
Times of Sand: Sedimentary History and Archaeology at the Sigatoka Dunes, Fiji

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The orthodox archaeological sequence at the Sigatoka Dunes site (VL 16/1) in Fiji proposes three phases of occupation spanning Fijian prehistory, each associated with a period of dune stability. It has been taken as the standard model of Fijian prehistory for more than 30 years. Recently, however, it has been argued that there is no stratigraphic support for three discrete levels and that the occupation history was fragmented, complex, and continuous within a volatile dune system. We present new data, from optical and radiocarbon dating, to argue that a three-phase model, although somewhat more complex in detail, remains the most robust interpretation of site history. The longest stable phase (Level 2) began 2500–2300 cal yr B.P. and is possibly associated with relatively low ENSO frequency. Substantial sand dune accumulation began after ~1300 cal yr B.P. © 2006 Wiley Periodicals, Inc.

INTRODUCTION

The sand dunes at Sigatoka River mouth, on the south coast of Viti Levu, Fiji, are among the largest (240 ha) and certainly the highest (53 m above sea level) in tropical Remote Oceania (Micronesia, Polynesia, and Melanesia east of the main Solomon Islands). They enclose, and periodically expose, a complex of cultural remains (notably site VL 16/1), which has been the primary focus of research in Fijian archaeology, both in fieldwork and sequence analysis (Gifford, 1951; Green, 1963a, 1963b; Green and Palmer, 1964; Dickinson, 1968; Palmer et al., 1968; Birks, 1973; Frost, 1979; Hunt, 1986, 1987; Southern, 1986; Best, 1987a, 1987b, 1989; Parry, 1987; Visser, 1988, 1994; Crosby, 1991a, 1991b; Hudson, 1994; Petchey, 1994, 1995; Burley, 1997, 2003; Dickinson et al.,

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1998; Wood et al., 1998; Marshall et al., 2000; Burley and Dickinson, 2004). The archaeological significance of the Sigatoka Dunes arises from the large area over which remains have been recorded, the comprehensive nature of a sequence that now includes ceramics from each of the early Lapita, late Lapita, Polynesian plainware, Navatu, and Vuda phases—effectively the full Remote Oceanic prehistoric sequence in its Fijian expression—and from the history of the dunes in relation to archaeological exposures, which has been taken as a general stratigraphic model for Fijian prehistory. The issue of whether that model is clearly illustrated in the stratigraphy and chronology of the dunes we take up here, prompted by a recent divergence of opinion.

Until recently, the history of dune formation and its enclosed sequence of archaeological occupations at Sigatoka had been comprehended within a culture-historical model that owed its origin to the systematization of the Fijian ceramic series. Green (1963a, 1963b; Green and Palmer, 1964) proposed that Fijian pottery could be grouped into four phases: Lapita and plainware assemblages in the Sigatoka phase (1200–100 B.C.), paddle-impressed wares in the Navatu phase (100 B.C.–A.D. 1100), incised and shell-impressed assemblages in the Vuda phase (A.D. 1100–1800), and ornate modern wares in the Ra phase (about A.D. 1800–1900).

From excavation in 1965–1966 of more than 2600 m² on the beachfront of the Sigatoka Dunes, Birks (1973) then argued that three successive and separate archaeological levels could be recognized, each represented by a paleosol (Dickinson, 1968), although that term was used more to designate a temporarily stable surface than to connote prolonged pedogenesis. Level 1 contained Lapita pottery (Sigatoka phase) exposed approximately 2 m above HWST (High Water Spring Tide). Level 2 contained pottery of the applied and relief tradition (cf. Navatu phase) at about 6 m above HWST, and Level 3 had pots of the early historical *kuro* type at about 8.7 m above HWST. Radiocarbon ages (Table II) for Level 1 (Gak-946) and Level 2 (Gak-1206) suggested that the two earlier occupations occurred at about 2650 and 1700 cal yr B.P., respectively (Birks, 1973, p. 57), and Birks (1973, p. 64) estimated a date of 1000 yr B.P. for Level 3. This is the conventional stratigraphic model (CSM) for site VL 16/1; it has underpinned three decades of research at the site and, in a wider context, has served to validate the archaeological credentials of the Fijian ceramic sequence.

THE SEQUENCE PROBLEM

The CSM (Birks, 1973, Figure 4) was explicitly idealized. Birks (1973, p. 10) pointed out that there was considerable spatial variation in the representation of ceramic assemblages, that of Level 2 being the most continuous, that of Level 3 the least. He thought that the paleosol surfaces rose toward the west (Level 2 up to 36.5 m elevation), and that Levels 2 and 3 rose toward the south or seaward side. However, these paleosols, which spanned some 2000 years, occurred in the lower part of the dunes, and most of the present high relief must have accumulated “at an obviously accelerated pace during the later history of the dune system” (Birks, 1973, p. 64). Relatively slow dune formation in early prehistory, followed by late rapid change, carried a plausible implication of considerable importance to thinking about the broad settlement pattern of Fijian prehistory. Assuming that the dune accumulation rate was

related to the sediment load carried in the Sigatoka River, and that, in turn, to the rate of erosion in the catchment because of forest firing (Birks, 1973, pp. 61, 64), then the Sigatoka Dunes sequence implied a history of relatively late population growth and settlement penetration into the island interior, as appears to be true elsewhere in the eastern and southern Lapita regions (Anderson, 2002).

Twenty-five years after Birks, Dickinson et al. (1998) examined the continuing utility of the CSM to accommodate the accumulating data, both archaeological and sedimentary. Their review of the evidence incorporated new stratigraphic and archaeological results arising from two projects that began in the lower Sigatoka valley in 1995–1996; one by Simon Fraser University (Burley, 1997) and the other by the Australian National University (Hope and Anderson, 1995; Anderson et al., 1996), in both instances in conjunction with the Fiji Museum. Dickinson et al. (1998) suggested that the artifact-bearing portion of Level 1 had been eroded away (Burley and Dickinson, 2004, show that is not so), noted variable elevations of Levels 2 and 3 and the different spatial and density distribution of cultural remains associated with each, and observed that Level 3 occurred within an actively expanding phase of dune development that could be dated to after 1600 cal yr B.P. Locating the origin of accelerated dune development explicitly within, rather than after, the sequence of paleosols, represented a revision of the CSM that can be called CSMr (Figure 1).

In a subsequent monograph, Marshall et al. (2000, p. 68) overlooked the CSMr difference and rejected the Dickinson et al. (1998) reading of the Sigatoka evidence as a:

...reductionist view of the dunes [sic] stratigraphy as a simple vertical layercake... By assuming in advance that the Birks sequence of paleosols is typical of the entire dune system, and that the sequence of human occupation is identical to and co-incident with that of the paleosols, Dickinson et al. eliminate from view all variety and diversity present in the archaeological data. (p. 8)

Marshall et al. (2000) based their opinion less upon a different dataset than upon a different approach. Their analysis is structured around a map of the dunes site that was made in 1992, from which they propose that the dunes need to be seen not as a generalized stratigraphic sequence but as complex and variable intercutting and overlapping surfaces (Marshall et al., 2000, p. 9). Their impetus toward this view arises from a theoretical perspective that complains of the constraining influence of earlier models (Marshall et al., 2000): “The continued filtering of archaeological data through the orthodox four-phase culture historical model, so eloquently represented by the Birks’ stratigraphy diagram [i.e., the CSM] is defeating attempts to theorise Fijian prehistory in a more sophisticated way” (p. 9).

A more sophisticated way would favor continuity of interaction and change, and resulting mosaics of cultural diversity and regional complexity over a broadly uniform but punctuated (and sometimes migrationist) perspective arising from the ceramic typology. There is merit in this theoretical argument but it opens a broader vista than can be dealt with adequately here, and it has empirical implications that need to be demonstrated generally for Fiji before its usefulness can be assessed. However, for Marshall et al. (2000, p. 8), as for us, it precipitates the necessity to look critically at the Sigatoka stratigraphy and chronology and ask to what extent it

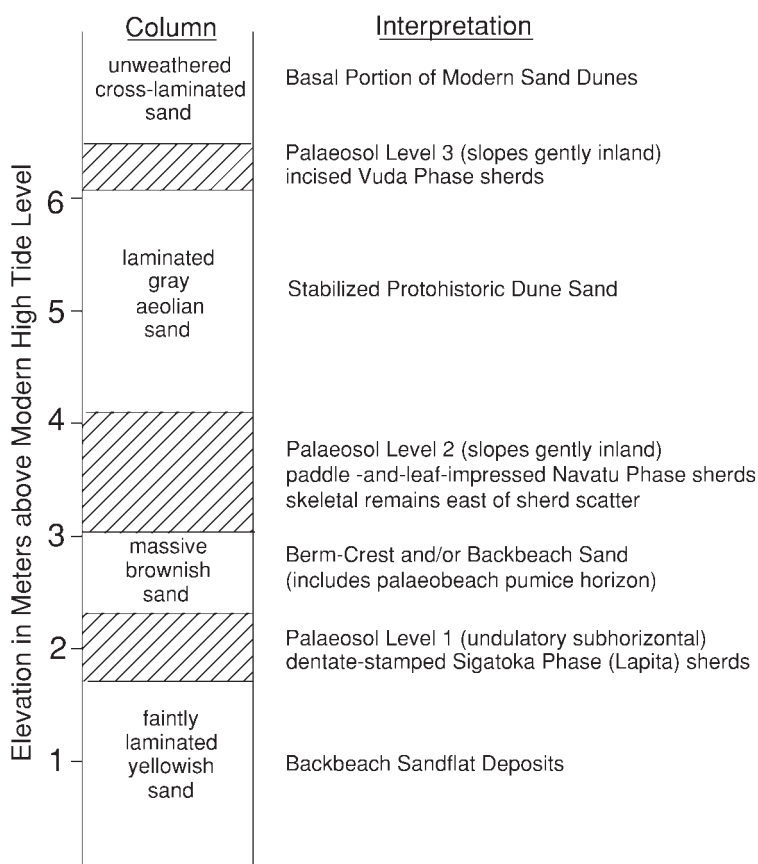


Figure 1. The Sigatoka sequence (CSMr). From “Geomorphic and Archaeological Landscapes of the Sigatoka Dune Site, Viti Levu, Fiji: Interdisciplinary Investigations,” by W.R. Dickinson, D.V. Burley, P.D. Nunn, A. Anderson, G. Hope, A. de Biran, et al., 1998. *Asian Perspectives*, 37, Figure 4. Copyright 1998. Reprinted with permission from *Asian Perspectives*.

still appears to justify its iconic status in Fijian prehistory. We bring to this task some important new data from optical and radiocarbon dating and integrate the results with those from recent archaeological investigations, notably by Burley (2003). From that evidence, we review the stratigraphic history to ask whether the Sigatoka archaeological sequence should indeed be regarded as “a nearly continuous mosaic of shifting settlement” (Marshall et al., 2000, p. 3).

