NEW ZEALAND JOURNAL OF ARCHAEOLOGY

The use of Multiple Isotope Signatures in Reconstructing Prehistoric Human Diet from Archaeological Bone from the Pacific and New Zealand

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ABSTRACT

The isotopes $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ were determined in a wide range of modern plants and the flesh of animals of relevance to prehistoric archaeological studies in the tropical Pacific and New Zealand. This was followed by similar analyses of collagen extract from both animal and human bones. Twenty-one human groups throughout the Pacific and New Zealand were examined, five from New Zealand in some detail. A stochastic simulation technique was used to estimate the relative dietary proportions of five basic groups of food: land plants, land animals, marine shellfish, marine fish, marine mammals. The contribution of both food weight and caloric energy from each of these foods is estimated in the diet of the communities examined. Finally, estimates are provided for the proportions of caloric energy deriving from protein, fat and carbohydrate in the diet.

Keywords: ARCHAEOLOGY, PREHISTORY, MULTIPLE ISOTOPE ANALYSIS, ^{13}C, ^{15}N, ^{34}S, DIET RECONSTRUCTION, OCEANIA, NEW ZEALAND.

INTRODUCTION

It has been known for many years that ^{13}C fractionates in nature, and that different species of plants and animals have different $\delta^{13}C$ values. Much of this knowledge until recently was generated in radiocarbon laboratories dating archaeological materials as well as carrying out routine background research relating to the radiocarbon method. Archaeologists also became familiar with the fact that if they used charcoal to date an archaeological site, the reported ^{14}C age would be accompanied by a $\delta^{13}C$ value of about -26 ‰. On the other hand, if it was a marine shell sample, the $\delta^{13}C$ value might be +1.0 ‰, and if it was human bone, it could be anywhere between -15 and -20 ‰. From this background in radiocarbon dating research emerged the idea that some aspects of the diet of an animal could be determined from the isotope values of its bones. In this regard, one of the first significant studies was by Vogel (1978), who showed that the dietary habits of ungulates were reflected in their isotope composition. In the same year, Van der Merwe and Vogel (1978) showed that aspects of

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the prehistoric diet of the Woodland people of North America could be revealed by $\delta^{13}C$ values in human bones, and in 1981 Bender *et al.* reported similar results relating to Hopewell agriculture. Although these initial studies were devoted to ^{13}C, it was not long before it was realised that ^{15}N was also a valuable isotope which could shed light on diet, and thus began the era of multiple isotope analysis (DeNiro and Epstein 1978, 1981).

From these small beginnings, the study of isotopes and diet has become almost a sub-discipline of archaeology, with numerous papers now published. Excellent reviews are by Sealy and Van der Merwe (1986), Schoeninger and Moore (1992), and DeNiro (1987). The underlying principle in this branch of archaeological science is that 'we are what we eat'; that is, if a human mainly consumes food from the marine ecosystem in preference to the terrestrial ecosystem, for example, then he/she will gain an isotope signature in their tissues which reflects this. This is because the isotopic character of organisms which live in the sea is different to that of the land. This differentiation is illustrated in Figure 1.

It can also be observed in Figure 1, that not only do these two great ecosystems have a different isotope character, but different plants and animals within each are also differentiated by their isotope values. These apparent complications may be a blessing in disguise, in the sense that they raise the possibility that more detailed interpretations might be possible from isotope values than simple proportions of marine and terrestrial components. Resolving more dietary details, however, requires more than two isotope signatures, and this is the reason why ^{34}S is added in this present paper.

In the region of the Pacific and New Zealand this field of research has been very slow to develop. One reason for this is probably the increasing difficulty in obtaining permission to examine human tissues from archaeological sites, either already in museums or when they are uncovered during archaeological excavation. Some preliminary research was carried out by the senior author in 1979 with analyses of $\delta^{13}C$ in collagen extract from dog bones from several dated provenances ranging from 2,500 BC to AD 1600 at the sites of Ban Chiang in Thailand and the Washpool site in New Zealand. Modern dog specimens were also included in this study. Although results ranged from -20 to -30‰, no obvious chronological or other pattern was observed. It is now suspected that incomplete acid digestion of samples might have obscured any meaningful patterns which were present, and this problem besets attempts to use the accumulated radiocarbon database relating to bones as a source of dietary data. This was followed by a more ambitious collaborative project in 1985 between two of the present authors (Leach and Lyon), who examined a large series of human remains from Nebira in Papua New Guinea and Taumako in the Solomon Islands (discussed in detail below), following excavations by Leach and Davidson in the Solomon Islands. The main reason for beginning this study was to try and quantify the role of plant foods in the economic system of Pacific Islanders over the last 3,500 years. At this time there was a suggestion, initially made by Groube (1971) after observing an apparent early emphasis on shellfish exploitation and coastal settlement in the Tongan islands, that the earliest explorers of these islands might have been 'oceanic strandloopers', living on marine resources, who expanded ahead of colonisation by agriculturalists. He proposed that the Lapita potters, initially at least, had a restricted maritime/lagoonal economy, and that either the development or introduction of a more viable horticultural economy enabled them to expand and survive in Fiji and Tonga and eventually colonise the remainder of the Pacific. Clark and Terrell (1978: 309–10) picked up the idea and incorporated it as one of four possible ways to model what they described as 'the Lapita problem'. The strandlooper model was questioned by Green (1979: 37, 1982: 13–14) and Kirch (1979: 297–298) on a number of grounds. This debate always seemed (to the senior author) to be a modern-day parody of

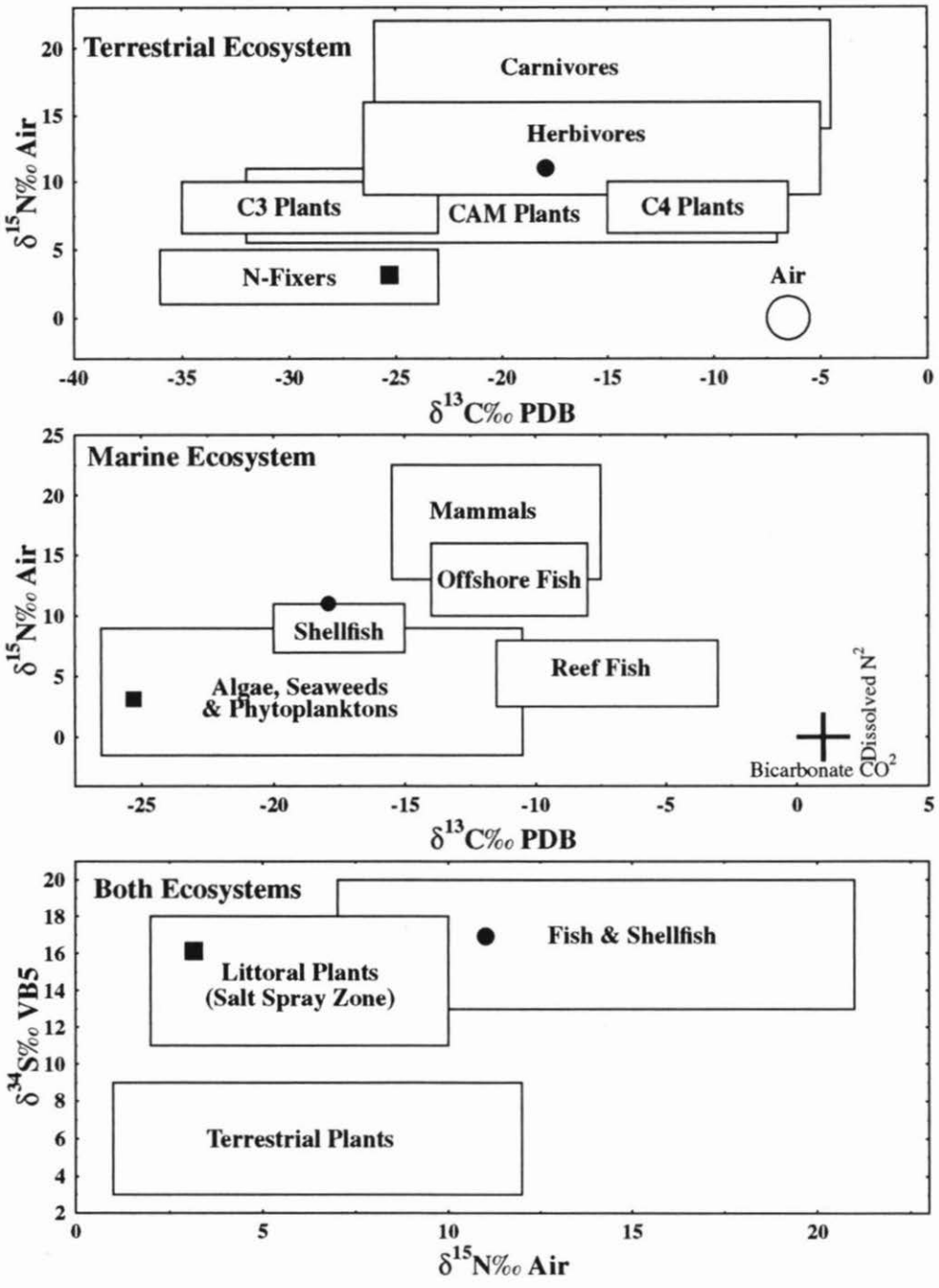

Figure 1: The range of isotope values for plants and animals (partly from de France *et al.* 1996: 299). The two black symbols indicate the standards used in the present study (filled circle = bone standard AY083, filled square = plant standard AA553). ^{13}C values are relative to the Peedee belemnite (PDB) standard reference carbonate.

Francis Bacon's exposition in 1592 on the number of teeth in a horse's mouth (Mees 1934). Aristotle had long since solved this riddle by direct observation in a horse's mouth. Similarly, the role of horticultural foods in the economy of ancient Pacific islanders is not able to be decided in a seminar room or by debating it in the pages of academic journals; like all other aspects of prehistoric reconstruction it requires direct archaeological evidence. The 'strandlooper hypothesis' could have been tested long ago using isotope analysis on human remains from Tonga and Fiji.

The main source of knowledge for economic prehistory is from the analysis of midden refuse, and although these sites are a rich source of quantitative information about the role of marine and terrestrial animals in human diet, for the Pacific and New Zealand, these sites are almost mute on the subject of plant foods (rare examples of carbonised kūmara [sweet potato] have been found). The main carbohydrate-rich plants which form the basis of horticulture in this region are root crops, such as taro, kūmara, and yam. These do not normally produce pollen, which is one of the best methods by which the beginnings of wheat and barley agriculture have been documented in other parts of the world. The obvious way of documenting the beginnings of, and the quantitative role of, plant foods in the Pacific region is by examining isotope values in human tissues from dated archaeological sites. This then is the reason why this present research project was first formulated — to develop a method by which the quantitative contribution of plant foods could be determined for Pacific and New Zealand archaeological communities.

Two separate events have greatly influenced the eventual direction and outcome of this research. The first was the publications by Peterson *et al.* (1985, 1986), which used the isotope ^{34}S, in addition to ^{13}C and ^{15}N, and thereby solved some important inherent weaknesses in the dual isotope approach. It will be seen below that our first attempts to use ^{34}S were dogged by technical difficulties, and this has greatly delayed publication. In the end the development of continuous flow mass spectrometry came to our aid. The second important event was in 1989 when the senior author was able to see at first hand the computer simulation technique which was developed by Minagawa in Japan. This is a highly significant step forward in modelling the relationship between isotope analysis and human diet, and has since been published (Minagawa 1992).

Although there have been a few archaeological outcomes of this research project already, some of which have a direct bearing on the issue of strandloopers (Quinn 1990; Leach *et al.* 1996, 2000; Davidson and Leach 2001; Pietrusewsky *et al.* 1998), no full treatment has been published of the methodology and accumulated database relating to these three isotopes in the Pacific region; this is the main purpose of this present paper. Only after a firm foundation has been laid down concerning methodology can we be confident that dietary reconstructions of prehistoric communities are a reasonable reflection of reality.

In selecting samples of prehistoric human bone for analysis, we are limited to what is available in the Pacific and New Zealand region, and what Museum curators and others will permit to be analysed destructively. Samples were not chosen with specific questions in mind relating to current archaeological issues. We collected samples from as wide a range as possible to cover both time and space and reflect various kinds of traditional economic systems. The contexts of the archaeological bone samples are described in Appendix 3. It is hoped that the accumulated database presented in Appendix 2, together with the methods developed here, can be used in future to help answer specific questions about prehistoric economics in the regions covered.

In what follows, considerable attention is first given to issues of methodology in order to identify, where possible, samples of human bone which may produce isotope results that are

liable to give misleading interpretations of prehistoric diet, and should be rejected. This is presented in four sections; first the method of pre-treatment of bone is considered; second amino acid composition is discussed, with special reference to analysis of sulphur isotopes; the third section is a description of the continuous flow mass spectrometry methods for $\delta^{34}S$; and the fourth discusses the use of standards and isotope integrity. The actual isotope results are then given in three separate sections, one for each isotope — $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$. These results are then incorporated into a stochastic model, designed to reconstruct prehistoric diet, using five human groups as test cases.

PRE-TREATMENT OF ARCHAEOLOGICAL BONE

Bone is a porous material and is easily contaminated by water-bearing salts and organics during hundreds or thousands of years in an archaeological site. To minimise physical contamination it is desirable wherever possible to use only lamellae or cortical bone which is dense and relatively impervious, and avoid cancellous or spongy bone. All bone samples were selected in this way and carefully cleaned with a soft brush, then further cleaned in an ultrasonic bath with deionised water, and then air dried at 35°C. Samples were ground to a fine powder in a tungsten carbide Temma mortar (a sample in a nest of sieves showed 60% was 100–75μ, 20% was 75–66μ, and 20% was <66μ), and kept in polycarbonate vials. Pellets were made of both bone powder and collagen extract[1] and wavelength dispersive XRF was carried out on them to test for contamination from the Temma mortar. No Lα was observed for W, and any contamination is less than 100 ppm.

Collagen extract was obtained from bone powder samples using 5% v/v phosphoric acid. This acid was used instead of the more common HCl extraction to minimise losses due to hydrolysis. As will be shown below, the amount of sulphur in archaeological samples of collagen extract is very low, and large samples of bone were necessary in order to obtain sufficient for analysis (*ca.* 50 g). In many cases it was very difficult to obtain adequate material for analysis, so it was desirable to obtain the maximum yield. It was found that acid digestion could take 3–5 days with coarse powder, whereas the fine powder obtained from the Temma mortar could be demineralised in less than one day. Extensive phosphoric acid treatment or any heating in the presence of acid (pH<4) also decreases the yield of protein. An average 30 g sample of bone powder required 1 litre of dilute acid. Foaming was reduced by using a magnetic stirrer. Successive use of fresh acid over a period of 3–5 days was sometimes necessary until CO_2 evolution finally ceased. The final solution was centrifuged at 4,000 rpm for 12 minutes, and then repeatedly washed and decanted with distilled water until pH above 3 was achieved, and then freeze dried to obtain the final collagen extract. The yield of collagen extract differs between archaeological sites, and possibly between individuals, reflecting differences in soil chemistry (Hedges and Wallace 1978). Our yields averaged 12% (range 0.64 to 30.6%). Yields less than 2% are potentially troublesome; in this study these are AX006 wallaby 0.64, AY787 Sigatoka 1.15, AY82 Lakeba 1.15, AY59 Watom 1.42 and AA725 Natunuku 1.71.

[1]The term 'collagen extract' is used throughout this paper to refer to the residue obtained following acid digestion of bone powder, in recognition that it is not pure collagen.

Two tests were carried out to check on the nature of the collagen extract. Firstly during the development of the acid digestion procedure, samples were subjected to analysis with an X-ray diffractometer to check for completeness of the digestion. A typical bone sample was first tested, and although no calcite was detected, an intense peak of aragonite at 3.39 Å occurred behind one of the more intense hydroxyapatite peaks. Twin peaks were also observed at $2\theta=22.5°$ and $2\theta=26.25°$. These are due to the presence of quartz in the sample. A collagen extract was then tested at greater intensity (4,000 cps). This showed that some quartz was still present, but no peaks for calcium carbonate, aragonite or hydroxyapatite were observed. Thus, the digestion process is judged to be very successful.

The second test was to establish the amount of collagen present in the collagen extract from archaeological bones. It was shown by Rawle (1980: 19) that there is 12.8% hydroxyproline in typical mammalian collagen, and this figure was used as a measure of purity. Several archaeological samples of collagen extract were tested for hydroxyproline, giving a mean value for collagen of 63%. Hedges and Wallace report a range of 80–90% as the proportion of collagen in the organic component of bone without specifying details of how this was arrived at (Hedges and Wallace 1978: 379). Dennison (1986a: 78) comments that "about half of the non-collagen organic component remains unidentified even in the most general terms", citing Leaver *et al.* (1975). Although it is not known what the unidentified portion of the collagen extract is, it probably consists of non-collagenous proteins and bone proteoglycans (Myers pers. comm. 1988), which would not be removed by the extraction process. The proportions of such compounds can be expected to vary from sample to sample, as they are less stable than collagen and tend to be broken down and lost more readily (Hedges and Wallace 1978: 384). The rate at which these organic components of bone are broken down may be a function of several factors, including environment, length of deposition and the species from which the bone originates (Hare 1980: 217). Bone proteoglycans contain a high percentage of sulphate groups, and for a given sample are presumed to have the same isotopic ratios of sulphur as would be found in the collagen (Myers pers. comm. 1988), although this needs to be confirmed. The collagen extracts generally require no further pre-treatment before isotope ratio mass spectrometry. In the case of ^{34}S, early analyses did require additional treatment, described below.

AMINO ACID COMPOSITION OF ARCHAEOLOGICAL BONE

Only three amino acids contain sulphur in their molecules — cysteine, cystine and methionine. Cysteine is not present in the collagen of higher vertebrates (Brown 1979: 365), and cystine (the oxidised form of cysteine) and methionine contain 26.7% and 21.5% by weight of sulphur respectively. The amount of these amino acids in degraded archaeological collagen extracts can be expected to vary. Modern collagen has about 0.1% cystine and 0.9% methionine (Oser 1965: 132). Thus 1 g of collagen should contain about 0.267 mg of sulphur from cystine and about 1.935 mg of sulphur from methionine; that is, a total of about 2.202 mg, or 0.22% by weight in collagen. The hydroxyproline tests described above showed that our collagen extracts have about 63% collagen, so we should expect about 1.4 mg/g of sulphur in our collagen extract samples. We obtained a mean yield of 1.5 ± 0.2 mg/g from our test runs, suggesting that we had a satisfactory procedure.

It must be remembered that amino acids are not the only component of collagen; this accounts for 72.4% of the organic content, the balance being 4.1% chondromucoprotein, 2.4% sialoprotein, and 24.6% non-dialysable organic matter (Myers pers. comm. 1988).

Analysis of amino acids in collagen extracts is a useful additional way of checking on the possibility of diagenic change over archaeological time which may cast suspicion on the integrity of the original isotope signature. For this reason, if diagenic change is an issue, it is useful to carry out amino acid analysis on collagen extracts. Figure 2 illustrates a typical amino acid profile for the collagen extract from a piece of human femur (AI094) from the site of Tina in New Caledonia. It can be observed that methionine is in the shoulder of the larger peak of valine, and difficult to resolve separately. For this reason, sometimes the area of the combined peak is partitioned in the ratio of 0.79 to 0.21 (valine to methionine) in order to estimate the abundance of the two amino acids relative to others.

Three amino acids stand out in all amino acid profiles of archaeological collagen extracts — they are glycine at about 33 mole %, proline at about 13 mole %, and hydroxyproline at about 7 mole %. In a series of papers on amino acids in archaeological bones of humans in the Pacific and New Zealand, Dennison found significant changes in the relative abundances of different amino acids. These came from a wide variety of populations with different pathologies, diet, and environment, and he concludes "These environmental and skeletal differences are accompanied by significant differences between the groups in the amino acid content of the bones" (Dennison 1986a: 77). In a subsequent paper he points out that although burial environment might be a factor in such changes, his earlier research (Dennison 1980) showed that "degradation of collagen and loss of its component amino acids is linear, and that there is not preferential retention of specific amino acids" (Dennison 1986b: 399). These somewhat contradictory findings suggest that we need to keep a close eye on the relative abundance of amino acids in archaeological samples.

Dennison's research was carried out on undigested human bone samples of 31 individuals from a wide range of localities in New Zealand and the Pacific, and given the additional degree of dilution that this is accompanied by, it is perhaps not surprising that 16% of his

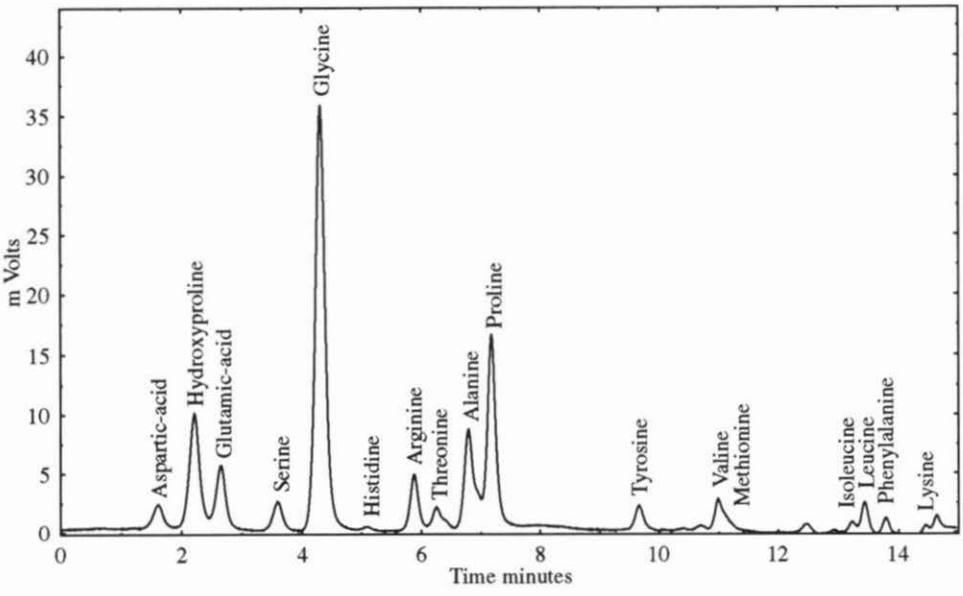

Figure 2: Amino acid profile of collagen extract from a sample of human femur from Tina in New Caledonia (Sample AI094). Note that the sulphur-bearing methionine is a small area on the shoulder of the valine peak.

values are reported with zero residues. We are able to compare Dennison's results with four additional samples of collagen extracts from archaeological sites in New Caledonia. The results are presented in Table 1 and Figure 3.

TABLE 1

Average values of amino acids in archaeological human bone specimens from the Pacific Islands and New Zealand, comparing collagen extracts (N=4, our data) with whole bone samples (N variable to 29, Dennison data)

		Collagen Extract				Bone Powder			
Amino Acid	Symbol	Mean		SD		Mean		SD	
Aspartic	D	44.5 ±	6.3	12.7 ±	4.4	69.4 ±	0.6	3.3 ±	0.4
Hydroxyproline	H	71.5 ±	1.4	2.9 ±	1.0	73.6 ±	1.6	7.1 ±	1.1
Glutamic	E	80.5 ±	5.1	10.3 ±	3.6	100.9 ±	1.1	5.7 ±	0.8
Serine	S	28.9 ±	1.0	2.1 ±	0.7	41.9 ±	0.8	4.8 ±	0.6
Glycine	G	359.2 ±	14.8	29.7 ±	10.5	348.4 ±	14.2	47.3 ±	10.0
Histidine	H	5.2 ±	0.5	1.0 ±	0.3	- -	-	- -	-
Arginine	R	48.1 ±	1.9	3.8 ±	1.3	80.9 ±	4.8	26.0 ±	3.4
Threonine	T	17.1 ±	0.3	0.6 ±	0.2	22.6 ±	0.3	1.8 ±	0.2
Alanine	A	95.7 ±	5.2	10.4 ±	3.7	126.1 ±	2.7	12.2 ±	1.9
Proline	P	132.8 ±	6.8	13.6 ±	4.8	143.7 ±	2.4	13.0 ±	1.7
Tyrosine	Y	9.3 ±	3.7	7.5 ±	2.6	5.1 ±	0.3	1.4 ±	0.2
Valine	V	28.7 ±	0.3	0.7 ±	0.2	34.3 ±	0.3	1.9 ±	0.2
Methionine	M	7.6 ±	0.0	0.1 ±	0.0	7.1 ±	0.2	1.2 ±	0.1
Isoleucine	I	10.4 ±	0.9	1.8 ±	0.6	14.6 ±	0.1	0.9 ±	0.1
Leucine	L	23.3 ±	0.7	1.4 ±	0.5	36.4 ±	0.2	1.6 ±	0.2
Phenylalanine	F	13.6 ±	0.8	1.6 ±	0.5	18.1 ±	0.3	1.9 ±	0.2
Lysine	K	22.9 ±	4.2	8.4 ±	2.9	36.3 ±	0.6	3.4 ±	0.4

The Z-scores of these data (Z = X - Xbar/SD) are especially interesting. These are plotted out in Figure 4, where it is evident that there is far greater variability in the bone powder determinations than in those obtained using collagen extract. Although it is very time consuming preparing the collagen extracts, the results are more consistent.

MASS SPECTROMETRY METHODS: $\delta^{34}S$

Analyses of samples were carried out at a number of different laboratories over a period of more than 20 years and some methods developed and improved in that time. The laboratories are listed in Appendix 2 where all data are reported. The analysis of both ^{13}C and ^{15}N have been standard procedures in numerous analytical mass spectrometry laboratories for many years, and only a few details will be provided. The analysis of ^{34}S is relatively new and rapidly changing so we will describe the procedures followed in more detail.

