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Evidence of Prehistoric Lapita Diet at Watom Island, Papua New Guinea, using Stable Isotopes

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ABSTRACT

Samples of human bone from six individuals from the Lapita burial ground at Reber-Rakival on Watom Island in New Britain were analysed for $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$. The mean values obtained were −18.1, 11.6 and 9.9 respectively. From existing knowledge of isotope values, calorific content and protein yields for the main Pacific food types, computer simulation was used to randomly generate a large number of possible food compositions, in order to find the type of diet which could have produced the isotope pattern at Watom. The simulation produced solutions which are within acceptable limits of the Watom isotope signature. The mean food composition per day was then estimated as follows:

Food Type	Weight %	Protein g	Energy kcal
C3 Plants	50.6	19.7	1301
C4 Plants	2.7	0.2	19
Land Herbivores	10.7	40.3	271
Marine Shellfish	8.7	20.3	108
Coral Reef Fish	6.0	20.8	105
Non-Reef Fish	21.3	72.5	368

This analysis shows that approximately 64% of the diet at Watom came from land-based foods and 36% from the sea. Plant foods contributed 53% by weight. It is notable that C4 plants were present in the diet. There are two possible sources of this — sugar cane, *Saccharum officinarum*, and/or a herbivore which browsed on the C4 grasslands of Papua New Guinea, such as *Saccharum spontaneum* (pit-pit) and *Imperata cylindrica* (kunai). Fish and land herbivores are the main sources of protein in the Watom diet, while plant foods contributed by far the most food energy.

Keywords: MELANESIA, NEW BRITAIN, WATOM, LAPITA, PREHISTORIC DIET, STABLE ISOTOPE DIET SIGNATURES, CARBON-13, NITROGEN-15, SULPHUR-34.

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INTRODUCTION

Eight human burials were excavated at the Reber-Rakival locality (SAC) of the Lapita site on Watom Island (Specht 1968; Green and Anson 1987; Green *et al.* 1989; Green and Anson 2000). Six samples of human bone were extracted from the burials being studied at the University of Otago. These were rib samples, which are not ideal for this type of research because they raise the possibility of soil chemical contamination. Approximately 50 g is required from each individual, most of this being used for determination of $\delta^{34}S$. All samples were carefully cleaned of obvious surface contaminants and washed in distilled water in an ultrasonic bath. Checks were made for soil-bearing nitrates during chemical pre-treatment for $\delta^{15}N$.

Bone samples were powdered with a tungsten carbide 'Temma' mortar, and a sub-sample used for $\delta^{15}N$ determination. An independent study was made of $\delta^{15}N$ in both bone powder and collagen extract to see if results from bone powder were satisfactory. In general they proved to be so, although a minor adjustment is required for results from bone powder (Quinn 1990: 180).

In the case of $\delta^{13}C$ and $\delta^{34}S$ it was necessary to extract the inorganic component, in order to cut down on the sheer bulk of the samples and, for $\delta^{13}C$ analysis, to eliminate those sources of carbon which may have come from surrounding soil. The samples were digested using 5% phosphoric acid, and then washed to neutral pH, centrifuged and dried. Tests were made with both XRF (looking for Calcium) and XRD (looking for hydroxyapatite crystals) to make sure that digestion of the inorganic component was completed. The final sample was a powder with a variable colour ranging from light to dark brown. Hydroxyproline analysis of samples showed there to be approximately 63% collagen in this residue, which is referred to here as collagen extract. The sulphur was extracted from this collagen extract using Parr bomb treatment yielding barium sulphate (Quinn 1990: 97 ff.).

The isotope values for $\delta^{34}S$ and $\delta^{13}C$ were obtained at the then Institute of Nuclear Sciences, and for $\delta^{15}N$ at the Ruakura Agriculture Centre.

Having obtained isotope values for a group of people the next step is to work out what kind of diet caused this isotope signature. This is not a simple problem. A particular prehistoric person (for example AY-57 from Watom) has a $\delta^{13}C$ bone signature of −18.25. We assume a value of 5.0 as the offset from the ingested diet to bone (following Keegan and DeNiro 1988: 329), so this person consumed food which had an average signature of −23.25. The value of $\delta^{13}C$ varies for different foods and it should be obvious that there are an infinite number of combinations of these different foods which could give an average signature of −23.25. For example, the person could have consumed the following:

81% C3 plants ($\delta^{13}C$= −26.0)	and 19% C4 plants	($\delta^{13}C$ = −11.5) or
19% C3 plants ($\delta^{13}C$= −26.0)	and 81% land herbivores	($\delta^{13}C$ = −22.6) or
77% C3 plants ($\delta^{13}C$= −26.0)	and 23% shellfish	($\delta^{13}C$ = −14.0) or
etc.	etc.	etc.

