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Testing the human factor: Radiocarbon dating the first peoples of the South Pacific.

Fiona Petchey[1], Matthew Spriggs[2], Foss Leach[3], Mike Seed[4], Christophe Sand[5], Michael Pietrusewsky[6], Katy Anderson[1].

1. Radiocarbon Dating Laboratory, University of Waikato, Hamilton, New Zealand.
2. School of Archaeology and Anthropology, The Australian National University, Canberra, ACT 0200, Australia.
3. Department of Anthropology, University of Otago, Dunedin, New Zealand.
4. Isoprime Ltd, Manchester, UK.
5. Institute of Archaeology of New Caledonia and the Pacific, Noumea.
6. Department of Anthropology, University of Hawaii at Manoa, Honolulu.

ABSTRACT

Archaeologists have long debated the origins and mode of dispersal of the immediate predecessors of all Polynesians and many populations in Island Melanesia. Such debates are inextricably linked to a chronological framework provided, in part, by radiocarbon dates. Human remains have the greatest potential for providing answers to many questions pertinent to these debates. Unfortunately, bone is one of the most complicated materials to date reliably because of bone degradation, sample pretreatment and diet. This is of particular concern in the Pacific where humidity contributes to the rapid decay of bone protein, and a combination of marine, reef, C_4, C_3 and freshwater foods complicate the interpretation of ^{14}C determinations. Independent advances in bone pretreatment, isotope multivariate modelling and radiocarbon calibration techniques provide us, for the first time, with the tools to obtain reliable calibrated ages for Pacific burials. Here we present research that combines these techniques, enabling us to re-evaluate the age of burials from key archaeological sites in the Pacific.

KEYWORDS: Oceania, Lapita, Post-Lapita, human bone, radiocarbon, calibration, diet

INTRODUCTION

The initial colonization of Remote Oceania occurred in the interval 3200-2800 BP by bearers of the Lapita culture; identified by its distinctive dentate-stamped pottery and an associated material culture and horticultural package that included pigs, chickens, possibly dogs, and up to two species of commensal rat. The proximate origins of this culture are in the Bismarck Archipelago where sites dating back to ~3350 BP are known. From here, the culture spread through the Solomons chain to the Reefs-Santa Cruz Group, Vanuatu and New Caledonia, and eventually into Fiji and Western Polynesia (Kirch 1997; Green 2003). In Fiji and further east increasing isolation is thought to have contributed to simplification of the decorated ceramics and some other artefact types (Smith 2002).

Numerous questions remain and have become the basis of much debate, including whether Lapita was largely an indigenous development in the Bismarck region (Allen 1984; Specht et al. 1991), whether it developed out of a continuous and long-standing zone of contact with Island Southeast Asia (Terrell and Welsch 1997, Terrell et al. 2001), or if it was largely a Southeast Asian intrusion, albeit with significant adoption of local food crops and some other local practices (Bellwood 1997; Kirch 1997; Spriggs 1997). The timing of the disappearance of dentate-stamped Lapita ceramics and evidence indicating that this process varied for each island group, impact on our understanding of subsequent cultural developments. The chronological backbone to these questions has been largely based on associated charcoal and shell ^{14}C determinations. These sample types, with their own particular radiocarbon issues (see Allen and Wallace 2007:1169; Petchey et al. 2008:382-388) have provided relatively limited chronological control in a region where the colonisation phase was brief and subsequent changes rapid (Spriggs 1996; Specht and Gosden 1997; Clark and Anderson 2001).

Since these debates concern the movements of people, it seems logical that they be tested using evidence gained directly from the people themselves. Throughout the South Pacific there are few early archaeological sites with human remains considered to be of Lapita or potentially immediately-descendant groups. Burials thought to be of early populations have been found on Watom (Anson et al. 2005) and Mussau (Kirch et al. 1989) in the Bismarck Archipelago, Efate in Vanuatu (Bedford et al. 2006, 2009; Buckley et al. 2008; Spriggs unpublished data), New Caledonia (Pietrusewsky et al. 1998; Valentin and Sand 2000; Valentin 2003; Valentin et al. 2004; Sand 2010), Viti Levu (Best 1987, 1989; Davidson et al. 1990; Davidson and Leach 1993), Waya (Pietrusewsky et al. 1997), Moturiki (Kumar et al. 2004; Nunn et al. 2007), and Lakeba (Best 1977) in Fiji, and on Tongatapu (Poulsen 1987) (Figure 1). Unfortunately, the strength of cultural association for each of these burials varies significantly and revision of radiocarbon chronologies that cover the transition from Lapita to later cultures in Fiji and Tonga (e.g., Anderson and Clark 1999; Burley et al. 1999; Hunt et al. 1999; Burley 2005) now places the exact affiliation of some in doubt. Although the recent find of a Lapita age burial ground at Teouma has increased the number of early remains available for study by nearly an order of magnitude (Bedford et al. 2006, 2009), the ultimate origins of Pacific peoples and subsequent cultural adaptations, as well as the timing of these processes, must be studied within a context that includes individuals from multiple sites of well established and differing age. Therefore, it is essential that all of these burials be dated accurately.

In many instances, direct dating of human bone should provide the most secure means of establishing the age of these burials. Several of the burials discussed here have previously been radiocarbon dated but anomalous radiocarbon ages, often at odds with cultural remains, have resulted in bone dates being viewed with mistrust (Pietrusewsky et al. 1998:33-34; Anderson and Clark 1999:36). In recent years, however, advances in radiocarbon bone pre-treatment chemistry have significantly improved the accuracy of such dates (Petchey and Higham 2000; Bronk-Ramsey et al. 2004) and dietary offsets are now the most significant hindrance to obtaining reliable calibrated ages. For Pacific burials the ability to resolve the marine contribution to the diet is essential because the surface ocean marine reservoir has an apparent radiocarbon age that is, on average, 400 years older than the terrestrial reservoir (Stuiver et al. 1986). $\delta^{13}C$ and/or $\delta^{15}N$ isotopic values are regularly used as quantitative measures of different dietary sources for radiocarbon calibration of human remains (Lanting and van der Plicht 1998; Arneborg et al. 1999; Schulting and Richards 2002). Calculating a suitable dietary correction for radiocarbon dates of human bone from the Pacific is, however, especially complex because of a possible combination of marine, reef and freshwater foods, as well as C_3 and C_4 plants which confuse $\delta^{13}C$ and $\delta^{15}N$ isotopic signatures and limit the usefulness of a dual isotope approach (e.g., Bonsall et al. 2004; Field et al. 2009; Jones and Quinn 2009). In situations like these, the use of a third isotope ($\delta^{34}S$) in combination with geographic, archaeological and metabolic information has been successful in evaluating diet for human remains throughout the tropical Pacific and New Zealand (Leach et al. 1996, 2000, 2003; Petchey and Green 2005; Beavan Athfield et al. 2008).

Here we present radiocarbon and stable isotope results for a number of burials obtained from sites of Lapita, immediately Post-Lapita, or of uncertain, but assumed early date. These analyses utilise the latest bone purification techniques combined with dietary information obtained from S, N, and C isotopes, following the methodology of Leach et al. (1996, 2003). Our aim is to demonstrate the value of human bone dates to the development of a robust chronological framework for the origin and spread of humans throughout the Pacific.

1. Sample Selection and Context.

Samples of finely ground bone from Watom (SAC site), Koné Site 13B (New Caledonia), Wakea (Lakeba, Fiji: site 196), Qaranipuqa Cave (Lakeba, Fiji: site 197), Sigatoka (Viti Levu, Fiji:VL/16) and Pea Village (Tongatapu:To-1) (Figure 1), were obtained from the University of Otago and the National Museum of New Zealand, Te Papa. These were collected during previous research into prehistoric diet (Pietrusewsky et al. 1998; Quinn 1990; Leach et al. 2003). Samples of whole bone from Koné Site 13 (New Caledonia), Natunuku (Viti Levu, Fiji:VL1/1) and Olo (Waya, Fiji:Y2-25) were provided by Pietrusewsky and Sand. The burials selected reflect availability of material. These skeletons have been considered to be early, and are usually attributed to Lapita or immediately Post-Lapita contexts.

Recently, Summerhayes (2009) has determined date ranges for Lapita in the Bismarck Archipelago of 3300-3000 BP for Early Lapita, 3000-2800 BP for Middle Lapita and 2700-c.2200 BP for Late Lapita. These dates are not applicable, however, for areas in Remote Oceania, and the date of the end of Lapita in the Bismarck Archipelago remains a controversial topic (Spriggs 2001). Initial Lapita settlement in the Southeast Solomons, Vanuatu and New Caledonia begins about 3200 BP and appears to have ended by about 2800 BP - at least in central Vanuatu and New Caledonia (Bedford 2006; Bedford et al. 2009; Sand 2010). In Fiji a date of 3000-2900 BP is generally accepted for the start of Lapita (Anderson and Clark 1999; Nunn 2007), while a slightly later date of 2900-2800 BP is accepted for Tonga and Samoa (Burley et al. 1999). The transition from Lapita ceramics to Plainware occurs in Fiji, Tonga and Samoa by about 2600-2500 BP (Best 2002:33; Burley and Connaughton 2007). By c. 1000 BP differences in the archaeological record imply significant social change across the region (Smith 2002:192-193).

In the brief review of each burial and site below, radiocarbon dates are presented in the same format as in the key publications listed.

Watom: In 1965–7, excavations were undertaken at the SAC site on Watom Island, just off the northeast coast of New Britain (Figure 1). The lower cultural deposit (Zone C2) contained the remains of domestic habitation, later Lapita-style pottery, fingernail-impressed pottery and burials (Specht 1968). An anomalously young radiocarbon age for human bone (ANU-37b) and questionable integrity of the deposits initially placed doubt on the Lapita designation of the burials, but this has largely been sorted by three new gelatin determinations that place the age of burials 1 and 3 to c. 2500 cal BP (Petchey and Green 2005; Beavan Athfield et al. 2008). These results are very broadly bracketed by shell ^{14}C determinations dated to c. 1850 cal BP and c. 3050 cal BP. We have obtained ground bone (subsample AY056; Table 1) from Burial 1.

Koné: Archaeological remains at Koné encompass three sites; 13, 13A and 13B, spread out along Foué Bay, on the west coast of Grande Terre, New Caledonia (Figure 1a). The deposits include Lapita-age and more recent material (Sand 1998). Two burials of uncertain age and association have been sampled for this study: WKO013B (subsample AB705 stored at the University of Otago) and WKO013C obtained from the former Department of Archaeology, New Caledonia Museum.