For analysis of ^{13}C, about 5 mg of sample was oxidised in a sealed quartz tube at 900°C using CuO powder and Ag wire for oxidation and removal of contaminants. The resulting CO_2 was purified and analysed. At INS this was made in a NAA 6-60 mass spectrometer

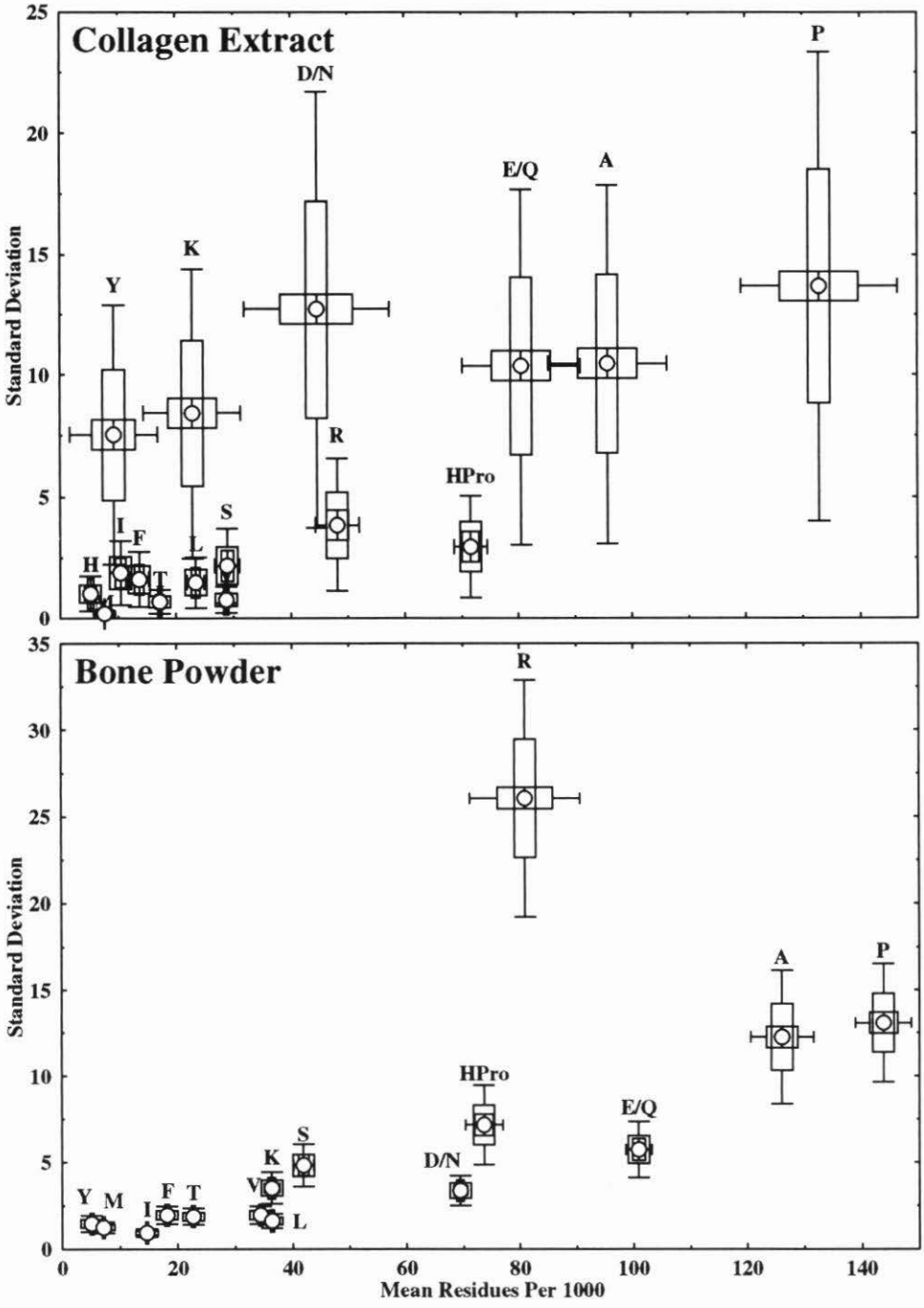

Figure 3: Mean and standard deviations of amino acids in archaeological human bone samples from the Pacific and New Zealand, comparing the results from bone powder with collagen extract. The larger SD for the collagen extract is due to the smaller number of samples (N=4, See Table 1).

with triple collector (Hirner and Lyon 1989). Some other laboratories used continuous flow analysis. All analyses for ^{15}N were carried out by standard continuous flow methods. Early analyses for ^{34}S at INS required the sample to be purified by concentration to a sulphur-rich form. Each collagen extract was combusted in a Parr bomb to produce sulphur dioxide which was absorbed into distilled water in the bomb, forming sulphuric acid. The liquid was then treated with $BaCl_2$ to precipitate $BaSO_4$ (Hirner and Robinson 1989). Each sample of *ca.* 1 g of dry collagen extract was compressed into a pellet. After weighing, the pellet was placed in the Parr bomb with 1 ml of distilled water. The bomb was filled with oxygen to 25 atmospheres and ignited. After 15 minutes the pressure was released and all components were thoroughly washed out with distilled water into a container, and 0.6 ml of 6N HCl was added for every 200 ml of bomb washings. After 1–4 days the bomb digests were processed to produce $BaSO_4$. Each bomb digest was transferred to a 400 ml beaker and warmed to *ca.* 70°C. A solution of 5% $BaCl_2$ was added until the liquid became cloudy. The precipitate was allowed to settle and a further 3–4 ml of $BaCl_2$ was added. The samples were evaporated under modest heat until reduced to 5–10 ml, and then stored for analysis by mass spectrometry. At INS, these samples were then converted to Ag_2S (Rafter 1967). Some samples were reacted with Kiba reagent directly to Ag_2S (van der Raaij *et al.* 1992). The Ag_2S was analysed on a Micromass 1202 mass spectrometer (Robinson and Kusakabe 1975). Later analyses were carried out by continuous flow methods at MIM, as this method required much less sample.

The technique of interfacing an elemental analyser (EA) to an isotope ratio mass spectrometer (IRMS) in continuous flow (CF) mode has since 1983 (Preston and Owens

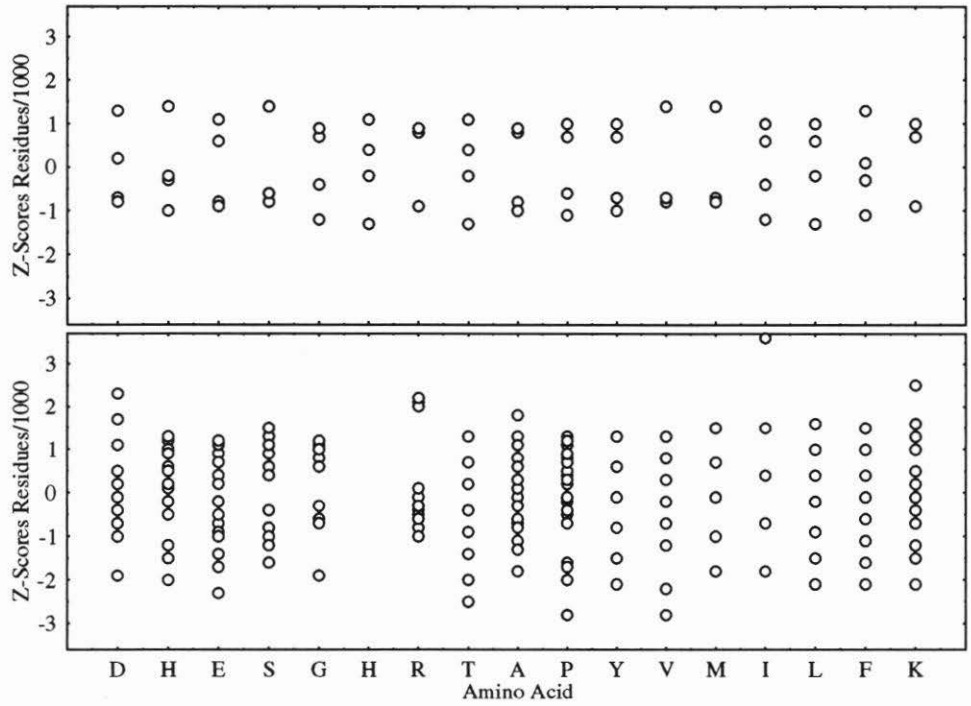

Figure 4: Z-scores for amino acids in archaeological human bones; upper = collagen extract, lower = bone powder. Note that the variation is less for collagen extract.

1983) proved highly successful in the study of nitrogen and carbon isotopes in application areas such as soil science and environmental science. The application of the technique to the measurement of sulphur isotopes is, however, only now beginning to become an established method capable of addressing both high S concentration inorganic samples and low S concentration high C:S ratio organic samples (Giesemann *et al.* 1994).

A Carlo Erba NA1500 elemental analyser configured to run sulphur is interfaced in CF mode to a Micromass Optima IRMS. The mass spectrometer is set up to monitor m/z 64 and m/z 66 simultaneously. Using a microbalance, samples are weighed into high purity tin capsules and then loaded on to the elemental analyser sample carousel. On commencement of the automatic analysis, samples are sequentially dropped into the combustion region of the elemental analyser at a temperature of 1030°C. Flash combustion of the sample in the presence of oxygen at a temperature of 1800°C is followed by a copper reduction stage at 800°C which ensures conversion of any SO_3 formed to SO_2. Water of combustion is removed by a magnesium perchlorate trap. The remaining combustion products N_2, CO_2, and SO_2 contained in a helium stream (100 ml per min) are then spatially separated by passing through a packed GC column (Poropack Q 80 cm). A portion of the effluent stream is continually sampled by the mass spectrometer ion source in an open split configuration. On arrival of the SO_2 peak the resultant m/z 66 and m/z 64 ion beams are integrated and compared to an independently introduced SO_2 reference pulse. In order to prevent the arrival of the large CO_2/N_2 pulse interfering with the introduction of the reference pulse, a Micromass diluter is used to reduce the amount of CO_2/N_2 entering the ion source by a factor of around 5000. The complete cycle time for an individual analysis is 6 minutes.

The samples analysed here all contain extremely high C:S ratios and sulphur concentrations from 0.2% to 0.02%. The C:S ratio of the latter is around 2500:1 and represents the extreme limits of the technique as described. The main problem associated with such a sample is that the amount of carbon combusted can be so great as to lead to incomplete combustion or poor separation of the SO_2. In order to minimise these effects the mass spectrometer sensitivity is increased in order to measure smaller quantities of S, so reducing the sample weight and the amount of carbon combusted. To this end a target S content of 10 μg and a maximum sample weight of around 6 mg are aimed at. In extreme cases samples containing as little as 2 μg S are measured in order to restrict the sample weight to no more than about 10–12 mg.

In the absence of any generally available organic isotope standard at these levels it was decided to use 2 out of a set of 6 pine needle samples previously measured classically for both $\delta^{34}S$ and %S and distributed by Dr H.R. Krouse of the University of Calgary as part of a previous study in validating the technique of CF Sulphur (Morrison 1996). These were:

> VB5 17.8 permil cdt and 0.65 %S used both as an isotopic and elemental standard.
> VB35 8.4 permil cdt and 0.55 %S used as an isotopic standard.

Previous analysis of these standards suggests that the elemental composition is in error for both (the value for VB5 is 30% greater than the reported value). As such, the reported values for the elemental concentration for the samples are underestimated by the same factor.

When samples containing very low quantities of sulphur were measured, the results were checked against a measurement of the standard containing an equally low quantity of sulphur. This is not an ideal safeguard since the standard and sample had widely different C:S ratios and conceivably could combust differently in the EA. However previous results

which do make a similar comparison indicate that this is not the case (Morrison 1996).

The values generated by the mass spectrometer are raw δ 66/64 values with a reference gas value of zero stipulated. The value reported must allow for the ^{18}O contribution to mass 66. The reference gas value is obtained by multiplying the raw 66 δ of the standard by 1.09 (oxygen correction) and subtracting from the quoted standard value. Final values reported for samples = (raw δ x 1.09 + ref gas value) cdt. (canyon diablo troilite).

Occasionally there is a drift correction to a linear change in raw delta associated with changes in the combustion/reduction conditions of the EA. The magnitude of this drift is small, ~0.5% over 90 samples, and when it occurs can be corrected easily.

Samples generally were run in duplicate. Because of the ability to add samples as the autorun proceeded it was possible to add checks in cases where results showed anomalies. Where possible each batch contained samples analysed from a previous batch to check consistency of analysis.

BONE AND PLANT STANDARDS AND TESTS OF ISOTOPE INTEGRITY

In addition to the use of normal laboratory standards mentioned above, it was considered desirable to develop two standards of more direct relevance to archaeological studies. It was envisaged that these would also be of value as 'blind-tests' when sending valuable archaeological samples to various analytical laboratories to check on results from those laboratories, by interleaving specimens with one of these standards. It was decided to develop two — a bone standard and a plant standard.

The bone standard was prepared from quantities of human bone from the Namu excavation in the Solomon Islands. These bones could not be provenanced to a specific burial during the excavation. Approximately 1.4 kg of bone from square H6 was cleaned in deionized water, dried at 35°C, and ground in a tungsten carbide Temma mortar. The bone powder was put through a random sample splitter and each portion sealed in a polycarbonate tub, labelled with its catalogue number (AY83) and portion number. Collagen extract is prepared as and when required using one tub at a time. Nine tubs of bone powder still remain, weighing an average of 29 g each.

The plant standard was prepared from freeze-dried taro (*Colocasia esculenta*) which was ground to a fine powder in a tungsten carbide Temma mortar. The powder was put through a random sample splitter and each of 128 portions sealed in a polycarbonate tub, labelled with its catalogue number (AA553) and portion number. One hundred and fifteen tubs still remain, weighing an average of 12 g each.

As will be seen later, some experiments were carried out to see whether reliable results for ^{15}N could be obtained from bone powder as well as from collagen extracts. Percent nitrogen was therefore assessed from duplicate 1 mg samples of each. The results ±3% were: 13.18 and 13.09 (collagen extract), and 0.95 and 1.26 (bone powder). The bone powder samples were boiled in distilled water to remove soluble nitrates before any analysis.

To provide a baseline for assessing possible diagenic changes in bones, the atomic C/N ratio and elemental weight % were measured in a series of independent runs of the standard collagen extract over a period of time. These details are provided in Table 2, together with similar data for the plant standard.

TABLE 2

Elemental weight % values and isotope results for the bone standard (AY83, collagen extract) and the plant standard (AA553) during various runs of archaeological samples. WAI-P refers to analyses made on bone powder, and WAI-C to collagen extract. Some plant standard ^{34}S data is published by Van der Raaij *et al.* (1992). See Appendix 2 for abbreviations (AIT, WAI, INS, MIM).

	Bone Standard	**Plant Standard**	**Bone Standard**		
	% S	**% S**	**% C**	**% N**	**C/N**
	0.31 MIM	0.020 MIM	41.34 WAI	12.67 WAI	3.81 WAI
	0.26 MIM	0.042 INS	40.40 WAI	12.34 WAI	3.82 WAI
	0.26 MIM	0.043 INS	41.13 WAI	12.72 WAI	3.77 WAI
	0.26 MIM	0.041 INS	41.47 WAI	13.16 WAI	3.68 WAI
	0.27 MIM	0.037 INS	40.09 WAI	12.50 WAI	3.74 WAI
	-	0.029 INS	39.53 WAI	12.65 WAI	3.65 WAI
	-	0.028 INS	40.12 WAI	12.59 WAI	3.72 WAI
	-	0.030 INS	40.54 WAI	12.69 WAI	3.73 WAI
	-	0.034 INS	-	-	-
	-	0.036 INS	-	-	-
	-	0.035 INS	-	-	-
	-	0.039 INS	-	-	-
	-	0.037 INS	-	-	-
	-	0.034 INS	-	-	-
Mean	**0.28**	**0.035**	**40.58**	**12.67**	**3.74**

	Bone Standard			**Plant Standard**		
	$\delta^{13}C$	$\delta^{15}N$	$\delta^{34}S$	$\delta^{13}C$	$\delta^{15}N$	$\delta^{34}S$
	-17.55 WAI	10.55 WAI-P	16.00 INS	-25.28 INS	2.05 WAI	16.10 AIT
	-17.57 WAI	10.60 WAI-P	16.78 MIM	-24.99 WAI	4.26 WAI	16.40 AIT
	-17.76 WAI	11.05 WAI-P	16.60 MIM	-25.12 WAI	4.11 WAI	16.70 AIT
	-17.85 WAI	11.65 WAI-P	18.27 MIM	-25.62 INS	4.15 WAI	17.10 AIT
	-17.96 INS	11.70 WAI-P	17.01 MIM	-25.64 INS	4.15 WAI	17.50 AIT
	-17.98 WAI	12.75 WAI-P	-	-25.09 WAI	4.22 WAI	16.70 INS
	-18.05 WAI	10.67 WAI-C	-	-25.50 WAI	4.66 WAI	15.00 INS
	-18.25 WAI	10.82 WAI-C	-	-25.42 WAI	4.84 WAI	15.90 INS
	-18.28 WAI	11.57 WAI-C	-	-25.40 WAI	4.14 WAI	16.10 INS
	-	11.75 WAI-C	-	-25.52 WAI	3.58 WAI	14.60 INS
	-	10.70 WAI-C	-	-25.51 WAI	4.30 WAI	15.00 INS
	-	10.89 WAI-C	-	-25.46 WAI	3.59 WAI	15.80 INS
	-	10.51 WAI-C	-	-25.46 WAI	-	16.60 INS
	-	11.00 WAI-C	-	-25.39 WAI	-	15.80 INS
	-	10.60 WAI-C	-	-25.43 WAI	-	16.00 INS
	-	10.51 WAI-C	-	-25.44 WAI	-	15.70 INS
	-	10.53 WAI-C	-	-	-	16.20 INS
	-	10.49 WAI-C	-	-	-	15.80 INS
	-	-	-	-	-	17.60 MIM
Mean	**-17.92**	**11.02**	**16.93**	**-25.39**	**4.00**	**16.14**

DeNiro (1986: 808) suggests that the acceptable range for the C/N atomic ratio is between 2.9 and 3.6, and these values are clearly on the upper side of this suggested range. There has been considerable published discussion on the issue of C/N ratios in bone collagen extract since DeNiro published this seminal work, and not all researchers discard isotope values when the C/N ratio is outside this suggested range. Ambrose and Norr (1992: 403) suggest that modern collagen has about 43% carbon and 16% nitrogen, and should have a C/N value of about 3.2 (Ambrose 1992). Our amino acid analyses of laboratory standard collagen provide values of about 41% carbon and 15% nitrogen, and atomic C/N ratios of about 2.8. Ambrose and Norr conclude that three criteria can be used for testing the reliability of collagen extracts for diet reconstruction: the atomic C/N ratio, the percent collagen yield, and the weight percent of carbon and nitrogen. Of the latter they comment "Carbon and nitrogen concentrations in 'collagen', expressed as weight % C and N, provide the most unambiguous though least widely used simple criterion for determining whether a sample contains usable organic matter" (Ambrose and Norr 1992: 403). They suggest that values dropping below 6.6% and 1.9% respectively are probably not usable. Moreover, they also make the useful observation that "a reduction of nitrogen indicates loss of total protein (including the carbon), and correspondingly, high C:N ratios indicate contamination from carbon-rich, nitrogen-poor sources, such as soil humic acids and/or lipids. In other words, if there is no nitrogen there is no protein" (ibid: 402). Thus, a low nitrogen yield combined with an aberrant C/N ratio is a good indication that the $\delta^{13}C$ and $\delta^{15}N$ may not be a useful reflection of the original diet.

A similar suggestion can be offered in the case of $\delta^{34}S$. Collagen extract from the bone standard has a mean yield of sulphur of 0.28 weight %. This is somewhat higher than the sulphur yield from results of amino acid analysis for the laboratory standard collagen of 0.16%. Any examples of elevated sulphur yield in archaeological bones may indicate contamination from soil. This is further discussed below in the section under ^{34}S results.

It can be seen in Table 2 that the range of results for C/N ratio was 0.17, which represents 4.5% of the mean value. The $\delta^{13}C$ range is similar at (0.73‰ = 4.1%), but both the $\delta^{15}N$ (2.26‰ = 20.5%) and $\delta^{34}S$ (2.3‰ = 13.4%) ranges are rather higher. On the whole, the use of these standards as blind tests proved very satisfactory in monitoring the true range of results we can expect in using different laboratories and runs. In cases where results for these blind standards appeared rather too high or too low, duplicate runs were made.

The various yield values for the archaeological bone collagen extracts in the present study are plotted out in Figure 5.

There is one archaeological sample not depicted in these graphs, because of its exceptionally high C/N ratio, off scale on the graphs. All other archaeological specimens listed in Appendix 1 and 2 (total=57) are present[2]. The exception is specimen AA725 from Natunuku in Fiji. This had an acceptable carbon yield (35.4%), but very low nitrogen (2.38%) providing an atomic C/N ratio of 17.35. This is just the kind of specimen which Ambrose warns against — very low nitrogen yield, meaning very low protein present. Most of the carbon must be from some contaminating source. It may be recalled from the foregoing that this specimen was identified as having a very low yield of collagen (1.71%). Despite these strong reservations, the isotope values seem perfectly reasonable ($\delta^{13}C$ -14.63, $\delta^{15}N$ 7.41, $\delta^{34}S$ 13.10).

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[2] In the text of this paper common names are used for organisms wherever possible. Their equivalent systematic names are provided in Appendix 1.

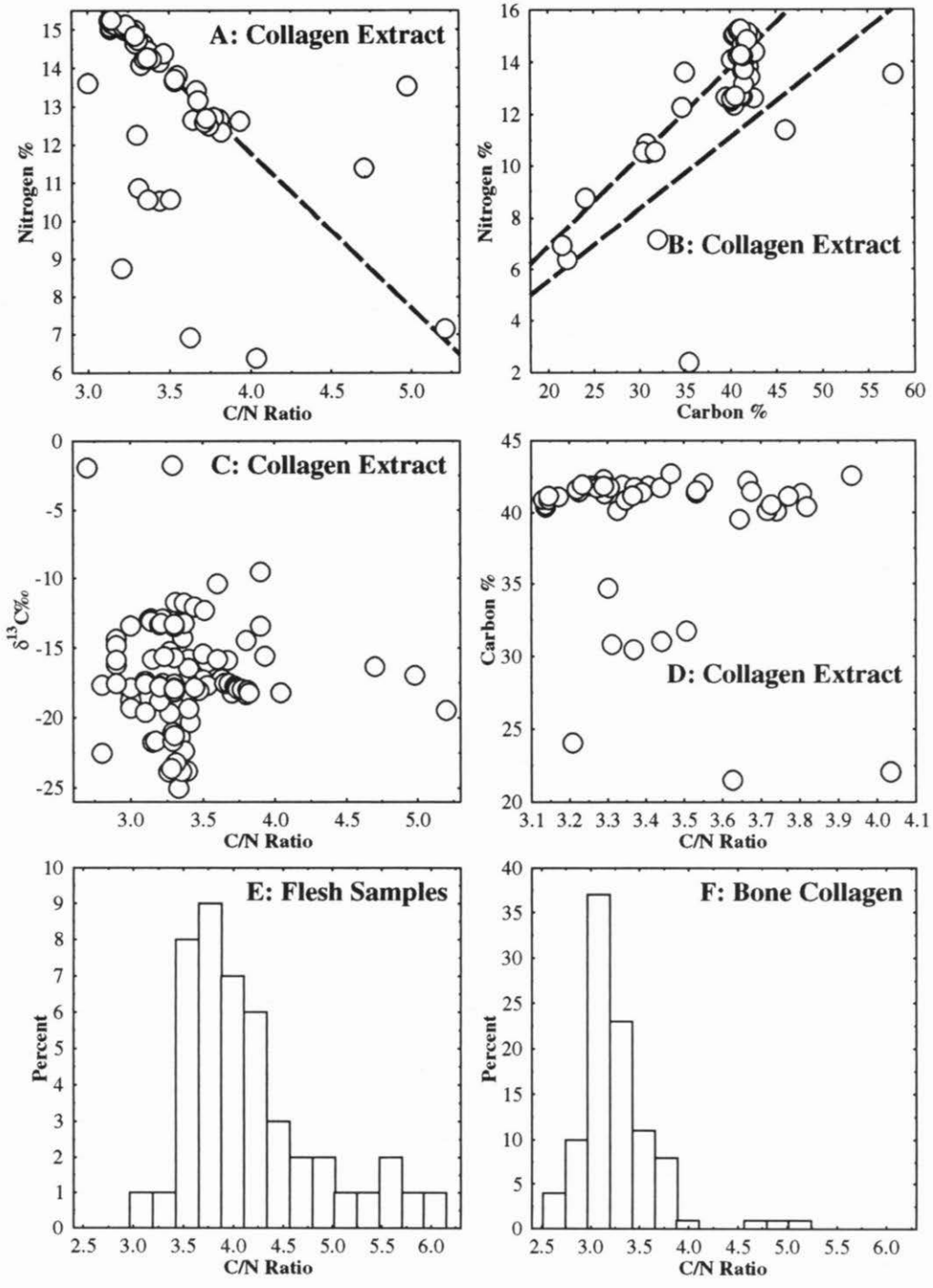

Figure 5: Various methods of detecting archaeological specimens which may produce isotope results unreliable for diet reconstruction (see text). In this study, 13 specimens are considered potentially unreliable. Only the method illustrated in graph A clearly identifies all these specimens.

It is evident in Figure 5F that the C/N ratios of the collagen extracts form a tight normal distribution, with a few outliers. The mean C/N ratio is 3.53 ± 0.15, with a standard deviation of 1.47 ± 0.11. The C/N ratios for the flesh samples in the modern comparative collection give a distinctly non-normal distribution with a mean of 4.70 ± 0.24 and a standard deviation of 1.70 ± 0.17 (Figure 5E).

In Figure 5C the C/N ratio is plotted against $\delta^{13}C$, and this shows a tight clustering, with a few outliers. The two very heavy $\delta^{13}C$ values plotted at the top of the figure have reasonable C/N ratios and are values for dugong (discussed later). There are three other outliers on this plot, on the right hand side, with C/N values >4.5. These are AY785B from Lakeba in Fiji (burnt bone specimen), AY787 from Sigatoka in Fiji, and AY069 from Namu in the Solomon Islands. Once again, these do not seem to have especially notable isotope results, but they will be flagged in future discussion.

Turning now to Figure 5D, where the C/N ratio is plotted against the carbon % by weight in collagen extract, it can be seen that there is a tight cluster around the 40% value. This accords well with the expected values mentioned above of 41–43%. There are nine outliers to the main cluster on this plot, with values less than 36% (including Natunuku AA725, which is off the right hand side of the plot with a C/N ratio of 17.35). These are: a moa specimen (AA507), one of the burials at Watom (AY058), one from Nebira (AX994), one from Motupore (AY499), and four runs on an individual from Site WKO-013B in New Caledonia (AA727). All these results are flagged in discussion below.

In Figure 5B the specimens are plotted using the percent yields of carbon and nitrogen. The two dashed lines represent the 2.9 and 3.6 boundaries in the C/N ratio suggested by DeNiro, discussed above. Although several specimens plot just outside the edges of the boundary, only five clearly fall outside it. These are individuals from Namu (AY069), Natunuku (AA725), Sigatoka (AY787), and Lakeba (AY785, AY785B). For most specimens on this graph, the loss of nitrogen and carbon co-vary. This is reflected in the correlation coefficient for these data r = 0.69 ± 0.07 (t = 7.0 with 53 df).