How then could one possibly work out any useful information about diet which corresponds to the $\delta^{13}C$ signature obtained for such an individual? With this information alone one cannot. However, by obtaining an additional signature of $\delta^{15}N$ many of the ambiguities disappear. The same person (AY-57) has a $\delta^{15}N$ signature of +12.17. The diet above of 81% C3 plants and 19% C4 plants would yield a bone signature for $\delta^{15}N$ of +6.60, so this diet is out of the question. Unfortunately, adding information about $\delta^{15}N$ alone does not solve all the ambiguities. This is why analysis of $\delta^{34}S$ is so useful. However, there is a trade-off. The use of three isotopes may effectively reduce the ambiguities, but it greatly complicates the search for dietary combinations which could produce any particular trivariate isotope signature.

An elegant solution to this problem has recently been achieved by Minagawa (Minagawa and Akazawa 1989, 1992; Minagawa 1992) using computer simulation, and that is the approach we have developed for use with prehistoric Pacific economies (Leach *et al.* 1996).

RESULTS AND DISCUSSION

The isotope signatures for the six individuals are provided in Table 1. This gives mean values for $\delta^{13}C$ of −18.05, for $\delta^{15}N$ of +11.55 and for $\delta^{34}S$ of +9.90.

In Table 2 the various assumptions which were made in the computer simulation are indicated. This is not the place to justify these, as all details can be found elsewhere (Leach *et al.* 1996). It will be noted that in the case of Watom, no archaeological information was considered to reject any simulations. This is because there is no information yet available on relative meat weights of fauna from midden studies. It should also be noted that a tolerance level of ± 2‰ was used for $\delta^{13}C$, and a lesser value of ± 1.5‰ for $\delta^{15}N$ and $\delta^{34}S$. The larger value for $\delta^{13}C$ was found necessary in order to achieve valid simulations. It will be seen in Table 1 that the ranges for these three isotopes for the Watom bone samples were 0.68, 5.22, and 3.20 respectively. The $\delta^{13}C$ values are reasonably tight, but both $\delta^{15}N$ and $\delta^{34}S$ are wide-ranging, indicating considerable dietary variability in the prehistoric group. This raises an important point as to the validity of reconstructing an average diet for a group which has highly variable isotope values. The average diet may not be a very appropriate reconstruction. An alternative strategy would be to reconstruct diets for each individual studied using their unique isotope signatures. Unfortunately the computing required for this approach is immense, requiring more power than we have access to. The results provided in Table 3 required 12 hours of CPU time. We carried out considerable experimentation with the tolerance values for each isotope for Watom, and found that reducing the tolerance for $\delta^{13}C$ to ± 1.5 greatly diminished the number of valid simulations. On the other hand, increasing or decreasing the tolerance limits for $\delta^{15}N$ and $\delta^{34}S$ made little difference. We compromised in the end by lowering the tolerance value for $\delta^{15}N$ (± 1.5) below the range found in the prehistoric group (5.22‰ or ± 2.6), and increasing the $\delta^{13}C$ tolerance value (±2.0‰) above the range for the group (0.68‰ or ± 0.34). This is not an ideal solution, and the problems encountered suggest that there is significant dietary variation in this group.

For each of the seven food types a flat distribution random generator was used from 0 to 100% (50 ± 50) except in the case of marine mammals (the seal family, whales and dolphins). It was judged that these are very unlikely to have figured in the diet at Watom. It is possible that some dugong could have been consumed, although there is no evidence of this in the fauna analysed. Dugong has a highly unusual isotope signature ($\delta^{13}C$ very marine looking, but $\delta^{15}N$ and $\delta^{34}S$ very land looking). This is because this animal is a marine herbivore eating sea grass in shallow inshore waters. Table 2 lists the assumed average isotope values for the seven basic food types used in this study, together with average values for food energy and protein levels.