Two preliminary matters concerning the pertinent evidence should be noted. First, we take the point (Marshall et al., 2000, p. 68) that there is more complexity in the use of the dunes for burial than is encompassed by the conventional stratigraphic model. That, however, is to be expected, for sand dunes were suited to burial when they might

not have been chosen for settlement. Nevertheless, Marshall et al. (2000, p. 53) concede that the great majority of the burials are associated with either the Level 2 or the Level 3 paleosol. It is not suggested here, nor was it by Dickinson et al. (1998), that the Sigatoka Dunes were sequestered from any human use during periods between those represented by the ceramic debris. The central debate, however, is about the stratigraphic distribution of the latter. Given that burial areas are concentrated toward the eastern and western extremities of the site, they can be left out of a discussion here that focuses on the nature of dune formation and archaeological sequence in the main settlement area between them, extending from about 400 m to 850 m in the Marshall et al. (2000, Figures 4.1, 5.1) plans and encompassing the area of the Birks (1973) excavations. In addition, as there has been much less research on the dunes to the west of the main site, it would be premature to assume that they exhibit precisely the same stratigraphic sequence, even if Level 2 can be traced well to the west, as noted below.

Second, it is difficult to discuss spatial distribution of archaeological features at the Sigatoka Dunes in detail because the most comprehensive map, produced in 1992 (Wood et al., 1998), and used by Marshall et al. (2000), could not be used at a small-scale resolution by research teams in 1996. The survey datum left no recognizable feature and lay 60 m or so outside the boundary of the printed map, while the 100-m datum marker poles to which the map was keyed had been washed away soon after it was made (these locational deficiencies remain in Wood et al., 1998 and Marshall et al., 2000). Further, in attempting to match the map to the distribution of recognizable features on the ground, it became apparent that there were discrepancies of up to 25% in distances, so that new maps of the Sigatoka Dunes site, made by total station survey, were required for the 1996 research (Clark and Anderson, 2005; Burley and Dickinson, 2004, note 2), one of them presented here as Figure 2.

SIGATOKA DUNES CHRONOLOGY

Optical Dating

Optical dating (Huntley et al., 1985; Aitken, 1998; Bøtter-Jensen et al., 2003) was used to estimate the time since the quartz sediments deposited at Sigatoka were last exposed to sunlight (“bleached”). Buried grains are exposed to the flux of ionizing radiation (the “dose rate”) from the nuclear decay of ^{238}U , ^{235}U , ^{232}Th (and their daughter products), and ^{40}K in the surrounding deposit (and, to a lesser extent, from radioactive inclusions internal to the quartz grains), with a minor contribution from cosmic rays. The burial dose (“paleodose”) can be measured using optically stimulated luminescence (OSL), and the optical age is calculated by dividing the paleodose by the dose rate.

Sample Collection and Preparation

Optically stimulated luminescence samples were collected from stratigraphic sections at six locations. Attention was concentrated on Area 1, or the “Lower Beach” excavation (Figure 2), where a broad and deep section of Level 2 was exposed. A 3×2 m excavation recovered the cultural material littering the surface and contained in the dune deposits to

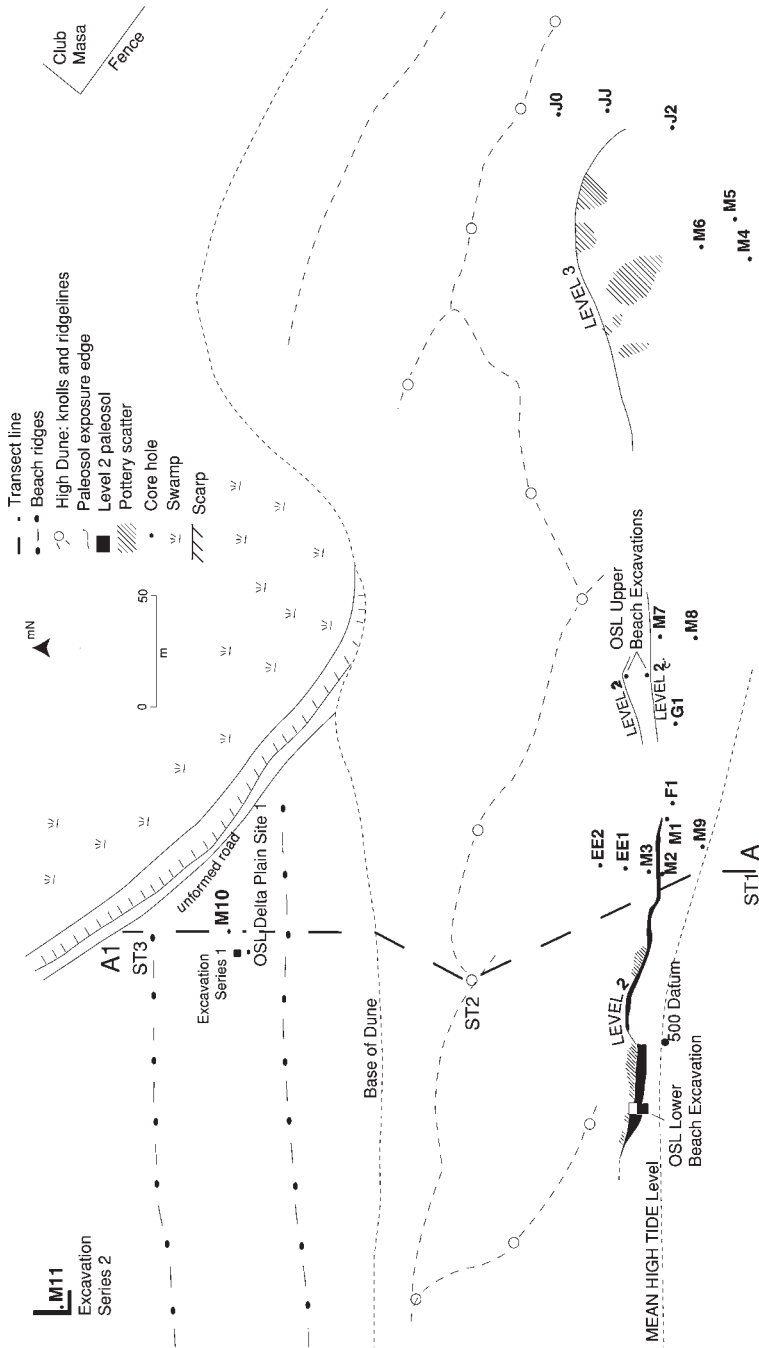


Figure 2. Sigatoka Dunes site area, as mapped in 1996, showing location of cores, optical (OSL) dating sample localities, dune transect (see Figure 3), and SFU excavation areas. From "The early prehistory and palaeoenvironment of Fiji," by G.R. Clark & A.J. Anderson (Eds.), 2005, unpublished manuscript. Reprinted with permission of the authors.

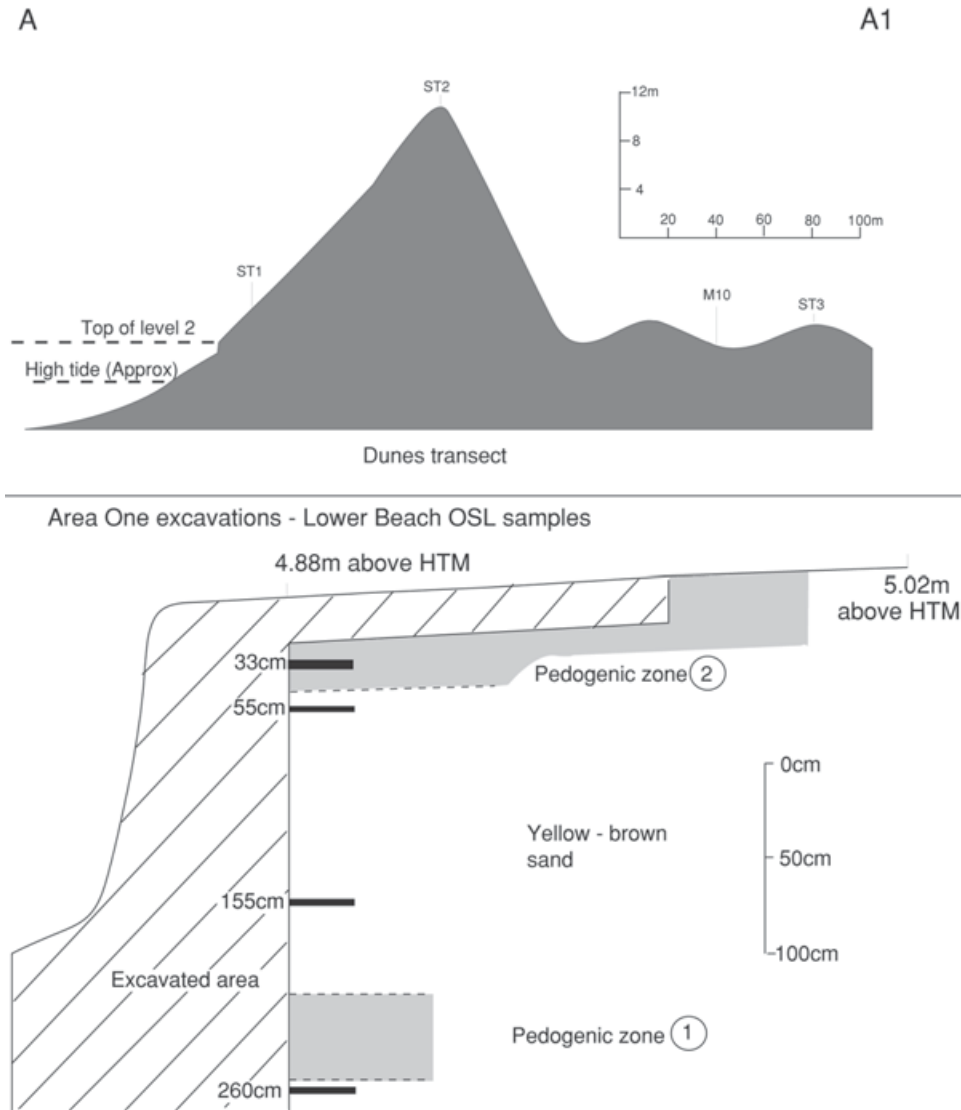


Figure 3. Elevation transect through the Sigatoka Dunes (see Figure 2), and location of OSL samples in the Lower Beach excavation.