In Figure 5A the C/N ratio is plotted against the % nitrogen yield. Specimens should plot in a straight line, assuming that the rate of loss of carbon and nitrogen during decay is a process which uniformly affects all amino acids. Thirteen of the 57 specimens do not conform to this straight line relationship. After rejecting these 13 the correlation coefficient r = -0.97 ± 0.01 (t = 25.9 with 40 df). The linear y on x regression equation is Nitrogen % = -4.09 x C/N Ratio + 28.14 ± 0.22. The 13 specimens which depart from this regression line have all been mentioned above; but this test is the only one which has clearly indicated the full complement of suspicious samples. Recalling Ambrose and Norr's comment above that loss of nitrogen means loss of protein, we suggest that examples of departure from this y on x equation may be an excellent guide to cases where isotope values may be a poor indicator of prehistoric diet. The suspicious samples are listed in Table 3.

In summary, there are several ways in which problems in isotope analysis of human bone collagen extracts can be identified. First and foremost we think that the regular use of suitable blind standards interspersed between important archaeological samples helps to identify any possible laboratory errors. Several examples of this were indeed found, although it is unusual. In such cases, duplicate runs are required. Of all the tests employed, we think that departure from the regression relationship of nitrogen weight % against the C/N ratio most clearly identifies all cases where the isotope results may be of doubtful use.

TABLE 3
Specimens which may not give reliable isotope results

Specimen	Catalogue	Details
1	AA507	Moa
2	AA725	Natunuku
3	AA727	Site 13B sub-sample
4	AA727	Site 13B sub-sample
5	AA727	Site 13B sub-sample
6	AA727	Site 13B sub-sample
7	AX994	Nebira
8	AY058	Watom
9	AY069	Namu
10	AY499	Motupore
11	AY785	Lakeba
12	AY785B	Lakeba burnt sub-sample
13	AY787	Sigatoka

RESULTS FROM ANALYSIS OF ^{13}C

Little is known of the isotope values of animals and plants in the Pacific and New Zealand which might have been consumed by prehistoric people, so a start has been made in building a database of reference material. It was felt that it would be worthwhile to obtain grab samples of some representative species, although it is recognised that ultimately one should carry out in depth multiple analyses of many specimens of each species to assess the range of variation and its causes. For example, a detailed study of $\delta^{13}C$ in green lipped mussel *Perna canaliculus* in the Marlborough Sounds in New Zealand (Lyon and Hickman 1993) suggests possible annual variations due to temperature-dependent changes in the values of the plankton on which the mussels are feeding.

Analyses of select specimens were carried out at several laboratories, and all details are provided in Appendices 1 and 2. The $\delta^{13}C$ values are plotted out in Figure 6, separating land-based organisms from those which are marine-based. It can be observed from this that there is very little overlap between the two data sets.

Some values are of special interest. Kunai grass, *Imperata cylindrica*, from Papua New Guinea is clearly a C4 grass, and plots next to values obtained from Pacific sugar cane (also a C4 grass). The flesh of a specimen of Polynesian rat, *Rattus exulans*, has the least negative of any land-based animal in this study. This specimen was a male from the small island of Tiritiri Matangi, off the Whangaparoa Peninsula in the Hauraki Gulf, and might be expected to have had a diet similar to this result in maritime areas in prehistoric times. Since there are no known C4 grasses in New Zealand, a dietary contribution from the marine environment is indicated by this $\delta^{13}C$ result, presumably from foraging along the sea shore. This issue is discussed further in the section on $\delta^{15}N$.

Amongst the marine organisms there are two outliers — muttonbird (*Puffinus griseus*) and marblefish (*Aplodactylus meandratus*). The muttonbird was a juvenile from the muttonbird islands in Foveaux Strait, and was collected at a local fish market in Wellington. These birds are killed before they have developed adult feathers and are entirely fed on partially digested food regurgitated by adults. As far as is known, this solely consists of sea food, so the $\delta^{13}C$ result of -23.4 is very surprising, as it sits exactly between the land and marine

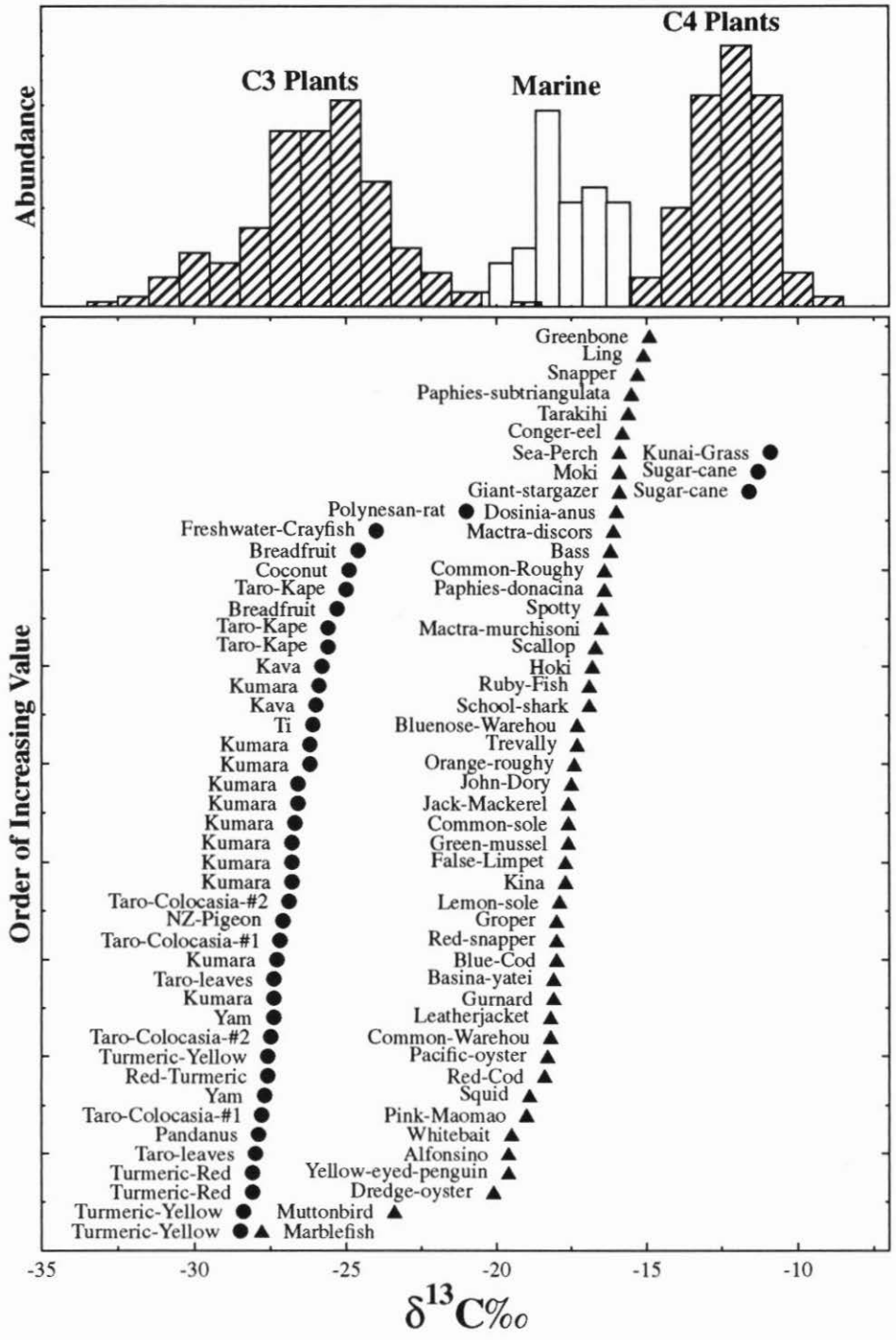

Figure 6: $\delta^{13}C$ values of plants and animals from New Zealand and the Pacific. Filled circles are land animals. Filled triangles are marine animals. The shaded histograms are of 351 species of grasses (from Vogel *et al.* 1978). The mean for C3 plants is -26.5‰, and for C4 plants is 12.5‰. The white histogram is of marine animals analysed in this study.

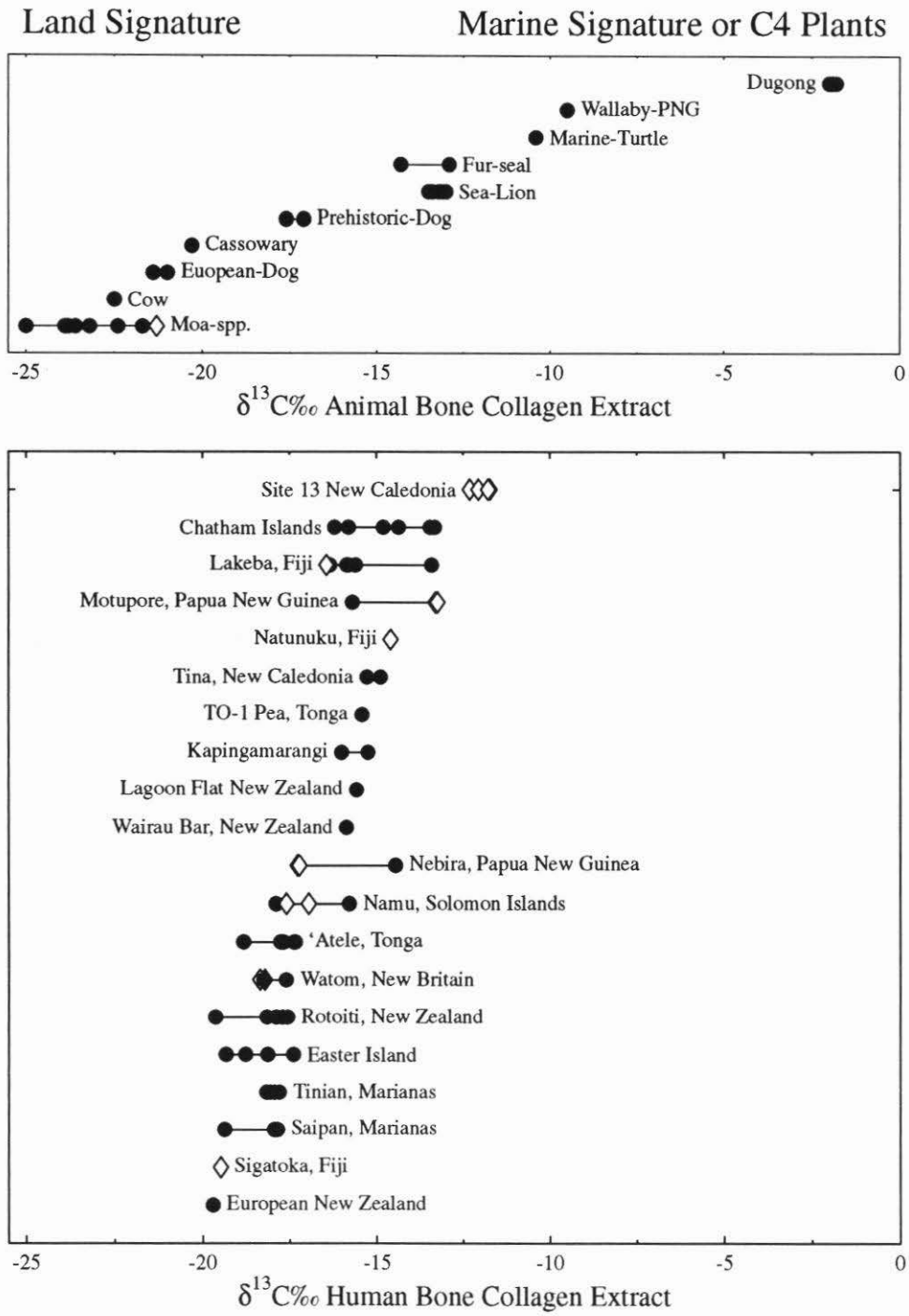

Figure 7: $\delta^{13}C$ results for collagen extract from archaeological bones analysed in this study. Thirteen results are considered potentially unreliable, and are designated with white diamond symbols.

organisms. The marblefish specimen was caught off Cape Palliser. This shallow water species feeds on algae and bryozoans. The $\delta^{13}C$ result of -27.8 is also unexpected. For both these species, further analyses are desirable.

This study of specimens of modern flora and fauna covers a broad range of possible food items of prehistoric people in this region, and although many more specimens of each species need to be studied in future, these initial results provide confidence that ^{13}C analysis will help to differentiate marine and terrestrial components in ancient human diet.

Turning now to analyses of collagen extract from bone, we provide in Appendix 1 and 2 results for 20 different prehistoric human groups from the Pacific and New Zealand, and 10 modern animal species. These results are summarised in Figure 7.

It should be noted that the distributions of $\delta^{13}C$ values in Figures 6 and 7 are not immediately comparable, as there is an offset value which needs to be considered. This is because carbon is fractionated by the body of animals during the assimilation of the isotope. Thus, the value in bone collagen is ~+5‰ higher than the value in the protein of the tissue being ingested (Leach *et al.* 1996: 7, 40–41). There might also be a change as one moves up trophic levels, for example a difference between the value for grass and the flesh of a herbivore eating that grass. Research on this point suggests that with ^{13}C, any difference between trophic levels is only of the order of ~+1‰, and not reliably discernible, except in the most controlled laboratory conditions (Schoeninger and Moore 1992: 258). Note also that specimens with results that might be questionable, on grounds discussed above in the section on standards and integrity, are indicated on Figure 7 with a white diamond symbol.

Eleven species of New Zealand moa are at the extreme end of the land dominated values obtained, and this is in line with present understanding of their diet and habitat. Two New Zealand prehistoric dog specimens (one from Kohika and the other from Shag River Mouth) have values which indicate they consumed some marine food, as C4 plants are not present in New Zealand. The wallaby specimen, from the site of Motupore in Papua New Guinea, shows a greatly enriched value of -9.5‰. With the suggested offset value of +5, this means that the diet of the wallaby would have an average value of ~-14.5‰. It has been argued elsewhere (Leach *et al.* 2000: 156) that this high value indicated a substantial contribution of C4 grasses, such as kunai, in the diet of this wallaby. Note that this specimen was earlier mentioned as having a very low yield of collagen extract (0.64%). Dugong have the most enriched values found in this study, with three values from two different laboratories ranging from -1.8 to -2.0‰. This species is a marine herbivore, feeding on sea grass. The reason for these unusual results is not known.

The spread of results from human bone collagen appears somewhat smaller than that of the terrestrial and marine animals in Figure 7. But if the extreme values for dugong, wallaby and marine turtle are set aside it will be seen that the human spread ranges almost as far as marine sea mammals, such as sea lion and southern fur seal. The European person presents the most terrestrial isotope signature, and the most marine looking values are from the Chatham Islands and Site 13B in New Caledonia. However, the Site 13B values are amongst those specimens which are somewhat suspicious, as noted above. In addition to the four values plotted in Figure 7 for Site 13B, other samples from the same individual were submitted for accelerator dating at two different laboratories (Pietrusewsky *et al.* 1998). These report $\delta^{13}C$ values of -9.6‰ (OXF) and -14.4‰ (INS). The four values plotted on Figure 7 (-11.7, -12.1, -12.3, -11.8 WAI) are different runs on the one sample. There is an important object lesson in these results. The methods for collagen extract preparation by the two dating laboratories are quite different from the strictly standardised methods used in this present study. The fact that two reputable dating laboratories have obtained values which

are not only different from those reported in this present study but wildly divergent from each other (4.7‰ apart) shows how important it is that identical collagen extraction methods are used within any one study of ancient human diet. The origin of the carbon, extracted for dating in this individual, is therefore in doubt. The INS Laboratory obtained a CRA date of 1061 ± 65 (NZA-3013), and the Oxford Laboratory obtained a CRA date of 2410 ± 55 (OxA-4908, Pietrusewsky *et al.* 1998: 33–34). These are clearly wildly divergent too.

Because C4 plants have a very heavy $\delta^{13}C$ value at the far end of the marine looking range (Fig. 6), any C4 plants in the diet of human communities will result in a bone collagen $\delta^{13}C$ signature which is pulled towards that end of the range. In other words, even if no marine food was consumed by the community, it would nevertheless produce a marine looking signature. Thus, the $\delta^{13}C$ signature alone cannot be used to assess the relative abundance of marine and terrestrial foods in diet in cases where C4 plants are present in the local botanical community. This problem also exists in cases where humans do not feed directly on the plants involved, but eat the flesh of herbivores which feed on such plants, because their $\delta^{13}C$ value will also be affected. Such is the case for the Watom community in New Britain (Leach *et al.* 2000), who were eating wallaby which were clearly browsing on C4 grasses. The consumption of other foraging animals, such as pigs and grass eating birds could of course present the same problem.

It is perhaps not fully appreciated by archaeologists just how widespread this problem might be in the tropical Pacific. In the Hawaiian Islands, for example, 40 of the 65 known native grasses are C4, and 95% of these are endemic to the eight major islands (Rundel 1980). There are also several native C4 sedges, and even several tree species of the *Euphorbia* genus which are C4 (Pearcy and Troughton 1975). C4 plants dominate in arid coastal flats and grasslands, dry woods and low-elevation ridges in the Hawaiian archipelago. There is a crossover to C3 species at about 1400 m above sea level.

There are extensive grasslands in parts of Papua New Guinea which are dominated by C4 plants also, for example, *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). The sword grass (kunai), *Imperata cylindrica*, is one of the main indigenous grasses on the alluvial plains of New Caledonia (Jaffre *et al.*, 1977).

In the case of plants which humans eat directly, the list of species is much more limited, but unfortunately, it is not always a simple matter to decide when a particular plant was first introduced on any island in the Pacific. Some plants were present long before humans arrived, prehistoric colonising humans introduced new species, and finally many species were introduced in the historic era. Sugar cane, *Saccharum officinarum*, is an obvious example of a C4 plant which we believe was widely distributed through prehistoric human agency, though not into New Zealand. In Papua New Guinea there are several other members of the *Saccharum* genus, which so far as we know are all C4 plants: *Saccharum spontaneum* (pit-pit), *Saccharum edule* (edible pit-pit, also called kunai by some people — see Waddell 1972: Appendix 5), and *Saccharum 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) and 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. He found that the average consumption per day (percent of total weight) was 4.9% for sugar cane and 0.8% 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 sugar cane contributing only 0.1% of their diet (1972: 119). Elsewhere Waddell 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, on the basis of these data, it seems unlikely that C4 plants would have contributed more than 10% by weight from direct consumption of plants and domesticated pigs.

In summary, $\delta^{13}C$ results for modern comparative collections of plants and animal flesh from New Zealand and the Pacific Islands show a similar range of values to other parts of the world, and there is a clear distinction between those deriving carbon from the terrestrial environment, and those from the sea. Terrestrial C4 plants are present in the Pacific, and in some cases make up a large portion of the ground species. A few of these C4 plants are eaten directly by humans, but there are others which are browsed upon by ground living animals which are then eaten in turn by humans. The $\delta^{13}C$ results presented here for human bone collagen extract cover a wide range, and this doubtless results from differences in the relative proportion of marine and terrestrial food consumed by different communities. Without an independent method for assessing the role of C4 plants in this mix, establishing this proportion is not possible. Fortunately, the use of multiple isotope analysis solves this problem. In this respect, New Zealand is exceptional in that C4 plants are not present.

RESULTS FROM ANALYSIS OF ^{15}N

The isotope ^{15}N is also known to fractionate in nature, and land animals and plants can be differentiated from those that live in the sea using the $\delta^{15}N$ ratio. Humans consuming food entirely from terrestrial sources therefore will have a different value in their bone collagen from those living exclusively or partly on food deriving from the marine environment.

As with ^{13}C studies, there are some complications with ^{15}N analysis. It will be recalled that there is an offset of the order of +5‰ between the $\delta^{13}C$ of the diet of an individual and the $\delta^{13}C$ in the bone collagen of the same individual. This also occurs in the case of $\delta^{15}N$, but is somewhat less and is estimated to be ~+3‰. However, there is an additional change between trophic levels too, and this is also of the order of ~+3‰ (Schoeninger and Moore 1992: 259; Sealy *et al.* 1987: 2710; Keegan and DeNiro 1988: 331). This latter phenomenon is of special relevance to studies of human communities living in tropical areas, because it may be possible to quantify the relative amounts of food deriving from the inshore reef areas and offshore deeper water. Nitrogen values for reef fish and other organisms are consistently lower than open ocean marine values, because of the increased amount of nitrogen fixation by blue-green algae in coral reef areas (DeNiro 1987: 189; Leach *et al.* 1996: 15). Keegan and DeNiro (1988: 331) suggest the following approximate ranges for marine organisms due to these changes in trophic level:

9.7–12.0‰	barracouta, sharks, etc.
6.2– 9.2‰	snapper, grouper, etc.
5.6– 6.3‰	parrotfish, surgeonfish, etc.
2.1– 6.3‰	molluscs, invertebrates, etc.
1.7– 6.2‰	algae
0.9– 2.0‰	sea grass

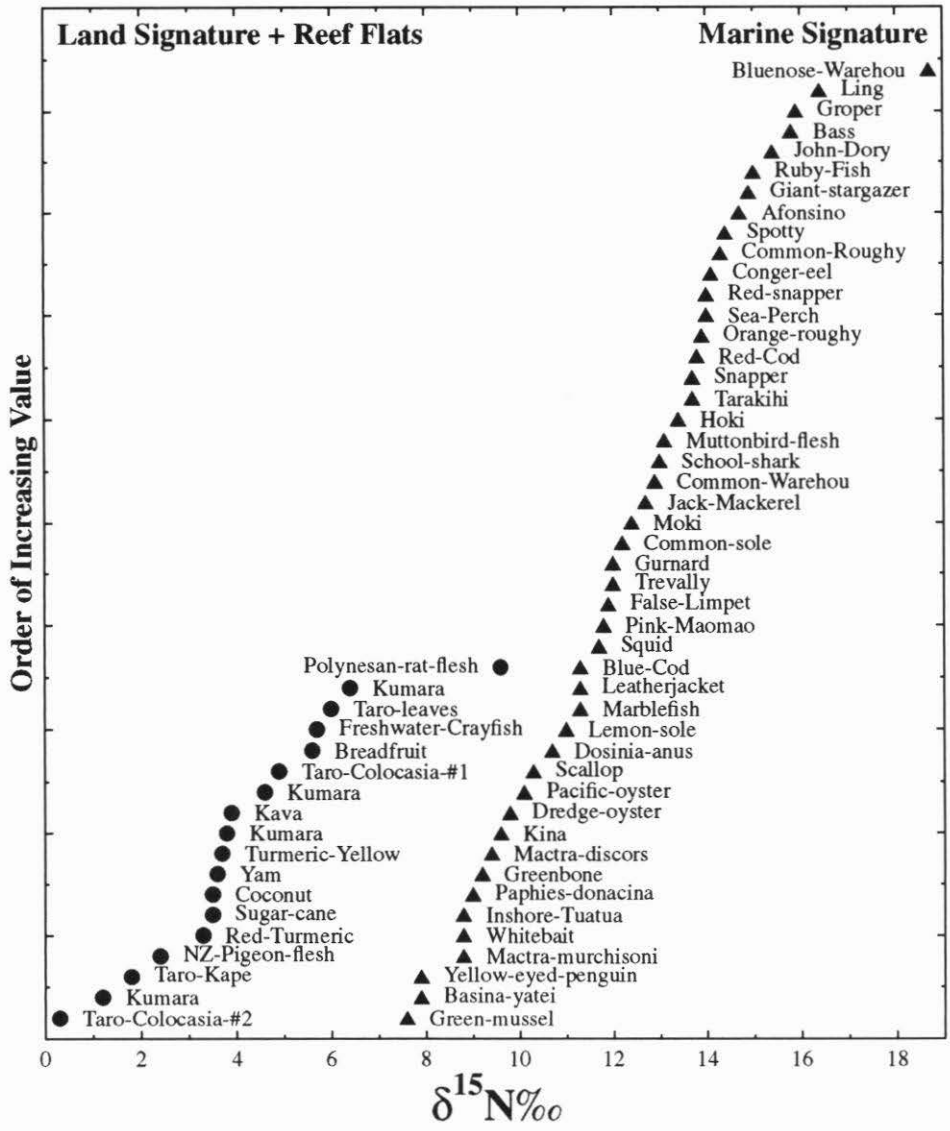

Figure 8: $\delta^{15}N$ values for reference plants and animals from New Zealand and the tropical Pacific. The filled circles are land-based organisms; the filled triangles are marine-based organisms.

Keegan and DeNiro (1988) have published $\delta^{13}C$ and $\delta^{15}N$ values for a considerable number of tropical plants and animals from the Bahamas, and many of these are of direct relevance to archaeological studies in the Pacific region. To this database, we can also add further $\delta^{15}N$ values for New Zealand marine and terrestrial plants and animals. These are presented in Appendices 1 and 2, and Figure 8. The results show a clear difference between organisms based on the land and those from the marine environment, although once again Polynesian rat is intermediate, suggesting marine food in its diet. It can also be noticed that muttonbird and marblefish show a clear marine signature for this isotope, unlike the case of $\delta^{13}C$.

The changes with trophic level are easily observed amongst the marine organisms illustrated in Figure 8. All the shellfish species have low $\delta^{15}N$ values, primary carnivores somewhat higher values, and top predators, such as bass, groper and bluenose warehou have the highest values. Values for a few tropical cultigens and the flesh of land animals are also given in Figure 8, and these are in a range below those for marine organisms. It will be recalled that the $\delta^{13}C$ values for the flesh of Polynesian rat suggested that this animal was obtaining some of its food from the marine environment; this view is reinforced by the $\delta^{15}N$ result which is higher than other terrestrial values. However, we should also expect an increased value due to the trophic effect. This example reveals one of the inherent weaknesses of trying to interpret food sources from one isotope value alone. Each isotope value presents an ambiguity. Since these ambiguities are not common from one isotope to another, the use of multiple isotope characterisation can serve to clarify these uncertainties. The change in isotope values from one trophic level to another can be documented in the case of the Polynesian rat using samples from a large number of partly carbonised coprolites which were found at a site at Orongorongo near Wellington. Ten of these were analysed (See Appendix 2), and gave the following results (Table 4). As stated above, we might expect an increase in isotope values from the coprolite to the flesh samples of about 1‰ in the case of $\delta^{13}C$, and about 3‰ in the case of $\delta^{15}N$. As Table 4 shows, the increases are of the order of +4.2 and +1.3 respectively. It must be remembered, however, that rats are highly adaptable, and we should expect to find seasonal and geographic variation in diet, and therefore variation in isotope values reflecting this. Moreover, flesh values are appropriate to diet over an extended period, whereas coprolite values relate to individual meals.