Skeleton WKO013B was found in a sandy layer at Site 13B that contained eroded sherds of Lapita and Podtanéan style pottery (shell-impressed and paddle-impressed wares generally encountered in Late Lapita and immediately Post-Lapita contexts)(Sand 2000). Sand (2010:82-83) suggests the burial cut was probably dug from the upper levels of Layer B in compact clay dated to c. 2300 cal BP (Beta-179503), though earlier re-deposited Lapita age material dating to c. 2700 cal BP occurred at the base of the site (Beta-92762, Beta-59964 and Beta-136943). Divergent radiocarbon dates and stable isotopes obtained from WKO013B by two separate radiocarbon laboratories (NZA-3013: 1061±65 BP, and OxA-4908: 2410±55 BP) drew attention to problems with different bone pretreatments at this time. This, combined with an inability to apply dietary corrections led Pietrusewsky et al. (1998:31-36) to consider all isotope results unreliable.

Skeleton WKO013C was found in a burial pit at the centre of the site in 1967 (now considered to be equivalent to site 13). A complete pot of Podtanéan style covered the skull, and the burial was interpreted as being immediately Post-Lapita in age (Valentin and Sand 2000:19; Valentin 2003:286). Renewed investigations of this area in the mid-1990s indicated that the early layers had been capped in places by shellfish midden, which provided protection from subsequent horticultural activities. Consequently, the site has a continuous sequence from earlier Lapita layers through to immediately Post-Lapita. An un-calibrated radiocarbon date on the burial (Beta-125136: 2710±80 BP) appeared to be consistent with dates from the earlier deposits, but could not be reliably calibrated, or interpreted, at the time (Valentin and Sand 2008:4).

Sigatoka: The Sigatoka sand dunes (site VL16/1), located on the south coast of Viti Levu, Fiji (Figure 1b), enclose a complex series of cultural deposits. Luminescence and radiocarbon dates place the lower Lapita layers (Level 1) between 2800 and 2600 cal BP, and later Level 2 occupation (Navatu phase) from 1700 to 1300 cal BP with several paleosols between the two (Anderson et al. 2006:146-7).

A number of burials with variable mortuary patterns have been discovered at the eastern extent of the dunes. Burley (2005:337) concluded that the cemetery had been used over an extended period of time by a socially diverse group. The burials have generally been assumed to belong to the Navatu phase (Level 2), based on an association with cross-hatched, paddle-impressed ceramics, but this style of decoration also appears in the earlier assemblages. A radiocarbon date on burial FC1 [Wk-996b: 1870±70 BP] was interpreted as being older than other Layer 2 dates (Anderson et al. 2006:146-7; Burley 2005:336). Inadequate ^{14}C bone pretreatment and unknown diet mean, however, that this result is questionable. Early attempts at relative dating using nitrogen have added to this uncertainty by indicating that burial FC1 was younger than burials West 1 and West 4. This was in opposition to Best's (1987:5) interpretation of the site. Relative dating using nitrogen is now recognised as unreliable (Leach and Davidson 2008:145).

Our sample, AY787 (Table 1) was obtained by Quinn (1990) during her study of the West 1 burial.

Natunuku: The Natunuku site (VL1/1) is situated on the north coast of Viti Levu, on a small sandy beach between the Ba River delta and the Vatia headlands (Figure 1b). The site itself has early re-deposited Lapita material at its base (Layer 6) dated to c. 3686-3216 cal BP at 95% probability (GAK-1218) (Davidson et al. 1990:131). Problems with the accuracy of early-run Gakushuin (GAK) dates have been previously reported in the literature (Spriggs 1989, 1990:16, and references therein) and this date is now considered unreliable.

A partial skeleton was first noticed at the base of Layer 4, Location C, and was originally thought to be associated with Layer 5 dated to c.2300 cal BP, but the mixed deposits meant an association with earlier Lapita occupation could not be ruled out **(**Davidson et al. 1990:131). On the strength of a bone radiocarbon date (NZA-2512) that returned an age of c. 2012-1578 cal BP (95% prob.), Davidson and Leach (1993:102-3) attributed the burial to non-Lapita levels. Again, inadequate pretreatment and an absence of isotopic values for dietary correction make this result questionable. Anderson and Clark's (1999) reassessment of the Fijian chronology associates the Natunuku burial date with Lapita-derived plainware populations or with later Navatu populations.

We obtained a subsample of long bone from the Department of Anthropology, University of Hawai`i.

Olo: A number of human remains have been found in the site of Olo (Y2-25), Waya Island in the Yasawa group, northwest of Viti Levu, Fiji (Figure 1b). These remains were recovered from early occupation deposits that were on top of a paleobeach stratum containing early plainwares and a few dentate-stamped ceramics (Hunt et al. 1999:22, 25). Two radiocarbon dates on charcoal (Beta-86839 and Beta-86840) from the base of the excavation, and one date on an articulated skeleton (Y2-25-1; CAMS-24946) from a nearby trash pit (LII, burial pit) provided an age of 2758–2503 cal BP (95% prob.) for these deposits. Lapita ceramics associated with the burial are thought to have come from earlier deposits disturbed during the digging of the burial pit (Pietrusewsky et al. 1997:358).

The Department of Anthropology, University of Hawai`i provided a rib from this skeleton for analysis.

Wakea and Qaranipuqa:. Two bone samples have been selected from Wakea (Site 196), and Qaranipuqa (Site 197) located on the northwest coast of Lakeba in the Lau Islands, Fiji (Figure 1b). Wakea is an open site, while Qaranipuqa is a limestone rock shelter located just south of Wakea (Best 1984).

The remains of two individuals were excavated from Trench 28 to the northeast corner of Wakea. The primary burial (196-28-B8) came from Layer B8 with the disturbed remains of a second burial a few centimetres below the primary burial. There are no radiocarbon dates for Trench 28, but the burials were considered to date between c. 2850-2559 cal BP on the basis of charcoal and shell dates from nearby squares. Dentate-stamped sherds were deposited throughout the site, but material of a range of ages was present in the upper deposits (Best 1984:100-105, 158). A subsample of the primary burial (subsample AY082; Table 1) was selected for dating in the current study, but insufficient material was available from the second, lower burial.

At Qaranipuqa Cave charred and fragmented human bone was found throughout the upper layers (above Layer O) (Best 1984:535). We selected a sample of un-charred bone from Layer M midway up the sequence (197-1-M-9: subsample of AY785; Table 1). The deposits had been sealed by culturally sterile sediment dated between c.1700 and 900 cal BP and a charcoal date on Layer M (NZ-4808) provided a calibrated age of 2010-2490 BP (95% prob.). Small amounts of dentate-stamped wares were found in the basal deposits (Best 1984:78).

Pea Village: A partial skeleton (Burial AK in pit AF, Trench III), was excavated in 1963/4 from site To-1, Pea village; a low-lying site on the edge of Havelu Lagoon, Tongatapu (Figure 1c). Poulsen (1987:81-83) associated the burial with early Horizon I (Lapita) material dated to c. 2750 BP. Radiocarbon dates from the interface of Horizons I and II in pit A, Trench 1, 49m away, gave divergent results; 2770±100BP (K-904; date reported with marine correction applied), 420±100 BP (K-961) and 464±82 BP (NZ-597). The date on shell (K-904) was thought to derive from earlier, re-deposited Lapita material, while the charcoal dates (K-961 and NZ-597) were thought to be from a later infilling of Pit A (Poulsen 1987:22-23).

We obtained a subsample of Burial AK (AY774; Table 1) taken for Quinn's (1990) study.

2. Sample preparation and Isotopic analysis

All samples were prepared at the Waikato AMS radiocarbon facility. Gelatin was extracted from each specimen using a modified Longin (1971) method, whereby the sample was decalcified in 2% w/v HCl at 4°C for 24 hours, then rinsed with distilled water. This acid insoluble collagen was then gelatinised by heating in weakly acidic water (pH = 3 at 90°C for 4 hours) and the supernatant ("gelatin") removed, ultrafiltered (cleaned Centriprep®, Ultracel YM-30 filters), and freeze-dried. Ultrafiltration separates high molecular weight components of the gelatinized collagen (>30kD) from the low molecular weight contaminant fractions (<30kD) and has been very successful in improving the quality of the extracted collagen (Bronk-Ramsey et al. 2004; Higham et al. 2006; Brock et al. 2007).

Gelatin stable C and N isotope measurements used for dietary reconstruction and quality control were measured at Agriculture and Life Sciences Division, Lincoln University on a PDZ Europa elemental analyser (GSL) connected to a continuous flow stable isotope mass spectrometer (20-20). Sulphur was measured at Isoprime Ltd, Manchester, using a Vario MICRO cube EA from Elementar GmbH, Germany, configured in sulphur mode and coupled to an Isoprime IRMS. Graphite targets were processed by the Waikato Radiocarbon Dating Laboratory in New Zealand, by the reduction of CO_2 with Zn in a reaction catalyzed by iron powder at a temperature of ~575°C. Targets were measured at the Keck Radiocarbon Laboratory, University of California, Irvine.

All bone gelatin was assessed for purity prior to analysis. %N, %C and C:N quality assurance (QA) parameters are well defined (Ambrose and Norr 1993:403; van Klinken 1999). Most well preserved archaeological bone protein ranges between 11 and 16%N, with an average 35%C and a C:N ratio range of 3.1 to 3.5. Values that fall outside this C:N range should be evaluated further. Acceptable parameters for sulphur are not as well documented. Nehlich and Richards (2009:68-69) recently revised the sulphur quality control parameters for modern mammalian bone collagen (S content = 0.28 ± 0.07 wt %; C:S = 313 to 696; N:S = 111 to 216) and archaeological bone collagen (S content = 0.15-0.35 wt %; C:S = 600±300; N:S = 200±100; see also Privat et al. 2007:1199) . Further refinement of these values is expected.

3. Dietary Evaluation

There is little doubt as to the mixed marine/terrestrial diet of most Pacific populations; however, the proportions of the two dominant food sources (marine and terrestrial) and how they changed over time is unknown. Linguistic reconstructions and cultural remains (Kirch 1997; Kirch and Green 2001) indicate early horticultural production by Lapita peoples. This is backed up by recent isotopic evidence that points to terrestrial foods being as important to early peoples, if not more so, as marine foods (see Leach et al. 2000, 2003; Petchey and Green 2005; Field et al. 2009; Valentin et al. 2010). Archaeo-environmental studies support an increasing presence of horticulture-based subsistence systems during later periods (Latham et al. 1983; Spriggs 1985, 1997; Nunn and Kumar 2004), while isotopic analyses of human and domesticate bones point to a decreasing emphasis on the direct consumption of marine foods and a greater reliance on domesticates (Valentin 2003; Valentin et al. 2006; Field et al. 2009; Richards et al. 2009; Jones and Quinn 2009). It is also apparent that significant regional dietary differences are possible depending on environmental, geographical and cultural constraints (Valentin et al. 2006; Field et al. 2009). This is demonstrated by the extreme case of reliance on marine foods by the Moriori of the Chatham Islands where an estimated 87% food energy was derived from the sea (Leach et al. 2003:71).