a depth of about 20 cm. A vertical face was then cut to 270 cm, which was as deep as it was possible to go safely. Four samples were collected for optical dating (Figure 3):

- LB33 from a depth of 33 cm, to date the lower half of the Level 2 pedogenic zone, which is Paleosol Level 2 in Figure 1
- LB55 from a depth of 55 cm, to date the sands immediately under Level 2

- LB155 from a depth of 155 cm, to date the sands between Level 2 and the Level 1 pedogenic horizon (= Paleosol Level 1 in Figure 1)
- LB260 from a depth of 260 cm, to date the sand immediately under assumed Level 1

Two OSL samples were also collected at the “Upper Beach” excavations, 200 m to the east. These were sketch-mapped and the stratigraphy recorded, but their precise locations were not mapped due to a miscommunication in the field. They were at about the points shown in Figure 2, where two lines of paleosol were exposed. As recorded during our mapping, the paleosol surfaces that were test-pitted for OSL sampling lay at about 9 m (Pit 1) and 4.4 m (Pit 2) above high-tide level and approximately 20 m apart, north–south. It was thought that Pit 1 sampled a Level 3 paleosol, partly from its elevation and partly because several pot sherds of possible Level 3 provenance were found on the surface. However, it can be very difficult to distinguish Level 2 from Level 3 material from a small sample (Marshall et al., 2000, p. 90), and, at the place in question, at approximately 330–350 m on their map, Marshall et al. (2000, Figure 7.4) show two lines of Level 2 paleosol about 15 m apart, the upper of which rises eastward to about 8 m in elevation. So, the dark-brown paleosol at 60 cm depth in Pit 1 was more likely Level 2 than Level 3. Sediment sample UB55 was taken at 55 cm for optical dating. Pit 2 was excavated to 130 cm. Below 50 cm of modern dune sand was a 65-cm-thick, dark-brown paleosol overlying uncompact yellow-brown sand. A thin charcoal lens and several undecorated body sherds were encountered at 40 cm depth in the paleosol (90 cm from the surface). Optically stimulated luminescence sample UB90 was collected from 90 cm depth in Pit 2 to date the middle of the paleosol.

On the “Delta Plain” close to core hole M10 and 5 m seaward of a recent excavation trench (excavation series 1 of Burley, 1997), a 1.0-m-deep test pit exposed a 65-cm-deep, dark-brown paleosol with Level 2 sherds (some paddle-impressed) near the surface (Figure 2). An OSL sample (DP72) was taken from 72 cm depth to provide an age for the sand immediately beneath this paleosol. Approximately 1 km to the northeast, where the most landward of the aeolian dune ridges could be recognized on aerial photos (at a point where the driveway from the Keli house reaches the main road, which here takes a right-angled bend close to the right bank of Vatueta Creek), another test pit was dug to a depth of 80 cm. This showed an upper cultivated horizon of very dark, brown soil and a few Level 2 sherds to a depth of 20 cm, overlying 30 cm of the same brown paleosol observed at the other Delta-Plain site (and elsewhere) and assumed to be Level 2. Below this, beginning at about 55 cm depth, was weathered, orange sand. Sediment sample DP65 was collected from a depth of 65 cm for optical dating of the sand immediately beneath Level 2.

In the laboratory, under dim red illumination, quartz grains of 180–212 μm diameter (Lower Beach samples) and 90–125 μm diameter (Upper Beach and Delta Plain samples) were extracted using standard purification procedures (Aitken, 1998; Galbraith et al., 1999) and etched in 40% hydrofluoric acid for 45 min to remove the alpha-dosed rinds. Etched grains were mounted on 10-mm-diameter stainless steel discs, using silicone oil spray as adhesive. The number of grains per disc (“aliquot”) was constrained to ~100 grains (Lower Beach samples) and ~800 grains (Upper

Beach and Delta Plain samples). The number of grains per aliquot could not be kept any smaller owing to the weak OSL emissions from the Sigatoka quartz grains. Typically, 27 individual aliquots of each sample were prepared. The OSL signals were measured using an automated Risø TL-DA-12 reader fitted with a Chance-Pilkington HA-3 filter (St. Asaph, North Wales, UK) and two 3-mm-thick Hoya U-340 filters (Tokyo, Japan) in front of an Electron Tubes Ltd 9235QA photomultiplier tube (Middlesex, UK); a calibrated $^{90}\text{Sr}/^{90}\text{Y}$ beta source for on-plate irradiations (delivering $\sim 1.4 \text{ Gy}/\text{min}^{-1}$ to quartz grains mounted on stainless steel discs); and a filtered tungsten-halogen lamp to provide $\sim 25 \text{ mW}/\text{cm}^{-2}$ of green-plus-blue (420–550 nm) illumination for optical stimulation (Galbraith et al., 1999).

Paleodose Determination

For each aliquot, the apparent paleodose was determined using a simplified regenerative-dose protocol that has proven reliable for other quartz samples where independent age control is available (e.g., Roberts et al., 1998a, 1999; Galbraith et al., 1999, 2005; Turney et al., 2001). We use the term “apparent” to denote that final estimation of the sample paleodose, from which the optical age is calculated, takes into account the amount of within- and between-aliquot variation in apparent paleodose.

Each aliquot was optically stimulated for 100 s at 125°C and the resulting OSL signal was integrated over the first 5 s of illumination, using the count rate over the final 20 s as background. Apparent paleodoses were calculated from the net OSL signals arising from the natural (field) dose, a subsequent test dose, a regenerative dose, and a second test dose. The OSL signals induced by the test doses (both $\sim 1 \text{ Gy}$), which were cut-heated to 160°C before optical stimulation, were used to correct for any changes in OSL sensitivity between the natural and regenerative dose cycles. Each aliquot received a regenerative dose of 2–3 Gy to closely match the natural dose, and the natural and regenerative doses were held (“preheated”) at 280°C for 10 s before illumination.

In a subsequent cycle, a second regenerative dose and a third test dose, both identical in size to the first, were given to each aliquot to check that the correct (known) dose could be recovered. Only those aliquots that yielded “double regenerative” doses consistent with the given regenerative dose at the 95% confidence interval were considered sufficiently reliable to determine an apparent paleodose. The numbers of such aliquots used to estimate the apparent paleodoses are listed in Table I.

For the determination of the sample paleodoses and optical ages, two different age models were considered. The *central age model* (Galbraith et al., 1999) is appropriate for samples that were well bleached at burial and for which the optical age may reliably be estimated from the weighted mean paleodose. This model takes into account any “overdispersion” (represented here by the symbol σ) of the apparent paleodoses beyond the spread due solely to measurement uncertainties, such as those arising from photon-counting statistics. Previous studies have reported that even well-bleached sediments commonly have overdispersed paleodose distributions, with σ values ranging from a few percent to almost 20% for aliquots composed of multiple or single grains (e.g., Roberts et al., 1998b, 2000; Jacobs et al., 2003a, 2003b; Olley et al., 2004a, 2004b; Galbraith et al., 2005). We used the central age model to calculate the σ values for all eight Sigatoka sam-

Table I. Dose rate data, paleodoses, and optical ages for sediment samples from the Sigatoka Dunes.

| Sample code / Grain size (μm) | Depth (cm) / Water content ^a (%) | ²³⁸ U | ²²⁶ Ra | ²¹⁰ Pb | ²²⁶ Ra | ²³² Th | ⁴⁰ K | Cosmic-ray dose rate ^c (mGy/yr ⁻¹) | Total dose rate ^d (mGy/yr ⁻¹) | Paleo- dose ^d (Gy) | Number of aliquots / σ^e (%) | Optical age ^d (yr B.P.) |
|--|---|------------------|-------------------|-------------------|-------------------|-------------------|-----------------|---|--|-------------------------------------|---|--|
| Lower Beach | | | | | | | | | | | | |
| LB33 / 180-212 | 33 / 4.4 | 6.4 ± 0.9 | 4.75 ± 0.16 | 2.6 ± 1.1 | 2.64 ± 0.31 | 2.82 ± 0.13 | 234 ± 2 | 0.22 | 1.06 ± 0.04 | 2.22 ± 0.12 | 16 / 20 ± 4 | 2140 ± 150 |
| LB55 / 180-212 | 55 / 3.8 | 2.5 ± 1.4 | 3.62 ± 0.25 | 0.4 ± 1.9 | 2.64 ± 0.51 | 1.93 ± 0.20 | 155 ± 10 | 0.20 | 0.72 ± 0.05 | 1.75 ± 0.08 | 15 / 13 ± 3 | 2420 ± 210 |
| LB155 / 180-212 | 155 / 4.0 | 3.0 ± 1.4 | 4.26 ± 0.26 | 2.9 ± 1.5 | 2.20 ± 0.58 | 2.36 ± 0.58 | 230 ± 10 | 0.17 | 0.96 ± 0.05 | 2.19 ± 0.07 | 21 / 9 ± 2 | 2280 ± 140 |
| LB260 / 180-212 | 260 / 2.9 | 4.0 ± 1.1 | 4.36 ± 0.17 | 3.5 ± 1.4 | 2.17 ± 0.36 | 2.52 ± 0.15 | 215 ± 12 | 0.15 | 0.91 ± 0.05 | 2.53 ± 0.07 | 26 / 5 ± 3 | 2770 ± 180 |
| Upper Beach | | | | | | | | | | | | |
| UB55 / 90-125 | 55 / 3.2 | 4.0 ± 1.3 | 4.06 ± 0.25 | 2.9 ± 1.4 | 2.04 ± 0.55 | 2.18 ± 0.21 | 180 ± 12 | 0.20 | 0.86 ± 0.05 | 2.12 ± 0.09 | 23 / 79 ± 12 | 2470 ± 190 |
| UB90 / 90-125 | 90 / 6.8 | 5.1 ± 0.9 | 4.99 ± 0.16 | 2.7 ± 1.1 | 2.80 ± 0.32 | 2.76 ± 0.14 | 240 ± 5 | 0.18 | 1.01 ± 0.05 | 1.86 ^{+0.21/-0.40} | 14 / 49 ± 9 | 1840 ^{+230/-400} |
| Delta Plain | | | | | | | | | | | | |
| DP65 / 90-125 | 65 / 8.3 | 5.2 ± 1.0 | 4.80 ± 0.19 | 3.9 ± 1.1 | 2.69 ± 0.42 | 2.52 ± 0.16 | 285 ± 20 | 0.18 | 1.16 ± 0.08 | 2.39 ^{+0.13/-0.14} | 20 / 46 ± 7 | 2060 ± 180 |
| DP72 / 90-125 | 72 / 5.2 | 4.3 ± 1.1 | 4.68 ± 0.17 | 3.9 ± 1.5 | 2.75 ± 0.37 | 2.95 ± 0.16 | 220 ± 14 | 0.18 | 0.97 ± 0.06 | 2.21 ± 0.09 | 20 / 61 ± 10 | 2290 ± 170 |