TABLE 4

Stable Isotope Results for *Rattus exulans* Flesh and Coprolites

Coprolites from Orongorongo 2, Site R28/27

^{14}C Date WK8490 paua $\delta^{13}C$ 1.8, CRA 770 ± 50 BP

Catal	**Type**	**%C**	**$\delta^{13}C$**	**%N**	**$\delta^{15}N$**
AA721	Flesh	50.36	-21.00	10.75	9.59
AL461	Coprolite	40.14	-26.57	2.49	8.26
AL462	Coprolite	38.82	-25.94	3.10	8.53
AL463	Coprolite	37.26	-24.99	3.60	8.32
AL464	Coprolite	34.32	-25.35	2.12	8.01
AL465	Coprolite	38.42	-25.91	1.78	7.61
AL466	Coprolite	35.67	-23.52	1.92	8.36
AL467	Coprolite	34.67	-24.16	2.13	9.81
AL468	Coprolite	34.75	-25.05	1.96	8.65
AL469	Coprolite	32.39	-25.92	2.10	8.24
AL470	Coprolite	34.17	-24.61	2.00	9.49
Mean	**Coprolite**	**36.06**	**-25.20**	**2.32**	**8.53**

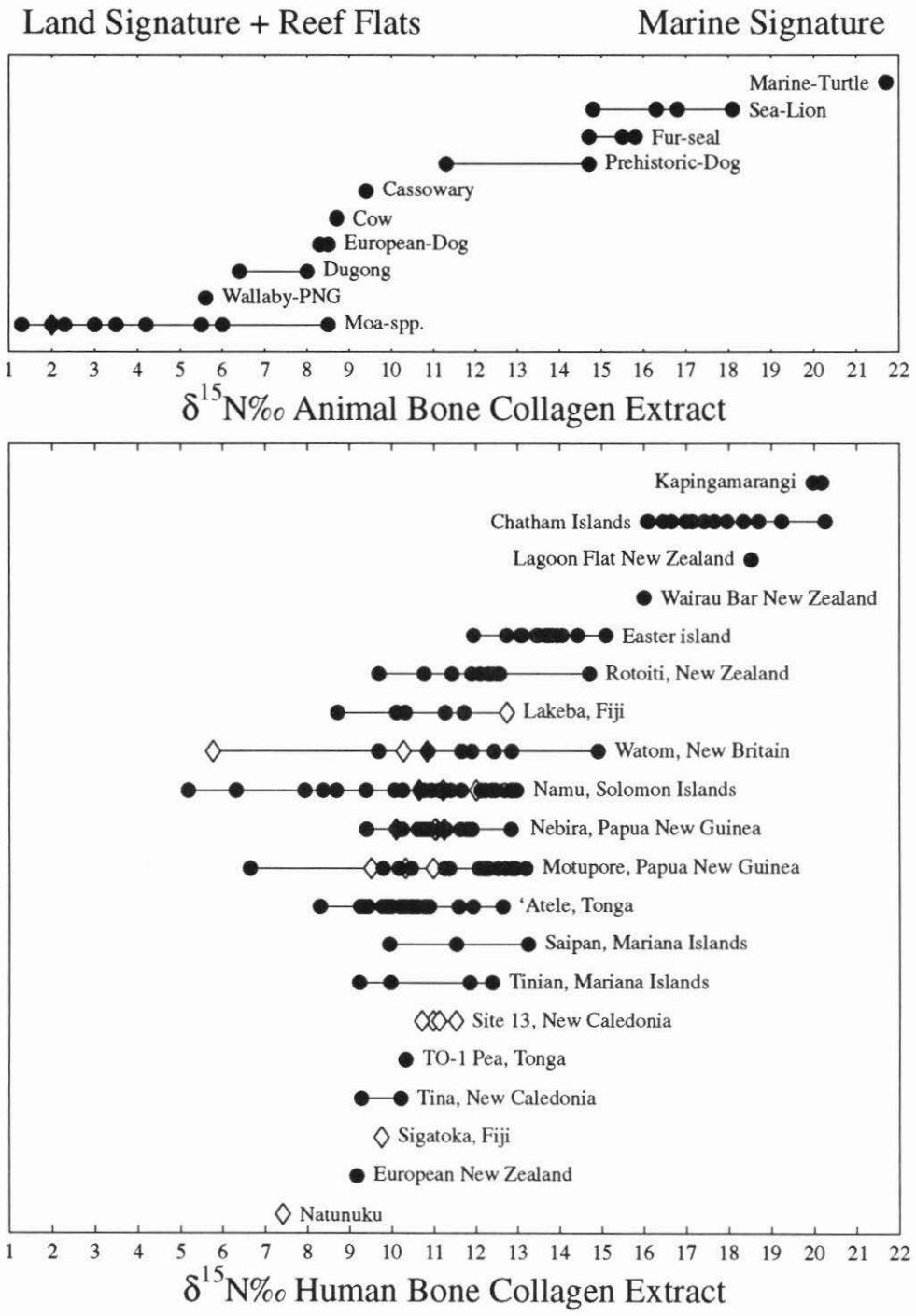

Figure 9: $\delta^{15}N$ results for collagen extract (and some bone powder, see Appendix 2) from archaeological bones analysed in this study. Thirteen results are considered potentially unreliable, and are designated with white diamond symbols.

We have analysed bones of modern animals in our comparative collection, and also of humans from a number of places in the Pacific and New Zealand (Appendix 1 and 2 and Figure 9). At an early stage in this research, we experimented with duplicate bone powder and collagen extracts to see whether satisfactory results could be obtained for $\delta^{15}N$ on bone powder alone. This was before we were able to carry out continuous flow mass spectrometry for ^{34}S analysis, and large samples of collagen extract had to be prepared using a Parr bomb process. Thirty samples of powdered bone, cleaned in the manner described above, were boiled in distilled water to remove water soluble nitrogen-bearing salts from archaeological soils. Collagen extracts were prepared from duplicate samples. The $\delta^{15}N$ results for the powdered samples were slightly higher on average (mean = $+0.83 \pm 0.25$, SD = 1.35 ± 0.17). However, the χ^2 value (8.9 with 29 df) is not significant p=0.10. This suggests that under good experimental conditions bone powder may be just as satisfactory as collagen extract for evaluating $\delta^{15}N$. The variation in results is close to the range of experimental variation. In Appendix 2, a code is used to show which results were obtained on bone powder and which were obtained on collagen extract (most are of the latter).

The 13 specimens which we earlier suggested might produce unreliable isotope results are indicated on Figure 9 with white diamond symbols. As with the ^{13}C analysis, New Zealand moa species stand out as having the strongest terrestrial ^{15}N signature along with wallaby. It is also noteworthy that dugong has a very light $\delta^{15}N$ value. Dugong is mostly herbivorous in habit, feeding on sea grass species such as *Halodule uninervis*, *Halophila ovalis*, and *Halophila ovata* (Anderson and Birtles 1978). They are also reported to feed on brown and green algae and some crabs. Keegan and DeNiro (1988: 325) give values for two species of sea grass as follows:

	$\delta^{13}C$	$\delta^{15}N$
Thalassia testudinum (turtle grass)	-6.2	+0.9
Syringodium filiforme (manatee grass)	-12.8	+2.0

While such values help to explain the very light $\delta^{15}N$ value for dugong, they do little to explain the very heavy value for turtle shown in Figure 9. Keegan and DeNiro have reported values for collagen from the green turtle (*Chelonia mydas*) from Antigua in the Caribbean of $\delta^{13}C$ -3.8 and $\delta^{15}N$ +5.1, compared with our results of -10.4 and +21.7 respectively. According to Marquez (1990) the sea grasses *Zostera, Thallasia, Cymodoces, Syringodium, Diplantera, Halodule* and *Halophila* along with assorted marine algae are the main food items for this species. The $\delta^{15}N$ value we have obtained may therefore be an error of some kind, which we are unable to explain at present. Unfortunately, the species of turtle used in this experiment has not been accurately determined, but consisted of bones of a small specimen from the Motupore site near Port Moresby in Papua New Guinea. It is either a juvenile of *Chelonia mydas* (the green turtle), or an older specimen of a smaller species, such as *Eretmochelys imbricata* (the hawksbill turtle). Juveniles of the former species have a mixed marine diet, and only become full herbivores when they reach adulthood; whereas the latter species feeds on sponges. The $\delta^{15}N$ value could therefore be correct. Further isotope research on marine turtles of different ages would be useful.

Apart from this problem, there is a clear distinction between the marine animals and those based on the land, with the two prehistoric dog specimens lying in between. The $\delta^{13}C$ results for these animals also indicated a mixed marine and terrestrial diet.

The values presented in Figure 9 for prehistoric human bone collagen extract cover a wide range from a dominance of terrestrial foods (the European individual) to strongly marine signatures (Chatham Islands and Kapingamarangi). It is also noteworthy that the results for some communities are quite variable. This raises the important question of whether isotope research can help to identify social differentiation in a community. In many Pacific island societies highly sought after foods, especially meat and fat, are preferentially allocated to high status people. This is particularly noticeable at feasts, but also happens on a day-to-day basis. Some societies are stratified, and others more egalitarian, but even in those without clear class structures some individuals have higher rank than others. The simplest form of differentiation is based on sex, so that males get better food than females, and children can be disadvantaged by being denied access to prestigious foods. The Namu results in Figure 9 show a wide range in $\delta^{15}N$ results, raising the distinct possibility of identifying social correlates. There is another implication of such wide ranges in one community — reconstruction of diet from multiple isotopes should in some cases be done on an individual to individual basis, rather than by averaging results from a number of individuals.

RESULTS FROM ANALYSIS OF ^{34}S

The use of ^{34}S as a means of tracing food webs is not as advanced as with ^{13}C and ^{15}N. Early studies of sulphate-sulphur in sea water samples showed only small and random variations of about 2‰, with an average of about +20.4‰ (Kaplan *et al.* 1963: 312). It was also quickly recognised that organisms exposed to fresh water sources of sulphate had impoverished ^{34}S values compared with sea water (Mekhitiyeva and Pankina 1968: 625). Conversely, it has also been found that sea spray or precipitation high in marine sulphate can be the principal source of sulphur for some organisms, not only in areas close to the sea, but also in inland areas with low rainfall (Mizutani and Rafter 1969; Kusakabe *et al.* 1976: 436). Although there have been a number of important studies of fractionation effects of ^{34}S in sea water, and atmospheric influences (Mekhitiyeva *et al.* 1976; Krouse 1977; Rees *et al.* 1978; Krouse and Ueda 1987), it is only relatively recently that the full potential of this isotope for exploring trophic and food web processes in nature has been recognised. For example, a study of $\delta^{34}S$ in cystine kidney stones led Krouse and Levinson to suggest that an individual in Papua New Guinea probably had a diet rich in sea food (Krouse and Levinson 1984: 191; Krouse *et al.* 1987: 210). However, the seminal study which most clearly showed the value of using multiple isotope ratios to trace the origin of food in organisms was by Peterson *et al.* (1985). This research was based on an estuarine salt marsh in Buzzards Bay in New England. By using the three isotopes ^{13}C, ^{15}N, and ^{34}S, they were able to trace the flow of organic matter throughout the food web in a highly convincing manner. Not only were they able to show regular isotope enrichment and depletion from upland to coastal profiles, but they were also able to estimate the relative proportions of different food sources consumed by the filter feeding ribbed mussel *Geukensia demissa*. Thus, in the interior of the salt marsh, this species had a diet consisting of 80% of the detritus of the marsh grass *Spartina alterniflora*; whereas the diet near the open areas of Buzzard Bay consisted of 70% plankton and only 30% of the marsh grass (ibid.: 1362). Peterson *et al.* (1986: 869) also showed that there are only small trophic changes in $\delta^{34}S$ with an increase of about -0.5‰ per trophic level. In these studies by Peterson and co-workers, the value of using these three isotopes was first fully recognised. This is precisely what is being attempted in this present study. Aufderheide *et al.* (1994) have also found the

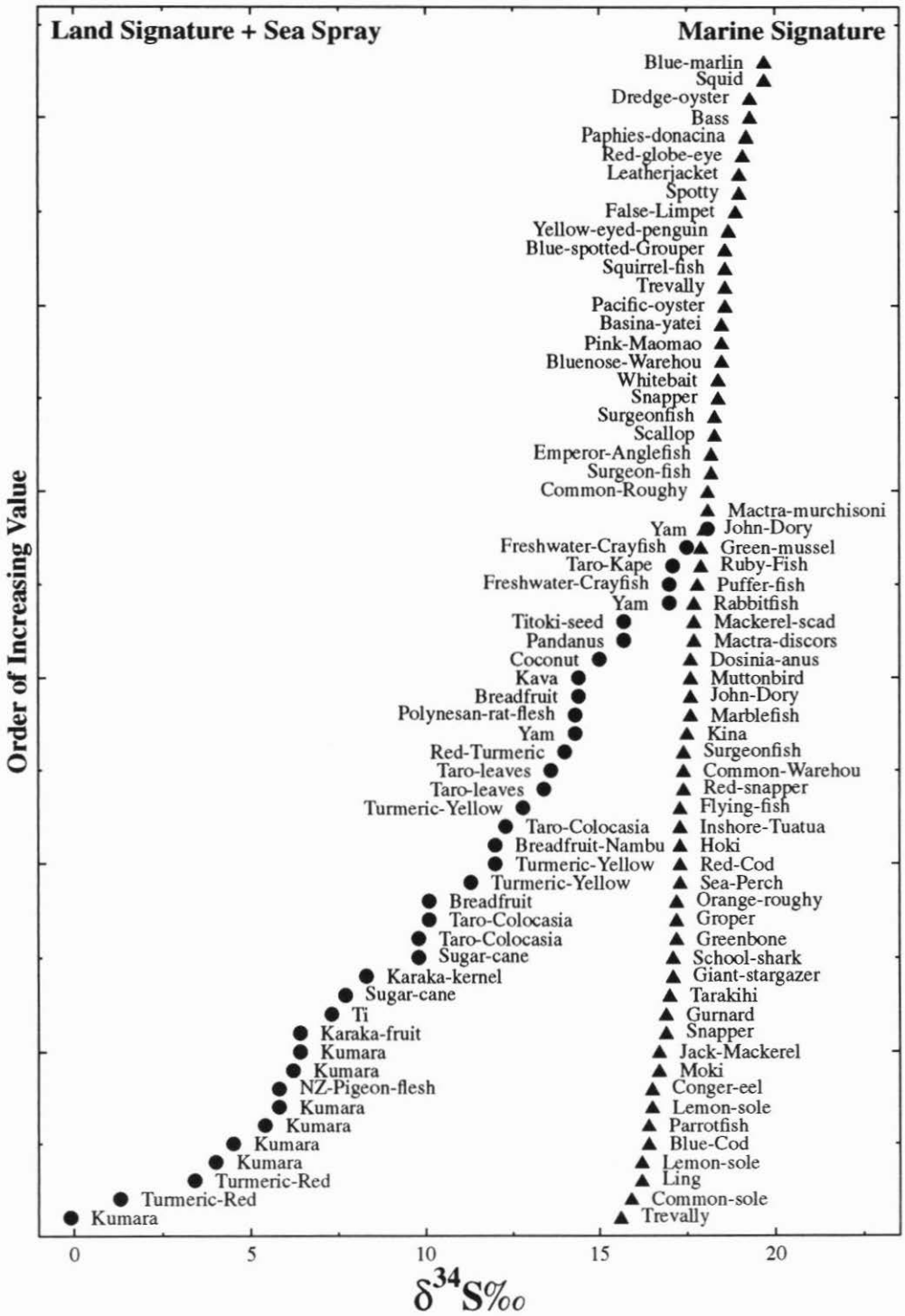

Figure 10: $\delta^{34}S$ values for plants and animals from New Zealand and the Pacific. The filled circles are land organisms, and the filled triangles are marine organisms.

greatly increased utility of using these three isotopes together. It has also been suggested that isotopes of hydrogen and oxygen and even trace elements may be added to this mix in order to understand ancient human diet (Krouse and Herbert 1988: 320).

In Figure 10 we present the results of $\delta^{34}S$ analysis on specimens of fauna and flora which are relevant to studies of ancient diet in the Pacific and New Zealand. It can be observed that the marine values form a very tight cluster, with a mean of +17.76‰ ± 0.12 (N=63), and a standard deviation of 0.95 ± 0.08.

Values for land-based plants and animals, however, do not form a tight clustering at all, ranging from -0.1 to +18.1. This is doubtless a reflection of the origin of the sulphur in the food chain which reaches the organisms involved, and in many cases must be derived from sea spray. In a detailed study of plants and animals on Heron Island on the Great Barrier Reef in Australia, the $\delta^{34}S$ values for many species of plants were found to be remarkably uniform at about +18‰, consistent with soil sulphate derived from sea spray. Moreover, feathers from birds, whether tree top dwellers, ground nesters, or fish eaters, produced equally consistent values of +17.9 ±0.4‰ (Krouse and Herbert 1988: 316).

The implication of this for dietary studies of prehistoric humans is that a $\delta^{34}S$ value of less than about +10 in human bone collagen will indicate strong reliance on land-based foods, but values greater than +10 can mean either significant intake of marine foods, or land foods in areas subject to sea spray. It would be relatively easy to distinguish between these two alternatives from the $\delta^{15}N$ and $\delta^{13}C$ values for the same individual. This again reveals the benefits of multiple isotope analysis. The Polynesian rat specimen gave an intermediate $\delta^{34}S$ result, suggesting some marine food in its diet, and this is in keeping with the earlier $\delta^{13}C$ and $\delta^{15}N$ values cited above.

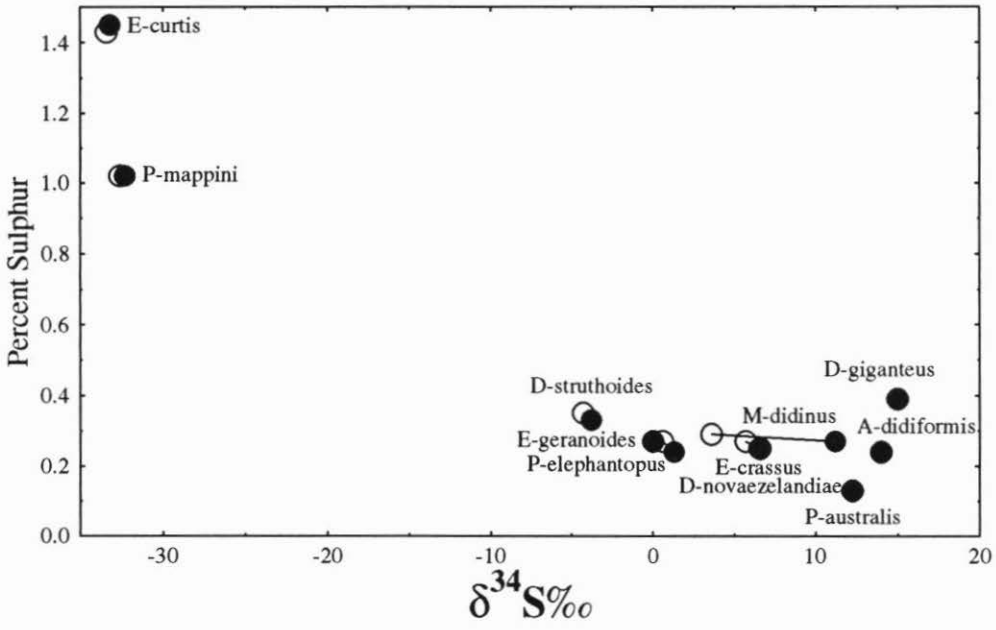

Figure 11: $\delta^{34}S$ values for 11 species of moa plotted against percent sulphur in collagen extract. Paired white and black circles indicate duplicate analyses.

In Figure 11 we show the $\delta^{34}S$ results obtained for moa bone collagen extract. The paired white and black circles indicate duplicate analyses, and show good agreement with one exception. It was noted earlier that the expected yield of sulphur from modern collagen should be 0.22%, and that in archaeological bones we obtain an average of about 0.15% by weight sulphur, reflecting some loss of protein over time. All but one of these moa bone samples are above this 0.22% threshold, raising the possibility of contamination with a sulphur compound which will have no bearing on diet reconstruction. Although this might not be a serious problem with most of the values in Figure 11, which form a loose cluster, the highly negative $\delta^{34}S$ values for *Pachyornis mappini* and *Euryapteryx curtis* are suspect, with sulphur yields greater than 1%. Further details of these moa specimens are provided in Table 5. There is no obvious pattern which would help explain such widely varying results, but the fact that none of these sites is archaeological may have a bearing. Each site is a natural deposit death assemblage. Much more research is required on moa remains to uncover the reasons for these divergent $\delta^{34}S$ results.

TABLE 5

$\delta^{34}S$ Results for Moa Specimens

$\delta^{34}S$	%S	**Catalogue Number, Species, Anatomy, Provenance, Approx. Age**
6.6	0.25	AA497 NMNZ S145. *Dinornis novaezelandiae*. Right tarsometatarsus, from Makirikiri, near Wanganui. Immature individual. Late Holocene. No dates. 1,000–6,000 Years BP.
0.0	0.27	AA498 NMNZ S317. *Euryapteryx geranoides*. Right tibiotarsus. Matariki, Nelson. No dates.
14.0	0.24	AA499 NMNZ S96. *Anomalopteryx didiformis*. Left tibiotarsus. Castle Rock, Southland. 15 dates 1,000–3,000 BP.
11.2	0.27	AA500 NMNZ S447. *Megalapteryx didinus*. Left tibiotarsus. Takahe Valley, Fiordland. No dates. Less than 10,000 BP.
3.6	0.29	AA500. Ditto
15.0	0.39	AA501 NMNZ S1015. *Dinornis giganteus*. Left fibula. Takapau Road, Manakau. No dates. 1,000–8,000 BP.
-32.3	1.02	AA502 NMNZ S154. *Pachyornis mappini*. Right tibiotarsus. Makirikiri, near Wanganui. Late Holocene. No dates. 1,000–6,000 Years BP.
-32.6	1.02	AA502. Ditto
-33.2	1.45	AA503 NMNZ S121. *Euryapteryx curtis*. Left tibiotarsus. Te Aute, Hawkes Bay. Three dates 10,600 to 11,600 BP.
-33.4	1.43	AA503. Ditto
-3.8	0.33	AA504 NMNZ S108. *Dinornis struthoides*. Right tarsometatarsus. Te Aute, Hawkes Bay. Three dates 10,600 to 11,600 BP.
-4.3	0.35	AA504. Ditto
1.3	0.24	AA505 NMNZ S196J. *Pachyornis elephantopus*. Right tarsometatarsus. Broken River, Otago. No dates.
0.6	0.27	AA505. Ditto
6.5	0.25	AA506 NMNZ S178. *Emeus crassus*. Left tarsometatarsus. Broken River, Otago. No dates.
5.7	0.27	AA506. Ditto
12.25	0.13	AA507 NMNZ S25872. *Pachyornis australis*. Right ischium, two phalanges. Honeycomb Hill cemetery, NW Nelson. 12,000 to 20,000 BP.

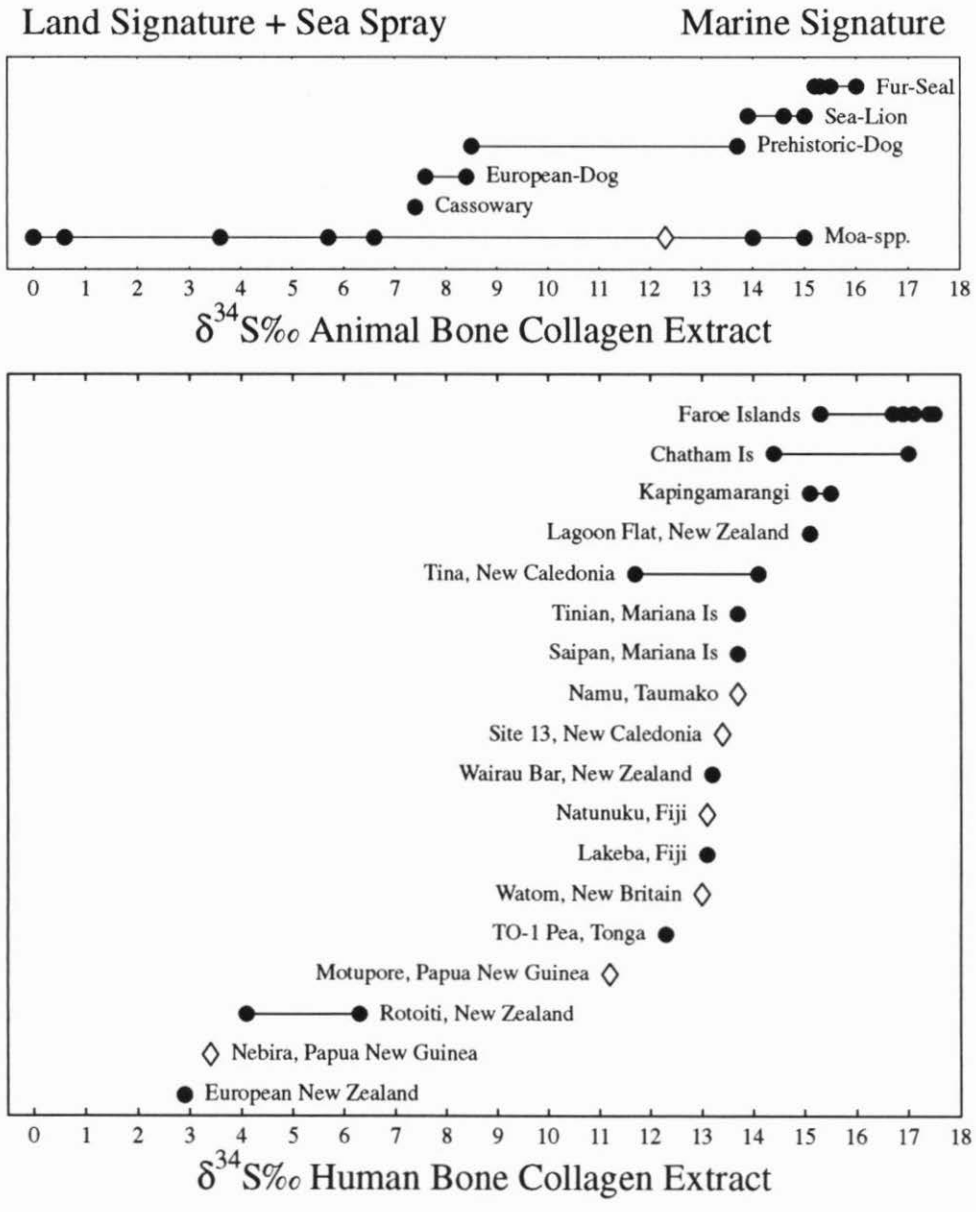

Figure 12: $\delta^{34}S$ results for collagen extract from archaeological bones analysed in this study. Seven results are considered potentially unreliable, and are designated with white diamond symbols. Two highly negative moa results are not plotted (see text).