The diets of 196-28-B8 (Wakea), 197-1-M-9 (Qaranipuqa Cave), West 1 (Sigatoka), Burial AK (Pea Village), Watom burials 1 and 3, and the primary burial from Natunuku were all evaluated by Quinn (1990) and Leach et al. (2003). This isotopic information is presented in Table 1. Quinn (1990:210, 242) interpreted the results as representing a predominantly terrestrial diet for Burial AK and West 1. A shift from a marine dominated diet at Qaranipuqa Cave to one with a higher component of terrestrial foods at Wakea was in keeping with archaeological evidence (Best 1984:653; Quinn 1990:209-10), but subsequent evaluation of Quinn's data by Leach et al. (2003) suggested no clear distinction between the two populations. Natunuku was too degraded to obtain reliable information (C:N = 17.4). Four separate analyses of diet have been undertaken on human remains from Watom using different food datasets and analytical methodologies (Horward 1988; Quinn 1990; Leach et al. 2000; Petchey and Green 2005; Beavan Athfield et al. 2008). Although there are slight variations between the results, broadly they agree that the diet was dominated by terrestrial foods with lesser amounts from the sea. In an isotopic study of burials recently excavated at Olo, from a similar cultural context as burial Y2-25-1, Field et al. (2009:1553) suggested the individuals had a strong dietary emphasis on marine resources. Dietary evaluation of WKO013B from Koné was hampered by differing and clearly aberrant isotopic values that prevented any evaluation of marine dietary input. C_4 plants were suggested as a probable source of the enriched δ^{13}C values (-9.6‰ and -14.4‰) (Pietrusewsky et al. 1998:34-35).

Because of the variable pretreatment methodologies used and discrepancies between some values we have obtained new stable isotopes for all burials. Where possible we have also used available data from associated archaeological midden to determine likely presence and absence of certain foods. Unfortunately, there are limitations to our methodology. Site disturbance makes it difficult to be sure of the contextual relationship between the burials and other cultural remains at some sites, as does the likely mobility of an acknowledged sea-faring people (Green 1996). Midden associated with a specific function or season may also introduce bias into the analysis since the carbon and nitrogen isotopes primarily represent the diet of the individual over the last 10-20yrs of life (Geyh 2001). With these limitations in mind we have assigned dietary parameters for each site based on the available radiocarbon and stable isotope data, archaeological faunal material, and geographic and ecological information. The assumptions made, and rationale behind them, are given in Appendix 1 and Table A1.

Stable isotope values were analyzed by the ISOSIM software based on the methodology and diet parameters outlined by Leach et al. (1996, 2003). This program incorporates geographic, archaeological and metabolic information to the calculation of the proportions of different foods in the diet by comparison to a database of δ^{13}C, δ^{15}N and δ^{34}S values obtained from Pacific sources. Modifications were made to the program in order to obtain the atomic ratio of weight of carbon from the land or sea rather than weight of food as previously used by Petchey and Green (2005). The ISOSIM population isotope and tolerance values used are given in Table A2. We stress this dietary evaluation is based on the specific individuals in this study and should not be taken as necessarily representative of the populations from each site as a whole.

4. Radiocarbon Calibration

The human bone determinations were calibrated using the mixed calibration option in OxCal v4.1.5 with curve resolution set at 10 (Bronk-Ramsey 1995, 2001, 2010). This program calculates the calibration curve valid for a given fraction of marine food by linear interpolation between the terrestrial calibration curves (Intcal09; Reimer et al. [2009] and SHCal04; McComac et al. [2004]) and the marine curve of Reimer et al. (2009). For ^{14}C purposes the boundary between the atmosphere of the Southern and Northern Hemispheres is considered to lie along the thermal equator, commonly called the Inter-Tropical Convergence Zone (ITCZ) (McCormac et al. 2004:1088). Fiji, Tonga and Papua New Guinea all lie within the South Pacific Convergence Zone (SPCZ), which merges with the ITCZ to the west, resulting in a possible mix between northern and southern atmospheres. Given the obvious difficulties with addressing this problem we have opted to use IntCal09 for all terrestrial calibrations from these islands. New Caledonia lies just south of the modern distribution of the SPCZ and the use of the Southern Hemisphere calibration curve (SHCal04: McCormac et al. 2004), derived from data collected in southern Chile, Pretoria and New Zealand, is more appropriate.

All ^{14}C determinations were calibrated ('prior' distribution), combined, and then assessed in the light of the combined data (the 'posterior' distribution). This posterior distribution is given an agreement index (A) that indicates the extent to which the posterior distribution overlaps the prior distribution. This can be tested further by calculating an overall agreement index (Amodel) calculated as a function of all constraints applied within the model. In both cases the agreement index should be questioned if it falls below 60%, which is equivalent to the 5% level of a χ^2 test (an unaltered index = 100%, and the value may rise above 100 where the final distribution overlaps with the highest part of the prior distribution) (Bronk-Ramsey 1995).

Given the limitations of the dietary evaluation we have used an uncertainty of ±10% for contribution from marine foods following the recommendations of Ambrose (1993:112). Location specific reservoir correction values (ΔR) have been applied for each island group in order to adjust for regional oceanic variation in ^{14}C (see Petchey et al. 2005, 2008:376-379 for values).

RESULTS

The $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ values and radiocarbon dates are given in Table 2 along with the probable % marine contribution to the diets as determined by ISOSIM. We recovered insufficient material for testing or dating from the Sigatoka and Natunuku burials. The burials from Koné Burial WKO013B, and Pea Village produced ultrafiltered gelatin that fell within the specified quality control parameters outlined above. The ultrafiltered gelatin from Wakea, Olo, Qaranipuqa Cave, Koné (WKO013C) and Watom burials all returned low %S values typical of protein loss. This is expected for archaeological bone from sites with high humidity, and based on current QA protocols we consider these suitable for dietary reconstruction and radiocarbon dating.

To further evaluate the success of our methodology we have compared ultrafiltered bone gelatin results from the seven remaining sites to radiocarbon determinations of other sample types from the same stratigraphic locations. The calibrated dates are shown in Figures 2a-g. All radiocarbon dates from associated contexts are given in Appendix 3.

Watom: The new ultrafiltered date for Burial 1 (Wk-15567b) agrees with the previous crude gelatin result for this individual (Wk-15567a). For comparison we have also recalculated the atomic % marine C values for gelatin dates Wk-15568 (Burial 3, flexed), Wk-15567a (Burial 1, extended supine) and NZA-13685 (also Burial 3) using ISOSIM (32%, 16% and 32% respectively). The new calibrated age for Burial 1 (Wk-15567a and 15567b) is 2800-2730 cal BP ($\chi^2_{1:0.05} = 0.10<3.84$); while Burial 3 (Wk-15568 and NZA-13685) dates to 2670-2640, 2610-2590 and 2510-2350 cal BP ($\chi^2_{1:0.05} = 0.32<3.84$). These results strengthen the possibility of an age difference between the two burials, with Burial 1 dating to Middle Lapita, but Burial 3 falling in the Late Lapita designation of Summerhayes (2009). Unfortunately, there is as yet no published stratigraphic information available to support this observation, but it is possible that the burial ground was in intermittent use for several centuries (Figure 2a). Ongoing excavations at Watom by Dimitri Anson and Hallie Buckley of Otago University can be expected to clarify this matter.

Koné: The two dates on WKO013B, measured at different laboratories (Wk-22480 and OxA-4908) using ultrafiltration and ion exchange techniques respectively, are statistically indistinguishable ($\chi^2_{1:0.05} = 2.30<3.84$) and give an age range of 2100-1990 cal BP (68% prob.) placing WKO013B firmly in the Post-Lapita period for New Caledonia (post 2800 cal BP) (Figure 2b). Both bone results are much older than NZA-3013 (CRA = 1061±65 BP); a date on bone pretreated using an acid wash. Stratigraphically, WKO013B is considered to be associated with the upper clay that capped the sandy Lapita deposits below (Sand 2010:82-83), but the exact association with other dates from the same area (Appendix 3) is uncertain because of multiple occupations and associated disturbance, as well as changing environmental conditions at the site. The calibrated 68% probability age range of 2330-2290 and 2260-2150 cal BP for charcoal sample Beta-179503 from this upper clay unit is closer to the new pooled calibrated age of the burial, but still does not overlap it at 68% probability.

Two dates are now available for burial WKO013C; Beta-125136 and Wk-23255. These are statistically indistinguishable ($\chi^2_{1:0.05} = 2.10<3.84$) and give a calibrated age range of 2500-2350 cal BP (68% prob.). This is in agreement with charcoal dates from slightly higher in the deposits (Figure 2c; Appendix 3), is in keeping with the close association with a pot of Podtanéan tradition and places the burial in the Post-Lapita period for this region.

Olo: There are two dates for burial Y2-25-1; CAMS-24946 and Wk-22473. These provide a combined age of 2440-2330 cal BP (68% prob.; $\chi^2_{1:0.05} = 0.67<3.84$). This overlaps with calibrated age ranges for two unidentified charcoal dates from a comparable context and support an immediately Post-Lapita date for the burial (Figure 2d; Appendix 3). Ceramics from the site were described as “terminal Lapita” by Cochrane (2005:16). Additional dating at this site should further refine the chronology.

Wakea: The ultrafiltered bone date from 196-28-B8 (Wk-22476) returned an age of 530-450 cal BP (68% prob.). There are only two other radiocarbon dates (NZ-4807 and NZ-4809) from deposits some distance away. These were considered by Best (1984:100-105) to be contemporary, but the burial date is clearly much younger than these results and is not Lapita or immediately Post-Lapita in age (Figure 2e), though it remains possible that the second, lower burial found at this location is.

