sup>®</sup> is developed as a descriptive and analytical tool that permits both the identification and characterisation of the contextual arrangement of clay minerals and associated geogenic, biogenic and anthropogenic sediments in clay-rich archaeological stratigraphy (see Edwards et al. 2017; Ward et al. 2017; Grono 2020).

### **Kuk Swamp: Background and Prior Investigations**

Multidisciplinary investigations at Kuk occurred in two broad, overlapping phases: excavations in 1971-1977 primarily under the direction of Jack Golson, with assistance from Philip Hughes in 1975-1977; and, excavations in 1998-1999 under the direction of Tim Denham and supervision of Jack Golson (Denham et al. 2004). The fieldwork was designed to investigate the antiquity and character of early and mid-Holocene plant exploitation practices at Kuk (Denham 2003a; Denham et al. 2003). Both sets of investigations adopted multidisciplinary, environmental archaeological approaches, seeking to integrate archaeology with archaeobotany, geoarchaeology, palaeoecology and radiocarbon dating (see Denham 2003a; Denham et al. 2009a, 2009b; Golson et al. 2017).

The prior investigations established an agricultural chronology at Kuk Swamp that represents a gradual expansion in the repertoire of cultivation practices through time: manipulation of the wetland margin and potentially nascent forms of cultivation at c. 10,000 cal BP (Denham 2004); swidden cultivation on the valley floor from c.10,000 cal BP to c. 7,000 cal BP (Hughes et al. 1991; Denham and Haberle 2008); cultivation using mounds at c.6400-6000 cal BP (Denham 2003b); and, periodic drainage of parts of the wetland from c. 4400-4000 cal BP to the present (Bayliss-Smith and Golson 1992a, 1992b; Denham 2005; Bayliss-Smith 2007). The global significance of Kuk has been recognised through its

successful nomination to UNESCO's World Heritage List in 2008 (Muke et al. 2007; Denham 2012; Muke and Denham 2017).

The generalised stratigraphic profile at Kuk (Fig. 2A, Table 1) comprises organic-rich Pleistocene sediments overlain by clay-rich Holocene sediments (Denham 2003a; Denham and Grono 2017; Hughes et al. 2017). The major sedimentary units of most relevance here are:

- 'black organic clay' (field designation) [Context 7] - a very dark grey to black (10YR 3/1 to 2.5Y 2.5/1 and 3/1), organic-rich clay, massive structure, deposited from c. 20,000 cal BP to c. 10,000 cal BP;
- 'grey clay' (field designation) [Context 5] - a dark grey to brown (10YR 4/1 to 7.5YR 4/2), clay, massive structure, deposited from c. 10,000 cal BP to c. 7000 cal BP;
- 'black clay' (field designation) [Context 4] – a black (10YR 2/1 to 2.5Y 2.5/1), clay, massive structure, deposited from c. 7000 cal BP to 2500 cal BP; and,
- 'crumby black' (field designation) [Context 3] – a black (10YR 2/1 to 2.5Y 2.5/1), clay to silty clay loam, spheroidal aggregate structure, deposited after 2500 cal BP and underlies current zone of cultivation within soil profile.

Episodic tephra lenses occur within these major stratigraphic units representing periodic volcanic ash fall events (Blong et al. 2017).

A mixed-method and multi-scalar, geoarchaeological approach has been central to reconstructing past plant exploitation and cultivation practices at Kuk. Multi-scalar investigations at the macro-scale (field recording), mesoscale (X-radiography) and micro-scale (thin section micromorphology) have been complemented by a variety of geochemical analyses (Denham 2003a, 2008; Denham et al. 2009a, 2009b; Denham and Grono 2017; Hughes et al. 2017; Lin 2016), as well as targeted investigations of tephras (Coulter et al. 2009; Blong et al. 2017). These suites of technical analyses have enabled complex site formation processes to be unravelled within the relatively shallow stratigraphy, in which 10,000 years can be represented by less than 1.5 m depth. Foremost, prior stratigraphic analyses have:

1. clarified sedimentary, pedogenic and anthropic contributions to the Holocene stratigraphy;
2. differentiated stratigraphic components associated with former palaeosols and cultivation; and,
3. provided robust assessments of sample integrity for archaeobotanical, palaeoecological and dating analyses.

In particular, X-radiography and thin section description of stratigraphic contexts were useful for the investigation of contexts associated with cultivation practices during the early and mid-Holocene (Denham and Grono 2017: 169):

1. The identification and characterisation of former palaeosol profiles and constituent horizons;

2. Evidence of clearance, disturbance and erosion including structure, pedofeatures and geochemical signals;
3. The heterogeneity of archaeologically significant units, potentially suggestive of anthropic disturbance; and,
4. Associations between artificially modified soils and other lines of evidence, e.g., features, artefacts, charcoal and microbotanical records.

However, the prior microstratigraphic analyses faced challenges in characterising aspects of site formation at Kuk, namely, the clay-rich stratigraphy. Clays dominate the Holocene stratigraphy at Kuk and several major stratigraphic units are opaque under plane-polarised light (PPL) and isotropic under cross-polarised light (XPL), including black organic clay [7], black clay [4] and crumby black [3]; the exception is the kaolinite dominated 'grey clay' [5] (Denham and Grono 2017). A major limitation of previous X-radiographic and optical microscopic investigations of this stratigraphy is the inability to clearly differentiate and characterise contributions of different clay fraction components within stratigraphic units and in heterogeneous feature fills associated with former cultivation practices (Denham and Grono 2017). Microstratigraphic techniques do not usually provide sufficient contrast to distinguish allophane, kaolinite and smectite in the clay fractions, except where there are clear optical differences, such as between the kaolinite-rich 'grey clay' [5] and the black underlying and overlying units [7 and 4, respectively]. Microstratigraphic assessment of these units [7, 4 and 3] has thus been limited to partial description of microstructure and the documentation of some pedofeatures and inclusions (Denham and Grono 2017).