In Figure 12 we plot the $\delta^{34}S$ results obtained for collagen extracts of archaeological specimens of humans and some fauna. As with the other isotopes, the specimens which are potentially unreliable are indicated with a white diamond. In this case only seven of the 13 had sufficient collagen extract remaining to be analysed. The extreme range of the moa results is evident in this Figure. Apart from the unusual values for moa, all other results are perfectly reasonable. As with the other isotopes, the European person gives the most land-

based signature, and the Chatham and Faroe Islands the two most marine. The fur seal and seal lion values are strongly marine looking, and the cassowary and European dog provide terrestrial signatures. The prehistoric New Zealand dogs have intermediate values, reflecting some marine food in their diet, also seen earlier with the $\delta^{13}C$ and $\delta^{15}N$ results, and this is supported by coprolite studies (Byrne 1973).

Although there is only a small database of $\delta^{34}S$ results for archaeological bones so far, it is clear that this isotope has a great deal to contribute to dietary studies from this type of research.

STOCHASTIC MODELLING OF ANCIENT DIET

The stable isotope results presented above provide only a qualitative indication of the type of diet which a particular individual may have had during their lifetime. Moreover, as will be obvious from the graphs of the three isotopes being considered, any one individual does not always plot in the same position on the scale of terrestrial signature on the left and marine signature on the right. This variable relative position on these three graphs is due to several factors — the complications of C4 plants in the case of $\delta^{13}C$, the complication of inshore marine signatures with $\delta^{15}N$, and sea-spray bearing sulphates in the case of $\delta^{34}S$. Despite the most rigorous attention to good analytical procedures and tests for veracity with standards, we must also recognise an unknown contribution of diagenic change and laboratory errors as a source of variation.

It might be thought that one way of overcoming several sources of variation would be to carry out analyses on a number of individual humans from one society, or several individuals of one species of animal and then average the results. There is a possible snag in this, because this could introduce yet another source of variation — variation in the dietary behaviour within a society for reasons of status or sex or some other social factor, and geographic variations in the feeding behaviour of adaptable animal species. On the other hand, if the results for any one isotope for one group of humans form a tight cluster with low coefficient of variation, then it would be an advantage to use the mean value for that isotope when attempting to reconstruct diet using multiple isotope values. The $\delta^{15}N$ results in Figure 9 show considerable variation in some groups, and this might argue against using the mean value for any of these groups. The $\delta^{13}C$ results in Figure 7 show somewhat tighter clustering, and might justify the use of mean values. To test this further, two prehistoric groups were looked at in further detail. Taumako and Nebira were chosen because they are both sizable collections and were readily available in the Anatomy Department at the University of Otago. All samples were treated at one laboratory (INS) under as near identical experimental conditions as possible. The results are given at the end of Appendix 2, and summarised in Table 6.

TABLE 6
$\delta^{13}C$ results for two Pacific Island Groups

	Taumako (N=18)			**Nebira (N=19)**		
Range	14.8	to	17.3	14.2	to	17.7
Mean	16.5	±	0.1	16.4	±	0.2
Standard Deviation	0.6	±	0.0	1.0	±	0.2
Coefficient of Variation	3.5	±	0.6	6.1	±	1.0

Taumako is a small high island in Temotu Province in the outer eastern Solomon Islands and the population speak a Polynesian language. The burials examined here are from the site known as Namu and are dated to 300–850 years BP (Whitehead *et al.* 1986). The site is adjacent to the sea. The traditional economy is based on breadfruit, but many other plant crops are grown, including taro, kūmara, sago, banana, etc. Pigs are domesticated on the island, but although these are highly prized they probably do not contribute as much protein in the diet as marine fish, since they only appear at special feasts. The thick layers of fat are the portions most sought after, and high status men get the greatest share.

Nebira is a 180 m high hill on the river plains beside the Laloki River about 17 km directly inland from Port Moresby in Papua New Guinea. The burials are from site ACJ in the saddle between twin peaks and date from the period of about AD 1000–1600 (Bulmer 1979: 14). Faunal remains include a wide range of animals from forest, grassland and sea. Fish could be from the river, but dugong and shellfish from the coast were also eaten (Bulmer 1979: 18). There is no direct evidence of cultivated plants at the site, but it is situated next to fertile river terraces which would provide good all-season garden land. The Port Moresby area is prone to drought and only yams and bananas grow well (ibid.: 22). Wild plant foods are also important to modern people in this area, particularly in times of famine.

The range of $\delta^{13}C$ results is only 2.5‰ for Taumako and 3.5‰ for Nebira, and both coefficients of variation are very small. This indicates very little dietary variation, as far as sources of ^{13}C are concerned. The mean values are practically identical despite the differences in the traditional economic systems of the two areas.

This is an instructive example because it is a clear case of different causes having the same ultimate effect. This is a fundamental problem in archaeology and has been dubbed 'the problem of equifinality' (Torrence 1986: 21–22; Torrence *et al.* 1992), and also 'the problem of multi-causality' (Leach 1996: 2). There are close similarities between the task of identifying the particular prehistoric diet which produced a certain pattern of isotope values in collagen and the task of identifying the geological source which produced a certain pattern of trace elements, such as is involved in tracing the origin of obsidian artefacts. In both cases we are working backwards from effect to cause, and it is important to take on board the fact that sometimes several causes can have the same effect. In the case of tracing the origin of stone tools, early research relied upon only one or two characteristics, such as hand specimen colour or refractive index or density. Problems of multi-causality here have led to more and more characteristics being added to solve the ambiguities of interpreting backwards from effect to cause. The most successful obsidian sourcing relies upon as many as 23 different characteristics and multivariate methods (Leach 1996; Leach and Manly 1982).

The lesson for diet reconstruction based upon isotope signatures is clear — it is advisable to use as many sources of information as possible. For the most part, we have been limited so far to a univariate or at most bivariate approach (^{13}C and/or ^{15}N), and have been employing relatively simple mathematical modelling. Krouse and Herbert suggested an approach called a 'box' or 'slot' model (1988: 320) using ^{13}C, ^{15}N, ^{34}S and possibly hydrogen and oxygen isotopes and even trace metals, the slot widths corresponding to the resolution of each characteristic, such as the $\delta^{13}C$ determination. In this way they envisaged that one could identify millions of potential dietary boxes from a much smaller number of analytical characters. A very similar approach to this has been attempted when sourcing obsidian artefacts (Leach and Warren 1981), and the suggestion by Krouse and Herbert is a welcome one for diet reconstruction.

Another useful suggestion has been made to expand the information base by incorporating the results from classical midden analysis into the interpretation of isotope signatures (Minagawa and Akazawa 1989: 10–11, 1992). This concept is a little like the 'box or slot' model, and consists of placing a series of Boolean filters along the path to dietary interpretation. It could also incorporate the filtering out of unlikely possibilities based upon ecological or geographic factors. For example, if one was investigating the diet of a group of people on an island where no C4 plants are found, then the part of the algorithm which calculates the contribution of C4 plants from a collagen $\delta^{13}C$ value can be ignored. This suggests adopting a more flexible approach when interpreting cause from effect in this field, and using a mixture of common sense Boolean logic as well as arithmetic and/or multivariate modelling.

In an important paper by Schwarcz (1991) it was argued that there is a strict theoretical limit to how many sources of food (causal elements) can be reconstructed from a specified number of isotope ratios (effects).

> Using analyses of a given number, N, of isotope elements (C, N, H, O, etc.) it is possible in principle to estimate the proportions of N+1 dietary compositions of known, well defined isotopic composition. For maximum effectiveness, any isotopic palaeodiet study should be preceded by an archaeological, archaeobotanical and -zoological study to define the lists of foods that were actually consumed (Schwarcz 1991: 273).

This strict theoretical limitation only applies in the case of what Minagawa has called the 'analytic feeding model' where an exact algebraic solution is sought (Minagawa 1992: 146–147). This requirement is unnecessarily harsh, and he suggests that it is possible to reconstruct >N+1 dietary constituents from N isotopes, if one takes a somewhat more relaxed stochastic approach to the matter, and sacrifices exact solutions in favour of probable ones. This seems perfectly reasonable, given the wide range of uncertainties and sources of variation in this whole field. There are basically two ways of adopting this more relaxed strategy:

> **Model 1:** Forward calculate the isotope values which would result from consuming all possible proportions of a series of food categories specified, and then check the archaeological bone isotope signature against these results to see what food proportions could have produced it.
>
> **Model 2:** Randomly choose proportions of the series of foods specified, calculate the isotope signature which would result from such a diet, and check the archaeological signature against this. If there is a reasonable match then store this away as one possible solution. After a period of such simulations, the various solutions can be examined to determine their ranges, and central tendencies.

The first approach would involve formidable computing, but has some merit. Minagawa's method follows the latter course, and also involves using some Boolean logic. For example, rejecting dietary solutions which would be harmful to human health, such as those which are outside the requirements of human metabolism for protein and energy.

Therefore, we suggest taking into account as much geographic, archaeological, and metabolic information as is available during the process of calculating the proportions of

different food types in the diet of a person, or group of people, from multiple isotope signatures. For the Pacific Island and New Zealand region, some steps have been made towards this end, employing Minagawa's model (Leach *et al.* 1996; Leach *et al.* 2000; Pietrusewsky *et al.* 1998). The stochastic model takes into account basic human metabolic and nutritional requirements, and only permits dietary solutions to an isotope signature which satisfies these requirements. For example, it only permits solutions which will provide a satisfactory daily intake of caloric energy; it will not permit solutions which exceed human limits of daily protein or fat consumption, etc. Sixty-three basic assumptions are built into the algorithm, such as the mean $\delta^{13}C$ value for C3 plants and the permitted range of acceptable values, the daily needs of protein which humans must obtain, and the upper limit which is toxic, etc. The details of these assumptions and an explanation of the stochastic process have already been described in full (Leach *et al.* 1996). It remains now to use some of the isotope results outlined in this paper and this stochastic model to reconstruct the diet of select groups of prehistoric people.

From the foregoing, a series of five individuals and groups are chosen from New Zealand: the European, Rotoiti, Wairau Bar, Lagoon Flat, and Chatham Islands. The European person was a male aged 87 buried in 1876 (Trotter and McCulloch 1989). Nothing is known directly about the diet of this person, but we can be reasonably confident that his diet was similar to that of other Europeans at this time in rural New Zealand. The Rotoiti group are from an inland location near Lake Rotoiti in the central North Island, and any sea foods consumed by this group would have to have been obtained by trade with coastal peoples. There is no date for this collection, but the yield of collagen extract was very high (19–31% by weight), so presumably they are of late prehistoric age. The Wairau Bar specimen was Burial 41 (43–50 cm depth) from site P28/21. A bone sample was dated as CRA 780 ± 80 years BP (NZ1835). The $\delta^{13}C$ value obtained during the ^{14}C dating was -20.9, compared with our assessment of this individual of -15.9. The dating was carried out in 1974 and at that time some bone samples may not have had all inorganic material removed during acid digestion, which might account for the $\delta^{13}C$ discrepancy (Lyon 1986 pers. comm.). The Lagoon Flat individual was Burial 4 in crouched position 25–35 cm deep in a large occupational site behind the beach, north of the Conway River mouth (site O32/31). This site has moa bone and artefacts of both early and later period characteristics, and was probably occupied several times. A sample of bone gave a CRA of 480 ± 60 years BP (NZ1834) with a $\delta^{13}C$ value of -16.5, compared with our value of -15.6, which is in better agreement. The group from the Chatham Islands are in the Anatomy Department, University of Otago and are a mixed collection. Two specimens from the site at Waihora date to within the last 400 years (Appendix 3).

The specific isotope values chosen to represent each group are shown in Figure 13, and the simulation parameters are set out in Table 7. In each case the tolerance levels are set at the beginning of the simulation, and are slightly different for each group. This is because of the need to balance between two competing requirements. On the one hand the tolerance level for each isotope value should be set as small as possible. This results in dietary solutions which are very precise, with low variance and high probability. On the other hand the number of valid simulations may be very low or even zero if the tolerances are set too narrow. In other words, one may not be able to find enough dietary solutions to give reasonable final statistics for each food type. The tolerance level therefore is widened slightly so that valid simulations begin to occur. When a reasonable rate of valid simulations is achieved, these tolerances are then fixed to these values, and the simulation runs for up to 48 hours of computing time at 133 MHz. Since there are no C4 plants and no coral reefs

in New Zealand, food from these sources was not included in the simulation conditions. In addition, direct consumption of marine mammals was not permitted for either the European person or the inland Rotoiti group. It is possible that the latter may have obtained some seal flesh by trade, but this would be insignificant, given their northern location, and it seemed reasonable to reject this along with C4 plants.

TABLE 7

Parameters used for diet simulation (see Leach *et al.* 1996)
Range of acceptable energy consumption 1800 to 3700 kcal per day
Range of acceptable protein consumption 25 to 200 g per day
Isotope offsets from food to collagen were set as follows:

$\delta^{13}C$	+5.0
$\delta^{15}N$	+3.0
$\delta^{34}S$	-0.5 for land foods
$\delta^{34}S$	-0.9 for marine foods

Isotope	**European**	**Rotoiti**	**Wairau Bar**	**Lagoon Flat**	**Chatham Is**
$\delta^{13}C$	-19.7	-18.2	-15.9	-15.6	-14.4
$\delta^{15}N$	9.2	12.2	16.0	18.5	17.4
$\delta^{34}S$	2.9	5.0	13.3	15.1	15.7
Tolerance					
$\delta^{13}C$	0.5	2.0	2.5	3.0	1.5
$\delta^{15}N$	0.5	2.5	2.5	3.0	1.5
$\delta^{34}S$	1.6	2.0	2.5	3.0	1.5

	Mean Values for each food				
	$\delta^{13}C$	$\delta^{15}N$	$\delta^{34}S$	**protein**	**kcal**
	‰	‰	‰	**g/100g**	**kcal/100g**
C3 Plants	-26.0	5.8	4.9	2.2	145
Land Animals	-22.6	5.4	4.4	23.1	155
Marine Shellfish	-14.0	7.2	18.6	12.9	69
Marine Fish	-16.5	14.0	17.7	19.7	100
Marine Mammals	-16.8	15.7	16.8	14.0	262

It is possible to run the simulation software in both forward and reverse directions. In the forward direction one uses the isotope values for a specific prehistoric group to estimate the proportions of different foods which might have produced this pattern. That is, the values listed in Table 7 are used to yield the values listed in Table 8. When the software is run in the reverse direction, one uses the amounts of each of the different foods to estimate the isotope pattern which would be the result (Table 8 used to derive Table 7). This dual procedure was initially developed as a means of debugging the software, but has since proved useful for other purposes.

TABLE 8

Results from Stochastic Simulation Analysis

	European		Rotoiti		Wairau		Lagoon		Chatham	
Simulations	**No.**	**Valid**	**No.**	**Valid**	**No.**	**Valid**	**No.**	**Valid**	**No.**	**Valid**
Results	650936	2880	1630769	26	521990	109	1787229	112	9315455	6071
Basic Results	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Food intake g/day	1654	308	1751	338	1419	133	1173	137	1183	139
Energy kcal/day	2447	449	2409	462	1977	219	2141	306	2193	313
Protein g/day	158	26	139	37	184	16	172	24	171	20
$\delta^{13}C$	-19.7	0.3	-18.7	0.7	-14.7	0.5	-13.2	0.4	-13.0	0.1
$\delta^{15}N$	8.8	0.0	9.8	0.2	13.8	0.4	15.9	0.4	16.3	0.3
$\delta^{34}S$	4.4	0.1	6.4	0.4	12.1	0.6	14.0	0.5	14.4	0.1
Food Weight %	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
C3 Plants	63.8	7.8	67.2	13.9	32.0	6.8	13.1	5.3	13.5	2.0
Land Animals	35.0	7.6	16.1	12.6	5.0	5.7	6.3	5.4	2.8	2.1
Marine Shellfish	0.0	0.0	4.7	3.3	5.6	4.9	4.3	3.1	3.3	2.3
Marine Fish	1.2	0.6	12.0	2.3	42.1	11.5	29.6	16.0	31.8	11.1
Marine Mammals	0.0	0.0	0.0	0.0	15.3	10.8	46.7	14.4	48.6	10.7
Protein g/day	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
C3 Plants	23	6	26	9	10	3	3	2	4	1
Land Animals	131	25	61	39	15	16	17	14	7	6
Marine Shellfish	0	0	11	8	10	9	7	5	5	4
Marine Fish	4	2	41	11	119	36	70	40	74	27
Marine Mammals	0	0	0	0	29	20	76	22	80	20
Energy kcal/day	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
C3 Plants	1548	426	1737	571	666	176	225	101	233	47
Land Animals	879	166	406	265	103	109	112	94	50	38
Marine Shellfish	0	0	56	41	55	49	35	25	27	20
Marine Fish	20	10	0	0	603	184	356	202	377	138
Marine Mammals	0	0	0	0	550	366	1413	408	1506	373

The results of the simulation experiment for each of the five human groups are listed in detail in Table 8, and the amount of each of the five major food components is illustrated in Figure 14. For the sake of clarity, a single worked example can be given to show the link between Table 8 and Figure 14. This is provided in Appendix 4. In Table 8 the European person shows a mean food intake of 1654 g/day, and a contribution of C3 plants as 63.8%. Thus, the g/day of C3 plants is 1654 x 0.638 = 1055 g/day. This is the value plotted on Figure 14. Both the European person and the Rotoiti group show strong emphasis on terrestrial foods, and this conforms to expectations. But it must be remembered that sea mammals were not permitted foods for these two in the simulation conditions. However, fish and shellfish were permitted, and their contribution to the diet was found to be very low. The other three groups show a strong emphasis towards marine foods, and once again this accords with expectations. Plant foods are very low for both the Chatham Islands group and the Lagoon Flat individual. It is interesting that the Wairau Bar specimen shows a somewhat greater amount of plant food than the other two prehistoric groups.

It might be noticed in Table 8 that the mean simulated isotope values are not quite the same as those initially assumed (Table 7), although bearing in mind the standard deviations, the fits are not too far from the expected values. For example, in the case of the Chatham Islands, the mean isotope values obtained after simulation were -13.0, 16.3 and 14.4 for

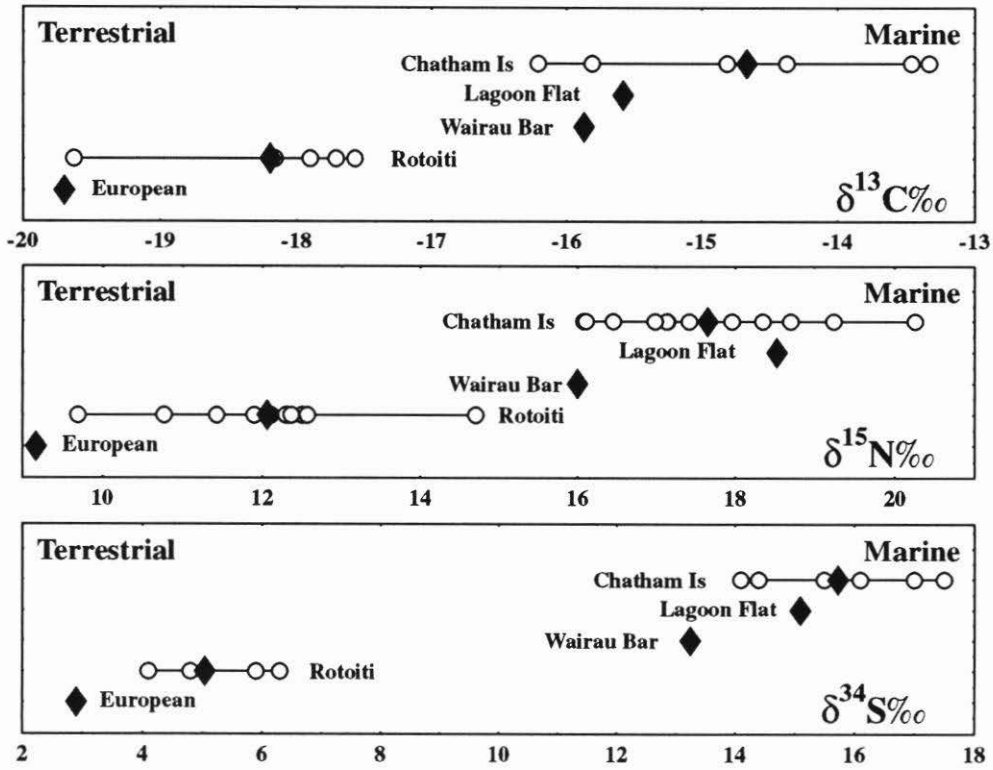

Figure 13: The isotope values for the five prehistoric groups chosen for detailed reconstruction of diet. The white circles are various values obtained for individuals, and the black diamonds are the values chosen for simulation analysis.

$\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ respectively. The actual values of the prehistoric group were -14.4, 17.4 and 15.7 respectively. In other words, the simulations were within about 1‰ in each case. It will be seen in Table 7 that a window of ±1.5‰ was permitted in this case. Using this window 6,071 valid solutions were found in 9.3 million iterations.

As pointed out earlier, this method of reconstructing diet from isotope signature does not yield exact solutions, but probable ones. This means that the estimated amounts of each food follow a probability distribution with a mean and standard deviation. This is best described using an illustration, given in Figure 15. This shows strong narrow peaks for shellfish, birds and plants, but much broader ones for fish and sea mammals. What this suggests is that although the first three food types contributed a fairly constant amount to the overall diet, the latter two might have been rather variable. In other words, a low proportion of fish might have been accompanied by a higher proportion of sea mammals on some occasions, and vice versa on others.

The final objective in this quest to reconstruct diet from isotope analysis is to try to estimate the contribution not just of protein and energy, but also of fat and carbohydrate. This is not as difficult as it might at first appear. Having arrived at various quantitative estimates of plant and marine foods in the diet, we can cautiously take the next step using existing knowledge of what plants and animals were actually available to each prehistoric group being considered, and published information of the nutritional values of each of these.

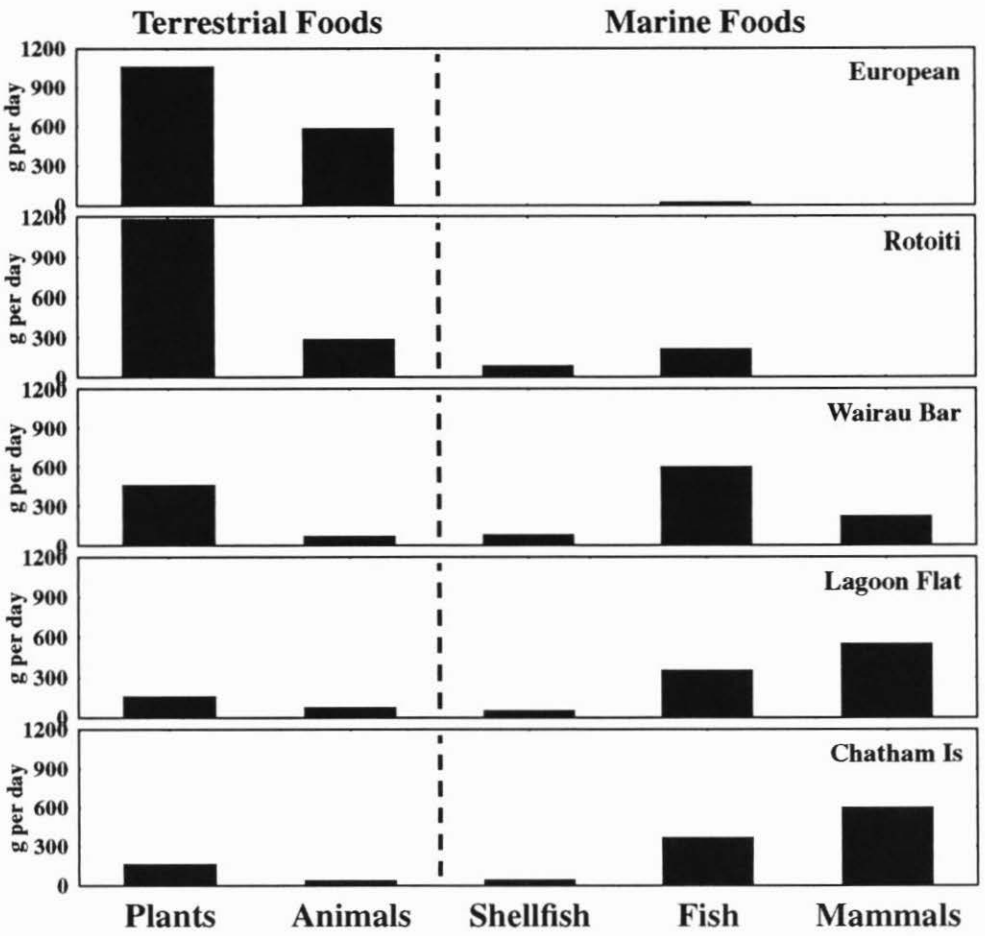

Figure 14: The estimated amounts of each of the five major food types consumed per day by each of the human groups chosen for study.

For example, if we have estimated how much marine shellfish was being consumed by a chosen group, we can easily convert this quantity to the appropriate values of protein, fat and carbohydrate using published proximate analysis data. Nutritional values for a wide range of Pacific and New Zealand plants and animals may be found in Leach *et al.* (1996: 49 ff.). Three important basic quantities are the energy which can be derived from protein, fat and carbohydrate. These are derived from the heat of combustion of a range of examples of each (eggs, meat, animal fat, olive oil, starch, glucose, etc.), from which the loss in urine can be subtracted. This shows that the available food energy from each is about 92, 95, and 99% respectively (Atwater and Benedict 1899), and led to the widely recognised values of 4, 9 and 4 kcal/g, known as the 'Atwater Factors' (Davidson *et al.* 1972: 9–10). These values are used by Smith in his discussion of the nutritive value of different foods in New Zealand prehistory (Smith 1985: 131), and are also adopted in this present study.