Qaranipuqa Cave: Burial 197-1-M-9 (Wk-22478) returned an age range of 2290-2220 and 2210-2100 cal BP (68% prob.). This date is supported by a charcoal determination (NZ-4808) from the same context (2320-2130 cal BP), and fits well with the overall chronology for the site (Figure 2f). A second charcoal date from Layer M (NZ-4594) is clearly displaced given the established chronological sequence (Appendix 3). This supports a Post-Lapita Plainware association for these remains (Fiji Lapita date extremes; 3000 - 2500 BP), a result that is in keeping with Best’s (1984:78) analysis of ceramic change.

Pea Village: There is limited radiometric dating evidence and considerable prehistoric disturbance at this site. Radiocarbon dates K-904 and K-961, from apparently contemporary deposits, date to c. 3100 cal BP and c. 420 cal BP respectively (Appendix 3). The age of Burial AK (Wk-22479) falls between these ages (1240-1090 cal BP [68% prob.]), and is clearly associated with cultural events that significantly post-date Lapita (Tonga Lapita date extremes; 2900 - 2500 BP) (Figure 2g). It should, therefore, be removed from discussion of Lapita and immediately Post-Lapita burials, where it has up to now had a prominent place (Houghton 1991; Pietrusewsky 1991, 1993, 2006; Hagelberg and Clegg 1993; Buckley et al. 2008).

DISCUSSION

Burial 196-28-B8 from Wakea and Burial AK from Pea Village have been found to post-date the Lapita phase by a considerable degree, and should be removed from future discussions and comparisons of Lapita and immediately Post-Lapita skeletons. The new ultrafiltered bone gelatin dates for WKO013B and WKO013C from Koné, Y2-25-1 from Olo and 197-1-M-9 from Qaranipuqa Cave, indicate that these burials are immediately Post-Lapita skeletons. Burials 1 and 3 from Watom fall within the designated Lapita age range for the Bismarck Archipelago. The West 1 burial (Sigatoka) and the primary burial from Natunuku were unable to be dated at the present time. Discrepancies between these ultrafiltered gelatin dates and previously published assessments of the burial ages can in part be attributed to site disturbance, but may have also been caused by sample specific ^{14}C issues as discussed below.

1. Bone pretreatment and preservation

The success of any bone isotope value is largely dependent on the preservation state (degree of contamination and degradation) and the pretreatment used to purify and isolate the bone protein (Petchey 1999:98-99; Leach et al. 2003:35-38). Therefore to fully appreciate the complexities of ^{14}C and stable isotope analysis and to demonstrate the reliability of these new ultrafiltered bone gelatin results, it is necessary to evaluate extant published isotopic values.

Within this group of burials several previous studies into age and diet have used an acid wash pretreatment (Natunuku [NZA-2512]; Sigatoka [Wk-996B]; Watom [ANU-37b]), or a combination of acid and base washes (Koné [NZA-3013 and Beta-125136] (Table 1). These pretreatments are no longer recommended for archaeological bone except where the preservation condition of the bones is excellent (van Klinken and Hedges 1995; Petchey 1998:192). This is unlikely in high humidity regions such as the tropical Pacific. For archaeological material, gelatinisation is demonstrably more successful (e.g.,Watom [Wk-15567a, Wk-15568 and NZA-13685]). Ultrafiltration, and ion exchange purification (Koné [OxA-4908]) techniques are considered to be the most reliable (Stafford et al. 1987:30-31; van Klinken et al. 1994), but in all cases the reliability of the bone date must be assessed for quality. We have been unable to obtain any pretreatment information for Y2-25-1 from Olo (CAMS-14946) from either the original submitter or laboratory.

Where available, QA data such as %N, %C and C:N support these conclusions (Table 1). Leach et al. (2000, 2003) and Quinn (1990) undertook a series of QA tests on a number of these burials on the fraction remaining after digestion of bone with phosphoric acid. Watom Burial 3 (AY057), Quaranipuqa Cave burial 197-1-M-9 (AY785), and Koné WKO013B (AA727) were identified as suspect on the basis of differential loss of C and N (Leach et al. 2000:152; 2003:46). The Natunuku skeleton was by far the worst with subsample AA725 returning a C:N of 17.4 (Leach et al. 2003:44). Our ultrafiltered gelatin procedure was successful at obtaining isotope data within QA ranges (Table 2). We were unable to get any protein from the Natunuku skeleton because the bone dissolved completely in acid, and therefore conclude that the NZA-2512 (1896±85 BP) is almost certainly a minimum age on non-collagenous material (cf. Stafford et al. 1987:31-32).

Also of interest are the available published isotopes for burials from the Sigatoka sand dunes. Our subsample from the West 1 burial produced insufficient protein for analysis. Houghton, in Best (1987:14), reported %N on whole bone for the FCI burial that ranged from 0.61-0.73% (modern bone has around 4%N) but got collagen yields significantly higher than this value would indicate. Analysis of the West 1 burial (subsample AY787) by Quinn (1990:211) also returned an anomalous C:N value of 5.2 and an even lower %N of 0.2-0.27. Again, given these anomalous stable isotope results it is likely that the date (Wk-996B: 1870±70 BP) for the FC1 burial is erroneous.

Recent isotopic analyses that used gelatin or ion exchange pretreatments (i.e.,skeletal material from Olo (Field et al. 2009), Watom (Petchey and Green 2005; Beavan Athfield et al. 2008) and Koné Site 13B (Pietrusewsky et al. 1998)) have QA values that fall within acceptable parameters (Table 1). These results are almost certainly at the limits of reliable radiocarbon dating because of the high level of contamination relative to in-situ bone protein.

2. Dietary uncertainties

The investigation of Pacific diets is a rapidly growing field, but available isotope information for Pacific plants and animals is limited. Moreover, the interpretation of dietary input from isotopes is a highly complex area with numerous assumptions (see Leach et al. 2003; Petchey and Green 2005; Field et al. 2009; Valentin et al. 2010 and references therein). Of specific note is our current limited understanding of the effect of sea spray on plant sulphur values, which could result in a heavier weighting towards marine foods. Even though Leach et al. (2003:66) concluded that a combination of δ^{34}S, δ^{15}N and δ^{13}C values enabled the distinction between marine and land foods in areas subjected to sea spray, the picture may be complicated by the consumption of animals that browse in this coastal zone (e.g., pigs [Beavan Athfield et al. 2008]). The incorporation of foods from freshwater sources (cf., Cook et al. 2001; Privat et al. 2007) is also of concern, especially since many of these sites are located near freshwater streams. This is an area that requires further research, but the solution remains elusive at present (Hedges and Reynard 2007:1244). Cannibalism has also been claimed for Olo and Qaranipuqa Cave (Houghton in Best 1984:A84; Field et al. 2009:1553), but consumption of human flesh usually has a specific ritual context and so we would not expect it to represent a significant part of the diet (Lindenbaum 2004; Macbetch et al. 2007). It is also possible that as populations became more reliant on domesticates the isotopic signature becomes more difficult to interpret. This may be reflected in the high ISOSIM tolerance limits needed for Burial 196-28-B8 from Wakea (Table A2).

Different pretreatments may also cause variability in isotope results. Privat et al. (2007:1200) suggested that ultrafiltration and separation of the higher molecular weight extract may remove residual sulphur containing contaminants. They also noted that the loss of smaller fragmented collagen strands of good isotopic integrity led to apparently increased sulphur content because of the higher likelihood of removal of N and C over S. This may account for apparent differences in $\delta^{34}S$ values between crude gelatin and ultrafiltered gelatin from Burial 1, Watom (6.5‰ and 10.2‰ respectively) (cf. Tables 1 and 2). Similar discrepancies have been attributed to insufficient removal of soil contaminants in crude gelatin (pers comm. M. Richards, Nov 09).

3. Sample type problems

Bone is by no means the only sample type that needs to be carefully evaluated prior to analysis. At many of these sites unidentified charcoal has been dated. A recent study of radiocarbon determinations from the Cook Islands by Allen and Wallace (2007) has demonstrated that un-calibrated wood charcoal samples identified to species can give radiocarbon results that are on average 64 ^{14}C yrs older than short-lived nutshell samples. Of even more concern is the possibility that some unidentified samples could be 300 or 400 years too old, especially in early sites where older wood sources were available (pers comm. R. Wallace, June 2009). This is potentially problematic for the sites of Koné, Watom and Olo.

Shells may also give erroneous ^{14}C results depending on species selected and ocean conditions. Research in the Pacific (Petchey et al. 2008) has demonstrated that the marine reservoir is fairly uniform in the southern gyre region, but that location-specific issues such as localised upwelling, hardwater or lagoon effects may have an influence on shell dates. Near Watom Island, upwelling of old deep ocean water is thought to make shells appear older than they are. Unfortunately, the current reservoir correction value (ΔR) for this location (Petchey et al. 2005) is based on less than ideal archaeological marine/terrestrial paired samples. Havelu Lagoon, Tongatapu has also been the subject of research into hardwater effects (Spennemann and Head 1998). Hardwaters contain large amounts of bicarbonate ions, which are generated by seepage through ^{14}C-depleted calcareous strata. Shellfish that live in these waters may yield ^{14}C ages that are excessively old (Petchey et al. 2008:385-386). Poulsen (1987:234) concluded that a large proportion of shellfish from Pea Village, site To-1, came from the inner lagoon. Consequently, it is possible that the shell date K-904 could be erroneous. This may also have an impact on human bone where marine food was part of the diet.

Unfortunately, re-evaluation of extant ^{14}C dates that have these sample issues, combined with the inherent uncertainties associated with the interpretation of archaeological sites, place major limitations on our ability to evaluate these new burial dates effectively. Of all the sites discussed in this study only Qaranipuqa Cave has sufficient stratigraphic and chronometric control to provide further evaluation of our % marine calculation and methodology. The deep stratigraphy at the site enables us to constrain the dates using the OxCal ‘sequence’, ‘boundary’ and ‘phase’ commands that place limitations on the calibrated age ranges (Bronk-Ramsey 2005). Although the charcoal dates are unidentified, the site does not represent first colonization and therefore old wood should hypothetically be of limited availability. Some support is given to this by the observed agreement between shell and charcoal ^{14}C results (Figure 3).

Figure 3 shows the expected ages using 66 atomic % marine carbon in the bones as calculated by ISOSIM, and 86% marine carbon following the linear interpolation method of Lanting and van der Plicht (1998) that uses $\delta^{13}C$ endpoint values of –12‰ for purely marine and –21‰ for purely terrestrial (C_3) diets (see Petchey and Green 2005:184 for methodology). The individual agreement index for Wk-22478 at 66 atomic % marine carbon is 102%, and the overall agreement for the sequence is good at 118%. This refines the calibrated age for the bone resulting in a date of 2300-2170 cal BP (68% prob.). Shifting the atomic % marine carbon by ~10% does little to change the overall agreement indices for the sequence, but at 86 atomic % marine carbon the individual agreement drops to 62%, and the over all agreement for the sequence is 89%. Although this is still an acceptable level of agreement, it is lower and places some doubt on the validity of the $\delta^{13}C$ linear interpolation methodology. This is clearly an area for further research.