^aMeasured (field) water content expressed as % of dry mass of sample; ^b Measurements made on dried and powdered samples by high-resolution gamma spectrometry, and also by X-ray fluorescence spectrometry for K₂O content. Concentrations of 1 p.p.m. ²³⁸U, 1 p.p.m. ²³²Th, and 1% ⁴⁰K correspond to activities of 12.4, 4.1, and 316 Bq kg⁻¹, respectively; ^c Time-averaged estimates for dry samples, each assigned an uncertainty of ± 10%; ^d Mean ± total uncertainty (68% confidence interval), calculated as the quadratic sum of random and systematic uncertainties. Paleodose uncertainty includes a systematic component of ± 2% associated with laboratory beta-source calibration. For dose rate and age calculations, a time-averaged water content of 4 ± 1% was used for all four Lower Beach samples and UB55, and a value of 6 ± 2% was used for both Delta Plain samples and UB90; ^e Number of aliquots used for paleodose determination, together with estimate of overdispersion (σ , the relative standard deviation of the apparent paleodoses after allowing for measurement uncertainties). Paleodoses of the Lower Beach samples ($\sigma \leq 20\%$) were obtained using the central age model, whereas paleodoses for the Upper Beach and Delta Plain samples ($\sigma > 20\%$) were calculated using the minimum age model. See text for details.

ples, and adopted the model estimate of the paleodose for those samples with σ values of 20% or less (following Olley et al., 2004b).

For those samples with σ values in excess of 20%, we used the *minimum age model* (Galbraith et al., 1999). For a deposit composed of a mixture of fully and incompletely bleached grains, the most fully bleached grains will be associated with those aliquots returning the smallest apparent paleodoses. When Olley et al. (2004a, 2004b) applied this model to independently dated sediments of Holocene and late Pleistocene age that were incompletely bleached at the time of deposition, it resulted in the correct optical ages.

Dose-Rate Determination

Beta and gamma dose rates were calculated from analyses of dried and powdered samples collected from the sphere of deposit surrounding each OSL sample to a distance of 30 cm. Concentrations of the lithogenic radionuclides ^{238}U , ^{226}Ra , and ^{210}Pb (in the ^{238}U decay series), ^{228}Ra and ^{228}Th (in the ^{232}Th series), and ^{40}K were measured by high-resolution gamma spectrometry at the CSIRO Land and Water facilities in Canberra (Olley et al., 2004a, 2004b) and converted to dose rates following Adamiec and Aitken (1998). Beta dose-attenuation factors were taken from Mejdahl (1979), cosmic-ray dose rates were calculated from published data (Prescott and Hutton, 1994), and an effective internal alpha dose rate of 0.03 mGy/yr^{-1} was assumed for each of the acid-etched quartz samples.

The beta and gamma dose rates for the dry samples were corrected (Aitken, 1985) for their estimated water contents, averaged over the full period of sample burial, and the dry cosmic ray dose rates were similarly adjusted (Readhead, 1987). The time-averaged water contents are representative of the measured (field) water contents (Table I), with uncertainties that should accommodate all likely long-term variations. Ages increase by $\sim 1\%$ for each 1% increase in water content.

Optical Dating Results

A condition of secular equilibrium presently exists in the ^{232}Th decay series for all eight samples but the ^{238}U series exhibits a systematic deficit of ^{210}Pb with respect to ^{226}Ra (Table I), with $^{210}\text{Pb}/^{226}\text{Ra}$ ratios centered around a value of 0.7 ± 0.1 (excluding the aberrant value for sample LB55). We attribute such ratios to the loss of radon gas (an intermediate decay product) to the atmosphere, as reported for many sedimentary deposits (Aitken, 1985, 1998), and assume that the measured ratios have prevailed throughout the period of sample burial. However, the uncertainties associated with disequilibrium in the ^{238}U series will exert an insignificant influence on the total dose rate, as ^{40}K is the major source of ionizing radiation in the Sigatoka sediments.

The distributions of apparent paleodose for all eight samples are shown in Figure 4 as frequency distributions in the left-hand column and as radial plots (Galbraith et al., 1999) in the right-hand column. As regards the latter, the apparent paleodose (in Gy) for an aliquot can be read by tracing a line from the y -axis origin through the point until the line intersects the radial axis on the right-hand side. The corresponding

Lower Beach

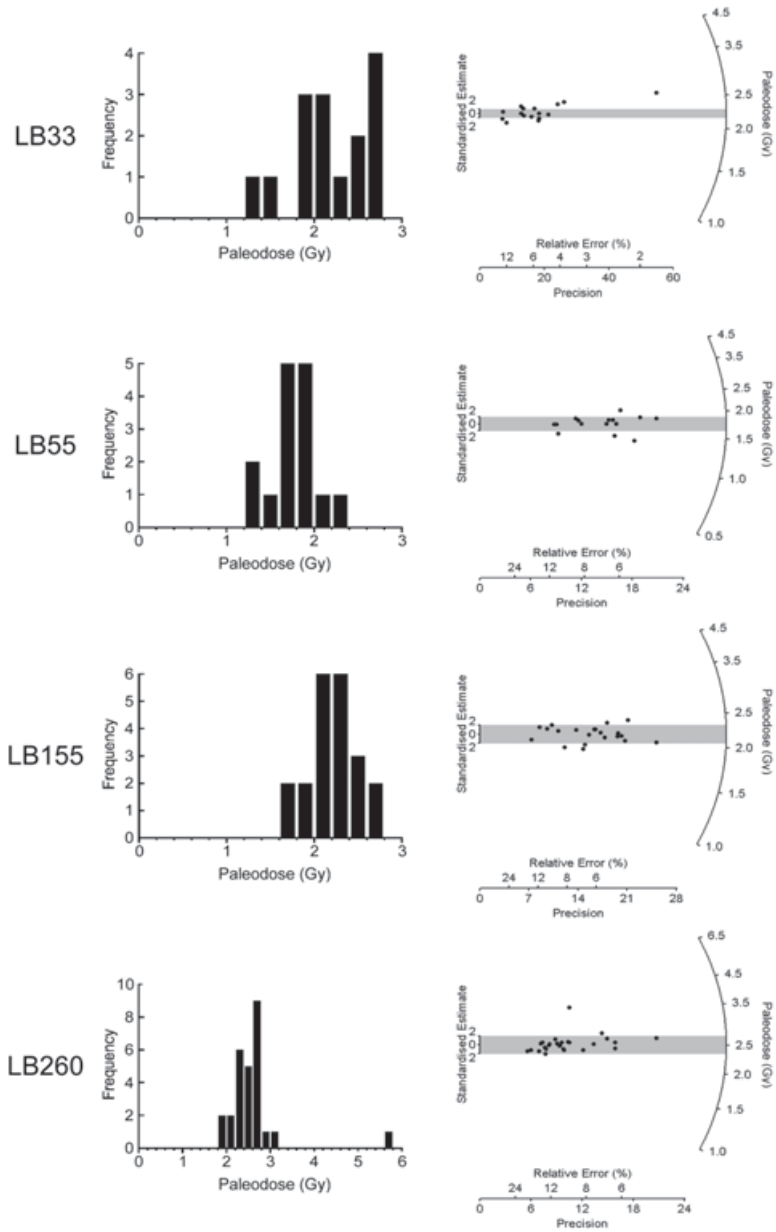
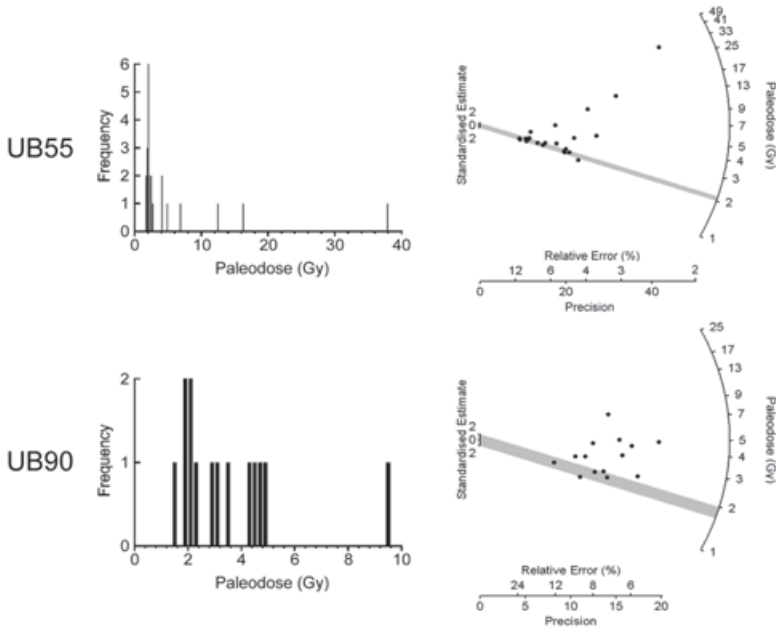


Figure 4. Frequency distributions (left-hand column) and radial plots (right-hand column) of the apparent paleodoses obtained using single aliquots of quartz extracted from eight OSL samples from the Sigatoka Dunes. The shaded bands on the radial plots are centered on the paleodoses used to determine the optical ages.