TABLE 1
Stable Isotope Results for Watom

There are several blank entries for $\delta^{13}C$ and $\delta^{34}S$ in this table. This is because there was insufficient collagen extract to carry out analyses. The letter B below refers to analyses for $\delta^{15}N$ carried out on bone powder, while the letter C refers to analyses on collagen extract. All $\delta^{13}C$ and $\delta^{34}S$ values were obtained from collagen extracts. The atomic C/N ratio was obtained for only three samples: AY57 3.7, AY58 3.8, AY59 3.3. DeNiro (1985: 808) suggests that these should be in the range of 2.9 to 3.6 to be sure there are no soil chemical diagenic effects. Two of the values obtained are just outside this suggested range, and this therefore raises a suspicion of diagenic change. Only three bone samples were large enough to extract collagen from. The sample weights and % yields of collagen for these were: AY57 37.0g, 3.62%; AY58 34.47g, 4.43%; AY59 34.42 g, 1.41%.

*1 For $\delta^{15}N$ values obtained from bone powder, it is necessary to make a small adjustment by subtracting 0.2‰ (Quinn 1990: 180).

*2 In this case there are two values from collagen extract and one from bone powder. Those obtained from collagen are preferred, and the final value listed is the mean of these two results.

*3 The first result obtained from bone powder of +5.766 seemed very unusual and was rejected in favour of a re-run.

*4 This is the second run on bone powder, which gave a more satisfactory result.

*5 This final value is the simple average of the two collagen extract results.

*6 A third run was made on this same sample using collagen extract, and this was used as the final result.

Accession	**Burial Number**	$\delta^{13}C$	$\delta^{15}N$	$\delta^{34}S$
AY56	Burial 01	-	+11.656 B	-
Final Value	-	-	**+11.46** *1	-
AY57	Burial 03	−18.25	+11.904 C	+11.50
	-	-	+12.436 C	-
	-	-	+12.852 B	-
Final Value		**−18.25**	**+12.17** *2	**+11.50**
AY58	Burial 04	−18.22	+5.766 B *3	+8.30
		−18.36	+10.275 B *4	-
	-	+10.840 C	-	
Final Value		**−18.29** *5	**+10.84** *6	**+8.30**
AY59	Burial 05	−17.61	+10.853 B	-
Final Value		**−17.61**	**+10.65** *1	-
AY60	Burial 06	-	+14.909 B	-
Final Value	-	**+14.71** *1	-	
AY61	Burial 07	-	+9.686 B	-
Final Value	-	**+9.49** *1	-	
Means		−18.05	+11.55	+9.90

TABLE 2
Assumptions used for Computer Simulation

Note: No filters were used to reject simulations inconsistent with archaeological findings, except that it was assumed that marine mammals did not contribute to the Watom diet to any significant degree (see text).

Target $\delta^{13}C$ and tolerance =	−18.05	2.0
Target $\delta^{15}N$ and tolerance =	+11.55	1.5
Target $\delta^{34}S$ and tolerance =	+9.90	1.5

	Random Generator of Food Proportions	
Food Type	Central Value	Margins
1 = C3 Plants	50.0	50.0
2 = C4 Plants	50.0	50.0
3 = Land Herbivores	50.0	50.0
4 = Marine Shellfish	50.0	50.0
5 = Coral Reef Fish	50.0	50.0
6 = Non-Reef Fish	50.0	50.0
7 = Marine Mammals	0.0	0.0

Lowest and highest acceptable energy levels (kcal)
1800
3700
Lowest and highest acceptable protein levels (mg)
25
200

	Isotope Value for Food			Offset Food to Collagen				
Food	$\delta^{13}C$	$\delta^{15}N$	$\delta^{34}S$	Protein	kcal	$\delta^{13}C$	$\delta^{15}N$	$\delta^{34}S$
1	−26.0	+5.8	+4.9	2.2	145.0	+5.0	+3.0	−0.5
2	−11.5	+10.0	+4.9	0.4	38.0	+5.0	+3.0	−0.5
3	−22.6	+5.4	+4.4	23.1	155.0	+5.0	+3.0	−0.5
4	−14.0	+7.2	+18.6	12.9	69.0	+5.0	+3.0	−0.9
5	−12.6	+7.9	+17.7	19.7	100.0	+5.0	+3.0	−0.9
6	−16.5	+14.0	+17.7	19.7	100.0	+5.0	+3.0	−0.9
7	−16.8	+15.7	+16.8	14.0	276.0	+5.0	+3.0	−0.9