CONCLUSIONS

Our results put Watom, Burial 1 as the oldest human remains studied here (Middle Lapita (3000-2800 BP), with Watom, Burial 3 dating to within the Late Lapita (2800-c.2200 BP) period, as currently defined for the Bismarck Archipelago. In Remote Oceania, Koné WKO013B and WKO013C, Olo Y2-25-1, and the skeleton 197-1-M-9 from Qaranipuqa Cave, all fall within the third millennium BP and are immediately Post-Lapita in age. The burials from Pea Village (Burial AK) and Wakea (196-28-B8) date to the period after 2000 BP.

In addition to burials from these five sites there are a number of early burials with a secure Lapita or immediately Post-Lapita provenance. A female skeleton from the Naitabale site on Moturiki Island in Western Fiji has been directly dated using purified bone gelatin (Nunn et al. 2007:121-125). Once dietary considerations are taken into account the most likely age for this burial falls post 2650 cal BP, in keeping with associated Late Lapita pottery. Some 80 individuals of unquestionable Lapita age are also known from Teouma, Vanuatu (authors' data, including 34 directly dated individuals). Fragmentary skeletal remains convincingly associated with Lapita-age deposits have also been found at the Talepakemalai site in the Mussau group (Kirch et al. 1989). In 2003 the partial remains of at least four additional individuals were discovered in a pit of Lapita date at Koné Site 13B (Beta-179504 and Beta-179505; Table A3) (Valentin et al. 2004; Sand 2010:209). This gives a total of some 9 reasonably intact skeletal assemblages dating to pre-2000 BP. The status of two more burials (Natunuku and Sigatoka West 1) could not be established by this study.

This research supports previous findings by Petchey and Green (2005:189) that bone from Pacific locations must have an absolute minimum pretreatment to gelatin to ensure the reliability of the radiocarbon results. Moreover, it is essential that QA data are obtained and verify the suitability of the sample for analysis. Currently, stable isotopes cannot identify all but the broadest shifts in diet, but shifts of ~10% have relatively little impact on ^{14}C calibrations at the level of precision reported here. Increasing ^{14}C precision, improved knowledge of sample type issues, routine adoption of statistical modelling, improved excavation methodologies and refinement of questions asked, mean that it is imperative that the issue of dietary correction for ^{14}C calibration is investigated further. Ultimately, direct dating of human remains provides the most secure means of establishing the age of burials, and is therefore invaluable to the refinement of theories investigating the timing and pattern of human expansion and settlement within the Pacific.

Appendix 1: Dietary assumptions.

Watom: Trace element analysis by Horward (1988:138) indicated that the diet was largely terrestrial. This is supported by midden remains that are dominated by pig, with lesser quantities of bandicoot, reptile, and unidentified bird bones (Green and Anson 2000:50–1). C_4 plants and animals that lived on these plants were available, but it is assumed that marine mammals did not contribute to the Watom diet (see Leach et al. 2000:151) (Table A1).

Koné: Sand (1998:19) describes the midden as containing turtle bones, rats, birds, bats and megapode bones. C_4 plants are available in New Caledonia and have previously been suggested as a probable source of an anomalous $\delta^{13}C$ signature for the WKO013B skeleton (Pietrusewsky et al. 1998:34-36).

Olo: Shellfish and reef fishes dominated the midden. Hunt et al. (1999:28-89) specifically note a lack of pelagic fish and a low abundance of mammalian remains (human, rat, turtle and bat). There was a small quantity of avifaunal remains and no introduced domesticates in the early deposits.

Wakea and Qaranipuqa Cave: Faunal and cultural evidence indicate a heavy reliance on reef and lagoon foods, with an almost complete exclusion of pelagic fish in early deposits. Turtles were present at all times but in relatively low frequencies. At both Wakea and Qaranipuqa Cave the domestic fowl was present, but dog and pig were only found in later deposits (Best 1984:532, A87). Recent analysis of human and faunal isotopes from both early (c. 2760 cal BP) and late (c. 500 cal BP) sites in the Lau Island group (Figure 1) support a diet composed largely of C_3 plants and reef resources including reef fish, reptiles and marine shellfish (Jones and Quinn 2009).

Pea Village: The midden at To-1was dominated by shellfish and reef fishes. Turtle was present in small quantities in the earlier deposits, and was rare at all inner lagoon sites that Poulsen (1987) excavated, but more common at sites located closer to the lagoon entrance (i.e., To-2) (see Poulsen 1987:234). Poulsen identified chicken, pig and rat in both early and late sites (1987:246), but evaluation of early Tongan sequences by Burley (1998:355) indicates that evidence for early pig is limited and controversial.

General comments: Most isotope studies (e.g., Valentin et al. 2006:1404; Richards et al. 2009:30) have assumed that the direct consumption by humans of C_4 plants such as sugar cane (*saccharum officinarum*) and duruka (*Saccharum edule*) do not result in a significant shift in the $\delta^{13}C$ values, except in extreme dietary situations, because they contain almost no protein that can be preferentially routed to collagen based on the findings of Ambrose and Norr (1993). Recent isotopic analysis of human remains from several early archaeological sites in the Lau Island group have, however, returned depleted $\delta^{13}C$ values suggestive of the consumption of C_4 plants (Jones and Quinn 2009:2750). Given the limited state of knowledge at present on Pacific diets we have assumed that no C_4 plants contributed to the diets of individuals from Fiji and Tonga (Table A1).

There is some evidence that pelagic fish may be absent from some assemblages (i.e., Olo, Qaranipuqa Cave and Wakea) and Butler (1988) has found minimal evidence for pelagic fish in Lapita-age sites. In the absence of more extensive midden analyses we have assumed that this food source was available at all sites. The degree of error this could potentially introduce for each burial is small (maximum difference was for Burial 1, Watom, where the % marine carbon shifted from 28% to 21% when non-reef fish were excluded).

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Figure 1. The Pacific Ocean showing sites mentioned in the text. The greyed area shows the approximate extent of the Inter-tropical and South Pacific Convergence Zones between 1968 and 1996, with maximum range indicated by dotted line (after Linacre and Geerts 1998). Inserts: (A) Koné, New Caledonia; (B) Fiji; (C) Tongatapu, Tonga.

Figure 2. Calibrated radiocarbon dates from: (A) Watom, Site SAC; (B) Koné, Site 13B; (C) Koné, Site 13; (D) Olo, Site Y2-25; (E) Wakea, Site 196; (F) Qaranipuqa Cave, Site 197; (G) Pea Village, Site To-1.

Figure 3. Modelled sequence at Qaranipuqa Cave (Site 197) showing the 68.2% and 95.4% probability calibrated age ranges. Human bone calibration for burial 197-1-M-9 (shown in grey) assuming 66 atomic % marine carbon input (see text for discussion). The outline date distributions show the calibrated ages for each individual sample. The solid

black distributions show the calculated ranges when applying the Bayesian model outlined in the text [quoted probabilities vary slightly by run).

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Table 1. Previously published bone isotope data from the sites investigated.

Site	Burial	Sample ID$	Pretreat.*	$\delta^{15}N$	$\delta^{13}C$	$\delta^{34}S$	%N	%C	C:N	CRA (BP)	Reference
Watom (Site SAC)	Burial 3	AY057	AWp	11.9 to 12.9	-18.3	11.5	-	-	3.7	-	Specht (1968:124); Leach et al. (2000); Petchey and Green (2005); Beavan Athfield et al. (2008)
		Wk-15568	Gel	11.1	-17.8	10.1	15.1	42.2	3.3	2633±33	
		NZA-13685	Gel	12.5	-17.6	10.0	-	-	-	2569±50	
	Burial 1	AY056	-	11.7^	-		-	-	-	-	
		Wk-15567a	Gel	10.9	-18.1	6.5	14.2	40.6	3.3	2757±32	
	Burials 1, 2 and possibly 3	ANU-37b	AW	-	-	-	-	-	-	2420±110	
	Burial 2	-	Gel	10.7	-18.5	7.5	13.9	39.1	3.3		
Koné (Sites 13 and 13B)	WKO013B	NZA-3013/ AA726#	ABA	-	-14.4	-	-	-	-	1061±65	Pietrusewsky et al. (1998:31-37); Valentin and Sand (2000:24); Valentin (2003:285-286)
		OxA-4908/ AB705#	IE	13.5	-9.6	-	-	-	3.3	2410±55	
		AA727#	AWp	μ= 11.1	μ=-12.2	-	μ=10.6	μ=31.1	μ=3.4	-	
	WKO013C	Beta-125136	ABA	-	-15.8	-	-	-	-	2710±80	Valentin and Sand (2000:19)
Olo (Y2-25)	Olo burials	-	Gel	8.8 to 11.1	-16.9 to -13.5	-	9.9-11.1	28.3-36.2	3.2-3.4	-	Field et al. (2009:1552)
	Y2-25-1	CAMS-24946	Unknown							2530±50	Pietrusewsky et al. (1997:358); Hunt (1999:25)
Wakea (Site 196)	196-28-B8	AY082	AWp	10.3^	-16.5	-	-	-	3.4	-	Quinn (1990); Leach et al. (2003:83-86)
	196-28-B8-Lower	AY784	AWp	11.7^	-15.8	15.9	-	-	3.6	-	
Qaranipuqa Cave (Site 197)	197-1-M-9	AY785	AWp	11.3^	-13.4	-	-	-	3.0	-	
Natunuku (VL1/1)	Primary burial	AA725	AW	7.4	-14.6	13.1	2.4	35.4	17.4	-	Leach et al. (2003)
		NZA-2512	AW	-	-14.8	-	-	-	-	1896±85	Davidson and Leach (1993:102)
Sigatoka (VL16/1)	Burial FC1	Wk-996B	AW	-	-15.9	-	-	-	-	1870±70	Best (1987:13)
	West 1	AY787	AWp	9.8^	-19.5	-	-	-	5.2	-	Quinn (1990); Leach et al. (2003:84-85)
Pea Village (To-1)	Burial AK	AY774	AWp	10.3^	-15.4	12.5	-	-	3.5	-	Quinn (1990); Leach et al. (2003:84-86)

*Pretreatment: AW – acid digestion; AWp - phosphoric acid digestion; ABA - acid, base, acid pretreatment; IE – ion exchange; Gel – gelatinisation.