### **Sample Contexts**

Four contexts associated with the most significant evidence for early plant exploitation and agriculture at Kuk Swamp are investigated using QEMSCAN<sup>®</sup> analyses: (a) plant exploitation on the wetland edge at c. 10,000 cal BP (Feature 1404); (b) deposition of 'grey clay' (c. 10,000 cal BP to c. 7000 cal BP) [5]; (c) cultivation using mounds at 6400-6000 cal BP (Feature 2000); and, (d) a sinuous drainage feature (Feature 504) associated with cultivation dated to c. 4800-4400 cal BP (Denham et al. 2003). The samples were collected during fieldwork in 1998 and 1999 (Figs. 2B-2D; Table 1). Microstratigraphic analyses including X-radiography and thin section description have been previously undertaken on the contexts and the results are summarised here (Fig. 3; Denham 2003a, Denham et al. 2009a; Lin 2016; Denham and Grono 2017).

#### *Feature 1404, c. 10,000 cal BP*

Feature 1404 is a shallow pit associated with former plant exploitation practices on a palaeosurface dated to c. 10,000 cal BP (Denham et al. 2003, 2017a; Denham 2004, 2018). The feature cuts into black organic clay [7] that has been subject to limited pedogenesis when exposed at the surface, forming a palaeosol with immature A horizon. After only a short-period of exposure, the feature was filled by 'grey clay' [5]. Previous meso-scale (X-

radiography) and micro-scale (thin section description) analyses of the stratigraphy have enabled detailed characterisation of various soil formation processes (Denham 2003a, Denham et al. 2009a; Denham and Grono 2017). Paired microfossil (diatom, phytolith, pollen and microcharcoal; Denham et al. 2003) and contiguous multi-proxy (diatom, pollen and microcharcoal; Denham et al. 2009a) analyses have been undertaken on the fills of this feature and underlying palaeosol.

X-radiography of a 1 cm thick sediment slice through the fill of feature 1404 and underlying black organic clay sediment depicts remnant palaeosol characteristics inherited from its initial formation, c. 10,000 years ago (Denham and Grono 2017). Limited pedogenesis of the unit underlying the feature is clearly visible within the X-radiograph, indicated by weakly delineated subangular blocky-to-granular peds that have been in-filled and buried by denser 'grey clay' sediments (Fig. 3A). These ancient characteristics are over-printed by a range of later soil formation processes, including: finer, unfilled, partially filled and filled channels derived from root activity and faunal burrowing; which in turn have been over-printed by larger, vertically-oriented, unfilled channels within the sediment representing the most recent phase of root penetration (based on visual inspection of root tissues) and faunal burrowing (based on uniform widths, sinuosity, smooth sides and lack of distributaries) (Denham et al. 2009a: 725-726).

Thin section analysis through the feature fill and underlying sediments enables more refined microstratigraphic characterisation (Denham and Grono 2017: 166-167). The basal black organic clay is comprised of amorphous, organic-mineral material, dark brown to black and locally opaque in PPL and isotropic in XPL. Pedofeatures within this basal unit include: limited spheroidal aggregate development, consistent with ped formation; dense complete infillings between aggregates (peds) of limpid to speckled, kaolinite clay, suggestive of illuvial clay; and, crescentic bow-like pedofeatures comprised of interleaved black organic clay groundmass and lighter-coloured infillings, which are indicative of a bioturbated soil fabric (Fig. 3A). These pedofeatures are consistent with the peds visible in the X-radiograph that are suggestive of soil formation when the base of the feature was exposed at the surface for a sufficiently long time to develop an immature A-horizon. Thin section description, as well as pollen signatures (Denham et al. 2009a: 726), indicate the basal portion of 'grey clay' fill within these palaeosurface features is admixed with underlying black organic clay suggesting pedogenesis continued during the initial phases of grey clay deposition before complete burial.

#### *Grey Clay, c. 10,000 cal BP to c. 7000 cal BP*

The 'grey clay' major stratigraphic unit [5] is part of a fan extending across the southern margin of the wetland at Kuk. Fan deposits reflect a combination of colluvial and alluvial processes and were deposited between c. 10,000 cal BP and c. 7000 cal BP. The sediments derive from soil erosion in the southern catchment, which is considered to result from swidden cultivation on the floor of the Upper Wahgi Valley (Hughes et al. 1991, 2017; Denham et al. 2003; Haberle et al. 2012).

The major stratigraphic unit is comprised of microcharcoal and phytoliths in a limpid-to-speckled kaolinite matrix (Denham 2003a; Denham and Grono 2017). At multiple scales of analysis – ranging from macro (field), meso (X-radiograph) to micro (thin section) – the unit exhibits a channel microstructure resulting from root penetration and faunal burrowing for various periods in the past (Fig. 3B). Recent channels are unfilled or contain roots, whereas ancient channels are filled with various sediment types derived from overlaying strata. The unit also exhibits characteristics of an argillic, Bt horizon, with frequencies of illuvial clay pedofeatures consistently being above 1% (Fig. 3B).

Grey clay exhibits evidence of recurrent oxic and waterlogged conditions, which are anticipated on a wetland margin periodically drained for cultivation (Denham 2003a; Denham and Grono 2017). Some oxic characteristics, such as the dominance of kaolinite, are primarily detrital, inherited from the highly weathered sediments eroded from the southern catchment, whereas others represent *in situ* weathering and soil formation within the profile during drier periods, such as the prevalence of illuvial clay pedofeatures. Anoxic characteristics reflecting periods of waterlogging include gleyans (unoriented clay coatings) and ferric hypocoatings of partially filled and unfilled voids. Anoxic pedofeatures often overlay the dominant oxic characteristics, although there is recurrent superimposition of pedofeatures associated with both environments of soil formation.

#### *Feature 2000, c. 6400-6000 cal BP*

Feature 2000 is a shallow depression, that interconnects with other features to form a palaeosurface that represents cultivation using mounds at c. 6400-6000 cal BP (Denham et al. 2003, 2017b; Denham 2003b, 2018). The feature cuts into grey clay [5] and is infilled with a basal 'R+W' deposit ['red and white', 27], comprised almost exclusively of phytoliths, intermixed with and overlain by material indistinguishable from black clay [4]. This feature has been investigated previously through thin section description (Denham 2003a; Denham and Grono 2017: 167-168).