In Table 3 the results of the simulation are given. The rate of successful simulations was fairly low (1 in more than 10,000), and the mean isotope values obtained are not as close to the experimental data as we would have liked. The two sets of data are compared below:

	Target Value		Simulated Value	
Isotope	Target	Tolerance	Mean	SD
$\delta^{13}C$	−18.05	2.0	−16.4	0.3
$\delta^{15}N$	+11.55	1.5	+10.9	0.5
$\delta^{34}S$	+9.90	1.5	+8.9	0.4

Although the results are a reasonable fit, the divergence for $\delta^{13}C$ is greater than we would have liked to achieve.

TABLE 3
Watom Diet Composition from Computer Simulation

Total number of simulations attempted	9,337,686
Number of successful simulations	928

Mean and SD of isotope values achieved in successful simulations

	Mean	SD
$\delta^{13}C$	−16.4	0.3
$\delta^{15}N$	+10.9	0.5
$\delta^{34}S$	+8.9	0.4

Mean and SD of energy and protein values achieved in successful simulations

	Mean	SD
kcal	2172.3	305.8
Protein g	173.8	19.3

Mean and SD of food weight percentage values achieved in successful simulations

	Mean	SD
1 = C3 Plants	50.6	6.7
2 = C4 Plants	2.7	2.1
3 = Land Herbivores	10.7	7.4
4 = Marine Shellfish	8.7	5.8
5 = Coral Reef Fish	6.0	4.9
6 = Non-Reef Fish	21.3	7.4
7 = Marine Mammals	0.0	0.0

Mean and SD of protein and energy contribution to diet from simulations

	Protein g		Energy kcal	
Food Type	Mean	SD	Mean	SD
1 = C3 Plants	19.74	5.11	1301.11	336.63
2 = C4 Plants	0.20	0.17	18.99	16.15
3 = Land Herbivores	40.34	25.27	270.71	169.56
4 = Marine Shellfish	20.26	14.92	108.36	79.83
5 = Coral Reef Fish	20.75	17.41	105.33	88.37
6 = Non-Reef Fish	72.46	24.53	367.80	124.49
7 = Marine Mammals	0.00	0.00	0.00	0.00

Figure 1 shows the histogram data for each of the food types. Although there are distinct signs of skewness, there are no obvious indications of binodality. Minagawa (1989: pers.comm.) has also found pronounced non-normality in his studies using this simulation technique.