$ Identifiers "AY-", "AB-" and "AA-" refer to subsamples taken by Leach et al. (2003) and Quinn (1990) for dietary analysis.

different bones from same individual (WKO013B).

^ isotope value on bone powder. Leach et al (2000:152) suggest a correction of 0.2‰ for $\delta^{15}N$ values measured on whole bone.

Table 2. New radiocarbon ages and stable isotope data on ultrafiltered gelatin from the burials included in study.

^{14}C Laboratory ID	Burial and Sample ID	CRA (BP)	$\delta^{15}N$	$\delta^{13}C$	$\delta^{34}S$	%N	%C	%S	C:N	N:S	C:S	Atomic % Marine C
Wk-15567b	Watom, Burial 1 (subsample of AY056)	2797±3̃	11.5	-18.4	10.2	13.9	41.5	0.2	3.5	168	583	28
Wk-22480	Koné, Burial WKO013B (subsample of AB705)	2316±3̃	11.7	-9.9	13.9	14.1	41.0	0.3	3.4	124	421	79
Wk-23255	Koné, Burial WKO013C	2587±3̃	11.6	-14.6	10.6	15.9	44.4	0.2	3.3	182	593	49
Wk-22473	Olo, Burial Y2-25-1	2598±3̃	11.1	-15.4	13.8	14.7	42.2	0.2	3.4	177	593	62
Wk-22476	Wakea, Burial 196-28-B8 (subsample of AY082)	671±3̃	10.1	-17.3	13.8	14.4	41.9	0.2	3.4	150	509	55
Wk-22478	Qaranipuqa Cave, Burial 197-1-M-9 (subsample of AY785)	2389±3̃	11.0	-13.2	13.8	14.9	42.6	0.2	3.3	190	631	66
Wk-22479	Pea Village, Burial AK (subsample of AY774)	1458±3̃	10.3	-14.8	13.8	14.1	41.3	0.3	3.4	124	424	60

$\delta^{13}C$ measured relative to VPDB with errors of ±0.1‰. $\delta^{15}N$ measured relative to AIR and with errors of ±0.2‰. $\delta^{34}S$ measured relative to IAEA-S-1 and IAEA-S-2 (both Ag_2S) and NBS123 (ZnS) with errors of ± 0.2‰.

Table A1. ISOSIM dietary assumptions: presence (x) and absence (o) of different foods.

	Watom (Burial 1)	**Koné**		**Olo** (Burial Y2-25-1)	**Lakeba**		**Pea Village** (Burial AK)
		Burial WKO013B	**Burial WKO013C**		**Wakea** (Burial 196-28-B8)	**Q Cave** (Burial 197-1-M-9)	
Food							
1 = C_3 Plants	X	X	X	X	X	X	X
2 = C_4 Plants	X	X	X	o	o	o	o
3 = Land Herbivores	X	X	X	X	X	X	X
4 = Marine Shellfish	X	X	X	X	X	X	X
5 = Coral Reef Fish	X	X	X	X	X	X	X
6 = Non-Reef Fish	X	X	X	X	X	X	X
7 = Marine Mammal	o	X	X	X	X	X	X

Table A2: ISOSIM results and population isotope and tolerance values.

Isotope	**Watom** (Burial 1)	**Koné**		**Olo** (Burial Y2-25-1)	**Lakeba**		**Pea Village** (Burial AK)
		Burial WKO013B	**Burial WKO013C**		**Wakea** (Burial 196-28-B8)	**Q Cave** (Burial 197-1-M-9)	

Tolerance							
$\delta^{13}C$	2.0	1.2	0.5	1.5	2.0	0.8	1.5
$\delta^{15}N$	1.8	1.2	0.5	1.5	3.0	0.8	1.5
$\delta^{34}S$	2.0	1.0	0.5	1.5	3.0	0.8	1.5
Total no. of simulations to achieve 1001 successful iterations	14816086	7177277	1360175	7565012	9059040	4461463	1879510

Appendix 3: Radiocarbon dates shown in Figure 2.

Site Name	Lab No.*	^{14}C Age$	Sample and Context	Calibrated Age
Watom (Site SAC)	ANU-5330	2390±80	*Tridacna maxima* shell. Sq G-14, Zone C1	1870-1550 BP (68%) 2050-2030, 2020-1390 BP (95%)
	ANU-5336	2530±90	*Tridacna maxima* shell. Pit feature, Sq I/J 13/14, Zone C2	2495±58 [$\chi^2_{1:0.05}$ = 0.3<3.8] 1980-1690 BP (68%) 2120-1540 BP (95%)
	Beta-16835	2470±75		
	Wk-15567a#	2757±32	Human bone (Burial 1)	2800-2730 BP (68%) 2850-2710 BP (95%)
	Wk-15567b#	2797±30	Human bone (Burial 1)	2800-2730 BP (68%) 2850-2710 BP (95%)
	Wk-15568#	2633±33	Human bone (Burial 3)	2670-2640, 2610-2590, 2510-2350 BP (68%) 2690-2630, 2620-2340 BP (95%)
	NZA-13685#	2569±50	Human bone (Burial 3)	2670-2640, 2610-2590, 2510-2350 BP (68%) 2690-2630, 2620-2340 BP (95%)
	ANU-5339	3490±80	*Trochus niloticus* shell. Sq G-10. Zone C/D interface	3240-3220, 3210-2870 BP (68%) 3350-2740 BP (95%)
Koné (Site 13B)	Beta-179503	2290±40	Charcoal. Oven (upper part of Layer B)	2330-2290, 2250-2150 BP (68%) 2350-2150 BP (95%)
	Wk-15068	2617±40	Charcoal. Oven (upper part of Layer B)	2760-2690, 2640-2610, 2590-2540 BP (68%) 2770-2660, 2659-2480 BP (95%)
	OxA-4908#	2410±55	Human bone (WKO013B)	2270-2230, 2210-2030 BP (68%) 2310-1970 BP (95%)
	Wk-22480#	2316±30	Human bone (WKO013B)	2070-1940 BP (68%) 2120-1900 BP (95%)
	Beta-59964	2870±70	*Anadara scapha* shell. Layer B (mid) 90cm	2730-2530 BP (68%) 2780-2390 BP (95%)
	Beta-92762	2660±40	Charcoal. Layer B (base) 100cm	2780-2710, 2630-2620 BP (68%) 2850-2820, 2800-2690, 2640-2610, 2600-2500 BP (95%)
	Beta-136943	2610±50	Charcoal. Layer B (base) 125cm	2750-2690, 2640-2610, 2600-2500 BP (68%) 2770-2460 BP (95%)
	Beta-136946	2560±50	Charcoal. In pot 3	2730-2670, 2650-2480 BP (68%) 2750-2430, 2420-2360 BP (95%)
	Wk-15070	2822±37	Charcoal. In pot 3	2930-2900, 2890-2790 BP (68%) 2960-2770 BP (95%)
	Wk-15069	2832±37	Charcoal. In pot 3	2930-2840, 2830-2790 BP (68%) 2970-2770 BP (95%)
	Beta-144344	2770±50	Charcoal. Complete long pot	2860-2760 BP (68%) 2930-2740 BP (95%)
	Beta-61955	2850±60	Charcoal. In pot 2	2970-2790 BP (68%) 3070-2760 BP (95%)
	Beta-179504	2870±40	Charcoal. Sample associated with burial pit Erica	2970-2850 BP (68%) 3070-2790 BP (95%)
	Beta-179505	2720±40	Charcoal. Sample associated with burial pit Erica	2850-2820, 2800-2740 BP (68%) 2870-2730 BP (95%)
Koné (Site 13A)	Beta-136955	2610±40	Charcoal. IV, F6 (30-50cm)	2750-2690, 2640-2610, 2590-2540, 2530-2510 BP (68%) 2760-2480 BP (95%)
	Beta-136949	2610±40	Charcoal. I, D3 (30-40cm)	2750-2690, 2640-2610, 2600-2540, 2530-2510 BP (68%)

				2760-2480 BP (95%)
	Beta-136951	2550±50	Charcoal. Zone I (base of pit)	2720-2480 BP (68%) 2740-2430, 2420-2360 BP (95%)
	Beta-136952	2470±40	Charcoal. Zone II, G3 (30-35cm)	2670-2640, 2490-2350 BP (68%) 2710-2630, 2620-2580, 2570-2560, 2550-2340 BP (95%)
	Beta-136954	2780±50	Charcoal. Zone II, G3 (64cm)	2870-2760 BP (68%) 2950-2740 BP (95%)
	Beta-136950	2810±50	Charcoal. Zone I, D3 (40-50)	2930-2900, 2890-2780 BP (68%) 2970-2750 BP (95%)
	Beta-136953	2860±40	Charcoal. Zone II, G3 (45cm)	2970-2850 BP (68%) 3060-3050, 2840-2780 BP (95%)
	Beta-75584	2900±120	Charcoal. Post hole sq 17U25 (80cm)	3150-2790 BP (68%) 3330-3280, 3270-2750 BP (95%)
	Beta-136956	2750±40	Charcoal. Zone I, D3 (50-60cm)	2850-2750 BP (68%) 2880-2740 BP (95%)
	Beta-136957	2730±40	Charcoal. Zone IV, F10 (base)	2850-2820, 2800-2740 BP (68%) 2870-2730 BP (95%)
	Beta-55998	2970±60	*Anadara scapha* shell. 18Y25 (base)	2820-2690 BP (68%) 2910-2600 BP (95%)
	Beta-125136#	2710±80	Human bone (WKO013C) Shutler excavations 1967	2740-2500 BP (68%) 2770-2350 BP (95%)
	Wk-23255#	25877±3	Human bone (WKO013C) Shutler excavations 1967	2480-2350 BP (68%) 2680-2630, 2620-2580, 2570-2560, 2550-2330 BP (95%)
Olo (Site Y2-25)	Beta-86839	2540±50	Charcoal. TU3, Layer II base	2750-2690, 2640-2610, 2600-2500 BP (68%) 2760-2460, 2390-2370 BP (95%)
	Beta-86840	2570±80	Charcoal. TU3, Layer II, Pit Feature 1	2770-2680, 2640-2490 BP (68%) 2840-2820, 2800-2360 BP (95%)
	CAMS-24946#	2530±50	Human bone. Layer II, burial pit	2440-2330 BP (68%) 2660-2640, 2610-2590, 2510-2290 BP (95%)
	Wk-22473#	2598±30	Human bone. Layer II, burial pit	2440-2330 BP (68%) 2660-2640, 2610-2590, 2510-2290 BP (95%)
Wakea (Site 196)	NZ-4809	2937±63	*Trochus niloticus* shell. Sq 19, Layer B20a	2780-2600 BP (68%) 2850-2470 BP (95%)
	NZ-4807	2698±107	Charcoal. Sq 25, Layer B18	2960-2730 BP (68%) 3140-3090, 3080-2480 BP (95%)
	Wk-22476	671±30	Human bone. Trench 28, Layer B8	530-450 BP (68%) 550-330 BP (95%)
Qaranipuqa Cave (Site 197)^	NZ-4904	382±74	Charcoal. Layer A2	510-420, 390-310 BP (68%) 540-290 BP (95%)
	NZ-4905	867±60	Charcoal. Layer E2	910-860 BP, 830-720 BP (68%) 920-680 BP (95%)
	NZ-4592	1717±89	Charcoal. Layer F3	1740-1520 BP (68%) 1860-1850, 1830-1410 BP (95%)
	NZ-4588	2065±34	*Tridacna maxima* shell. Layer F3	1690-1560 BP (68%) 1750-1510 BP (95%)
	NZ-4593	2045±91	Charcoal. Layer K1	2130-1890 BP (68%) 2310-2220, 2210-1820 BP (95%)
	NZ-4591	2498±35	*Turbo bruneus* shell. Layer K4	2250-2080 BP (68%) 2300-2020 BP (95%)
	NZ-4594	2873±67	Charcoal. Layer M	3140-3120, 3110-3090, 3080-2880 BP (68%) 3220-2840, 2820-2800 BP (95%)
	NZ-4808	2195±74	Charcoal. Layer M	2320-2130 BP (68%) 2350-2000 BP (95%)
	Wk-22478	2389±30	Human bone. Layer M	2290-2220, 2210-2100 BP (68%) 2310-2030 BP (95%)
	NZ-4589	2855±36	*Lambis lambis* shell. Layer T	2700-2530 BP (68%) 2730-2440 BP (95%)
	NZ-4596	2540±127	Charcoal. Layer T	2760-2450, 2380-2360 BP (68%) 2930-2900, 2890-2330 BP (95%)
	NZ-4595	1082±86	*Cocos nucifera* endocarp charcoal. Layer W	1130-1110, 1090-920 BP (68%) 1230-1200, 1190-790 BP (95%)
	NZ-4590	3079±46	*Conus leopardus* shell. Layer W.	2890-2750 BP (68%) 2970-2720 BP (95%)