In the field, the fills of features associated with this palaeosurface were indistinguishable, except for the basal R+W deposit, from the massively structured, opaque (PPL) and isotropic (XPL) black clay [4] unit. However, X-radiography indicated that whereas overlaying black clay had been homogenised, the black clay fills of features preserved channel microstructures indicative of fine roots, presumably from vegetation when these fills were at or near the surface (Denham et al. 2009a).

Thin section analysis of this feature fill indicates a reddish to dark brown isotropic organic-mineral groundmass, massively structured and heterogeneous (Fig. 3C; Denham and Grono 2017). Heterogeneity includes: displaced grey clay granules, voids infilled with illuvial clay, the 'R+W' deposit composed of grass phytoliths, as well as the black clay groundmass. These constituents are highly admixed at the base of the fill and indicate a variety of processes associated with the formation of the feature in the past. The primary fill represents inwashed, rolled and slumped material from the edge of a newly constructed and unvegetated mound. The phytolith-rich deposit, which often occurs in deeper features

between mounds, is suggestive of the clearance and burning or mulching of grasses during mound construction and the washing of detrital materials into adjacent features where they became concentrated near the base of the deeper features. The primary fill was subsequently buried by black clay.

#### *Feature 504, c. 4800-4400 cal BP*

Feature 504 is a sinuous and shallow curvilinear runnel that facilitated localised drainage on a cultivated palaeosurface. Charcoal inclusions within the fills of the feature dated to c. 4800-4400 cal BP (Denham 2005, 2018; Denham et al. 2017b: 213-215). The highly heterogeneous feature fills reflect redeposition of materials associated with clearance and cultivation of the immediate vicinity (Lin 2016) and contain the highest frequencies of banana (*Musaceae*) phytoliths (16% of total phytoliths) recorded in any context at Kuk (Denham et al. 2003; Lentfer and Denham 2017).

Thin section analysis through the basal and upper fills of Feature 504 indicate intercalated heterogeneous clays with common organic and mineral staining, abundant phytoliths and few charcoal inclusions (Fig. 3D; Lin 2016). The basal fill is slightly lighter (10YR 3/1) than the upper fill, which contains a greater frequency of black (2.5Y 2.5/1 mottles). The basal fill contains few aggregates of displaced granules of lighter sediment and reworked pedofeatures intermixed within the groundmass. Abundant (c. 20%) filled macro-to-mega channels and chambers decrease in frequency with depth and are filled with material similar to the groundmass. The upper fill is similar to the basal fill except it is darker, and is opaque (PPL) and isotropic (XPL); the hierarchy of channels includes a greater percentage of recent (unfilled) voids relative to filled (ancient) voids; higher silt to medium sand-sized mineral fraction; and abundant authigenic phosphatic granules that were uncommon in the basal fill.

Thin section description for Feature 504 indicates the fills were heterogeneous at the time of deposition, representing the inwashing and admixture of a variety of mineral and organic components from adjacent land surfaces (Lin 2016). These materials were then subject to sequential and varying degrees of pedogenesis, including weathering, organic degradation, bioturbation and neoformation.

### **QEMSCAN® Methodology**

#### *A Tool in Microstratigraphic Analysis*

Here, QEM-EDS employing QEMSCAN® technology is applied as a tool in microstratigraphic analysis to overcome limitations with prior X-radiographic and thin section descriptions of key early agricultural contexts at Kuk. Microstratigraphic analysis is a type of stratigraphic analysis that is conducted at millimetre to centimetre scales (Mallol and Mentzer 2017). It shares the same objective as site and landscape scales of stratigraphic analysis, namely, to

reconstruct site formation processes and identify past human practices, yet it achieves this at much higher spatial and temporal resolution (e.g., Karkanas and Goldberg 2017; Mallol and Mentzer 2017).

QEM-EDS utilises an automated scanning electron microscope equipped with multiple energy-dispersive X-ray spectrometers to optimise X-ray count rate. QEMSCAN® is a commercial version of QEM-EDS. QEMSCAN® provides *in situ* elemental and mineralogical identifications and quantifications in the form of maps which preserve qualitative, *in situ* contextual distributions and associations (Pirrie et al. 2004; Haberlah et al. 2011a). Archaeological sites are complex arenas of minerals encompassing geogenic, biogenic and anthropogenic components that potentially undergo a host of diagenetic transformations post-burial (Weiner et al. 2002; Karkanas 2010). Thus, the ability to map mineral and elemental distributions within sediments is valuable to reconstructing site formation, assessing stratigraphic integrity and inferring past human activities. An additional strength of the technique is that it provides a meso-scale visual and readily-interpretable link between lower resolution, field observations and higher resolution, thin section description (Edwards et al. 2017).

Only recently has QEM-EDS technology been applied to archaeological stratigraphy (Edwards et al. 2017; Ward et al. 2017; Grono 2020). Edwards et al. (2017) and Ward et al. (2017) utilised QEMSCAN® to map mineral distributions within clastic sediments and soils in order to infer processes of site formation. The suitability of the technique to investigate clay-rich contexts has not been thoroughly investigated (although see Cattle and Smith 2018).

### *Field Sampling*

*In situ* monoliths were collected from the base and walls of excavation units in cut-to-measure sections of zinc pipe. The zinc pipe was square in cross-section, measured 8 cm across and was readily pushed into the ground without too much compaction of the encased deposit (usually less than 2 cm for a 25 cm long monolith). The cut edge of the pipe was slightly serrated facilitating insertion. Each monolith was padded, wrapped and sealed in airtight bags for airfreight transportation to Canberra. Monoliths had been stored under refrigerated conditions (3-4 °C) in an approved Australian Quarantine and Inspection Service (AQIS) facility at the School of Archaeology and Anthropology, Australian National University.

### *Sample Preparation*

Monoliths were air-dried for long periods (over a week) at low temperature (in an autoclave at 40°C) in order to minimize stress features associated with drying. Samples were then resin impregnated to enable subsampling for thin section preparation: grey clay and Features 1404 and 2000 originally used by Denham (2003a) and Denham and Grono (2017);

and, Feature 504 originally used by Lin (2016). These previously impregnated blocks were then reused for the current study to yield new QEMSCAN® billets.