We will illustrate the process of arriving at estimates of protein, fat and carbohydrate using the Chatham Islands group as an example. Firstly we must choose some representative

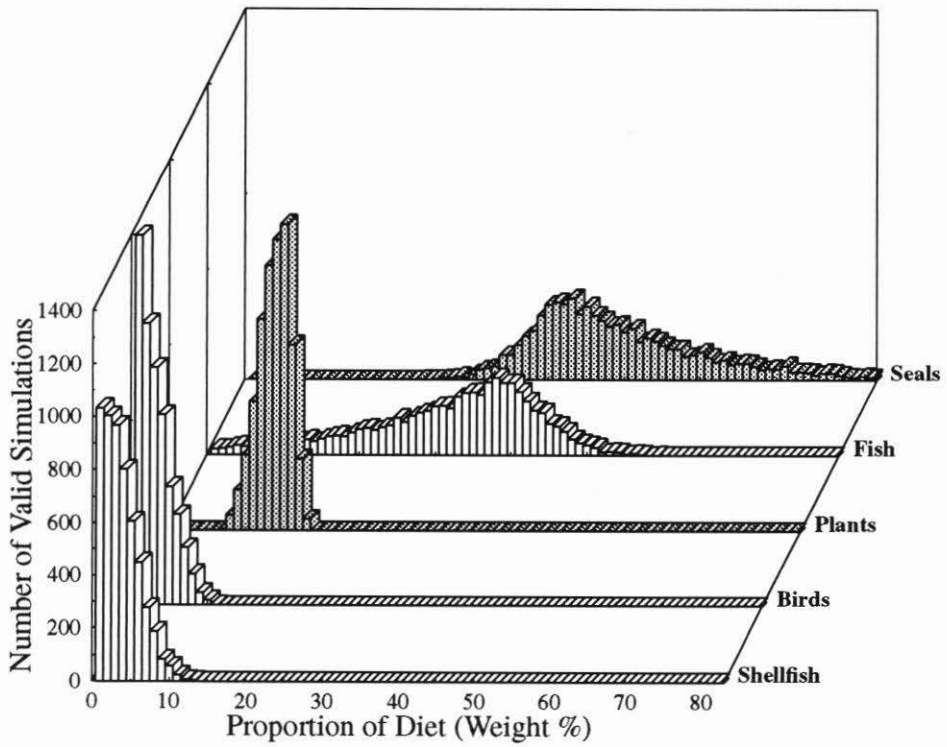

Figure 15: The probability distributions of each major food type in the diet of the Chatham Island group.

values of the amounts of each of these three components in the main food types consumed by the group. These are given in Table 9, and follow suggestions made by Smith (1985: 132, 491) and Vlieg (1988) for land animals (mainly birds), shellfish, fish, and marine mammals. Choosing representative values for plants is more difficult because there is considerable variation from one plant to another, and also seasonally. Typical kūmara (*Ipomoea batatas*) values are 4, 0.9, and 66 g/100g respectively for the three constituents; whereas fern root (*Pteridium esculentum*) values during the best part of the season are 4, 0.4, and 32 g/100g. Tī (*Cordyline australis*) is known to have been a food for Polynesians, and this has highly variable nutritive values depending on season and part of plant eaten, ranging from 1–7 for protein, 2–18 for fat, and 29–75 g/100g for carbohydrate (Fankhauser 1989: 205, 216). Karaka trees (*Corynocarpus laevigatus*, known as kopi in the Chatham Islands) are very numerous in the Chatham Islands, and may have been a useful plant food to these people. Values for the kernel are 20, 12, and 45 g/100g respectively. Choosing a representative value for our Chatham Island example is not easy, but typical values for tī of 2.2, 6.0 and 30.0 g/100g respectively, are intermediate amongst those cited, and are used in Table 9. For the Chatham Island group, the contribution of plant foods to the diet is so small anyway (less than 14% of weight of daily intake, see Table 8), that it does not matter a great deal what nutritive values are chosen for the plant foods.

TABLE 9

Amount of nutritional components in ingested food g/100g
Chatham Island values. See text for further details.

Food 100g	**Protein g**	**Fat g**	**Carbohydrate g**
C3 Plants	2.0	6.0	30.0
Land Animals	16.0	29.0	0.1
Marine Shellfish	19.0	1.0	3.0
Marine Fish	20.0	2.0	0.1
Marine Mammals	14.0	22.0	2.0

The results of the simulation analysis, presented in Table 8, may be combined with the assumed values in Table 9 with simple arithmetic to produce representative estimates of protein, fat and carbohydrate for each of the main food types for the Chatham Islands group, together with their contribution to the energy budget. This information is given in Table 10.

TABLE 10
Estimated nutritional components in Chatham Island diet

Weight (g/day)	**Protein**	**Fat**	**Carb**	**Total**
C3 Plants	3.5	9.6	47.9	61.0
Land Animals	7.4	9.6	0.0	17.0
Marine Shellfish	5.1	0.4	1.2	6.7
Marine Fish	74.2	7.5	0.0	81.7
Marine Mammals	80.5	126.5	11.5	218.5
Totals	**170.8**	**153.6**	**60.6**	**385.0**
Percent	**44.4**	**39.9**	**15.7**	**100.0**
Energy (kcal/day)	**Protein**	**Fat**	**Carb**	**Total**
C3 Plants	11.3	68.8	153.0	233.1
Land Animals	12.8	37.1	0.0	49.9
Marine Shellfish	19.4	3.4	4.5	27.2
Marine Fish	306.8	70.0	0.0	376.8
Marine Mammals	322.0	1138.4	46.0	1506.4
Totals	**672.2**	**1317.7**	**203.4**	**2193.4**
Percent	**30.6**	**60.1**	**9.3**	**100.0**

The same simple calculations can be carried out on the other groups in this study, using the results of the simulation analysis in Table 8 and some assumptions about the nutritive value of common foods which would be available to each of these groups. The bottom line in these reconstructions is the proportions of the total energy deriving from protein, fat and carbohydrate. For the five groups being considered, these estimates are given in Table 11, and illustrated in Figure 16.

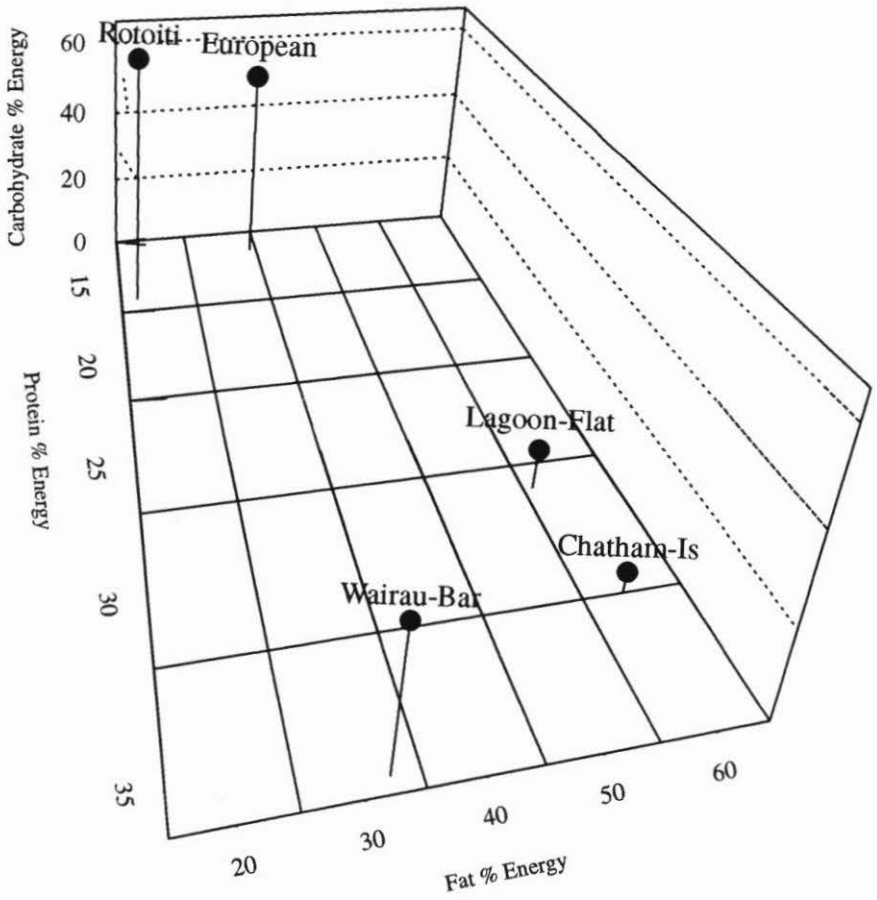

Figure 16: The relative proportion of energy deriving from protein, fat and carbohydrate in the five study groups.

TABLE 11

The main dietary constituents in select prehistoric groups
Percent of mean daily energy consumed

Group	Protein	Fat	Carbohydrate	Total	Total kcal/day
European	10.5	31.0	58.5	100	2447
Rotoiti	18.3	16.2	65.6	100	2409
Wairau Bar	36.6	31.8	31.6	100	1977
Lagoon Flat	30.5	60.3	9.2	100	2141
Chatham Is	30.6	60.1	9.3	100	2193

Again, for the sake of clarity, a worked example can be provided, to show the links between Tables 8, 9, 10, 11 and Figure 16. This is provided in Appendix 4.

The European person in this study is estimated to have eaten just over 1 kg of starchy foods each day (probably bread and potato), and nearly 600 g of land herbivore meat (probably sheep). There are very small signs of marine food, judged to have been fish, averaging only about 600 g per month.

The average diet at Rotoiti, in the interior of the North Island, is more like that of the European person than that of any of the other groups, and this might possibly be expected, given the inland location. However, some sea food is certainly present in the diet. Starchy plant food is assessed as about 1200 g per day, probably mostly kūmara and/or fern root. Some 280 g per day is from a terrestrial animal source, such as forest birds, rats, freshwater crayfish, etc. It is interesting that sea foods have contributed as much as 82 g of shellfish and 200 g of fish per day on average. This is a surprisingly high amount, but must provide evidence either that sea foods were being brought inland through a trade system, or that the people occasionally visited the coast and partook of large amounts of sea food at irregular intervals. The real situation could be a combination of both.

It is interesting to compare the diet of this inland New Zealand group with those of the Kitava people in the Trobriand Islands and the Baegu people of Malaita in the Pacific Islands, for which there is published information (Lindeberg and Vessby 1995; Ross 1976). All three groups gained a similar amount of energy from fat sources (about 18–21%), the Rotoiti people were better off as far as energy from protein sources is concerned (16% compared with 10–11% for the Pacific groups), and the Pacific Islanders had a somewhat greater share of energy from carbohydrate sources (69–75%), compared with the Rotoiti people (66%).

Despite the similarities, the Rotoiti people were able to gain access to rather more sea foods than their Pacific Island cousins. Their diet was also within recommended daily allowances for protein and fat, but slightly above that recommended for carbohydrates (55–60% of daily energy intake). Basically, this is a horticultural community with a well balanced diet. The general character of this diet does not represent a marked difference from that of the two Pacific Island societies mentioned.

Any similarity with the tropical Pacific ends at this point. The diets of the other three communities (Lagoon Flat, Wairau Bar and Chathams) illustrated in Figures 14 and 16 are quite different. Archaeological excavations in the Chatham Islands have revealed sites containing not only very large amounts of fish remains, but also large amounts of sea mammals. This is evident in the dietary reconstruction shown in Figure 14. Plant foods form a low proportion of this diet. Of some surprise is the finding that the Lagoon Flat individual had a similar diet to the Chatham Islands people. The Lagoon Flat site is a 'moa-hunting' site about 500 years old (Davidson 1984: 252), but these people must have had much easier access to sea mammals than moa, because food from these animals far exceeds the contribution from land herbivores.

The result from Wairau Bar is also very interesting. The reconstructed diet suggests that this individual, like the Lagoon Flat person, did not consume a significant amount of moa flesh. Some sea mammals were eaten, but fish represents by far the greatest component in the diet by weight of animal foods. It is also notable that food from plants was of greater significance to this individual than at Lagoon Flat.

There is still a widely held view that moa provided the main meat component of the diet of many early communities in New Zealand. This is not borne out by the isotope results from the two archaeological sites discussed here. In this respect, it is interesting to note that Smith (n.d.), reviewing 49 fully analysed faunal assemblages from 37 sites in New Zealand (excluding the Chatham Islands), found that fish followed by sea mammals were the main

sources of meat, with moa the principal source in only three of the assemblages studied (Kaupokonui, Pleasant River Early, and Papatowai Ush) (Smith n.d. Tables 5, 6).

In all the reconstructions presented in Figure 14, shellfish contribute only a minor portion of the overall diet. It would be interesting to see whether this was so for communities in the Auckland region or the Bay of Plenty, where sites with very large amounts of shellfish remains are found. The contribution of fish to these diets was significant at Wairau Bar, Lagoon Flat and in the Chatham Islands, but the results clearly show that marine mammals were a prominent item. An important point to remember here is that marine mammals provided access to fat, of paramount importance as a source of caloric energy in areas where carbohydrate-rich plants were in short supply.

The recommended daily allowances for protein, fat and carbohydrate can be expressed as a percentage of the total energy requirements. These are (after Leach n.d.):

Protein	10–15 %
Total Fat	≤30 %
Carbohydrate	55–60 %

These recommendations can be compared with the reconstructions presented in Figure 16 and Table 11. What this reveals is that with the exception of the Rotoiti people in the North Island, the pre-European Māori and Moriori had diets well outside recommended margins of safety. The Lagoon Flat and Chatham Island results are closely aligned with those of Arctic Inuit in that carbohydrate foods have been almost totally replaced as a source of food energy by fat, in this case from the blubber reserves of marine mammals. Of course the recommended daily allowances are only a guideline and the Inuit lead a perfectly normal life with such an extreme diet. We must conclude, therefore, that the unusual diet, evident at both Lagoon Flat and in the Chatham Islands, would have been satisfactory too. It is less certain whether the Wairau Bar individual, with by far the highest value of protein in this series, had a satisfactory diet. Unfortunately, little else is known about this individual.

CONCLUSIONS

The research discussed in this paper has taken place over an extended number of years, and during this period there have been significant new developments which have been taken advantage of as they occurred. Two have been particularly important. The first was the advent of continuous flow mass spectrometry, which has permitted very small samples to be analysed with similar precision and reproducibility as traditional mass spectrometry. Although this has not affected the analysis of ^{13}C or ^{15}N, it has revolutionised studies of natural abundance ^{34}S, and in particular in human bone collagen extracts. This has placed before archaeologists a powerful new tool, which enables the ambiguities inherent in diet reconstructions based on the former two isotopes alone to be resolved.

The second major development was the stochastic simulation method pioneered by Minagawa in Japan. Until this was formulated, dietary reconstructions were doomed to very simple interpretations at best — partitioning food into broad groups, such as that deriving from the sea or the land. By sacrificing exact quantitative solutions in favour of probability distributions, Minagawa's technique has opened the door to completely new avenues of dietary interpretation from archaeological sites. We can expect a greatly enhanced version of economic prehistory to emerge as a result. That is not to say that traditional forms of

economic archaeology, such as those based upon quantitative analysis of midden refuse, will become less important — on the contrary, they will continue to have a central role. Minagawa's method allows us for the first time to weave together seamlessly the results of midden analysis with isotope studies within the same mathematical model.

In this paper we provide a detailed description of the methods used to obtain collagen extract and sulphur-rich residues from samples of human bone from the tropical Pacific and New Zealand. Amino acid analysis was performed on some samples as a means of checking for potentially unreliable specimens which may have suffered diagenic changes, and also to quantify the amount of collagen in the acid-digested collagen extract using the amount of hydroxyproline present. Our collagen extracts are found to contain about 63% collagen; the remainder is not identified, but probably consists of non-collagenous proteins and bone sulphur-rich proteoglycans. The percent carbon, percent nitrogen, and atomic C/N ratio were examined on samples and compared with collagen extract yields, again as a means of identifying potentially unreliable samples with isotope values which may not reflect the original diet. It was found that the most reliable method for detecting unreliable samples was to plot samples on a graph of the C/N ratio against the percent nitrogen. These should lie along a straight line, with the regression equation Nitrogen % = -4.09 x C/N Ratio + 28.14, with a standard error of the estimate of ± 0.22%. In this way 13 specimens were found which may have misleading isotope results.

The $\delta^{13}C$ isotope values reported in this paper of select modern plants and animals from the Pacific and New Zealand show clear differentiation between the terrestrial and marine ecosystems. There are C4 plants present in the tropical Pacific, and these produce results in line with studies in other countries. It may not be widely appreciated that C4 plants could have played a significant economic role in some Pacific Island communities, and this is something to be kept in mind in future. Some of these plants, such as sugar cane, are directly consumed by humans. Other plants are significant foods for browsing animals such as wallaby and pigs, and humans eating the flesh of these animals will show a marine-looking $\delta^{13}C$ isotope signature. Additional isotopes which are not affected by this C3/C4 differentiation can be used to estimate the contribution which C4 plants may have made to specific diets. The $\delta^{13}C$ values for human and animal bone collagen extracts showed a similar range to the modern comparative collection, illustrating the range of diets present in the Pacific and New Zealand.

The $\delta^{15}N$ results for modern comparative material provide clear evidence of increasing value as one moves up trophic levels in the marine environment, as well as a clear difference from plants and animals from the land. This trophic level phenomenon provides the basis for estimating the amount of shellfish in human diet. The $\delta^{15}N$ values for humans showed greater variation within any one group than was present in the case of $\delta^{13}C$, but the reasons for this are not known at present. It is possible that this indicates diet differences within communities based on social factors such as gender or status. This is a matter for future investigation, when single communities are examined in detail.

The variation in $\delta^{34}S$ results gave the opposite pattern to $\delta^{15}N$, with a very narrow range for the entire marine ecosystem, and a much broader range for plants and animals on the land. This is due to sulphur of marine origin becoming incorporated in the metabolism of land plants through sea spray, and then getting into animals which browse on those plants. The $\delta^{34}S$ values for moa species were anomalous. While some irregular values may be attributed to diagenic change on the grounds that the amount of sulphur in collagen extract was far too high, indicating contamination from soil, others are not so easy to interpret. This is a case where considerable further research is required before a solution will be found. The

human bone $\delta^{34}S$ signatures do not show signs of any such anomalies, and the pattern and spread of results is reasonably in line with archaeological expectations.

The isotope results from five New Zealand human groups were then incorporated into the stochastic simulation method in order to estimate the relative abundance of five basic food types which would have contributed to their diets. Using some reasonable estimates of the amounts of protein, fat and carbohydrate in each of these five foods, the amounts of these three ingredients were then estimated for each of the five human groups. One of the values inherent in a simulation model is that one can easily adjust operational assumptions to observe what effect this has on the outcome. In this way, especially sensitive assumptions can be identified, and where necessary refined with further research. In the end, the final test of any model is whether the results conform to expectations, when tested against known conditions, for therein lies its predictive power when used in solving problems where the outcomes are completely unknown. This stochastic model can be used in both forward and reverse direction, and this is one of several useful tests. In the forward direction the known conditions are the isotope values and the unknown is the mix of five basic foods which might have produced this. In the reverse direction, the amount of each food is known and the isotope values are unknown. The stochastic model passes this test by producing near identical results in both directions.

The second test of whether the results conform to expectations is somewhat more difficult because here we are dealing with archaeological specimens, about which imperfect knowledge exists. However, the five human communities examined fall into two groups. The European person and the inland Rotoiti group were expected to show a strong emphasis on foods from the land, and this indeed was the outcome. The other three, Lagoon Flat, Wairau Bar and the Chatham Islands were expected to show clear signs of marine foods, and in this respect the outcome also conforms to expectations. It is known from archaeological studies of midden refuse in the Chatham Islands that the prehistoric people there consumed large amounts of sea mammals, and this was abundantly indicated in the simulation results. However, a very similar pattern was revealed for the Lagoon Flat individual, and this was somewhat surprising. Finally, the Wairau Bar specimen, although most closely aligned to the Lagoon Flat individual and the Chatham Islands group, also revealed significant intake of plant foods, and this was not expected. Whether this plant food was fern root or the carbohydrate rich product from cabbage tree or kūmara is not known at this stage. The first two certainly grow in abundance in the South Island, and it has recently been shown that traditional varieties of kūmara can be grown very successfully close to Wairau Bar (Harris *et al.* 2000). None of these possibilities can therefore be ruled out.

This research has been essentially exploratory in nature, using a broad brush approach covering the entire tropical and temperate areas of the Pacific, with human specimens ranging in age from 3,500 years to the nineteenth century. It has been aimed not at understanding the dietary habits of particular human communities in any detail, but at providing the framework which, it is hoped, will support this in the near future. However, one cannot help but comment on the preliminary findings relating to the Chatham Islands in particular. The results presented in Table 8 suggest that these people were obtaining 84% of their food from the sea (87% of their food energy). This is directly comparable to the Inuit of Alaska, whose diet is known to have been composed of nearly 85% marine mammals (Schoeninger *et al.* 1983: 1381). Isotope values for these people range from -12 to -14.5‰ for $\delta^{13}C$ and +17 to +20‰ for $\delta^{15}N$ (ibid.: 1382), and are very similar to those reported here for the Chatham Island people (there are no $\delta^{34}S$ results reported for Inuit). This points to a remarkable economic adaptation by a tropical Polynesian community,

finding themselves on a small island surrounded by temperate southern waters, presumably without the benefit of being able to grow any of the tropical root crop cultigens. It would be possible in the Chatham Islands to have developed an economy with a significant carbohydrate base to it, using fern root and/or karaka berries, but this did not apparently occur. Instead the abundant sea mammals in the region provided an energy source which is an acceptable alternative to carbohydrate, notably blubber from sea mammals. As both the Inuit and European arctic explorers have found, a diet consisting entirely of meat and blubber is perfectly satisfactory for long periods. But while the Inuit may have been forced to accept such an economic system through lack of choice, the Chatham Islanders had several choices in front of them, and chose to adopt an economy based on fat in preference to carbohydrate. In the southern parts of mainland New Zealand, environmental conditions are similar in many respects to the Chatham Islands; it remains to be seen whether the pioneers of this land adopted a similar or different economic strategy to the Chatham Islanders.

ACKNOWLEDGEMENTS

Although the bulk of the research reported in this paper was carried out from 1985 onwards, it began in April 1979 when the senior author first became aware of the potential use of stable isotope analysis for reconstructing diet from archaeological bones. The first samples analysed were dog bones from the Washpool site in Palliser Bay in New Zealand and from the Ban Chiang site in Thailand. We would like to acknowledge the early contributions made to this project by Hank Jansen and Charlie McGill at the then Institute of Nuclear Sciences in Lower Hutt. We would also like to thank Don Myers of the Wellcome Medical Research Institute, Otago Medical School for assistance with hydroxyproline determinations and useful discussions about amino acids in collagen; Diana Carne of the Protein Microchemistry Facility at the Department of Biochemistry, University of Otago, for amino acid analyses; and Trevor Worthy for useful comments on dates of natural moa deposits. A number of people provided much needed samples for analysis including Judith Huntsman, Department of Anthropology, University of Auckland; Ann Conray, Peter Smith and Larry Paul, National Institute of Water and Atmospheric Research; John Darby, Otago Museum; Phil Millener, then Curator of fossil birds at the National Museum of New Zealand; Richard Walter, Anthropology Department, University of Otago. The senior author would like to thank Misao Minagawa, Mitsubishi Kasei Institute of Life Sciences, Tokyo, for sharing unpublished information on his stochastic approach to isotopes and dietary research and for very useful discussions in his laboratory on the subject. The Scientific Distribution Committee of the New Zealand Lottery Grants Board gave financial support for this project, and we would like to express our gratitude for this.