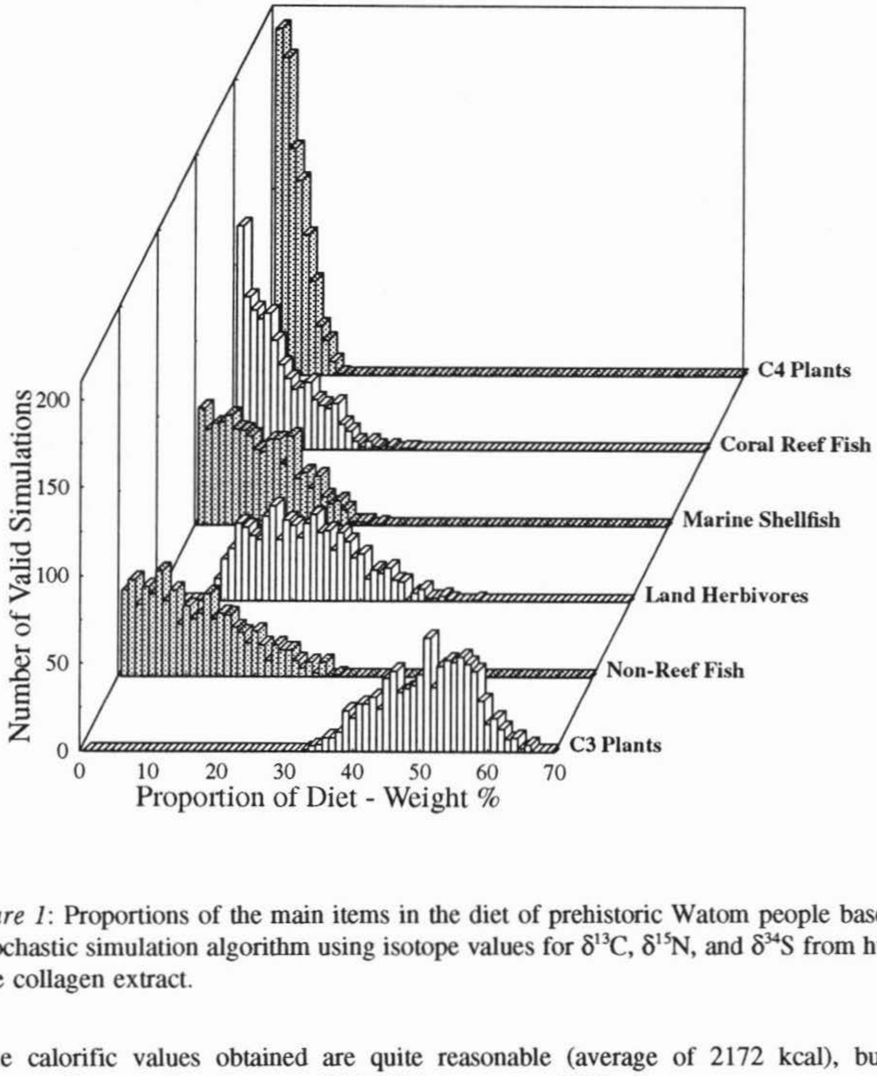

Figure 1: Proportions of the main items in the diet of prehistoric Watom people based on a stochastic simulation algorithm using isotope values for $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ from human bone collagen extract.

The calorific values obtained are quite reasonable (average of 2172 kcal), but the corresponding protein values are fairly high (average of 174 g).

The corresponding diet composition (Table 3) shows a strong dependence on land-based foods, with the total contribution from the marine environment being about 36% by weight.

C3 Plants	50.6	% by weight
C4 Plants	2.7	
Land Herbivores	10.7	
Marine Shellfish	8.7	
Coral Reef Fish	6.0	
Non-Reef Fish	21.3	

It is interesting that C4 plants appear to have contributed to this diet at Watom. One source is bound to have been sugar cane, *Saccharum officinarum*, which is a C4 plant, but this may not have been the only source of C4 food. The bulk could have been indirect, through eating browsing animals, such as wallabies or feral pigs which themselves ate C4 plants. There are several issues involved in this which warrant separate comment.

FRACTIONATION AND SECONDARY CONSUMPTION

It is important to note that the widely assumed value of 5‰ fractionation offset for $\delta^{13}C$ from plant foods to the flesh and collagen of a herbivore only applies at this first step in the food chain. If, for example, a human feeds entirely on the meat of wallaby, which feeds entirely on C4 plants (with $\delta^{13}C = -10.9$, which is our figure for *I. cylindrica*, see below), both the human and the wallaby will have $\delta^{13}C$ values in their flesh and collagen of −5.9. The effect of this is to make it somewhat difficult to distinguish between the source of food from different trophic levels. This is where multiple isotope signatures can be very helpful. It would be very useful to carry out isotope analysis of bones from modern day feral pigs in Papua New Guinea to see how much they relied on C4 plants. Our study of wallaby bones from Motupore gave a $\delta^{13}C$ value of −9.3. This is only 1.6‰ greater than the figure for *I. cylindrica*. This seems to show that the offset value of 5‰ is not uniform in the animal kingdom.

C4 PLANTS IN PAPUA NEW GUINEA

There are extensive grasslands in parts of Papua New Guinea dominated by *Saccharum spontaneum* (pit-pit) and *Imperata cylindrica* (sword grass or kunai) (Paijmans 1976: 55). Unfortunately, there is little data published on stable isotopes for this region, but at least some members of the *Imperata* genus are known to have C4 anatomical features (Schoch and Kramer 1971: 51; Cowling 1983: 123), and $\delta^{13}C$ values for unlocalised *Imperata cheesmanii* and *I. cylindrica* have been reported as −12.8 and −12.2 (Troughton and Card 1972). Our own analysis of *I. cylindrica* from Taurama Beach near Motupore Island in Papua New Guinea gave a value of −10.9. These values confirm the C4 character of these species. Kunai grass is encouraged by fire, and in some environments may be a fire-climax vegetation (Brookfield and Hart 1971: 53).