QEMSCAN® analyses were conducted on polished billets (c. 500 µm) that had been ground to a constant thickness, mounted onto glass slides, cleaned and then coated with a 20 nanometre layer of carbon using a Dynavac CS300 coating unit. Carbon-coating reduces the build-up of static charge during exposure to the electron beam during QEMSCAN® scanning. Following QEMSCAN® analysis, the billets were then ground down, mounted on a glass slide, polished and cover-slipped to produce 25 µm thick slides for thin section description. Thin sections of approximately 25 µm thickness were produced to enable optical inspection of microstratigraphic features in the dense clay-rich matrices (following A. Ringrose-Voase pers. comm. to Denham 1999; see Denham 2003a), as opposed to the more standard thickness of 30 µm (Bullock et al. 1985: 13).

#### *QEM-EDS (QEMSCAN®) Instrumentation*

QEMSCAN® analysis was undertaken at the Centre for Advanced Microscopy (CAM), ANU. Samples were analysed using a FEI QEMSCAN® 650F in field-scan mode, 15 kV accelerating voltage, 10 nA probe current and a step size of 4.9 µm, yielding almost 12 million data points (pixels) per sample. Scanning time varies depending upon scan settings, but can commonly last for 24 hours. Processing of elemental spectra was undertaken using iDiscover and Nanomin software. Based on elemental composition, each pixel is assigned a mineral species from the Species Identification Library, or SIP (Haberlah et al. 2011a) represented by a different colour. However, there are limitations to the technique: impregnated resin and organic material are recorded as background, while poorly-ordered (amorphous) materials are unclassified. Both background and unclassified are represented as black in images here.

Although comparable to other well-established microanalytical methods (Goodall et al., 2005), QEMSCAN® is not always highly accurate in the discrimination of clay minerals or minerals with similar chemical compositions (Pirrie et al. 2004; Knappett et al. 2011; Ayling et al. 2012; Edwards et al. 2017). A potential source of error in mineralogical identifications using QEMSCAN® is the assignment of minerals on a 'first match basis' according to the Species Identification Profile (SIP), or a ranked database of mineral spectra. The ranking hierarchy within the SIP thus influences the assignment of minerals to spectra (Haberlah et al. 2011b).

Two steps have been adopted in the current analyses to limit the effects of these types of assignment error. First, clay mineral classifications are provided at high-level clay mineral groupings – namely, kaolin group, smectite group, illite group and chlorite group – rather than at low-level mineral identifications. The intention is to avoid the erroneous misclassification of clay minerals with similar spectra.

Second, XRD of major and minor stratigraphic units at Kuk provided a supplementary database to adjust the mineral rankings within the SIP (Table 2). The sub-database was incorporated using FEI Mineral Reference Editor. A confidence threshold of 83% was

assigned to the mineral identification. Any spectra that could not be assigned above this threshold were left unclassified. After the automated classification, a supervised classification was attempted on any unidentified spectra. Of note, quartz minerals (derived from the weathering of rocks) are not differentiated from biogenic silica (derived from diatoms and phytoliths) in QEMSCAN®.

### *Descriptive Terminology*

QEMSCAN® mineral maps are described using an adapted version of terminology developed for thin section description. Terminology follows Bullock et al. (1985), with some minor amendments derived from Stoops (2003; also Stoops et al. 2018). Bullock et al. (1985) provide generic descriptive terminology appropriate for well-developed soils that is designed to be readily transferable between macro (field), meso (X-radiography, QEMSCAN®) and micro (thin section) scales. The terminology had previously been used for microstratigraphic analyses including thin section description (Denham 2003a; Denham and Grono 2017) and amended for X-radiograph description at Kuk (Denham 2003a).

## **QEMSCAN® Results**

### *Feature 1404*

QEMSCAN® analysis of deposits near the base of the feature, namely, basal fills and underlying deposits, reveal a composition of kaolinite clay (77.00%), smectite (17.43%) and biogenic silica (5.16%). The structure of this sample is massive with recent cracking and frequent chamber and vugh voids. The groundmass (c/f ratio of <5 µm) is primarily comprised of fine material (94%) and coarse material is predominantly quartz, which thin section micromorphology indicates to be biogenic silica.

There are two distinct zones within the mineral map (Fig. 4). The top half of the sample represents the kaolinite-rich 'grey clay', with rare mineral inclusions. The diffuse regions of smectite clay and biogenic silica within this zone correspond to intermixing during initial grey clay deposition noted in aforementioned thin section descriptions and pollen signatures. This zone contains few void structures in the form of channels and chambers as well as recent planar cracks (products of sample drying and processing). The lower zone is more admixed, and represents the smectite and biogenic silica-rich black organic clay. Like in the X-radiograph, the boundary between grey clay fill and black organic clay is abrupt and broken (Figs. 4A-4B). Pure to speckled kaolinite in this bottom section infills former chamber and channel void structures within the smectite-rich groundmass (Fig. 4A and 4C). The respective clay distributions are consistent with kaolinite-rich grey clay infilling inter-pedal voids within a subangular, granular-to-blocky microstructure. The peds are comprised of the smectite-rich and biogenic silica-rich, black organic clay.

Biogenic silica is clearly denser within the smectite clays than in the kaolin clays (Fig. 4). Illite is rare (<0.20%) and speckled throughout the deposits. Chlorite is present only as a trace (0.01%), and is distributed as cappings or crescentic coatings on voids.

### *Grey Clay*

QEMSCAN® analysis of the grey clay sample indicates a relatively homogenous groundmass comprised of kaolinite (97.48%) (Fig. 5). The groundmass consists almost exclusively of fine material (>99%) with coarse material being primarily biogenic silica (c/f ratio of <5 µm). The groundmass is massive, with channel microstructure and recent cracking.

Overall, kaolinite occurs in a highly dense and concentrated form throughout the entire slide with moderate (c. 15%) porosity. There are loosely and discontinuously filled channels and chambers, as well as cracks that have been partially filled with kaolinite. Smectite (1.80%) is scattered throughout the deposit, with minor concentrations in partially filled voids towards the middle and bottom of the sample (Figs. 5A and 5C). Biogenic silica (0.54%) occurs in slightly higher concentrations within the smectite relative to the kaolinite.