APPENDIX 1: Catalogue of specimens analysed for ^{13}C, ^{15}N, and ^{34}S isotopes
(See Appendix 3 for further details on human bone samples)

AA346	*Cordyline australis* - Tī, Cabbage tree root, Dunedin
AA347	*Curcuma longa* - Turmeric Yellow, Auckland imported
AA348	*Curcuma longa* - Turmeric Red, Auckland imported
AA349	*Alocasia macrorrhiza* - Taro Kape, Auckland imported
AA350	*Saccharum officinarum* - Sugar cane, Auckland imported
AA351	*Colocasia esculenta* - Taro leaves, Auckland imported
AA352	*Cocos nucifera* - Coconut, Auckland imported
AA353	*Ipomoea batatas* - Yellow kūmara, Auckland
AA354	*Ipomoea batatas* - Yellow kūmara, Auckland
AA355	*Ipomoea batatas* - Yellow kūmara, Auckland
AA356	*Ipomoea batatas* - Yellow kūmara, Auckland
AA357	*Dioscorea* sp. - Yam, Auckland imported
AA358	*Colocasia esculenta* - Taro, Auckland imported
AA359	*Colocasia esculenta* - Taro, Auckland imported
AA360	*Canis familiaris* - Dog bone, Kohika D2 No. 5
AA488	*Altocarpus altilis* - Breadfruit, Auckland imported
AA489	*Piper methysticum* - Kava, Auckland imported
AA490	*Canis familiaris* - Dog Shag Mouth SM/C, L4
AA491	*Arctocephalus forsteri* - Fur Seal Shag Mouth, SM/C, L-7
AA492	*Phocarctos hookeri* - Sea Lion Shag Mouth, SM/C, F6, L-10
AA493	*Canis familiaris* - Dog modern Alsatian FA471, New Zealand
AA494	*Arctocephalus forsteri* - male Fur seal modern FA20, L humerus, Tautuku
AA495	*Phocarctos hookeri* - Sea Lion modern FA874, L Humerus, Enderby Island
AA496	*Casuarius* sp. - Cassowary tibiotarsus Te Papa uncatalogued
AA497	*Dinornis novaezelandiae* - Moa NMNZ S145, R tarsometatarsus
AA498	*Euryapteryx geranoides* - Moa NMNZ S317, R tibiotarsus, Matariki, Nelson
AA499	*Anomalopteryx didiformis* - Moa, NMNZ S96, L tibiotarsus, Castle Rock
AX1000	Human Nebira ACJ/2 PNG
AX848	Human Namu Burial 160 Taumako
AX852	*Bos taurus* - Modern cow bone
AX859	Human Rapanui rib 8-324 Ahu Kihi Kihi Rau Mea B1
AX860	Human Rapanui rib 8-324 Ahu Kihi Kihi Rau Mea B1
AX861	Human Rapanui rib 12-471a, Oroi Cave B1
AX862	Human Rapanui rib 12-469, Oroi Cave B1
AX863	Human Rapanui rib 12-469, Oroi Cave B2
AX864	Human Rapanui rib 31-1, Ahu Mahatua B2
AX865	Human Rapanui rib 14-21a, Ahu One Makihi B2
AX866	Human Rapanui rib 7-584, Ahu Akahanga B4A
AX867	Human Rapanui rib 7-598, Akahanga Cave B1
AX868	Human Rapanui rib 7-584, Ahu Akahanga B1
AX869	Human Rapanui rib 31-4, Mahatua Poe Poe B1
AX870	Human Rapanui rib 31-4, Mahatua Poe Poe B2
AX989	Human Nebira ACJ25 PNG
AX990	Human Nebira ACJ 30 PNG
AX991	Human [Nebira] POM 1 PNG
AX992	Human Nebira ACJ 10 PNG
AX993	Human Nebira ACJ 31 PNG
AX994	Human Nebira POM 22B 35 PNG
AX995	Human Nebira ACJ 11 PNG
AX996	Human [Nebira] AAK 3/15 PNG
AX997	Human [Nebira] POM 6 PNG
AX998	Human [Nebira] POM 9 PNG
AX999	Human Nebira ACJ 3 PNG
AY009	Human Atele TOAT1/34 young adult male subgroup A(1)

AA500	*Megalapteryx didinus* - Moa, NMNZ S447, L tibiotarsus, Takahe Valley
AA501	*Dinornis giganteus* - Moa, NMNZ S1015, L fibula, Takapau Road, Manakau
AA502	*Pachyornis mappini* - Moa, NMNZ S154, R Tibiotarsus, Makirikiri
AA503	*Euryapteryx curtus* - Moa, NMNZ S121, L tibiotarsus, Te Aute
AA504	*Dinornis struthoides* - Moa, NMNZ S108, R tarsometatarsus
AA505	*Pachyornis elephantopus* - Moa, NMNZ S196J, R tarsometatarsus
AA506	*Emeus crassus* - Moa, NMNZ S178, L tarsometatarsus
AA507	*Pachyornis australis* - Moa, NMNZ S25872, Part R ischium & 2 phalanges
AA508	Human Wairau Bar, SK390A, Burial 41A, R4745/2
AA509	Human Lagoon Flat, SK532, Conway River, R4745/1
AA510	Human European, 19th Century, Canterbury, Part distal R femur
AA553	Standard Plant
AA555	Human Kapingamarangi #1, parts of two femurs
AA556	Human Kapingamarangi #2 part femur
AA557	*Pandanus* sp. Auckland imported
AA563	*Aplodactylus meandratus* - Marblefish
AA569	*Odax pullus* - Greenbone
AA684	*Polyprion oxygeneios* - Groper
AA685	*Helicolenus* sp. - Sea Perch
AA686	*Nemadactylus macropterus* - Tarakihi
AA687	*Hoplostethus atlanticus* - Orange roughy
AA688	*Latridopsis ciliaris* - Blue moki
AA689	*Polyprion moeone* - Bass
AA690	*Hyperoglyphe antarctica* - Bluenose warehou
AA691	*Kathetostoma giganteum* - Giant stargazer
AA692	*Caprodon longimanus* - Pink maomao
AA693	*Beryx splendens* - Afonsino
AA694	*Centroberyx affinis* - Red snapper
AA695	*Genypterus blacodes* - Ling
AA696	*Plagiogeneion rubiginosus* - Ruby Fish
AY010	Human Atele TOAT 1/10 adult male subgroup A(4)
AY011	Human Atele TOAT 1/14 adolescent unsexed subgroup A(4)
AY012	Human Atele TOAT 1/6 middle aged male subgroup B(7)
AY013	Human Atele TOAT 2/25 adult female period 4
AY014	Human Atele TOAT 2/30 adult female period 4
AY015	Human Atele TOAT 1/19 adult unsexed subgroup A(3)
AY016	Human Atele TOAT 2/42 adult male period 5
AY017	Human Atele TOAT 2/18 old male period 4
AY018	Human Atele TOAT 2/6 young male period 3
AY019	Human Atele TOAT 1/29A adult male subgroup A(1)
AY020	Human Atele TOAT 2/40A old female period 2
AY021	Human Atele TOAT 1/7 aged male subgroup B(6)
AY022	Human Atele TOAT 2/41 old male period 2
AY023	Human Atele TOAT 2/4 middle aged female period 4
AY024	Human Atele TOAT 2/27 adult female period 2
AY025	Human Atele TOAT 1/11 adult female subgroup A(4)
AY026	Human Atele TOAT 2/26 adult female period 2
AY027	Human Atele TOAT 2/11 adult female period 4
AY028	Human Atele TOAT 2/1C middle to old female period 4
AY035	Human Nebira ACJ 43 PNG
AY036	Human Nebira ACJ 04 PNG
AY037	Human Nebira ACJ 17 PNG
AY038	Human Nebira ACJ 20 PNG
AY039	Human Chathams E25
AY040	Human Chathams E26
AY041	Human Chathams E27
AY042	Human Chathams E32
AY043	Human Chathams E34
AY044	Human Chathams E171 Waihora Burial 1
AY045	Human Chathams E172 Waihora Burial 2 AD 1500

AA697 *Pagrus auratus* - Snapper
AA698 *Tiostrea lutaria* - Dredge oyster, Tasman Bay
AA699 *Crassostrea gigas* - Pacific oyster
AA700 *Notolabrus celidotus* - Spotty
AA701 *Notodarus* sp. - Squid
AA702 *Mactra discors* - surf clam
AA703 *Mactra murchisoni* - surf clam
AA704 *Bassina yatei* - surf clam
AA705 *Benhamina obliquata* - False Limpet
AA706 *Paratrachichthys trailli* - Common roughy
AA707 *Pseudophycis bachus* - Red cod
AA708 *Zeus faber* - John Dory
AA709 *Galeorhinus australis* - School shark
AA710 *Pseudocaranx dentex* - Trevally
AA711 *Parika scaber* - Leatherjacket
AA712 *Trachurus declivis* - Jack mackerel
AA713 *Chelidonichthys kumu* - Red gurnard
AA714 *Parapercis colias* - Blue Cod
AA715 *Pelotretis flavilatus* - Lemon sole
AA716 *Peltorhamphus novaezeelandidae* - Common sole
AA717 *Seriolella brama* - Common warehou
AA718 *Conger verreauxi* - Conger eel
AA719 *Galaxias maculatus* - Inanga whitebait, Otaki
AA721 *Rattus exulans* - Male Polynesian rat flesh, Tiritiri Matangi Is.
AA723 *Megadyptes antipodes* - Yellow-eyed penguin, Otago Pen.
AA724 *Hemiphaga novaeseelandiae* - Pigeon flesh, Kaikoura
AA725 Human Natunuku Fiji
AA726 *Paranephrops zealandicus* - Freshwater Crayfish Otago
AA727 Human New Caledonia Site 13, WKO-013B
AA736 *Puffinus griseus* - Muttonbird flesh

AY046 Human Chathams E173 Waihora Burial 3 AD 1800
AY047 Human Chathams E174 Waihora Burial 4
AY048 Human Rotoiti E83/1
AY049 Human Rotoiti E83/2
AY050 Human Rotoiti E83/3
AY051 Human Rotoiti E83/4
AY052 Human Rotoiti E83/5
AY053 Human Rotoiti E83/6
AY054 Human Rotoiti E83/7
AY055 Human Rotoiti E83/8
AY056 Human Watom SAC 01 PNG
AY057 Human Watom SAC 03 PNG
AY058 Human Watom SAC 04 PNG
AY059 Human Watom SAC 05 PNG
AY060 Human Watom SAC 06 PNG
AY061 Human Watom SAC 07 PNG
AY062 Human Namu 01 Taumako
AY063 Human Namu 23 Taumako
AY064 Human Namu 32 Taumako
AY065 Human Namu 35 Taumako
AY066 Human Namu 37 Taumako
AY067 Human Namu 48 Taumako
AY068 Human Namu 57 Taumako
AY069 Human Namu 63 Taumako
AY070 Human Namu 64 Taumako
AY071 Human Namu 73 Taumako
AY072 Human Namu 85 Taumako
AY073 Human Namu 87 Taumako
AY074 Human Namu 88 Taumako
AY075 Human Namu 89 Taumako

AA737	*Perna canaliculus* - Green mussel, Marlborough
AA740	*Pecten novaezelandiae* - Scallop, Coromandel Pen.
AA741	*Macruronus novaezelandiae* - Hoki, Cook Strait
AA742	*Paphies donacina* - Subtidal tuatua, Cloudy Bay
AA767	*Dosinia anus* - surf clam, Cloudy Bay
AA779	*Paphies subtriangulata* - Intertidal tuatua, Otaki
AA788	*Evechinus chloroticus* - Kina, Chatham Islands
AB289	*Alectryon excelsus* - Titoki seed
AB301	*Myripristis berndti* - Squirrel fish flesh Cook Is
AB302	*Acanthurus olivaceus* - surgeon fish flesh Cook Is
AB303	*Cypselurus simus* - Flying fish flesh Cook Is
AB304	*Ctenochaetus striatus* - Surgeonfish flesh Cook Is
AB305	*Priacanthus cruentatus* - Red globe eye flesh Cook Is
AB306	*Cephalopholis argus* - Blue spotted grouper flesh Cook Is
AB307	*Diodon hystrix* - Puffer fish flesh Cook Is
AB308	*Acanthurus achilles* - Surgeonfish flesh Cook Is
AB309	*Decapterus pinnulatus* - Mackerel scad flesh Cook Is
AB310	*Pomacanthus imperator* - Emperor Anglefish flesh Cook Is
AB311	*Siganus spinus* - Rabbitfish flesh Cook Is
AB312	*Calotomus* sp. - Parrotfish flesh Cook Is
AB340	Human fragments Faroe Islands
AB343	Human fragments Faroe Islands
AB344	Human fragments Faroe Islands
AB345	Human fragments Faroe Islands
AB346	Human fragments Faroe Islands
AB348	Human fragments Faroe Islands
AI093	Human femur New Caledonia Tina 1
AI094	Human femur New Caledonia Tina 2
AI331	*Corynocarpus laevigatus* - Karaka kernel
AI332	*Corynocarpus laevigatus* - Karaka fruit
AY076	Human Namu 90 Taumako
AY077	Human Namu 91 Taumako
AY078	Human Namu 94 Taumako
AY079	Human Namu 95 Taumako
AY080	Human Namu 103 Taumako
AY081	Human Namu 104 Taumako
AY082	Human Lakeba Wakea, Lau Islands
AY083	Bone Standard
AY488	Human Motupore fragments Burial M3 H16-11 SK 1
AY489	Human Motupore fragments Burial K21-3-4
AY490	Human Motupore fragments Burial I17-111 SK 2
AY491	Human Motupore fragments Burial M27 H16/11-1V/2 SK 1
AY492	Human Motupore fragments Burial I 17/III SK 1
AY493	Human Motupore fragments Burial K20-III-5
AY494	Human Motupore fragments Burial K21-III-2, Pit A
AY495	Human Motupore fragments Burial H 17-111
AY496	Human Motupore fragments Burial I16-4 WP SK 1
AY497	Human Motupore fragments Burial K20/IVSB/2
AY498	Human Motupore fragments Burial M47 I/17/11/4
AY499	Human Motupore fragments Burial M1 H16-5B SK-1
AY500	Human Motupore fragments Burial K20/III/3
AY501	Human Motupore fragments Burial G16/IV/6
AY774	Human Tonga Pea To-1 rib
AY778	Human Tinian Latte House
AY779	Human Tinian Latte House
AY780	Human Tinian Latte House
AY781	Human Saipan Latte House
AY782	Human Saipan Marianas High School
AY784	Human Lakeba Wakea, 196-28-B8, below complete burial
AY785	Human Lakeba Qaranipuqa, 197-1-M-9

AI333	*Altocarpus altilis* - Breadfruit dried 'Nambu' Taumako
AT083	*Makaira mazara* - Blue marlin bone Marianas
AX002	*Dugong dugon* - Sea cow bone, Motupore AAK/1
AX004	Turtle bone (*Chelonia mydas* or *Eretmochelys imbricata*, Motupore, AAK/1
AX006	*Macropterus agilis* - Wallaby bone, Motupore, AAK/1
AX008	*Phocarctos hookeri* - Sea Lion bone, Auckland Is
AY785B	Human Lakeba Qaranipuqa, 197-1-M-9 Burnt
AY786	Human Lakeba Qaranipuqa, 197-3-C Top of rockshelter
AY787	Human Sigatoka (S Best) Fiji
R11560	*Imperata cylindrica* - Kunai PNG
REF	Standard Sucrose

APPENDIX 2: Isotope Results for Archaeological Bones and Modern Fauna and Flora

Abbreviations:

AIT	Auckland Institute of Technology
INS	Institute of Nuclear Sciences, Lower Hutt (now part of Institute of Geological and Nuclear Sciences)
MIM	Micromass UK Ltd
OXF	Research Laboratory for Archaeology and the History of Art, Oxford
WAI	Waikato University Isotopes Laboratory
*	Indicates specimens with yaws disease
†	Indicates bone powder used for $\delta^{15}N$ analysis

^{13}C Results

-26.1	AA346	WAI
-27.6	AA347	WAI
-28.4	AA347	WAI
-28.5	AA347	INS
-27.6	AA348	WAI
-28.1	AA348	INS
-28.1	AA348	INS
-25.0	AA349	WAI
-25.6	AA349	INS
-25.6	AA349	INS
-11.3	AA350	WAI
-11.6	AA350	INS
-27.4	AA351	WAI
-28.0	AA351	INS
-24.9	AA352	WAI
-26.8	AA353	WAI
-27.3	AA353	INS
-27.4	AA353	INS
-26.2	AA354	WAI
-26.7	AA354	INS
-26.8	AA354	INS
-26.2	AA355	WAI
-26.8	AA355	INS
-25.9	AA356	WAI
-26.6	AA356	INS
-26.6	AA356	INS
-27.4	AA357	WAI
-27.7	AA357	INS
-27.2	AA358	WAI
-27.8	AA358	INS
-26.9	AA359	WAI
-27.5	AA359	INS
-17.6	AA360	WAI
-24.6	AA488	WAI
-25.3	AA488	INS
-25.8	AA489	WAI
-26.0	AA489	INS
-17.1	AA490	WAI
-14.3	AA491	WAI
-13.1	AA492	WAI
-21.4	AA493	WAI
-21.0	AA493	WAI
-12.9	AA494	WAI
-12.9	AA494	WAI
-13.0	AA495	WAI
-13.1	AA495	WAI
-20.3	AA496	WAI
-23.8	AA497	WAI
-22.4	AA498	WAI
-21.7	AA499	WAI
-21.7	AA500	WAI
-23.9	AA501	WAI
-25.0	AA502	WAI
-23.8	AA503	WAI
-21.7	AA504	WAI
-23.2	AA505	WAI
-23.6	AA506	WAI
-21.3	AA507	WAI
-15.9	AA508	WAI
-15.6	AA509	WAI
-19.7	AA510	WAI
-25.3	AA553	INS
-25.0	AA553	WAI
-25.1	AA553	WAI
-25.6	AA553	INS
-25.6	AA553	INS
-25.1	AA553	WAI
-16.0	AA555	WAI
-15.3	AA556	WAI
-27.9	AA557	WAI
-27.8	AA563	WAI
-14.9	AA569	WAI
-18.0	AA684	WAI
-15.9	AA685	WAI
-15.6	AA686	WAI
-17.4	AA687	WAI
-15.9	AA688	WAI
-16.2	AA689	WAI
-17.3	AA690	WAI
-15.9	AA691	WAI
-19.0	AA692	WAI
-19.6	AA693	WAI
-18.0	AA694	WAI
-15.1	AA695	WAI
-16.9	AA696	WAI
-15.3	AA697	WAI
-20.1	AA698	WAI
-18.3	AA699	WAI
-16.5	AA700	WAI
-18.9	AA701	WAI
-16.1	AA702	WAI
-16.5	AA703	WAI
-18.1	AA704	WAI
-17.7	AA705	WAI
-16.4	AA706	WAI
-18.4	AA707	WAI
-17.5	AA708	WAI
-16.9	AA709	WAI
-17.3	AA710	WAI
-18.2	AA711	WAI
-17.6	AA712	WAI
-18.1	AA713	WAI
-18.0	AA714	WAI
-17.9	AA715	WAI
-17.6	AA716	WAI
-18.2	AA717	WAI
-15.8	AA718	WAI
-19.5	AA719	WAI
-21.0	AA721	WAI
-19.6	AA723	WAI
-27.1	AA724	WAI
-14.6	AA725	WAI
-24.0	AA726	WAI
-9.6	AA727	OXF
-11.7	AA727	WAI
-11.8	AA727	WAI
-12.1	AA727	WAI
-12.3	AA727	WAI
-14.4	AA727	INS
-23.4	AA736	WAI
-17.6	AA737	WAI
-16.7	AA740	WAI
-16.8	AA741	WAI
-16.4	AA742	WAI
-16.0	AA767	WAI
-15.5	AA779	WAI
-17.7	AA788	WAI
-14.9	AI093	WAI
-15.3	AI094	WAI
-1.8	AX002	WAI
-1.9	AX002	INS
-2.0	AX002	INS
-10.4	AX004	INS
-10.4	AX004	INS
-9.5	AX006	INS
-13.2	AX008	INS
-13.4	AX008	WAI
-13.5	AX008	INS
-15.8	AX848	INS
-22.5	AX852	INS
-18.1	AX859	INS
-18.8	AX860	INS
-19.3	AX861	INS
-17.4	AX865	INS
-14.5	AX990	INS
-17.3	AX994	INS
-17.2	AX994	WAI
-17.4	AY009	INS
-17.8	AY022	INS
-18.8	AY025	INS
-17.7	AY028	INS
-17.4	AY028	WAI
-14.4	AY039	INS
-13.5	AY040	INS
-16.2	AY041	INS
-15.8	AY041	WAI
-13.3	AY043	INS
-14.8	AY045	INS
-17.9	AY050	INS
-17.6	AY051	INS
-18.2	AY052	INS
-17.7	AY052	WAI
-19.6	AY053	INS
-18.3	AY057	INS
-18.2	AY058	INS
-18.4	AY058	WAI
-17.6	AY059	INS
-17.9	AY067	INS
-17.6	AY069	INS
-17.0	AY069	WAI
-16.5	AY082	INS
-17.5	AY083	WAI
-17.6	AY083	WAI
-17.8	AY083	WAI
-17.9	AY083	WAI
-18.0	AY083	INS
-18.0	AY083	WAI
-18.0	AY083	WAI
-18.3	AY083	WAI
-18.3	AY083	WAI
-15.7	AY498	INS

-13.3	AY499	INS
-13.3	AY499	WAI
-15.4	AY774	INS
-18.0	AY778	INS
-17.8	AY779	INS
-18.1	AY780	INS
-18.2	AY780	WAI
-19.4	AY781	INS
-17.9	AY782	INS
-18.0	AY782	WAI
-15.8	AY784	INS
-13.4	AY785	INS
-16.4	AY785B	INS
-15.9	AY786	INS
-15.6	AY786	WAI
-19.5	AY787	INS
-10.9	R11560	INS
-10.8	REF	WAI
-10.6	REF	WAI
-10.7	REF	WAI
-10.7	REF	WAI

^{15}N Results

3.7	AA347	WAI
3.3	AA348	WAI
1.8	AA349	WAI
3.5	AA350	WAI
6.0	AA351	WAI
3.5	AA352	WAI
3.8	AA353	WAI
6.4	AA354	WAI
1.2	AA355	WAI
4.6	AA356	WAI
3.6	AA357	WAI
4.9	AA358	WAI
0.3	AA359	WAI
11.3	AA360	WAI
5.6	AA488	WAI
3.9	AA489	WAI
14.3	AA490	WAI
14.7	AA491	WAI
16.8	AA492	WAI
8.3	AA493	WAI
8.5	AA493	WAI
15.9	AA494	WAI
15.5	AA494	WAI
14.8	AA495	WAI
16.3	AA495	WAI
9.4	AA496	WAI
1.3	AA497	WAI
3.0	AA498	WAI
6.0	AA499	WAI
2.3	AA500	WAI
3.5	AA501	WAI
5.5	AA502	WAI
5.5	AA503	WAI
8.5	AA504	WAI
2.0	AA505	WAI
4.2	AA506	WAI
2.0	AA507	WAI
16.0	AA508	WAI
18.5	AA509	WAI
9.2	AA510	WAI
2.0	AA553	WAI
4.3	AA553	WAI
20.0	AA555	WAI
20.2	AA556	WAI
11.3	AA563	WAI
9.2	AA569	WAI
15.9	AA684	WAI
14.0	AA685	WAI
13.7	AA686	WAI
13.9	AA687	WAI
12.4	AA688	WAI
15.8	AA689	WAI
18.7	AA690	WAI
14.9	AA691	WAI
11.8	AA692	WAI
14.7	AA693	WAI
14.0	AA694	WAI
16.4	AA695	WAI
15.0	AA696	WAI
13.7	AA697	WAI
9.8	AA698	WAI
10.1	AA699	WAI
14.4	AA700	WAI
11.7	AA701	WAI
9.4	AA702	WAI
8.8	AA703	WAI
7.9	AA704	WAI
11.9	AA705	WAI
14.3	AA706	WAI
13.8	AA707	WAI
15.4	AA708	WAI
13.0	AA709	WAI
12.0	AA710	WAI
11.3	AA711	WAI
12.7	AA712	WAI
12.0	AA713	WAI
11.3	AA714	WAI
11.0	AA715	WAI
12.2	AA716	WAI
12.9	AA717	WAI
14.1	AA718	WAI
8.8	AA719	WAI
9.6	AA721	WAI
7.9	AA723	WAI
2.4	AA724	WAI
7.4	AA725	WAI
5.7	AA726	WAI
11.0	AA727	WAI
10.7	AA727	WAI
11.5	AA727	WAI
11.1	AA727	WAI
13.1	AA736	WAI
7.6	AA737	WAI
10.3	AA740	WAI
13.4	AA741	WAI
9.0	AA742	WAI
10.7	AA767	WAI
8.8	AA779	WAI
9.6	AA788	WAI
10.2	AI093	WAI
9.3	AI094	WAI
6.4	AX002	WAI
8.0†	AX002	WAI
21.7†	AX004	WAI
5.6†	AX006	WAI
16.3	AX008	WAI
18.1†	AX008	WAI
9.4†	AX1000	WAI
9.4	AX848	WAI
10.7†	AX848	WAI
8.7†	AX852	WAI
13.4†	AX859	WAI
13.5†	AX860	WAI
13.8†	AX861	WAI
11.9†	AX862	WAI
13.1†	AX863	WAI
14.1†	AX864	WAI
13.1†	AX865	WAI
13.7†	AX866	WAI
12.7†	AX867	WAI
13.9†	AX868	WAI
14.4†	AX868	WAI
13.7†	AX869	WAI
15.1†	AX870	WAI
11.3†	AX989	WAI
10.8	AX990	WAI
12.8†	AX990	WAI
10.8†	AX991	WAI
11.8†	AX992	WAI
11.9†	AX993	WAI
11.2	AX994	WAI
11.1†	AX994	WAI
11.0†	AX994	WAI
10.1	AX994	WAI
11.2†	AX995	WAI
10.2†	AX996	WAI
10.2†	AX997	WAI
11.6†	AX997	WAI
10.6†	AX998	WAI
10.6†	AX999	WAI
12.6†	AY009	WAI
10.9	AY009	WAI
10.0†	AY010	WAI
10.3†	AY011	WAI
10.6†	AY011	WAI
10.8†	AY012	WAI
11.6†	AY012	WAI
11.9†	AY013	WAI
10.2†	AY014	WAI
9.9†	AY015	WAI
10.6†	AY016	WAI
10.6†	AY017	WAI
9.3†	AY018	WAI
10.5†	AY019	WAI
10.2†	AY020	WAI
9.4†	AY021	WAI
10.9†	AY022	WAI
9.3†	AY023	WAI
9.8†	AY023	WAI
10.0†	AY024	WAI
9.4	AY025	WAI
8.3†	AY025	WAI
9.3†	AY026	WAI
9.4†	AY027	WAI
10.3†	AY028	WAI
10.5	AY028	WAI
10.8†	AY035	WAI
10.7†	AY036	WAI
10.1†	AY037	WAI
10.9†	AY038	WAI
17.1†	AY039	WAI
16.5	AY039	WAI
16.1†	AY039	WAI
16.1	AY039	WAI
20.3†	AY040	WAI
18.7	AY041	WAI
19.2†	AY041	WAI
18.4	AY041	WAI
18.0†	AY042	WAI
17.7†	AY043	WAI
17.1†	AY044	WAI
17.0†	AY045	WAI
17.4†	AY046	WAI
17.6†	AY047	WAI
11.4†	AY048	WAI
12.1†	AY049	WAI
10.8†	AY050	WAI
12.3†	AY050	WAI
12.3†	AY051	WAI
14.7	AY051	WAI
12.1	AY051	WAI
12.5†	AY052	WAI
11.9	AY052	WAI
9.7†	AY053	WAI
12.4†	AY054	WAI
12.6†	AY055	WAI
11.7†	AY056	WAI
11.9	AY057	WAI
12.4	AY057	WAI
12.9†	AY057	WAI
5.8†	AY058	WAI
10.3†	AY058	WAI
10.8	AY058	WAI
10.9†	AY059	WAI
14.9†	AY060	WAI
9.7†	AY061	WAI
11.6†	AY062	WAI
12.5†	AY063	WAI
10.8†	AY064	WAI
10.2†	AY064	WAI
11.1	AY065	WAI
13.0†	AY065	WAI
6.3	AY066	WAI
11.6†	AY066	WAI
11.4†	AY067	WAI
12.1	AY067	WAI
8.7	AY068	WAI
10.3†	AY068	WAI
11.2†	AY069	WAI
12.0	AY069	WAI
10.6	AY069	WAI

5.2†	AY070	WAI
7.9†	AY070	WAI
12.9†	AY071	WAI
8.4†	AY072	WAI
11.1	AY073	WAI
12.8†	AY073	WAI
12.2†	AY074	WAI
10.7†	AY075	WAI
12.1†	AY076	WAI
12.7†	AY077	WAI
12.4†	AY078	WAI
11.3†	AY079	WAI
10.9†	AY080	WAI
10.1†	AY081	WAI
10.3†	AY082	WAI
10.6†	AY083	WAI
10.6†	AY083	WAI
10.7	AY083	WAI
10.8	AY083	WAI
11.0†	AY083	WAI
11.6†	AY083	WAI
11.6	AY083	WAI
11.7†	AY083	WAI
11.7	AY083	WAI
10.7	AY083	WAI
10.9	AY083	WAI
10.5	AY083	WAI
11.0	AY083	WAI
12.8†	AY083	WAI
10.6	AY083	WAI
10.5	AY083	WAI
10.5	AY083	WAI
10.5	AY083	WAI
12.9†	AY488	WAI
12.9†	AY489	WAI
12.2†	AY490	WAI
11.3†	AY491	WAI
10.2†	AY492	WAI
10.5†	AY493	WAI
12.3†	AY494	WAI
13.2†	AY494	WAI
12.1†	AY495	WAI
12.7†	AY495	WAI
12.3†	AY496	WAI
12.2†	AY496	WAI
12.2†	AY497	WAI
12.5†	AY498	WAI
11.4	AY498	WAI
9.5†	AY499	WAI
11.0	AY499	WAI
10.3	AY499	WAI
9.8†	AY500	WAI
6.6†	AY501	WAI
10.3†	AY774	WAI
12.4†	AY778	WAI
11.9†	AY779	WAI
10.0†	AY780	WAI
9.2	AY780	WAI
11.5†	AY781	WAI
13.2†	AY782	WAI
9.9	AY782	WAI
11.7†	AY784	WAI
11.3†	AY785	WAI
12.7†	AY785B	WAI
10.1†	AY786	WAI
8.7	AY786	WAI
9.8†	AY787	WAI