There are several members of the Saccharum genus in Papua New Guinea, which so far as we know are all C4 plants. *Saccharum officinarum* (sugar cane), *S. spontaneum* (pit-pit), *S. edule* (edible pit-pit, also called kunai by some people — see Waddell 1972: Appendix 5), and *S. robustum* (wild sugar cane, also called pit-pit, refer Mihalic 1971: 356).

Sugar cane is indigenous to Melanesia and is found in all gardens. It is propagated vegetatively (Barrau 1955: 60). It is a general item of diet, chewed between meals, and primarily used for thirst quenching. Edible pit-pit is a type of wild sugar cane with edible fruit resembling an unripe ear of maize. The stems of pit-pit are also used for light walls and fences. Waddell (1972) provides dietary data on these plants for the Raiapu people at Modopa in the Papua New Guinea highlands. Although the diet of a coastal island people such as the Lapita community at Watom was probably considerably different from that of the Raiapu, Waddell's figures are a useful starting point from which to assess the potential role of C4 foods from modern data. Waddell found that the average consumption per day (percent of total weight) was 4.87% for sugar cane and 0.75% for edible pit-pit (1972: 114). This gives a total direct consumption of C4 plants of 5.62%. Although these people kept pigs and engaged in some hunting (1972: 101), meat contributed very little to their diet. However, it is of interest that their domesticated pigs were largely fed on sweet potato, with

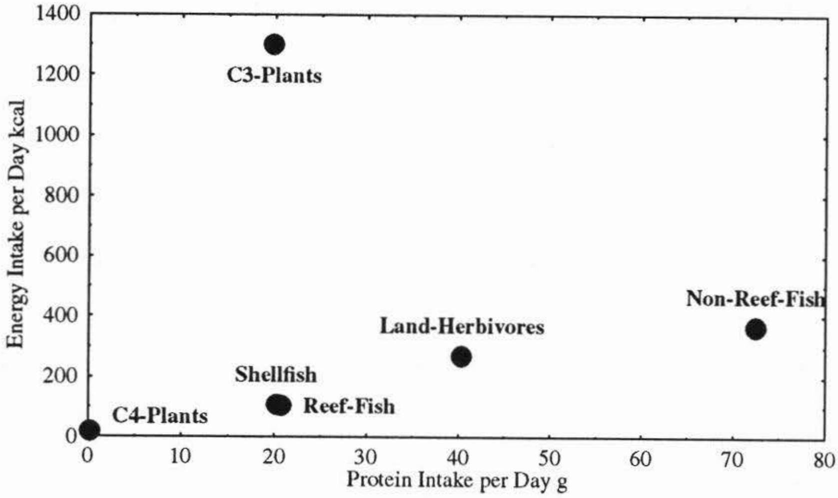

Figure 2: Daily energy and protein intake for the prehistoric Watom people based on a stochastic simulation algorithm using isotope values for $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ from human bone collagen extract. Note that the contributions from shellfish and reef fishes are indistinguishable (see text).

sugar cane contributing only 0.05% of their diet (1972: 119). Elsewhere he reports that sugar cane made up 7% by weight of the diet and meat and fish 1.5% (1972: 124). His figures show, on average, a daily intake of 2390 kcal and 32 g protein (1972: 126). On the whole, based on this data, it seems unlikely that C4 plants would have contributed more than 10% by weight from direct consumption of plants and domesticated pigs. The total value we obtained of 2.7% for Watom is perfectly reasonable, and may well have derived from both direct consumption of C4 plants as well as secondary consumption of wild browsing herbivores.

OTHER FOODS

Meat from other land herbivores (primarily living on C3 plants) such as birds, fruit bat and domestic pigs accounts for about 11% of the food consumed, so the total food from the land would have been about 64% overall.

The amount of marine foods consumed was about 36%, most of which appears to have come from non-reef fishes. There were smaller contributions from marine shellfish and coral reef fishes. It will be observed in Table 2 that the underlying assumptions do not permit these two latter sources of food to be distinguished (Figure 2). That is, the value of the three isotopes is very similar for these two food sources. This is where archaeological data from midden analysis can be used in the algorithm to differentiate between these two foods. Unfortunately, quantitative data is not available for Watom which would permit this.