Minor mineral groups are very rare within this sample, comprising plagioclase inclusions (0.04%) and a light speckling of illite (0.03%). Chlorite (0.02%) occurs as incomplete coatings on large channel voids, which also exhibit weakly impregnated, ferric hypocoatings.

### *Feature 2000*

QEMSCAN® analysis indicates a highly heterogeneous deposit with an admixed distribution reflected in kaolinite-rich and kaolin-poor zones (Fig. 6). Overall, the groundmass is kaolinite-rich (60.09%) and comprises mainly fine material (c. 82%; c/f ratio of <5 µm). Smectite (21.86%) is distributed relatively evenly through the sample, as well as in diagonal striations through the groundmass and across void structures in a highly compacted 'scarring', potentially an artefact of slide preparation. Similarly, biogenic silica (16.52%) is distributed evenly throughout the sample, potentially reflecting the distribution of smectite rather than the kaolinite.

Sample heterogeneity is suggestive of a palaeosol comprised of:

- granules of clay, some of which are heterogeneous and comprised of admixed kaolinite and smectite (Fig. 6A), while others are more kaolinite-rich (Fig. 6B);
- argillans of kaolinite (Fig. 6C); and,
- a large, infilled channel running vertically through the sample that contains smectite and biogenic silica, but little kaolinite (Fig. 6D).

Weak subangular blocky ped development overprints the palaeosol characteristics; the overprinting is recent because the medium-sized inter-pedal voids are unfilled.

Mineral grains (50–200 µm) of plagioclase (0.37%) and alkali (0.26%) feldspars appear in some admixed zones of kaolinite/smectite clay. Illite (0.29%) appears as a loose scattering of

speckles (2-50  $\mu\text{m}$ ) in the upper portion of the sample and is faintly speckled throughout the sample; while chlorite (0.20%) appears rarely around voids in a capping or crescent structure. Neof ormation occurs in the form of moderately to strongly impregnated ferric hypocoatings along pre-existing channel microstructures, which have now been filled.

#### *Feature 504*

Kaolinite (77.17%) comprises the majority of the heterogenous groundmass. Fractured granules of kaolinite, smectite, mullite and corundum occur throughout the groundmass (Fig. 7). Smectite (14.12%) is distributed throughout the kaolinite-rich groundmass, as well as in highly-weathered granules, and occurs as loose, discontinuous fills within recent voids. The unfilled pore structure represents recent pedogenic activity overprinted onto the feature fill. Kaolinite argillans also occur throughout the sample (Fig. 7A).

Fine material makes up c. 85% (c/f limit of 5  $\mu\text{m}$ ) of the groundmass. Thin section micromorphology indicates that quartz (6.29%) occurs as silt-sized biogenic silica derived from diatoms and phytoliths, and as sand-sized mineral fragments presumably derived from the weathering of tephra (Lin 2016). Biogenic silica is evenly distributed throughout the entire sample with no particular zones of concentration.

Speckles of illite (0.13%) occur throughout the groundmass, and chlorite (0.03%) occurs as partial coatings of recent voids. Neof ormed iron occurs as moderately to strongly impregnated ferric hypocoatings around recent (unfilled) voids and as strongly impregnated to pure neof ormed nodules within the groundmass.

## **Discussion**

### *QEMSCAN® as a Diagnostic Tool for Clay-Rich Stratigraphy*

The analyses presented here demonstrate that QEMSCAN® has utility as a diagnostic mineralogical mapping tool for microstratigraphic analysis of clay-rich, as well as previously investigated clastic-rich (Edwards et al. 2017; Ward et al. 2017) archaeological stratigraphy. Clay mineralogy at Kuk Swamp had been previously characterised using XRD of bulk sediments of major and minor stratigraphic units, however the use of disaggregated samples precluded the examination of the contextual arrangement of the sedimentary matrix. Prior *in situ* microstratigraphic analyses, including X-radiography and thin section description, were not able to identify and characterise the distribution of clay minerals within sediment slices and thin sections derived from monoliths, respectively. The results of the current study demonstrate that QEMSCAN® enables the identification and differentiation of major clay mineral groups as well as the characterisation of the spatial distribution and contextual associations of the clays within archaeological stratigraphy.

QEMSCAN® has generated mineral maps for major stratigraphic units at Kuk, hereby exemplified with respect to the kaolinite-rich grey clay [5] unit, as well as for heterogeneous features fills associated with plant exploitation and/or cultivation practices dated to 10,000 cal BP (Feature 1404), 6400-6000 cal BP (Feature 2000) and 4400-4000 cal BP (Feature 504). As with previous microstratigraphic work at Kuk (Denham 2003a; Denham and Grono 2017) the heterogeneous nature of feature fills is in stark contrast to the homogenised character of the major stratigraphic units. The admixed character of the clay mineral components within the feature fills provides additional corroborative information on pedogenic processes associated with use of palaeosurfaces in the past (Denham and Grono 2017: 169).

In this research, QEMSCAN® was used conservatively to investigate clay mineralogy, namely, minerals were allocated to major clay groupings rather than to the level of a specific clay mineral. The intention was to limit the potential for the misallocation of clay minerals of similar composition, especially given the often complex geochemistry of clays within soils (Velde and Meunier 2008). Although the data points were collected at a step interval of 4.9 µm, thereby generating c. 12 million spatially referenced data points per sample, there was still potential for the overlapping of individual clay minerals within a given sampling point, notwithstanding the potential for the interstratification of clay minerals, as well as the likely confounding effects of poorly-ordered aluminosilicates, such as allophane, and amorphous, organic-clay complexes. Future work can refine the application of QEMSCAN® to accurately differentiate clays within major groupings.

Even though applied conservatively, each major mineral grouping has different, recurrent associations within the early and mid-Holocene stratigraphy at Kuk:

- Kaolinite-rich contexts tend to be depauperate in biogenic silica relative to smectite-rich contexts, which may indicate partial dissolution of biogenic silica (especially diatoms; cf. Denham et al. 2009a) within intensely weathered kaolinite.
- Smectite-rich contexts tend to be concentrated in biogenic silica relative to kaolinite-rich contexts, which may indicate the greater stability of smectitic contexts for the preservation of biogenic silica, especially fragile diatoms.
- Illite tends to occur as speckles, which are more frequent within smectitic relative to kaolinitic contexts, reflecting the more extreme chemical weathering of the latter.
- Chlorite tends to occur as coatings within partially filled, or unfilled voids, in various stratigraphic contexts indicating that these are recent.