Upper Beach



Delta Plain

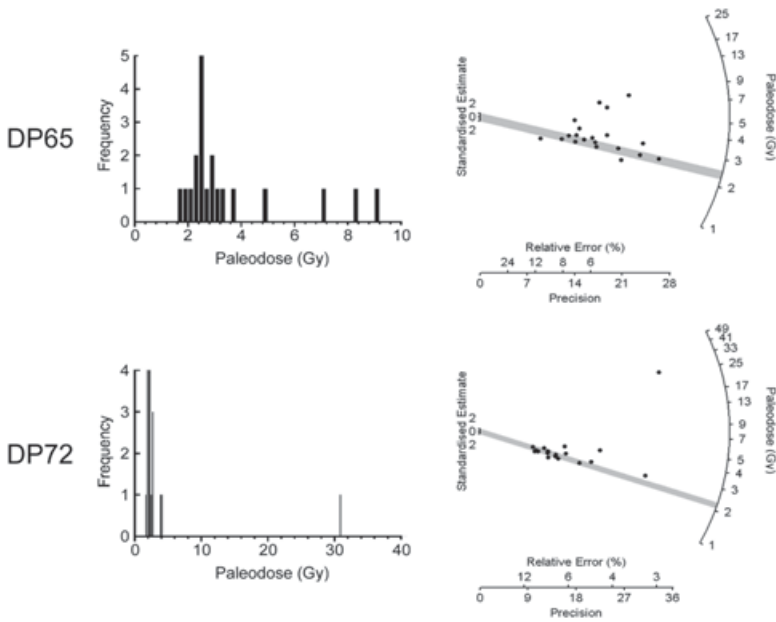


Figure 4. Continued.

standard error for this estimate can be read by extending a line vertically to intersect the x -axis, which has two scales: one shows the relative standard error (in %) and the other ("Precision") plots the reciprocal standard error. Hence, apparent paleodoses measured with the highest precision and the smallest relative error lie closest to the radial axis on the right of the diagram, and the least precise estimates plot furthest to the left. Points contained within the shaded bands are consistent with each other at the 95% confidence interval. As is typical for natural sediments, each of the Sigatoka samples has an overdispersed distribution of apparent paleodoses, with several points lying outside the shaded bands. Estimates of overdispersion are listed in Table I.

The distributions of apparent paleodose, and the overdispersion values of $5 \pm 3\%$ (LB260) to $20 \pm 4\%$ (LB33), for the four Lower Beach samples are consistent with these sediments having been well bleached at deposition. The frequency distributions do not exhibit the positive skewness that characterizes partially bleached sediments (e.g., Olley et al., 1999, 2004a), and the mean overdispersion value of $12 \pm 3\%$ is close to the average also reported for well-bleached natural quartz grains from Aeolian deposits (Jacobs et al., 2003a, 2003b), deep-sea sediments (Olley et al., 2004b), archaeological deposits (Galbraith et al., 2005), and laboratory-dosed samples (Roberts et al., 2000). For each of the Lower Beach samples, therefore, the central age model was used to estimate the burial dose absorbed by the sediment grains since the most recent bleaching event.

Taking their associated uncertainties into account, the optical ages for the Lower Beach samples are in correct stratigraphic order, increasing from 2140 ± 150 yr B.P. at 33 cm depth to 2770 ± 180 yr B.P. at 260 cm depth, with the intermediate samples yielding statistically indistinguishable ages. The age of sample LB55 is influenced by the anomalously low but imprecise estimate of ^{210}Pb concentration. If, instead, a ^{210}Pb value of 2.5 ± 1.5 Bq kg $^{-1}$ is assumed (this being the measured ^{226}Ra concentration for sample LB55 multiplied by the average Sigatoka $^{210}\text{Pb}/^{226}\text{Ra}$ ratio of 0.7), then the age is reduced to 2330 ± 190 yr B.P., which accords more closely with the age of sample LB155. The paleodose, overdispersion, and age shown for sample LB260 in Table I exclude the outlying apparent paleodose of 5.7 ± 0.5 Gy (see Figure 4), which we presume represents an aliquot contaminated by incompletely bleached grains. If this outlier is included, then the optical age increases by only 40 years.

In terms of the archaeological sequence at the Lower Beach excavation, the upper (Level 2) paleosol formed in sediments deposited after 2280 ± 140 yr B.P. (LB155) until at least 2140 ± 150 yr B.P. (LB33). The latter sample was collected from the lower part of the paleosol and not above it, so its optical age does not signal the end of this period of dune formation, which was preceded by the rapid accumulation of 1 m of sand within one or two centuries (i.e., from a depth of 155 cm to 55 cm over a shorter time span than can be resolved from the uncertainties associated with the optical ages). The age of 2770 ± 180 yr B.P. for sample LB260 probably marks the beginning of Level 1.

In contrast with the Lower Beach samples, the distributions of apparent paleodose for the Upper Beach and Delta Plain samples suggest heterogeneous bleaching of the quartz grains at the time of deposition. All four distributions are positively skewed (Figure 4), with overdispersion values of $46 \pm 7\%$ to $79 \pm 12\%$ (Table I). The overdispersion value of $61 \pm 10\%$ for sample DP72 is chiefly the result of a single aliquot with

an apparent paleodose of 30.9 ± 0.9 Gy; omitting this aliquot reduces σ to $22 \pm 4\%$, but this still exceeds the range documented for well-bleached sediments. These overdispersion values are much larger than those values of the Lower Beach samples, despite the Upper Beach and Delta Plain aliquots containing eight times as many grains as the Lower Beach aliquots; all other factors being equal, the variation in apparent paleodose should be less for larger aliquots (Galbraith et al., 2005).

The widely spread and positively skewed Upper Beach and Delta Plain paleodose distributions could be interpreted as the result of postdepositional mixing of grains, but displacement of a significant number of grains would have obliterated the paleosols, as well as the charcoal lens preserved at 90 cm depth in Pit 2 (Upper Beach), and archaeological materials would have been distributed throughout the stratigraphic profile. Also, some of the Upper Beach and Delta Plain aliquots yielded large apparent paleodoses that are commensurate with a late Pleistocene age, but there is no local source for grains of this age. By contrast, the presence of some incompletely bleached grains in these samples, and the lack of significant postdepositional disturbance, explains both the occurrence of aliquots with large apparent paleodoses and the preservation of stratigraphic integrity beneath the remobilized surficial cover of drift sand.

For partially bleached sediments, the burial dose will be most closely approximated by the population of aliquots returning the smallest apparent paleodoses (Olley et al., 1999), and the minimum age model provides a statistically rigorous means of determining the burial dose under such circumstances (Olley et al., 2004a, 2004b). Before running the model, we added (in quadrature), to the measurement uncertainty for each aliquot, an estimate of the overdispersion that would have been present had the sample been well bleached at the time of burial. We chose a value of 12% for the latter, as the well-bleached Lower Beach samples had an average σ value of $12 \pm 3\%$, and we expected the Sigatoka sediments to be similar in terms of their provenance and OSL characteristics.

As regards the archaeology, sample UB55 (Pit 1) was thought to be associated more probably with Level 2 than with Level 3, and the age of 2470 ± 190 yr B.P. is consistent with this interpretation. Sample UB90 (Pit 2) was collected from a dark-brown paleosol, nominally Level 2, and returned an age of 1840^{+230}_{-400} yr B.P. Although this age barely overlaps with that of 2140 ± 150 yr B.P. (LB33) from the lower part of the Level 2 paleosol at the Lower Beach excavation, we cannot rule out the possibility of contemporaneity about 2000 years ago, given the large age uncertainties associated with sample UB90. Alternatively, dune stabilization and pedogenesis may have taken place simultaneously at both locations but later, bearing in mind that the optical ages correspond to the time of sediment deposition and not paleosol formation.

The two Delta Plain samples were collected from immediately beneath the Level 2 paleosol. The ages of 2060 ± 180 yr B.P. (DP65) and 2290 ± 170 yr B.P. (DP72) are statistically indistinguishable (pooled mean age of 2190 ± 130 yr B.P.) and are concordant with those obtained for the samples taken from beneath (2280 ± 140 yr B.P.) and within (2140 ± 150 yr B.P.) the level of paleosol exposed at the Lower Beach excavation.

Table II. Radiocarbon and thermoluminescence ages for the Sigatoka Sand Dunes.