The description of diet provided here has been in terms of relative weights of the different food types. The simulation software also provides information on the calorific and protein contributions for each of the food types. This information is listed in Table 3 and plotted out in Figure 2. This shows the importance of fish and land herbivores as the main sources of protein in this diet. On the other hand, it is the plant foods which contribute by far the most food energy.

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REFERENCES

Barrau, J. 1955. *Subsistence agriculture in Melanesia*. South Pacific Commission, Noumea.

Brookfield, H.C. and Hart, D. 1971. *Melanesia: a geographical interpretation of an island world*. Methuen, London.

Cowling, R.M. 1983. The occurrence of C3 and C4 grasses in fynbos and allied shrublands in the South Eastern Cape, South Africa. *Oecologia* 58: 121–27.

DeNiro, M.J. 1985. Postmortem preservation and alteration of in vivo bone collagen isotope ratios in relation to palaeodietary reconstruction. *Nature* 317: 806–809.

Green, R.C. and Anson, D. 1987. The Lapita site of Watom: New evidence from excavations in 1985. *Man and Culture in Oceania* 3 (Special Issue): 121–31.

Green, R.C. and Anson, D. 2000. Excavations at Kainapirina (SAC), Watom Island, Papua New Guinea. *New Zealand Journal of Archaeology* 20 (this volume).

Green, R.C., Anson, D. and Specht, J. 1989. The SAC burial ground, Watom Island, Papua New Guinea. *Records of the Australian Museum* 41: 215–21.

Keegan, W.F. and DeNiro, M.J. 1988. Stable carbon- and nitrogen- isotope ratios of bone collagen used to study coral-reef and terrestrial components of prehistoric Bahamian diet. *American Antiquity* 53 (2): 320–36.

Leach, B.F., Quinn, C.J. and Lyon, G.L. 1996. A stochastic approach to the reconstruction of prehistoric human diet in the Pacific from bone isotope signatures. *Tuhinga, Records of the Museum of New Zealand* 8: 1–54.

Mihalic, F. 1971. *The Jacaranda dictionary and grammar of Melanesian pidgin.* The Jacaranda Press.

Minagawa, M. 1989. Personal Communication. Mitsubishi-Kasei Institute of Life Sciences, Tokyo.

Minagawa, M. 1992. Reconstruction of human diet from $\delta^{13}C$ and $\delta^{15}N$ in contemporary Japanese hair: a stochastic method for estimating multi-source contribution by double isotope tracers. *Applied Geochemistry* 7 (2): 145–58.

Minagawa, M. and Akazawa, T. 1989. Dietary patterns of Japanese Jomon hunter-gatherers: stable nitrogen and carbon isotope analyses of human bones. Unpublished paper presented at Circum Pacific Prehistory Conference, Seattle.

Minagawa, M. and Akazawa, T. 1992. Dietary patterns of Japanese Jomon hunter-gatherers: stable nitrogen and carbon isotope analyses of human bones. *In* C.M. Aikens and S.N Ree (eds), *Pacific Northeast Asia in prehistory: Recent research into the emergence of hunter-fisher-gatherers, farmers, and sociopolitical elite*, pp. 59–67. University of Washington Press, Seattle.

Paijmans, K. 1976. Vegetation. pp 23 ff *In* K. Paijmans (ed.), *New Guinea Vegetation*, pp.23 ff. Australian National University Press, Canberra.

Quinn, C.J. 1990. Stable isotopes and diet: Indications of the marine and terrestrial component in the diets of prehistoric populations from New Zealand and the Pacific. Unpublished MA Thesis, Anthropology Department, University of Otago, Dunedin.

Schoch, E. and Kramer, D. 1971. Korrelation von merkmalen der C4- photosynthese bei vertretern verschiedener ordnungen der angiospermen. *Planta* 101: 51–66.

Specht, J. 1968. Preliminary report on excavations on Watom Island. *Journal of the Polynesian Society* 17 (2): 117–34.

Troughton, J.H. and Card, K.A. 1972. Carbon isotope fractionation by plants. Report 380, Physics and Engineering Laboratory, DSIR. 50pp.

Waddell, E. 1972. *The mound builders: Agricultural practices, environment, and society in the central highlands of New Guinea.* University of Washington Press, Seattle.

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