These major mineral groupings reflect different environments of formation and degrees of weathering (Velde and Meunier 2008). For instance, illite can be weathered into smectite, which in turn can be further weathered through hydrolysis and leaching of base cations into kaolinite. Depending upon soil water conditions, especially concentrations of base cations, some clay weathering pathways are reversible. Significantly for understanding site formation processes at Kuk, illite speckles likely represent recent processes of neof ormation, given that they would have been weathered into smectite if present for millennia. Smectite is associated with moister soil water conditions in the black clay [4] above and black organic clay [7] below the impervious, kaolinitic grey clay [5]. Significantly,

kaolinitic grey clay [5] is mostly detrital, having been eroded from highly weathered soil profiles within the catchment (Hughes et al. 1991, 2017; Denham and Grono 2017).

As well as providing minerals maps related to palaeosols and cultivation practices, QEMSCAN® provides highly detailed elemental maps. These can be used to investigate the distribution and relationships of elements within the soil that are only poorly resolved using X-rays and optical techniques. Of greatest significance for periodically drained and waterlogged contexts, such as those at Kuk Swamp, is the distribution of iron, especially neoformed nodules within the groundmass and ferric hypocoatings around voids. The mapping of iron, as well as other elements, like aluminium, manganese and titanium, can provide considerable additional information on secondary, redoximorphic processes within buried contexts.

### *Augmenting our Understanding of Early Cultivation Practices*

Agriculture by its very nature involves the anthropogenic modification of soils. Variability in the impact of agricultural practices on soils worldwide and in the preservation and visibility of cultivation signals in ancient soils necessitate the use of microstratigraphic techniques to disentangle complex hierarchies of site formation processes in order to accurately reconstruct past human-plant interactions (e.g., Macphail *et al.* 1990; Gebhardt 1995; Carter and Davidson 1998; Macphail 1998; Lewis 2012; Huisman and Raemaekers 2014; Deák *et al.* 2017; Adderley *et al.* 2018; Storozum *et al.* 2018). Previous microstratigraphic analyses of prehistoric agricultural soils principally used thin section analysis, among other techniques such as integrated phytolith studies and X-radiography. The current study demonstrates the novel use and value of QEMSCAN® as an automated elemental and mineral mapping tool in microstratigraphic analysis of prehistoric agricultural sites.

The contribution of QEMSCAN® analysis to elucidating site formation processes in clay-rich archaeological contexts at Kuk is shown to vary according to the type of stratigraphic context or feature under investigation. For stratigraphic units that are relatively homogenous, QEMSCAN® provides only complementary data to previous microstratigraphic analyses (Denham 2003a, Denham et al. 2009a; Denham and Grono 2017). This is exemplified by the grey clay [5] unit at Kuk which was deposited between c. 10,000-7000 cal BP (Hughes et al. 1991, 2017). The highly weathered, kaolinite-dominated clay with phytoliths, yet sparse diatoms (Denham et al. 2009a), reflects the inwashing of detrital materials from the southern catchment as well as, potentially, limited *in situ* pedogenesis. Pedogenic attributes include those associated with an oxic, argillic (Bt) horizon.

By contrast, QEMSCAN® has augmented the characterisation of anthropogenic features that demonstrate relatively high heterogeneity and the mixing of sedimentary sources. This is exemplified by features associated with former plant exploitation buried by grey clay (Feature 1404), as well as those associated with cultivation practices cut into grey clay (Features 2000 and 504). The mineral map for the fill of Feature 1404 provides a readily interpretable visualisation of soil formation c. 10,000 years ago, as well as the initial stages of burial under grey clay. Smectite-rich peds are clearly defined by kaolinite fills of former

inter-pedal voids. The kaolinite fills comprise limpid to impure clay, suggestive of translocated clay and contrasting with the impure groundmass of the grey clay unit [5]. The mineral maps for Features 2000 and 504 represent highly heterogenous fills suggestive of digging activities on adjacent palaeosurfaces. Although heterogeneity was visible in thin sections from both features (Denham and Grono 2017: Fig. 7; Lin 2016), more complexity is revealed in the mineral maps. At the base of Feature 2000, a range of contrasting kaolinite-rich, smectite-rich and admixed zones represent numerous superimposed pedofeatures suggestive of the incorporation of displaced granules from adjacent contexts and *in situ* physical admixture. The fill of Feature 504 is less heterogenous, although there has clearly been displacement of granules from adjacent contexts, including those into which the feature had been cut: grey clay [5], as well as corundum, ilmenite, mullite and rutile are detrital and likely derived from weathered, Pleistocene-aged igneous and metamorphic materials within the catchment. The identification of the mineral composition of displaced granules and of fills within pedofeatures enables greater specificity in determining stratigraphic sources, which in turn enables greater certainty in terms of site formation processes.

#### *Methodological Advantages and Complementarity of QEMSCAN®*

QEMSCAN® marries the capabilities of compositional identification previously monopolised by bulk XRD with the advantages of *in situ* microstratigraphic techniques that preserve contextual arrangements and relationships within the sedimentary matrix. Standard bulk sample techniques such as XRD, while suited to clay mineral identification, homogenise and blend microstratigraphic layers and contextual associations. QEMSCAN® analysis provides simultaneous clay mineral identification and *in situ* distributions, enabling spatial associations and hierarchical (temporal) relationships to be discerned.