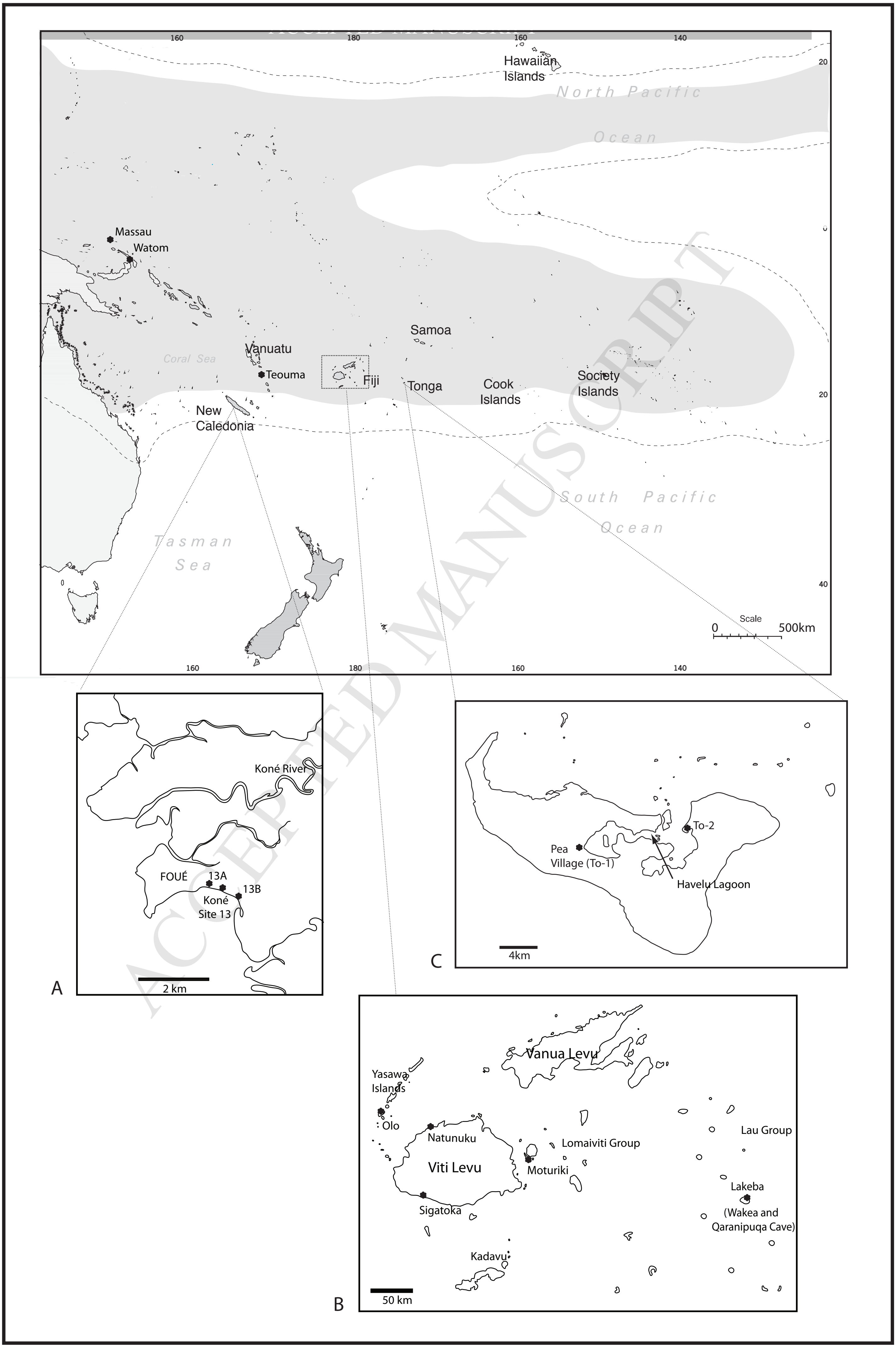
Pea Village (Site To-1)	K-904	3180±100	*Gafrarium pectinatum* shell. Interface of Horizons I and II, Pit A,Trench 1	3120-2830 BP (68%) 3250-2740 BP (95%)
	NZ-597	545±71	*Cocos nucifer* endocarp charcoal. Interface of Horizons I and II, Pit A, Trench 1	640-590, 570-510 BP (68%) 670-490 BP (95%)
	K-961	420±100	*Cocos nucifer* endocarp charcoal. Interface of Horizons I and II, Pit A, Trench 1	540-420, 400-320 BP (68%) 650-580, 570-280, 170-150 BP (95%)
	Wk-22479	1458±30	Human bone. Burial AK in pit AF, Trench III	1240-1090 BP (68%) 1280-1050 BP (95%)

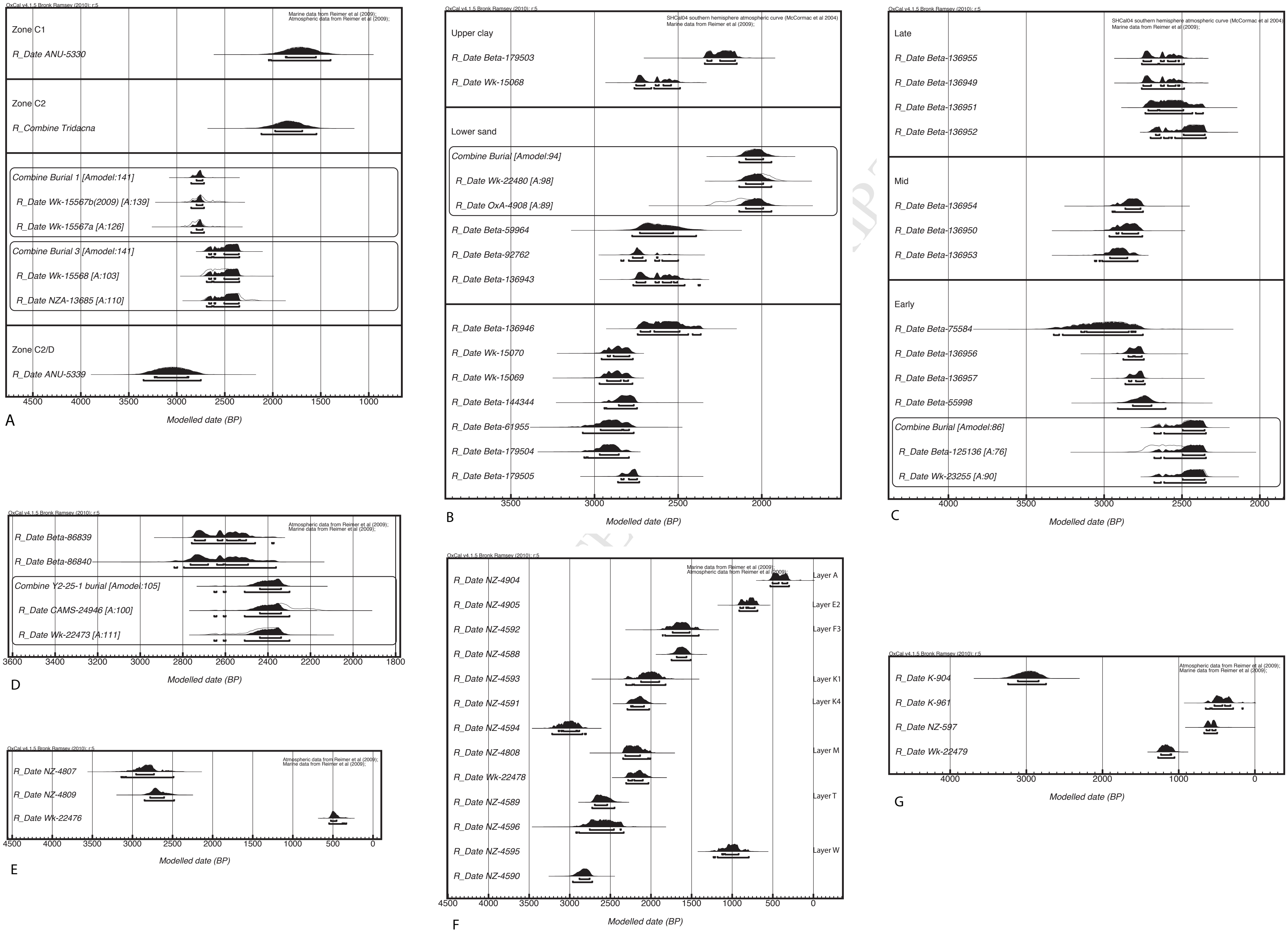
*Lab prefixes: Wk = Waikato Radiocarbon Dating Laboratory; CAMS = Lawrence Livermore National Laboratories; Beta = Beta Analytic; ANU = Australian National University; NZ(A) = Rafter Radiocarbon Laboratory; K= National Museum, Denmark; OxA = Oxford Radiocarbon Accelerator Unit.