| Lab No. | CRA | Cal. Yr B.P. | Material | $\delta^{13}\text{C}$ | Reference |
|---------------------------|----------------|-------------------|---------------------|-----------------------|----------------------------|
| Radiocarbon | | | | | |
| Level 1 | | | | | |
| NZ 4789 | 2630 \pm 80 | 2920 (2750) 2490 | Charcoal | -25.8 | Petchey, 1995 |
| CAMS 68196 | 2510 \pm 40 | 2750 (2620*) 2360 | Charcoal | -24.3 | Burley, 2002 |
| CAMS 48566 | 2490 \pm 50 | 2750 (2610*) 2350 | Charcoal | -21.4 | Burley and Shortland, 1997 |
| CAMS 48565 | 2470 \pm 50 | 2740 (2640*) 2350 | Charcoal | -23.7 | Burley and Shortland, 1997 |
| GAK 946 | 2460 \pm 90 | 2750 (2650*) 2330 | Charcoal | — | Birks, 1973 |
| Wk 8239 | 2740 \pm 80 | 3060 (2810*) 2740 | Charcoal | — | De Biran, 2001 |
| Level 2 | | | | | |
| WK 996b | 1870 \pm 70 | 1990 (1820) 1610 | Human bone | -15.9 | Best, 1987 |
| GAK 1206 | 1720 \pm 80 | 1820 (1680*) 1420 | Charcoal | — | Birks, 1973 |
| NZ 7599 | 1680 \pm 60 | 1710 (1560) 1420 | Charcoal | — | Best, 1989 |
| CAMS 68194 | 1620 \pm 40 | 1610 (1530) 1410 | Charcoal | -25.5 | Burley, 2003 |
| CAMS 68191 | 1550 \pm 40 | 1530 (1410) 1330 | Charcoal | -27.4 | Burley, 2003 |
| CAMS 68192 | 1540 \pm 40 | 1530 (1410) 1330 | Charcoal | -26.0 | Burley, 2003 |
| CAMS 70921 | 1360 \pm 30 | 1310 (1290) 1250 | Charcoal | -24.6 | Burley, 2003 |
| CAMS 70920 | 1480 \pm 40 | 1510 (1350) 1300 | Charcoal | -25.5 | Burley, 2003 |
| CAMS 70091 | 1430 \pm 40 | 1410 (1310) 1290 | Charcoal | -27.4 | Burley, 2003 |
| CAMS 70090 | 1400 \pm 40 | 1350 (1300) 1260 | Charcoal | -26.0 | Burley, 2003 |
| Wk 8341 | 1640 \pm 160 | 1920 (1530) 1270 | Bulk paleosol humin | — | De Biran, 2001 |
| Wk 8328 | 1410 \pm 150 | 1690 (1300) 990 | Charcoal | — | De Biran, 2001 |
| Wk 9030 | 1400 \pm 40 | 1350 (1300) 1260 | Charcoal | — | De Biran, 2001 |
| Level 3 | | | | | |
| WK 5333 | 590 \pm 60 | 660 (610*) 510 | Charcoal | -26.3 | Dickinson et al., 1998 |
| CAMS 32252 | 510 \pm 60 | 650 (530) 470 | Charcoal | -25.9 | Burley, 2003 |
| CAMS 32251 | 230 \pm 40 | 420 (290) 0 | Charcoal | -27.8 | Burley, 2003 |
| Wk 8900 | 690 \pm 50 | 690 (660) 550 | Charcoal | — | De Biran, 2001 |
| Wk 8361 | 570 \pm 70 | 660 (610*) 510 | Bulk paleosol humin | — | De Biran, 2001 |
| Wk 8342 | 450 \pm 60 | 620 (510) 320 | Bulk paleosol humin | — | De Biran, 2001 |
| Wk 8345 | 440 \pm 160 | 670 (510) 0 | Bulk paleosol humin | — | De Biran, 2001 |
| Wk 8344 | 360 \pm 60 | 520 (350*) 290 | Bulk paleosol humin | — | De Biran, 2001 |
| Thermoluminescence | | | | | |
| | Age yr B.P. | | Ceramic | | Reference |
| TL date (5) | 2200 \pm 200 | — | Sherd with nubbins | | Petchey 1995 |
| VL 16/22/X/5/1 | 2200 \pm 250 | — | Dentate stamped | | Prescott et al., 1982 |
| VL 16/22/X/5/2 | 1650 \pm 180 | — | Paddle impressed | | Prescott et al., 1982 |
| VL 16/22/X/5/3 | 1600 \pm 105 | — | Paddle impressed | | Prescott et al., 1982 |
| VL 16/22/X/6/4 | 1700 \pm 500 | — | Paddle impressed | | Prescott et al., 1982 |
| VL 16/22/X/6/5 | 1740 \pm 200 | — | Paddle impressed | | Prescott et al., 1982 |

* Median value of multiple intercepts. CRA = conventional radiocarbon age. Calibrations by OxCal v. 3.9.

Radiocarbon and Thermoluminescence Dating

The radiocarbon ages in Table II are all those currently available for the Sigatoka Dunes archaeological site. They were collected and submitted in projects based on the stratigraphic and ceramic correlates of the CSM or CSMr, so they constitute a test of the extent to which those models, derived ultimately from Birks (1973), reflect a

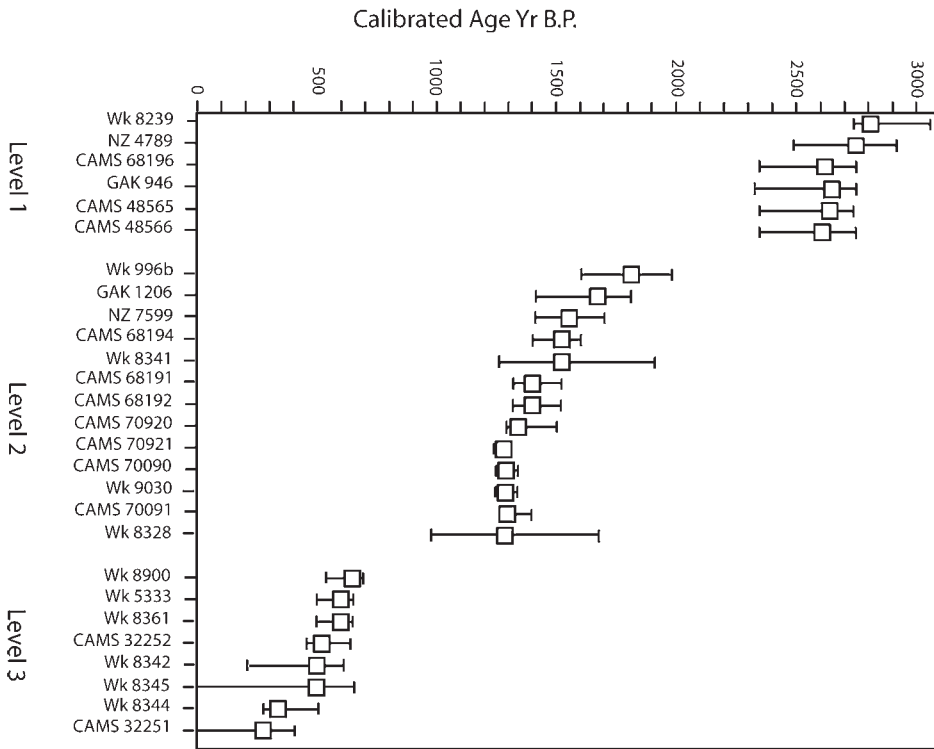


Figure 5. Calibrated radiocarbon ages and uncertainties (at the 95% confidence interval) for the Sigatoka Dunes samples.

continuing stratigraphic reality through the course of archaeological research. Figure 5 shows that the radiocarbon dates are indeed split into three groups, none of which overlaps at the 95% confidence interval.

According to these data, Level 1 dates to around 2800–2600 cal yr B.P., which is consistent with an optical age of about 2800 yr B.P. (Table I). Leaving aside the age determination on human bone (Wk-996b), a difficult material, the Level 2 radiocarbon (median) ages extend from 1700 to 1300 cal yr B.P. The deep paleosol that underlies Level 2 yielded optical ages between about 2300 and 2100 yr B.P. in the Lower Beach series, and between about 2500 and 1800 yr B.P. elsewhere (Table I). These data are in the correct stratigraphic order but suggest some lapse of time between sediment deposition, the formation of the Level 2 paleosol, and its eventual occupation. This is also indicated by the concentration of archaeological material towards the top of the paleosol. Level 3 radiocarbon dates are mostly in the 600–500 cal yr B.P. range, consistent with the late ceramic material.

Thermoluminescence ages on pottery (Table II) refer to samples from the Naqarai site (VL 16/22) located in the dunes approximately 3.7 km west of the main dunes

site. They are somewhat at variance with the other data. The results for dentate-stamped sherds seem too young by several hundred years, while those for paddle-impressed samples are all toward the older extreme of their expected ages. There are several reasons why the TL ages may be slight underestimates. First, Prescott et al. (1982, p. 146) assumed that the pottery and the surrounding sediments were both completely dry. However, the sediment samples in our study contained 2.9–8.3% water when collected (Table I). If the same water contents applied to the pottery locations, then the TL ages would increase marginally. Second, the potassium values reported by Prescott et al. (1982, Table II) for the soil samples at the VL 16/22 site correspond to ^{40}K activities of about 370 Bq/kg⁻¹. This value is much higher than the 155–285 Bq/kg⁻¹ range measured for the OSL samples (Table I). If the latter values more faithfully reflect the potassium activities at the pottery sites, then the TL ages would increase further. Third, Prescott et al. (1982, p. 144) reported no escape of radon from their soil samples (which were measured by thick-source alpha counting in sealed and unsealed cells), whereas the average $^{210}\text{Pb}/^{226}\text{Ra}$ ratio of about 0.7 measured for the OSL samples indicates the loss of about 30% radon. As radon and its decay products are responsible for the majority of the dose rate in the ^{238}U decay series, its deficit in the sediments at the pottery sites would give rise to an increase in the TL ages. There are grounds, therefore, to expect the TL ages to be slightly too young.

Taken together, the chronological data, especially the radiocarbon ages, indicate quite clearly that occupation was episodic, not continuous, and that estimates of the ages of the different levels that had been obtained in earlier investigations are broadly supported by the later results.

DISCUSSION

In their critique of previous research, Marshall et al. (2000) compared their observations with the idealized CSM of Birks (1973), and found that:

... an overwhelming body of evidence has emerged that the dunes were not as previously thought: the three soil layers do not form discrete horizontal planes, they are not always separated by sterile sand, they were not the only venue for occupation on the dunes, and the occupation debris contained within, and between, each soil layer is much more varied than previously thought. The archaeology of the dunes is no longer analogous of a culture history sequence of discrete stylistic phases. Rather, the indication is of a complex array of often subtle but significant archaeological traits, which simultaneously split and bridge the geological strata, and of a series of lived-upon surfaces that vary in their form and the nature of their occupation across the dunes environment. (p. 9)

Their view that human occupation of the site was more or less continuous, and that Aeolian dunes were growing throughout site occupation, is derived from observations of apparent conflation or amalgamation of the cultural levels at intervals along the eroding seaward face of the modern dune field. However, surface scatters of sherds, discussed in detail by Marshall et al. (2000), are not reliable as indicators of the underlying stratigraphy. As noted by Birks (1973, p. 8), patterns of surface scatter change from day to day because of “capricious deposition and removal of

wind-blown sand.” Two main processes shift and mingle sherds on the beach face and the seaward face of the dune field. Swash from storm waves, and even from normal surf at high tide when strong trade winds are blowing, erodes Levels 1 and 2 to redistribute derivative sherds alongshore, upward on the beach face, and even into the toes of adjacent higher dunes. In addition, deflation of the dunes and the dry upper reaches of the beach face allows sherds to creep downward from Levels 2 and 3. In the immediate aftermath of storm events that expose eroded edges of cultural horizons, *in situ* sherds can be seen protruding temporarily from the sand layers in which they are embedded. At other times, however, the redistribution of sherds on the beach face and the dune slope gives rise to confusing mixtures of sherds from multiple horizons within a thin surficial cover of drift sand. Given the presently active sedimentological environment of the site, only excavations continued beneath the remobilized cover can resolve site stratigraphy with confidence, by demonstrating the true depositional context of sherds of different age and typology.