The unique combination of elemental and mineral mapping is not readily achievable using other microstratigraphic methods. The *in situ* geochemical technique of Micro-X-ray Fluorescence (Micro-XRF) spectroscopy produces elemental maps excellent for detecting human activity signatures and post-depositional movement of elements driving major diagenetic processes, but it does not permit mineral identification and mapping (Mentzer 2017; Holcomb and Karkanas 2019). Micro Fourier transform-infrared (Micro-FTIR) spectroscopy identifies material substances including clay minerals but does not enable elemental characterisation, and analyses are limited to micro-spot analysis of targeted microscopic features on thin sections, rather than mapping across a wide area (Berna 2017). Similarly, Electron Probe X-ray Microanalysis (SEM-EPMA) is routinely used for point analysis to obtain elemental spectra of specific microscopic features; mapping functions are available but are generally restricted to an area typically less than 4 mm<sup>2</sup> (Wilson 2017). X-ray Microdiffraction (or micro-XRD) performed on uncovered thin sections enables mineral identification including clay minerals, but is achieved through spot analysis and locally resolved phase mapping; moreover the technique does not permit elemental characterisation (Shillito et al. 2009; Berthold and Mentzer 2017). Identification of clay minerals under petrographic light microscopy (thin section micromorphology) is tentative,

based on visual attributes such as colour, limpidity and interference colour, attributes which differ across sediment types and may be influenced by a range of other variables (Stoops 2003).

QEMSCAN® is thus unique in its ability to discriminate between clay mineral groups while simultaneously mapping the distribution and contextual relationships between different clay minerals as well as between other geogenic, biogenic and anthropogenic components. The technique enables the deposition, formation and movement of different generations of clays in the stratigraphy to be incorporated into a hierarchy of formation processes that is demonstrated here to provide more nuanced reconstructions of stratigraphically complex archaeological sites. However, the technique is unable to discriminate amorphous materials, including poorly-ordered crystalline materials such as allophane, and to differentiate biogenic silica from geogenic quartz. The present study confirm the findings by Edwards et al. (2017) who proposed that the strength of QEMSCAN® lies in its suitability to characterise heterogeneity and meso-scale processes. As such, the technique is particularly effective in visualising anthropogenic inputs and impacts on stratigraphy and is thus a powerful addition to the microstratigraphic toolkit to aid archaeological interpretation (see also Edwards et al. 2017; Ward et al. 2017; Grono 2020). QEMSCAN® was used here specifically to investigate agricultural contexts, but it is equally applicable to other archaeological deposits and problems of site formation. Microstratigraphic techniques are ideal to incorporate into the research design of new archaeological projects; as demonstrated here, they also provide a means to revisit historic investigations to test the validity of prior interpretations as well as add complementary insights.

## **Conclusion**

The investigation of early and mid-Holocene contexts at Kuk Swamp clearly demonstrates the value of QEMSCAN® as a diagnostic tool for the investigation of clay-rich stratigraphy. QEMSCAN® provides high-resolution qualitative and quantitative data on elemental and mineral distributions, thereby complementing and enhancing the interpretation of archaeological stratigraphy at the macro (field), meso (X-radiography) and micro (thin section description) scales. At Kuk, QEMSCAN® aids the interpretation of processes of original site formation associated with the use of features on former palaeosurfaces, as well as secondary processes subsequent to burial, including palaeosol development and redoximorphic processes resulting from repeated drainage/waterlogging. Although preliminary, these findings highlight the potential value of QEMSCAN® for the microstratigraphic investigation of clay-rich contexts at archaeological sites, especially highly-weathered stratigraphy in the wet tropics, which hitherto have only been poorly characterised using X-radiography and optical microscopy.

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## Figure Captions

Figure 1. Left: Maps depicting the location of Kuk Swamp in Papua New Guinea (upper left) and the Upper Wahgi Valley (lower left). Right: A plan of the archaeological excavations in the southeastern portion of the site marks the locations of the stratigraphic sections investigated here: Feature 1404 (Trench A12b/98-2), Feature 2000 (Trench A12b/98-1) and Feature 504 (Trench A12b/99-4).

Figure 2. (2A) Schematic section of the stratigraphy in the southeastern portion of Kuk Swamp (Denham et al. 2009a: Fig. 2). (2B)-(2D) Stratigraphic sections recorded in the field for Features 504 (2B), 2000 (2C) and 1404 (2D). Sample locations of QEMSCAN® billets shown in red. See Table 1 for descriptions of stratigraphic units in Panels B-D.

Figure 3. Micromorphological and X-radiographic images of key stratigraphic samples. (3a) X-ray image (left) of a monolith containing the fill of Feature 1404 and underlying black organic clay [7] with photomicrographs depicting a crescentic, reworked soil fabric in PPL (middle) and XPL (right), at sequentially higher degrees of magnification (upper to lower). (3b) Photograph (left) and X-radiograph (middle) of a monolith within grey clay [5], with detailed photomicrographs (right) of grey clay groundmass in PPL (upper) and XPL (lower). (3c) Thin section of the heterogeneous fill of Feature 2000 (left) with detailed photomicrographs (right) of the phytolith-rich 'R+W' matrix (upper) and included granules (lower) with higher resolution PPL and XPL images. (3d) Thin section (left) of the heterogeneous basal fill of Feature 504, with photomicrographs (right) of included granules in PPL. (Multipanels incorporate some images from Denham and Grono 2017)

Figure 4. QEMSCAN® mineral map of the fill of Feature 1404 and underlying black organic clay [7] (left) with insets (second-left column) focussing on the abrupt and broken boundary marking the basal edge of the feature (4A-4B) and kaolinitic infilling of inter-pedal voids between smectite-rich aggregates (4A, 4C). The double-panel beneath inset 4A shows kaolinite (left) and smectite (right) distributions. The double-panel beneath inset 4B shows smectite (left) and quartz (right) distributions. Three labelled panels on the right show individual mineral distribution maps of quartz, smectite and kaolinite (in the left panel all minerals are combined in the one map). Refer to Table 2 for mineral percentages and key.

Figure 5. QEMSCAN® mineral map of grey clay [5] showing kaolinite-rich groundmass (left) with insets (right) focussing on homogenous composition (5A) and weakly impregnated ferric hypocoatings around recent, partially-filled voids (5B and 5C, with paired panel insets showing iron distribution in green). Refer to Table 2 for mineral percentages and key.