^Two marine turtle bone dates (NZ-4906 and NZ-4810) are excluded. These are of acid washed material and are almost certainly contaminated.

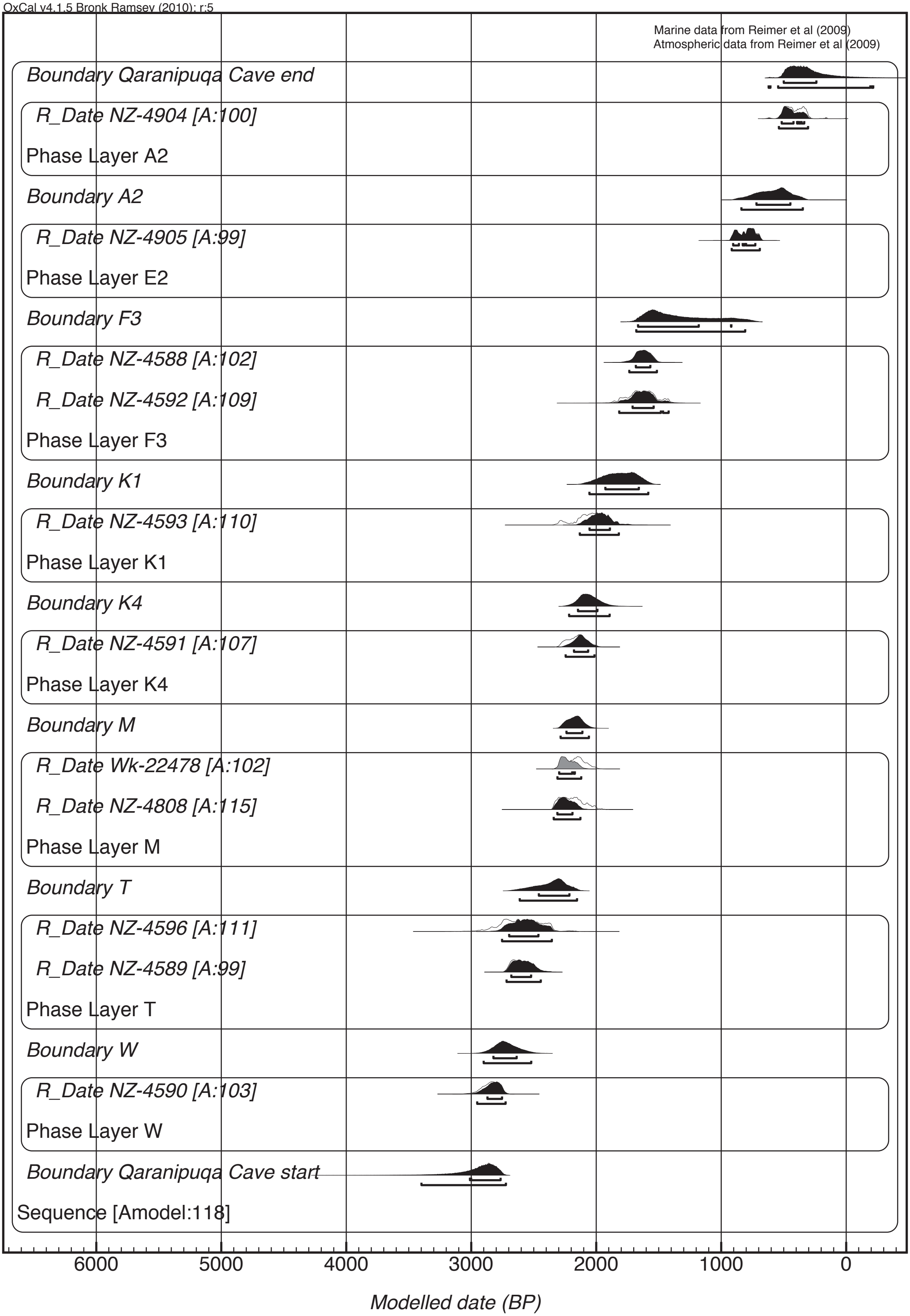
$ Radiocarbon dates have been brought into line with ^{14}C convention (Stuiver and Polach 1977) and may differ from original publications.

Bones calibrated with atomic % marine C value obtained from this study.


Hawaiian Islands
North Pacific Ocean
Massau
Watom
Samoa
Vanuatu
Coral Sea
Teouma
Fiji
Tonga
Cook Islands
Society Islands
New Caledonia
South Pacific Ocean
Tasman Sea
Scale
0
500km
Koné River
FOUÉ
13A
13B
Koné Site 13
2 km
A
Pea Village (To-1)
To-2
Havelu Lagoon
4km
C
Vanua Levu
Yasawa Islands
Olo
Natunuku
Lomaiviti Group
Lau Group
Viti Levu
Moturiki
Lakeba
(Wakea and Qaranipuqa Cave)
Sigatoka
Kadavu
50 km
B



OxCal v4.1.5 Bronk Ramsey (2010); r:5
Marine data from Reimer et al (2009);
Atmospheric data from Reimer et al (2009);
Zone C1
R_Date ANU-5330
Zone C2
R_Combine Tridacna
Combine Burial 1 [Amodel:141]
R_Date Wk-15567b(2009) [A:139]
R_Date Wk-15567a [A:126]
Combine Burial 3 [Amodel:141]
R_Date Wk-15568 [A:103]
R_Date NZA-13685 [A:110]
Zone C2/D
R_Date ANU-5339
4500 4000 3500 3000 2500 2000 1500 1000
Modelled date (BP)
A
OxCal v4.1.5 Bronk Ramsey (2010); r:5
SHCal04 southern hemisphere atmospheric curve (McCormac et al 2004)
Marine data from Reimer et al (2009);
Upper clay
R_Date Beta-179503
R_Date Wk-15068
Lower sand
Combine Burial [Amodel:94]
R_Date Wk-22480 [A:98]
R_Date OxA-4908 [A:89]
R_Date Beta-59964
R_Date Beta-92762
R_Date Beta-136943
R_Date Beta-136946
R_Date Wk-15070
R_Date Wk-15069
R_Date Beta-144344
R_Date Beta-61955
R_Date Beta-179504
R_Date Beta-179505
3500 3000 2500 2000
Modelled date (BP)
B
OxCal v4.1.5 Bronk Ramsey (2010); r:5
SHCal04 southern hemisphere atmospheric curve (McCormac et al 2004)
Marine data from Reimer et al (2009);
Late
R_Date Beta-136955
R_Date Beta-136949
R_Date Beta-136951
R_Date Beta-136952
Mid
R_Date Beta-136954
R_Date Beta-136950
R_Date Beta-136953
Early
R_Date Beta-75584
R_Date Beta-136956
R_Date Beta-136957
R_Date Beta-55998
Combine Burial [Amodel:86]
R_Date Beta-125136 [A:76]
R_Date Wk-23255 [A:90]
4000 3500 3000 2500 2000
Modelled date (BP)
C
OxCal v4.1.5 Bronk Ramsey (2010); r:5
Atmospheric data from Reimer et al (2009);
Marine data from Reimer et al (2009);
R_Date Beta-86839
R_Date Beta-86840
Combine Y2-25-1 burial [Amodel:105]
R_Date CAMS-24946 [A:100]
R_Date Wk-22473 [A:111]
3600 3400 3200 3000 2800 2600 2400 2200 2000 1800
Modelled date (BP)
D
OxCal v4.1.5 Bronk Ramsey (2010); r:5
Atmospheric data from Reimer et al (2009);
Marine data from Reimer et al (2009);
R_Date NZ-4807
R_Date NZ-4809
R_Date Wk-22476
4500 4000 3500 3000 2500 2000 1500 1000 500 0
Modelled date (BP)
E
OxCal v4.1.5 Bronk Ramsey (2010); r:5
Marine data from Reimer et al (2009);
Atmospheric data from Reimer et al (2009);
R_Date NZ-4904
Layer A
R_Date NZ-4905
Layer E2
R_Date NZ-4592
Layer F3
R_Date NZ-4588
R_Date NZ-4593
Layer K1
R_Date NZ-4591
Layer K4
R_Date NZ-4594
R_Date NZ-4808
Layer M
R_Date Wk-22478
R_Date NZ-4589
Layer T
R_Date NZ-4596
R_Date NZ-4595
Layer W
R_Date NZ-4590
4500 4000 3500 3000 2500 2000 1500 1000 500 0
Modelled date (BP)
F
OxCal v4.1.5 Bronk Ramsey (2010); r:5
Atmospheric data from Reimer et al (2009);
Marine data from Reimer et al (2009);
R_Date K-904
R_Date K-961
R_Date NZ-597
R_Date Wk-22479
4000 3000 2000 1000 0
Modelled date (BP)
G


OxCal v4.1.5 Bronk Ramsey (2010); r:5
Marine data from Reimer et al (2009)
Atmospheric data from Reimer et al (2009)
Boundary Qaranipuqa Cave end
R_Date NZ-4904 [A:100]
Phase Layer A2
Boundary A2
R_Date NZ-4905 [A:99]
Phase Layer E2
Boundary F3
R_Date NZ-4588 [A:102]
R_Date NZ-4592 [A:109]
Phase Layer F3
Boundary K1
R_Date NZ-4593 [A:110]
Phase Layer K1
Boundary K4
R_Date NZ-4591 [A:107]
Phase Layer K4
Boundary M
R_Date Wk-22478 [A:102]
R_Date NZ-4808 [A:115]
Phase Layer M
Boundary T
R_Date NZ-4596 [A:111]
R_Date NZ-4589 [A:99]
Phase Layer T
Boundary W
R_Date NZ-4590 [A:103]
Phase Layer W
Boundary Qaranipuqa Cave start
Sequence [Amodel:118]
6000
5000
4000
3000
2000
1000
0
Modelled date (BP)