We suspect that the presence of a Plainware ceramic component in Level 2 (Burley, 2003, in press) may have led Marshall et al. (2002) to suppose erroneously that Level 1 sherds occur within Level 2 and, therefore, at higher elevations than is actually the case. Reports by Birks (1973) and Marshall et al. (2002) that Level 2 rises to elevations in excess of 20 m westward in the dune field stem, in our view, from mis-correlation of Level 2 and Level 3 sherds. We have not observed Level 2 at elevations higher than 10–12 m, which is comparable to the surface elevation of the delta plain behind the present dune field, and de Biran’s (2001) ground-penetrating radar survey confirmed this point. It is difficult to envisage how a well-developed paleosol like that immediately underlying Level 2 could form within an active dune field, where stability of the land surface was not assured. Further, given that even desert dwellers do not build villages in active dunes, it seems unlikely that occupations of the Sigatoka Dunes would have occurred in loose sand, as Marshall et al. (2000) appear to envisage, between the stable (paleosol) phases. In such circumstances, drift sand would bank rapidly against structures and contaminate food and possessions. The evidence indicates that the Sigatoka Dunes were occupied during times of dune stability, quite unlike the conditions that exist today.

Our current assessment of the sedimentary and archaeological sequence at the Sigatoka Dunes is as follows. As observed by Birks (1973) and Dickinson et al. (1998), there is variation in the sand type, strike, and dip of the Sigatoka paleosols and in the distribution of cultural remains associated with them. From textural study of sand samples collected during the Birks excavation, we argue that beach sand occurs beneath Level 1 and between Levels 1 and 2, whereas dune sand occurs between Levels 2 and 3 and above Level 3 (Figure 1). This is based on the heavy mineral content and granulometry of the sand layers (Dickinson, 1968). The total percentage of ferromagnetic oxide minerals in the beach sands stratigraphically below Level 2 is only 5–7%, as opposed to 14–17% in the dune sands that lie above Level 2. The skewness of the beach sands is consistently greater, and the kurtosis consistently less, than that of the dune sands. Sorting of beach and dune sands is similar, but the beach sand is somewhat coarser-grained (median grain diameter > 0.25 mm) than the dune sand (median grain diameter < 0.25 mm). This size relationship is expected for

derivation of the dune sand from deflation of the beach sand. The presence of a layer of seaborne pumice between Levels 1 and 2 (Dickinson et al., 1998) provides direct confirmation of a beach environment. We conclude that dune growth along the seaward fringe of the Sigatoka delta was deferred until after the human occupations of Levels 1 and 2 but that Level 3 was formed during the evolution of the dune field.

Level 1 is not a paleosol; it is a dark-colored sand with small quantities of organic material that are probably of anthropogenic origin. There is no evidence for pedogenesis in the underlying beach sand. Level 1 is discernibly subhorizontal, extending landward beneath the overlying beach and dune sands (Birks, 1973), and it represents a gently sloping pre-dune beach that served, perhaps, as a canoe landing (Burley and Dickinson, 2004). It extends both east and west of the seaward end of an east-facing cutbank on the western edge of a Sigatoka River paleochannel that is incised into the delta plain behind the coastal dune field (Dickinson et al., 1998). There is no sign of dune development, although low coastal dunes may have been present along the crest of the beach berm. Level 1 is reliably dated (Tables I, II) to about 2600 cal yr B.P. or older.

Level 2 overlies a well-developed paleosol with a humus-rich A horizon and a 1-m-thick B horizon discolored by iron staining. Human occupation of Level 2 spanned the interval 1550–1300 cal yr B.P. (Burley, 2003, in press), after pedogenesis had begun, up to 600 years earlier. We infer that the Level 2 paleosol represents the seaward continuation of the surface of the delta plain behind the present dune field. The elevation of Level 2 on the present beach face and seaward fringe of the dune field rises inland from an estimated 5–6 m at its eroded edge to perhaps 10–12 m on the seaward dune face and on the delta plain. In the seaward dune face, the Level 2 paleosol probably represents the front of a fossil beach ridge paralleling the shoreline along the delta front. Correlation of the pedogenically altered deposits beneath Level 2 with the very similar soil horizon on the delta plain is supported by indistinguishable optical ages ($n = 7$) for these sedimentary units. An undated paleosol horizon, indistinguishable morphologically from the Level 2 paleosol and standing at ~3 m elevation, was fortuitously exposed beneath Aeolian drift sand in a sea cliff at Naqarai (S16/22), west of the main dune field, by storm surf in 1999. It suggests that the Level 2 paleosol also extends along the coastal fringe of the delta, at about the same elevation as elsewhere. De Biran's (2001) ground-penetrating radar survey traced Level 2 westward to the vicinity of Naqarai Creek.

Level 3 is an undulatory humus-rich horizon that evidently represents a temporarily stabilized surface within an evolving dune field. The occurrences of this level within the dunes and westward toward Naqarai may not represent the same continuous surface, because correlation of Level 3 through blowouts in the parabolic dune field and beneath the higher dune crests is not feasible. We conclude, however, that Level 3, in all its local manifestations, reflects transient human usage of stable surfaces in the evolving dune field after 1300 cal yr B.P. and, based on the radiocarbon ages, generally after 700 cal yr B.P.

The Sigatoka sedimentary sequence probably reflects environmental changes in the Sigatoka catchment, as Birks (1973) and Dickinson et al. (1998) have argued, although our recent sedimentary and palynological investigations in the Sigatoka

valley have not yet disclosed a clear pattern of change. A core at Volivoli swamp, approximately 2 km inland from the dunes, shows substantial clay accumulation beginning at a depth of 122 cm and charcoal influx from 105 cm. A pollen radiocarbon sample at 89.5 cm dates to 4030 ± 50 yr B.P. (OZF-531) and one on *Turbo* shell at 28 cm to 1010 ± 70 yr B.P. (ANU-9925), suggesting that at least some environmental change preceded human colonization. A core at Doge-Doge swamp, located about 12 km upriver from the dunes, indicates that clay infilling had begun before 2100 yr B.P., and this is consistent with the evidence from Southern's (1986) Nadrau Swamp core, which shows that forest disturbance had begun in the highlands, near the source of the Sigatoka River, by at least 2100 yr B.P. These data support the contention that accelerated disturbance had begun by the late third millennium B.P., but they provide no precise chronology. There are few archaeological data on the early settlement of the Sigatoka catchment, but some evidence suggests that settlement had begun by about 2000 yr B.P. in the middle reaches of the valley (Field, 2004; Clark and Anderson, 2005), and associated deforestation is a plausible explanation of the features observed in the core records.

Another approach to this issue is through evidence of long-term climatic change. In the tropical Pacific, ENSO conditions create marked climatic instability, often involving both drought and floods in close juxtaposition. A long-term record of ENSO frequency (Moy et al., 2002) discloses a substantial period of relatively low activity at 2400–1600 cal yr B.P. This period of comparative climatic stability correlates well with the optically dated deposit in which the Level 2 paleosol formed, and it may account for the much greater development of this paleosol than of others at the site. Similarly, evidence of high ENSO activity and inferred instability at 900–200 cal yr B.P. is consistent with accelerated dune formation late in prehistory, including archaeological evidence (Dickinson et al., 1998, p. 19) that sites on the hill slopes behind the Sigatoka delta were not cut off from regular access to the sea until around 1000 cal yr B.P. It is worth proposing, therefore, that long-term climatic change was also a significant factor in forming the sedimentary sequence at the Sigatoka Dunes.

CONCLUSIONS

Alternative constructions of Fijian prehistory are welcome, and we suspect that there is merit in aspects of the theoretical position advanced by Marshall et al. (2000). However, the empirical test of that model fails at Sigatoka Dunes, VL 16/1. Recent archaeological research has confirmed the stratigraphic validity of the three-phase model, while demonstrating that there is more variety within each of the earlier two phases than was thought originally. Recent research on the sedimentary sequence, and especially the new evidence from optical and radiocarbon dating, likewise confirms that the three stable phases are widely separated temporally. There is no evidence that occupation of the Sigatoka Dunes occurred continuously.

It is not possible to offer a conclusive explanation for the pattern of sedimentary history at the Sigatoka Dunes, but several propositions are plausible. It is probable that increasing anthropogenic transformation of the Sigatoka watershed, with consequences for sediment load in the Sigatoka River, was a significant factor in the

history of dune formation, but it is also possible that human-induced disturbance was assisted significantly by substantial climatic instability during the last millennium. The long-term record of ENSO frequency also suggests a potential explanation for the major periods of sedimentary stability and instability.

These conclusions can be regarded only as provisional. Despite the long history of research, the history of the Sigatoka Dunes is not easily disentangled in satisfactory detail. We think the original model, with some improvements, remains robust, but research in all respects needs to continue at this important site.