Figure 6. QEMSCAN® mineral map of the fill of Feature 2000 (left) with insets (right) focussing on pedofeatures indicative of pedogenic processes: granules (6A, right inset panel shows quartz; and 6B, right inset panel shows kaolinite); kaolinitic argillan (6C, right inset panel shows smectite); and, infilled void (6D, with additional inset panels showing quartz [top-right], smectite [bottom-left] and kaolinite

[bottom-right]). Four labelled panels on the right show individual mineral distribution maps of quartz, smectite and kaolinite (in the left panel all minerals are combined in the one map), and an elemental distribution map of iron (green) with trace manganese (red). Refer to Table 2 for mineral percentages and key.

Figure 7. QEMSCAN® mineral map of the fill of Feature 504 (left) with insets (right) focussing on heterogeneity of kaolinite-rich groundmass: kaolinitic argillans (7A, right inset panel shows smectite); weathered granule of mullite with minor corundum (7B, right inset panel shows quartz); granule of mullite (7C); and, kaolinitic granules (7D, upper inset panel shows smectite). Four labelled panels on the right show individual mineral distribution maps of quartz, smectite and kaolinite (in the left panel all minerals are combined in the one map), and an elemental distribution map of iron (green) with trace manganese (red). Refer to Table 2 for mineral percentages and key.

**Table 1.** Field descriptions of stratigraphy for Feature 504 (Fig. 2B), Feature 2000 and grey clay [5] (Fig. 2C) and Feature 1404 (Fig. 2D) sections

<b>Context</b>	<b>Name</b>	<b>Description</b>
<i>Feature 504 section</i>		
3	Crumbly black	Black (2.5Y 2.5/1) clay, spheroidal, very firm, very sticky, very plastic, few-to-common roots (dry – very dark grey, 10YR 3/1, very hard)
7	Black organic clay (above Ep ash)	Black (2.5Y 2.5/1) clay, massive, very firm, very sticky, very plastic, few roots (dry – very dark grey, 10YR 3/1, extremely hard)
7	Black organic clay (below Ep ash)	Black (2.5Y 2.5/1) clay, massive, very firm, very sticky, very plastic, few roots (dry – dark grey, 10YR 4/1, hard with common, medium mottles of grey, 10YR 5/1)
28	Ep ash	Brown (10YR 4/3), weakly cemented loamy silt, very firm, slightly sticky, slightly plastic, few roots (dry – very pale brown, 10YR 8/3, hard granules)
504a	Fill of Feature 504	Very dark grey (10YR 3/1) clay, massive, very firm, very sticky, very plastic, few roots with many coarse black (2.5Y 2.5/1) mottles and few fine granules of dark yellowish brown (10YR 4/4) loamy silt (dry – very dark grey, 10YR 3/1, slightly hard with many medium granules of very pale brown, 10YR 7/3 tephra)
<i>Feature 2000 and grey clay [5] section</i>		
1	Topsoil	Black (7.5 YR 2.5/1) silty clay loam, subangular blocky, firm, very sticky, very plastic, many fine roots (dry – very dark grey, 10YR 3/1, hard)
3	Crumbly black	Black (10YR 2/1) silty clay loam, spheroidal, firm, slightly sticky, slightly plastic, few fine roots (dry – very dark grey, 10YR 3/1, hard)
4	Black clay	Black (10YR 2/1 to 2.5Y 2.5/1) clay, massive, very firm, sticky, very plastic, very few, fine roots (dry – very dark grey, 10YR 3/1, very hard)
5	Grey clay	Dark grey (10YR 4/1) clay, massive, firm, very sticky, very plastic, few fine roots, with very dark grey (Gley N 3/) and dark brown (7.5YR 3/3) mottles, latter represents ferric iron deposition (dry – dark grey, 10YR 4/1 to brown, 7.5YR 4/2, very hard)
2000a	'R+W ash' [27] fill of Feature 2000	Yellowish brown (10YR 5/4), very fine sandy silt, very friable, nonsticky, nonplastic, considerable heterogeneity in the colour of this unit in the field (dry – very pale brown, 10YR 7/3 to 10YR 7/4, soft)
<i>Feature 1404 section</i>		
5	Grey clay [5]	Dark grey (10YR 4/1) to brown (7.5YR 4/2), clay, massive, firm, very sticky, very plastic, few fine roots, few-to-common very dark grey (10YR 3/1), reddish brown (5YR 4/3), dark brown (7.5YR 3/3) and black (2.5Y 2.5/1) mottles
7	Black organic clay [7]	Very dark grey (10YR 3/1) to black (2.5Y 3/1), clay, massive, very firm, slightly sticky, plastic, common very fine roots, few brown (10YR 4/3) and reddish brown (5YR 4/3) mottles, few granules of pale yellow (2.5Y 7/4) silt
1404a	Fill of Feature 1404	Dark grey (7.5YR 4/1) clay, massive, firm, very sticky, very plastic, few roots, common very dark grey (10YR 3/1) mottles

**Table 2.** Mineral library and resultant mineral percentages from QEMSCAN analysis of early agricultural contexts at Kuk Swamp. Colour coding for clay mineral groupings and individual minerals represents the key for Figures 4-7.

<b>Class</b>	<b>Group</b>	<b>Mineral</b>	<b>Colour Code</b>	<b>Feature 1404</b>	<b>Grey Clay [5]</b>	<b>Feature 2000</b>	<b>Feature 504</b>
Silicate	Quartz/Silica	Quartz/Silica		5.16	0.54	16.52	6.29
	Feldspars	Alkali Feldspar		0.10	0.01	0.26	0.09
		Plagioclase		0.02	0.04	0.37	0.33
	Clay Minerals	Kaolinite		77.00	97.48	60.09	77.17
		Illite		0.19	0.03	0.29	0.13
		Chlorite		0.01	0.02	0.20	0.03
		Smectites		17.43	1.80	21.86	14.12
	Pyroxenes	Pyroxene		0.02	0.00	0.03	0.06
	Neosilicate	Mullite		0.00	0.00	0.00	1.06
Oxide	Iron	Hematite		0.00	0.00	0.04	0.01
	Titanium	Rutile		0.00	0.00	0.00	0.03
	Titanium-Iron	Ilmenite		0.00	0.00	0.00	0.11
	Aluminium	Corundum		0.00	0.00	0.00	0.22
Unclassified				0.07	0.08	0.33	0.36