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REFERENCES

- Adamiec, G., & Aitken, M.J. (1998). Dose-rate conversion factors: Update. *Ancient TL*, 16, 37–50.
- Aitken, M.J. (1985). *Thermoluminescence dating*. London: Academic Press.
- Aitken, M.J. (1998). *An introduction to optical dating*. Oxford: Oxford University Press.
- Anderson, A.J. (2002). Faunal collapse, landscape change and settlement history in Remote Oceania. *World Archaeology*, 33, 375–390.
- Anderson, A.J., Burke, C., & Clark, G.R. (1996). Prehistoric colonisation and settlement of Fiji: An initial report to the Fiji Museum. Suva, Fiji Islands: Fiji Museum.
- Best, S.B. (1987a). A preliminary report on the Sigatoka Burials. *Domodomo*, 3, 2–15.
- Best, S.B. (1987b). Sigatoka dune burials (Site VL 16/1). A preliminary report. Auckland, New Zealand: University of Auckland, Anthropology Department.
- Best, S.B. (1989). The Sigatoka dune burials (Site VL 16/1). Suva, Fiji Islands: Fiji Museum.
- Birks, L. (1973). Archaeological excavations at Sigatoka dune site, Fiji. *Bulletin of the Fiji Museum*, 1.
- Burley, D.V. (1997). *Archaeological research Sigatoka sand dune national park*. Suva, Fiji Islands: Fiji Museum.
- Burley, D.V. (2003). Dynamic landscapes and episodic occupations: Archaeological interpretation and implications in the prehistory of the Sigatoka Sand Dunes. In C. Sand (Ed.), *Pacific archaeology: Assessments and prospects* (pp. 307–315). Noumea, New Caledonia: Les Cahiers de l'Archéologie en Nouvelle-Calédonie.
- Burley, D.V. (in press). Mid-sequence archaeology at the Sigatoka Sand Dunes with interpretive implications for Fijian and Oceanic culture history. *Asian Perspectives*.
- Burley, D.V., & Dickinson, W.R. (2004). Late Lapita occupation and its ceramic assemblage at the Sigatoka Sand Dune site, Fiji and their place in Oceanic prehistory. *Archaeology in Oceania*, 39, 12–25.
- Bøtter-Jensen, L., McKeever, S.W.S., & Wintle, A.G. (2003). *Optically stimulated luminescence dosimetry*. Amsterdam: Elsevier Science.
- Clark, G.R., & Anderson, A.J. (Eds.). (2005). *The early prehistory and palaeoenvironment of Fiji*. Unpublished manuscript.
- Crosby, A.D. (1991a). Proposal for archaeological survey of Sigatoka Sand Dunes. Suva, Fiji Islands: Fiji Museum.
- Crosby, A.D. (1991b). Further burials at the Sigatoka Sand Dunes (Site VL 16/1). Suva, Fiji Islands: Fiji Museum.
- De Biran, A. (2001). *The Holocene geomorphic evolution of the Sigatoka Delta, Viti Levu, Fiji Islands*. Unpublished doctoral dissertation, University of the South Pacific, Suva, Fiji Islands.
- Dickinson, W.R. (1968). Sigatoka Sand Dunes, Viti Levu (Fiji). *Sedimentary Geology*, 2, 115–124.

- Dickinson, W.R., Burley, D.V., Nunn, P.D., Anderson, A., Hope, G., De Biran, A., et al. (1998). Geomorphic and archaeological landscapes of the Sigatoka Dune Site, Viti Levu, Fiji: Interdisciplinary investigations. *Asian Perspectives*, 37, 1–31.
- Field, J.S. (2004). Environmental and climatic considerations: A hypothesis for conflict and the emergence of social complexity in Fijian prehistory. *Journal of Anthropological Archaeology*, 23, 79–99.
- Frost, E.L. (1979). Fiji. In J.D. Jennings (Ed.), *The prehistory of Polynesia* (pp. 61–81). Canberra: Australian National University Press.
- Galbraith, R.F., Roberts, R.G., Laslett, G.M., Yoshida, H., & Olley, J.M. (1999). Optical dating of single and multiple grains of quartz from Jinnium rock shelter, northern Australia: Part I, experimental design and statistical models. *Archaeometry*, 41, 339–364.
- Galbraith, R.F., Roberts, R.G., & Yoshida, H. (2005). Error variation in OSL palaeodose estimates from single aliquots of quartz: A factorial experiment. *Radiation Measurements*, 39, 289–307.
- Gifford, E.W. (1951). *Archaeological excavations in Fiji*. University of California Anthropological Records, 13, 189–288.
- Green, R.C. (1963a). A suggested revision of the Fiji sequence. *Journal of the Polynesian Society*, 72, 235–253.
- Green, R.C. (1963b). Two collections of pottery from Sigatoka, Fiji. *Journal of the Polynesian Society*, 72, 261–264.
- Green, R.C., & Palmer, J.B. (1964). Fiji sequence: Corrections and additional notes for Sigatoka. *Journal of the Polynesian Society*, 73, 328–332.
- Hope, G., & Anderson, A.J. (1995). A reconnaissance survey of Holocene deposits on Viti Levu and Vanua Levu, Fiji. Unpublished manuscript, Australian National University, Canberra, Australia.
- Hudson, E. (1994). *Sigatoka Sand Dune Site Archaeological Rescue Project 1993*. Auckland, New Zealand: Auckland Uniservices Limited.
- Hunt, T.L. (1986). Conceptual and substantive issues in Fijian prehistory. In P.V. Kirch (Ed.), *Archaeological approaches to evolution and transformation* (pp. 20–32). Cambridge: Cambridge University Press.
- Hunt, T.L. (1987). Patterns of human interaction and evolutionary divergence in the Fiji Islands. *Journal of the Polynesian Society*, 96, 299–334.
- Huntley, D.J., Godfrey-Smith, D.I., & Thewalt, M.L.W. (1985). Optical dating of sediments. *Nature*, 313, 105–107.
- Jacobs, Z., Wintle, A.G., & Duller, G.A.T. (2003a). Optical dating of dune sand from Blombos Cave, South Africa: I—Multiple grain data. *Journal of Human Evolution*, 44, 599–612.
- Jacobs, Z., Duller, G.A.T., & Wintle, A.G. (2003b). Optical dating of dune sand from Blombos Cave, South Africa: II—Single grain data. *Journal of Human Evolution*, 44, 613–625.
- Marshall, Y., Crosby, A., Matararaba, S., & Wood, S. (2000). *Sigatoka: The shifting sands of Fijian prehistory*. Oxford: Oxbow Books.
- Mejdahl, V. (1979). Thermoluminescence dating: Beta-dose attenuation in quartz grains. *Archaeometry*, 21, 61–72.
- Moy, C.M., Seltzer, G.O., Rodbell, D.T., & Anderson, D.M. (2002). Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch. *Nature*, 420, 162–165.
- Olley, J.M., Caitcheon, G.G., & Roberts, R.G. (1999). The origin of dose distributions in fluvial sediments, and the prospect of dating single grains from fluvial deposits using optically stimulated luminescence. *Radiation Measurements*, 30, 207–217.
- Olley, J.M., Pietsch, T., & Roberts, R.G. (2004a). Optical dating of Holocene sediments from a variety of geomorphic settings using single grains of quartz. *Geomorphology*, 60, 337–358.
- Olley, J.M., De Deckker, P., Roberts, R.G., Fifield, L.K., Yoshida, H., & Hancock, G. (2004b). Optical dating of deep-sea sediments using single grains of quartz: A comparison with radiocarbon. *Sedimentary Geology*, 169, 175–189.
- Palmer, J.B., Shaw, E., Dickinson, P., & Sykes, M. (1968). Pottery making in Sigatoka, Fiji. *Records of the Fiji Museum*, 1(3), 45–79.
- Parry, J.T. (1987). The Sigatoka valley—Pathways into prehistory. *Fiji Museum Bulletin*, 9.
- Petchey, F. (1994). Pottery and stone analysis. In E. Hudson (Ed.), *Sigatoka Dune site archaeological rescue project 1993* (pp. 28–39). Auckland, New Zealand: Auckland Uniservices Limited.
- Petchey, F. (1995). *Archaeology of Kudon: Archaeological analysis of Lapita ceramics from Mulifanua, Samoa and Sigatoka, Fiji*. Unpublished master's thesis, University of Auckland, New Zealand.

- Prescott, J.R., Robertson, G.B., & Green, R.C. (1982). Thermoluminescence dating of Pacific island pottery—Successes and failures. *Archaeology in Oceania*, 17, 132–142.
- Prescott, J.R., & Hutton, J.T. (1994). Cosmic ray contributions to dose rates for luminescence and ESR dating: Large depths and long-term time variations. *Radiation Measurements*, 23, 497–500.
- Readhead, M.L. (1987). Thermoluminescence dose rate data and dating equations for the case of disequilibrium in the decay series. *Nuclear Tracks and Radiation Measurements*, 13, 197–207.
- Roberts, R., Bird, M., Olley, J., Galbraith, R., Lawson, E., Laslett, G., et al. (1998a). Optical and radiocarbon dating at Jinnium rock shelter in northern Australia. *Nature*, 393, 358–362.
- Roberts, R., Yoshida, H., Galbraith, R., Laslett, G., Jones, R., & Smith, M. (1998b). Single-aliquot and single-grain optical dating confirm thermoluminescence age estimates at Malakunanja II rock shelter in northern Australia. *Ancient TL*, 16, 19–24.
- Roberts, R.G., Galbraith, R.F., Olley, J.M., Yoshida, H., & Laslett, G.M. (1999). Optical dating of single and multiple grains of quartz from Jinnium rock shelter, northern Australia: Part II, results and implications. *Archaeometry*, 41, 365–395.
- Roberts, R.G., Galbraith, R.F., Yoshida, H., Laslett, G.M., & Olley, J.M. (2000). Distinguishing dose populations in sediment mixtures: A test of single-grain optical dating procedures using mixtures of laboratory-dosed quartz. *Radiation Measurements*, 32, 459–465.
- Southern, W. (1986). The late Quaternary environmental history of Fiji. Unpublished doctoral dissertation, Australian National University, Australia.
- Turney, C.S.M., Bird, M.I., Fifield, L.K., Roberts, R.G., Smith, M., Dortch, C.E., et al. (2001). Early human occupation at Devil's Lair, southwestern Australia 50,000 years ago. *Quaternary Research*, 55, 3–13.
- Visser, E.P. (1988). Hotel Masa Survey—Sigatoka. Unpublished manuscript. Suva, Fiji Islands: Fiji Museum.
- Visser, E. (1994). The prehistoric people from Sigatoka: An analysis of skeletal and dental traits as evidence of adaptation. Unpublished doctoral dissertation, University of Otago, New Zealand.
- Wood, S., Marshall, Y., & Crosby, A. (1998). Mapping Sigatoka Site VL 16/1: The 1992 field season and its implications. Suva, Fiji Islands: Fiji Museum.

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