^{34}S Results

7.3	AA346	MIM
12.0	AA347	MIM
12.8	AA347	AIT
11.3	AA347	INS
14.0	AA348	AIT
1.3	AA348	INS
3.4	AA348	MIM
17.1	AA349	INS
7.7	AA350	MIM
9.8	AA350	INS
13.4	AA351	MIM
13.6	AA351	INS
15.0	AA352	MIM
6.2	AA353	MIM
-0.1	AA353	INS
6.4	AA354	INS
5.4	AA355	AIT
4.0	AA355	INS
5.8	AA356	MIM
4.5	AA356	INS
14.3	AA357	MIM
18.1	AA357	AIT
17.0	AA357	INS
12.3	AA358	MIM
9.8	AA358	INS
10.1	AA359	INS
8.5	AA360	MIM
14.4	AA488	MIM
10.1	AA488	INS
14.4	AA489	INS
13.7	AA490	MIM
15.5	AA491	MIM
13.9	AA492	MIM
7.5	AA493	MIM
7.6	AA493	MIM
8.4	AA493	MIM
15.2	AA494	MIM
16.0	AA494	MIM
14.6	AA495	MIM
17.0	AA495	AIT
15.0	AA495	MIM
7.4	AA496	MIM
6.6	AA497	MIM
14.0	AA499	MIM
3.6	AA500	MIM
11.2	AA500	MIM
15.0	AA501	MIM
-32.6	AA502	MIM
-32.3	AA502	MIM
-33.4	AA503	MIM
-33.2	AA503	MIM
-4.3	AA504	MIM
-3.8	AA504	MIM
0.6	AA505	MIM
1.3	AA505	MIM
5.7	AA506	MIM
6.5	AA506	MIM
12.3	AA507	MIM
13.2	AA508	MIM
13.3	AA508	AIT
15.1	AA509	MIM
2.9	AA510	MIM
16.1	AA553	AIT
16.4	AA553	AIT
16.7	AA553	AIT
17.1	AA553	AIT
17.5	AA553	AIT
16.7	AA553	INS
15.0	AA553	INS
15.9	AA553	INS
16.1	AA553	INS
14.6	AA553	INS
15.0	AA553	INS
15.8	AA553	INS
16.6	AA553	INS
15.8	AA553	INS
16.0	AA553	INS
15.7	AA553	INS
16.2	AA553	INS
15.8	AA553	INS
17.6	AA553	MIM
15.1	AA555	MIM
11.7	AA555	AIT
15.5	AA556	MIM
15.7	AA557	MIM
17.6	AA563	MIM
17.2	AA569	MIM
17.2	AA684	MIM
17.3	AA685	MIM
17.0	AA686	MIM
17.2	AA687	MIM
16.7	AA688	MIM
19.3	AA689	MIM
18.5	AA690	MIM
17.1	AA691	MIM
18.5	AA692	MIM
17.4	AA694	MIM
16.2	AA695	MIM
17.9	AA696	MIM
16.9	AA697	MIM
18.4	AA697	AIT
19.3	AA698	MIM
18.6	AA699	MIM
19.0	AA700	MIM
19.7	AA701	MIM
17.7	AA702	MIM
18.1	AA703	MIM
18.5	AA704	MIM
18.9	AA705	MIM
18.1	AA706	MIM
17.3	AA707	MIM
18.0	AA708	MIM
17.6	AA708	AIT
17.1	AA709	MIM
15.6	AA710	MIM
18.6	AA710	AIT
19.0	AA711	MIM
16.7	AA712	MIM
16.9	AA713	MIM
16.4	AA714	MIM
16.2	AA715	MIM
16.5	AA715	MIM
15.9	AA716	MIM
17.4	AA717	MIM
16.5	AA718	MIM
18.4	AA719	MIM
14.3	AA721	MIM
18.7	AA723	MIM
5.8	AA724	MIM
13.1	AA725	MIM
17.5	AA726	MIM
17.0	AA726	MIM
13.4	AA727	MIM
17.6	AA736	MIM
17.9	AA737	MIM
18.3	AA740	MIM
17.3	AA741	MIM
19.2	AA742	MIM
17.6	AA767	MIM
17.3	AA779	MIM
17.5	AA788	MIM
15.7	AB289	MIM
18.6	AB301	MIM
18.2	AB302	MIM
17.3	AB303	MIM
18.3	AB304	MIM
19.1	AB305	MIM
18.6	AB306	MIM
17.8	AB307	MIM
17.4	AB308	MIM
17.7	AB309	MIM
18.2	AB310	MIM
17.7	AB311	MIM
16.4	AB312	MIM
16.7	AB340	MIM
15.3	AB343	MIM
17.4	AB344	MIM
17.1	AB345	MIM
16.9	AB346	MIM
17.5	AB348	MIM
11.7	AI093	MIM
14.1	AI094	MIM
8.3	AI331	MIM
6.4	AI332	MIM
12.0	AI333	MIM
19.7	AT083	MIM
9.2	AX002	MIM
9.8	AX002	INS
13.0	AX004	INS
15.3	AX008	MIM
16.4	AX008	INS
11.1	AX848	INS
12.3	AX852	INS
14.4	AX860	INS
1.8	AX990	INS

4.3	AX994	INS	**Taumako (All INS)**				
3.4	AX994	MIM	**$\delta^{13}C$**	**C/N**	**Burial**		
11.4	AY009	INS	16.6	2.8	001	Tibia	
12.2	AY022	INS	16.8	3.1	016	Tibia	
14.6	AY025	INS	17.2	3.7	106	Tibia	
13.1	AY028	INS	16.6	3.3	110	Tibia	
12.3	AY028	MIM	15.7	3.1	140	Femur*	
14.1	AY039	INS	16.3	2.4	145	Tibia	
17.0	AY040	MIM	16.2	3.0	146	Femur	
15.5	AY040	INS	16.4	3.1	147	Femur	
14.4	AY041	MIM	16.1	3.0	148	Femur	
17.5	AY041	INS	16.4	2.8	159	Tibia	
15.5	AY043	INS	16.6	3.0	179	Fibula	
16.1	AY045	INS	16.5	2.9	184	Femur	
5.9	AY050	INS	14.8	3.1	187	Tibia	
-2.9	AY051	INS	16.5	2.9	188	Humerus*	
4.8	AY052	INS	16.2	2.6	188	Ulna*	
4.1	AY052	MIM	17.3	2.7	196	Tibia	
4.1	AY053	INS	17.1	2.8	197	Tibia	
6.3	AY054	MIM	16.8	2.9	216	Tibia	
11.5	AY057	INS					
8.3	AY058	INS	**Nebira (All INS)**				
13.0	AY058	MIM	**$\delta^{13}C$**	**C/N**	**Burial**		
15.6	AY067	INS	17.1	3.2	01	Radius	
13.7	AY069	MIM	15.4	3.1	02	Fibula	
16.9	AY069	INS	14.2	3.5	03	Fibula	
16.0	AY083	INS	16.1	3.3	09	Fibula	
10.9	AY498	INS	15.3	3.9	10	Fibula	
11.8	AY499	INS	16.6	3.0	11	Fibula	
11.2	AY499	MIM	15.8	3.5	12	Fibula	
12.5	AY774	INS	16.9	3.4	16	Fibula	
14.5	AY778	INS	15.8	3.8	17	Radius	
16.9	AY779	INS	17.2	3.4	20	Fibula	
15.4	AY780	INS	17.1	3.1	23	Fibula	
13.7	AY780	MIM	17.4	3.1	24	Fibula	
17.6	AY781	INS	17.3	3.1	25	Radius	
14.5	AY782	INS	14.6	3.3	30	Fibula	
13.7	AY782	MIM	15.8	3.5	31	Fibula	
15.9	AY784	INS	17.2	3.7	35	Scapula	
13.1	AY786	MIM	16.6	3.1	38	Tibia	
13.4	AY786	INS	16.9	3.5	40	Tibia	
			17.7	3.4	43	Fibula	

Rat Coprolites			
$\delta^{13}C$			
-26.57	AL461	WAI	
-25.94	AL462	WAI	
-24.99	AL463	WAI	
-25.35	AL464	WAI	
-25.91	AL465	WAI	
-23.52	AL466	WAI	
-24.16	AL467	WAI	
-25.05	AL468	WAI	
-25.92	AL469	WAI	
-24.61	AL470	WAI	
Rat Coprolites			
$\delta^{15}N$			
8.26	AL461	WAI	
8.53	AL462	WAI	
8.32	AL463	WAI	
8.01	AL464	WAI	
7.61	AL465	WAI	
8.36	AL466	WAI	
9.81	AL467	WAI	
8.65	AL468	WAI	
8.24	AL469	WAI	
9.49	AL470	WAI	

APPENDIX 3: The contexts of the human bone samples analysed

'Atele, Sites ToAt-1, ToAt-2, Tongatapu, Tonga (Davidson 1969; Pietrusewsky 1969). Samples AY009–028. Two small commoners' burial mounds, both stratified. Eight individuals from ToAt-1 and twelve from ToAt-2. Thought to be pre-European and to date between 1000 and 250 BP.

Chatham Islands, New Zealand. Samples AY039–043. Five individuals, thought to be Chatham Islands Moriori, in the collection of the Anatomy Department, University of Otago.

Chatham Islands, Waihora (Site C240/283), Chatham Island, New Zealand. Samples AY044–047. From four individual burials in pre-European Moriori settlement dating between *ca.* AD 1500 and 1800 (Sutton 1982).

European, Canterbury, New Zealand. Sample AA510. One individual, buried in AD 1876 (Trotter and McCulloch 1989). Sample provided by Canterbury Museum.

Faroe Islands, Denmark. Samples AB340, 343–346, 348. Fragments from six individuals from the Sand site, dating to the Early Medieval Period (Nielsen *et al.* 1982). Samples provided by Pia Bennike.

Kapingamarangi Atoll, Federated States of Micronesia (Leach and Ward 1981; Houghton 1981). Samples AA555–556. From remains of two individuals of six collected on the foreshore after erosion in the vicinity of Putau (Site KA3). The stratified site of KA3 dates from about 700 BP to present; the human remains are thought to be pre-European.

Koné (Site WKO-013B), New Caledonia. Sample AA727. One individual, probably dating from about 500 BC (Pietrusewsky *et al.* 1998).

Lagoon flat (Site O32/31), Marlborough, New Zealand. Sample AA509. One of several burials at the site, age uncertain, but definitely pre-European, possibly 400 to 500 BP (Trotter 1982: 97).

Lakeba, Lau Islands, Fiji (Best 1984; Houghton 1989b). Samples AY082, AY784–786. Four individuals from two adjacent sites, both with long chronologies. One individual (sample AY784) from the large open site of Wakea (Site 196), dates to 600–900 BC; AY082 is slightly more recent. Of the two individuals from Qaranipuqa rock shelter (Site 197), AY785 dates to 200–300 BC, while AY736 is less than 500 years old.

Motupore (Site AAK), small island in Bootless Inlet near Port Moresby, Papua New Guinea (Allen 1976). Samples AY488–501. Fourteen individual burials, probably of similar age to those from ACJ at Nebira.

Namu (Site SE-DF-14), Taumako, Duff Islands, Temotu Province (Santa Cruz Group), Solomon Islands (Davidson and Leach 1991; Houghton n.d.; Whitehead *et al.* 1986). Samples AX848, AY062–081. Twenty-one individuals from a large cemetery, probably in use between about 300 and 850 years ago.

Natunuku (Site VL1/1), Viti Levu, Fiji (Davidson and Leach 1993; Pietrusewsky 1989). Sample AA725. A single pre-European burial from a stratified site. Originally thought to be an early Lapita burial, now considered to be about 2000 years old.

Nebira (Site ACJ), one of several sites on and around a hill inland from Port Moresby, Papua New Guinea. Samples AX989–1000. Site ACJ was a residential area and stratified burial ground in the saddle of the hill. The samples are from individual burials dating to *ca.* AD 1000–1600 (Bulmer 1979; Pietrusewsky 1976). Four samples included in this group, made available as part of the Nebira sample, have bag numbers indicating that they may not be from Nebira. AX996 has the site number of Motupore (AAK), and AX991, 997, and 998 may be from other sites in the Port Moresby Area. This may not be able to be clarified.

Pea (Site To-Pe-1, formerly To-1), Tongatapu, Tonga (Poulsen 1987: 21–22; Houghton 1989c). Sample AY774. Individual burial. Post-Lapita but pre-European.

Rapanui (Easter Island) (Shaw 2000a, 2000b; Seelenfreund 2000). Samples AX859–870. From 10 burials in 8 sites. Site names and numbers given in Appendix 1. The burials are thought to date to the Late Period or in some cases possibly the Protohistoric Period.

Rotoiti, Central North Island, New Zealand. Samples AY048–055. Eight individuals from an inland-dwelling Māori group. Little is known about these burials, but they are thought to date before AD 1860. In the collection of the Anatomy Department, University of Otago.

Saipan, Northern Mariana Islands (Pietrusewsky and Batista 1980). Samples AY781–782. One individual, dated to about 700 BP, from the Grotto, a Latte site at the northern end of Saipan, one from a group of at least five individuals recovered from Mariana High School and undated. Both individuals were recovered during salvage excavations.

Sigatoka (Site VL16/1), Viti Levu, Fiji. Sample AY787. A single sample from a burial ground in the Sigatoka Dunes (Best n.d.; Visser 1994).

Tina (Site SNA-023), New Caledonia. Samples AI093, 094. Two individuals, dating to approximately 850 years BP.

Tinian, Northern Mariana Islands (Pietrusewsky and Batista 1980). Samples AY778–780. Three individuals from separate burials in a latte site. One dated to about 300 years BP.

Wairau Bar, Site P28/21, Marlborough, New Zealand (Duff 1950; Houghton 1975; Higham *et al.* 1999). Sample AA508. From Burial 41A. Pre-European, age uncertain, but probably about 600 BP.

Watom (Site SAC), island off the northeast tip of New Britain, Papua New Guinea (Green and Anson 2000; Houghton 1989a). Samples AY056–061. Six individuals from a late Lapita burial ground probably dating between 300 and 100 BC.

APPENDIX 4: A worked example deriving percent energy obtained from protein, fat and carbohydrate.

We will give the details relating to the consumption of sea mammals for the Chatham Islands group. Please note that in this example we use figures with greater precision than some of the values appearing in the Tables to avoid significant rounding errors during calculation. Referring to Table 8, results from the simulation for sea mammals are 80.49 g/day protein, 1506.38 kcal/day energy, and 574.95 g/day ingested meat and blubber (48.65% of a total of 1183 g). In Table 9 we use the values for sea mammals of 14.0, 22.0 and 2.0 g/100g for protein, fat and carbohydrate respectively, and 4, 9, and 4 kcal/g for energy deriving from each of these components (already cited).

From these data we can calculate the weights of each of the main food components. Protein is 80.49 g (given in Table 8), fat is 126.488 g (22/100*574.95), and carbohydrate is 11.499 g (2/100*574.95), making a total of 218.48 g of nutrient food (which is about 38% of the total food ingested). These are the values appearing in Table 10.

The energy from each main food component can now be calculated as: 321.96 kcal (80.49*4), 1138.396 kcal (126.488*9) and 45.996 kcal (11.499*4), giving a total of 1506.381 (also appearing in Table 8). These energy values appear in Table 10.

The same calculations are repeated for the remaining four of the five main food types, and the energy deriving from each component added up, giving totals of 670.9 kcal, 1319.4 kcal, and 203.1 kcal for protein, fat and carbohydrate respectively (these values appear in Table 10), and a total energy intake of 2193.4 kcal/day (appearing in Tables 8 and 10).

The percent of food energy deriving from protein is 30.6% (670.9/2193.4*100), from fat is 60.1% (1319.4/2193.4*100), and from carbohydrate is 9.3% (203.1/2193.4*100), and these values appear in Table 11 and are plotted in Figure 16.

REFERENCES

Allen, J. 1976. Fishing for wallabies: trade as a mechanism for social interaction, integration, and elaboration on the Papuan south coast. *In* M. Rowlands and J. Friedman (eds), *The Evolution of Social Systems*, pp. 419–55. Duckworth, London.

Ambrose, S.H. 1992. Isotope analysis of paleodiets: Methodological and interpretive considerations. *In* M.K. Sanford (ed.), *Investigations of Ancient Human Tissue: Chemical Analysis in Anthropology*, pp. 59–130. Gordon and Breach, New York.

Ambrose, S.H. and Norr, L. 1992. On stable isotopic data and prehistoric subsistence in the Soconusco region. *Current Anthropology* 33 (4): 401–404.

Anderson, P.K. and Birtles, A. 1978. Behaviour and ecology of the dugong, *Dugong dugon* (Sirenia): observations in Shoalwater and Cleveland Bays, Queensland. *Australian Wildlife Research* 5: 1–23.

Atwater, W.O. and Benedict, F.G. 1899. *Experiments on the metabolism of matter and energy in the human body*. Bulletin 69. Department of Agriculture, Washington.

Aufderheide, A.C., Kelley, M.A., Rivera, M., Gray, L., Tieszen, L.L., Iversen, E., Krouse, H.R., and Cerevic, A. 1994. Contributions of chemical dietary reconstruction to the assessment of adaptation by ancient highland immigrants (Alto Ramirez) to coastal conditions at Pisagua, North Chile. *Journal of Archaeological Science* 21: 515–524.

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

Bender, M., Baerreis, D.A. and Steventon, R.L. 1981. Further light on carbon isotopes and Hopewell agriculture. *American Antiquity* 46: 346–353.

Best, S.B. 1984. Lakeba. The prehistory of a Fijian Island. Unpublished PhD thesis, University of Auckland (University Microfilms, Ann Arbor, 1989).

Best, S.B. n.d. Sigatoka dune burials (Site VL 16/1). Unpublished preliminary report (1987).

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

Brown, W.H. 1979. *Introduction to Organic Chemistry*. Willard Grant Press, Boston, Massachusetts.

Bulmer, S. 1979. Prehistoric ecology and economy in the Port Moresby region. *New Zealand Journal of Archaeology* 1: 5–27.

Byrne, D. 1973. Prehistoric coprolites. Unpublished MA thesis, Anthropology Department, University of Auckland.

Clark, J.T. and Terrell, J.E. 1978. Archaeology in Oceania. *Annual Review of Anthropology* 7: 293–319.

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.

Davidson, J, 1969. Archaeological excavations in two burial mounds at 'Atele, Tongatapu. *Records of the Auckland Institute and Museum* 6 (4–6): 251–86.

Davidson, J.M. 1984. *The prehistory of New Zealand*. Longman Paul, Auckland.

Davidson, J. and Leach, F. 1991. Bird-man amulets and *Tridacna* shell discs from Taumako, Solomon Islands. *In* A. Pawley (ed.), *Man and a Half. Essays in Pacific Anthropology and Ethnobiology in Honour of Ralph Bulmer*, pp. 478–83. Polynesian Society Memoir 48. The Polynesian Society, Auckland.

Davidson, J. and Leach, F. 1993. The chronology of the Natunuku Site, Fiji. *New Zealand Journal of Archaeology* 15: 99–105.

Davidson, J.M. and Leach, B.F. 2001. The strandlooper concept and economic naivete. *In* G. Clark, A.J. Anderson and T. Sorovi-Vunidilo (eds), *The Archaeology of Lapita Dispersal*

in Oceania. Papers from the Fourth Lapita Conference, June 2000, Canberra, Australia, pp. 115-123. Pandanus Books, Australian National University, Canberra.

Davidson, S., Passmore, R. and Brock, J.F. 1972. *Human nutrition and dietetics*. Churchill Livingstone, Edinburgh.

de France, S.D., Keegan, W.F. and Newsom, L.E. 1996. The archaeological, bone isotope, and zooarchaeological records from Caribbean sites in comparative perspective. *In* E.J. Reitz, L.E. Newsom and S.J. Scudder (eds.), *Case studies in environmental archaeology*, pp. 289–304. Plenum Press, New York.

DeNiro, M.J. 1986. Postmortem preservation and alteration of in vivo bone collagen isotope ratios in relation to palaeodietary reconstruction. *Nature* 317: 806–809.

DeNiro, M.J. 1987. Stable isotopy and archaeology. *American Scientist* 75 (2): 182–191.

DeNiro, M.J. and Epstein, S. 1978. Influence of diet on the distribution of carbon isotopes in animals. *Geochimica et Cosmochimica Acta* 42: 495–506.

DeNiro, M.J. and Epstein, S. 1981. Influence of diet on the distribution of nitrogen isotopes in animals. *Geochimica et Cosmochimica Acta* 45: 341–351.

Dennison, K.J. 1980. Amino acids in archaeological bone. *Journal of Archaeological Science* 7: 81–86.

Dennison, K.J. 1986a. Amino acids in archaeological bone. *In* G.K. Ward (ed.), *Archaeology at ANZAAS Canberra*, pp. 75–79. Canberra Archaeological Society.

Dennison, K.J. 1986b. Amino acids in archaeological bone (2). *Journal of Archaeological Science* 13: 393–401.

Duff, R.S. 1956. *The Moa-Hunter Period of Maori Culture* (Canterbury Museum Bulletin 1). Government Printer, Wellington.

Fankhauser, B. 1989. The nutritive value and cooking of Cordyline australis (*Tī kouka*). *In* D.G. Sutton (ed.), *Saying So Doesn't Make it So: Papers in Honour of B. Foss Leach*, pp. 199–221. New Zealand Archaeological Association Monograph 17.

Giesemann, A., Jager, H.J., Norman, A.L., Krouse, H.R. and Brand, W.A. 1994. On line sulphur-isotope determination using an elemental analyser coupled to a mass spectrometer. *Analytical Chemistry* 66 (18): 2816–2819.

Green, R.C. 1979. Lapita. *In* J.D. Jennings (ed.), *The Prehistory of Polynesia*, pp. 27–60. Harvard University Press, Cambridge Massachusetts.

Green, R.C. 1982. Models for the Lapita cultural complex: an evaluation of some current proposals. *New Zealand Journal of Archaeology* 4: 7–19.

Green, R.C. and Anson, D. 2000. Excavations at Kainapirina (SAC), Watom Island, Papua New Guinea. *New Zealand Journal of Archaeology* 20 (1998): 29–94.

Groube, L.M. 1971. Tonga, Lapita pottery, and Polynesian origins. *Journal of the Polynesian Society* 80 (3): 278–316.

Hare, P.E. 1980. Organic geochemistry of bone and its relation to the survival of bone in the natural environment. *In* A.K. Behrensmeyer and A.P. Hill (eds), *Fossils in the Making*, pp. 208–219. University of Chicago Press, Chicago.

Harris, G., Burtenshaw, M., Davidson, J.M. and Leach, B.F. 2000. An experimental kumara garden at Robin Hood Bay near Port Underwood, Marlborough. *Archaeology in New Zealand* 43 (4): 301–313.

Hedges, R.E.M. and Wallace, C.J.A. 1978. The survival of biochemical information in archaeological bone. *Journal of Archaeological Science* 5: 377–386.

Higham, T.F.C., Anderson, A.J., and Jacomb, C. 1999. Dating the first New Zealanders: the chronology of Wairau Bar. *Antiquity* 73: 420–427.

Hirner, A.V. and Lyon, G.L. 1989. Stable isotope geochemistry of crude oils and of possible source rocks from New Zealand — 1: carbon. *Applied Geochemistry* 4: 109–120.

Hirner, A.V. and Robinson, B.W. 1989. Stable isotope geochemistry of crude oils and of possible source rocks from New Zealand — 2: sulfur. *Applied Geochemistry* 4: 121–130.

Houghton, P. 1975. The people of Wairau Bar. *Records of the Canterbury Museum* 9: 231–246.

Houghton, P. 1981. Appendix 10. The human biology of Kapingamarangi. *In* F. Leach and G. Ward, *Archaeology on Kapingamarangi Atoll, a Polynesian Outlier in the Eastern Caroline Islands*, pp. 142–144. Privately published by B.F. Leach.

Houghton, P. 1989a. Watom: the people. *Records of the Australian Museum* 41 (3): 223–233.

Houghton, P. 1989b. The Lapita-associated human material from Lakeba, Fiji. *Records of the Australian Museum* 41 (3): 327–329.

Houghton, P. 1989c. Comment on the human skeletal material from Pea, Site To.1. *Records of the Australian Museum* 41 (3): 331–332.

Houghton, P. n.d. The people of Namu. Unpublished manuscript, Anatomy Department, University of Otago (1980).

Jaffre, T., Latham, M. and Schmid, M. 1977. Aspects de l'influence de l'extraction du minerai de nickel sur la végétation et les sols en Nouvelle Calédonie. *Cahiers ORSTOM* 12 (4): 307–321.

Kaplan, I.R., Emery, K.O. and Rittenberg, S.C. 1963. The distribution and isotopic abundance of sulphur in recent marine sediments off southern California. *Geochimica et Cosmochimica Acta* 27: 297–331.

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): 320–336.

Kirch, P.V. 1979. Subsistence and ecology. *In* J.D. Jennings (ed.), *The Prehistory of Polynesia*, pp. 286–307. Harvard University Press, Cambridge Massachusetts.

Krouse, H.R. 1977. Sulphur isotope abundance elucidate uptake of atmospheric sulphur emissions by vegetation. *Nature* 365: 45–46.

Krouse, H.R. and Herbert, H.K. 1988. Sulphur and carbon isotope studies of food webs. *In* B.V. Kennedy and G.M. LeMoine (eds), *Diet and subsistence*, pp. 315–322. The Archaeological Association of the University of Calgary.

Krouse, H.R. and Levinson, A.A. 1984. Geographical trends of carbon and sulphur isotope abundances in human kidney stones. *Geochimica et Cosmochimica Acta* 48: 187–191.

Krouse, H.R., Levinson, A.A., Piggott, D. and Ueda, A. 1987. Further stable isotope investigations of human urinary stones: comparison with other body components. *Applied Geochemistry* 2: 205–211.

Krouse, H.R. and Ueda, A. 1987. Sulphur isotope analysis of trace sulphide and sulphate in various materials using Kiba agent. *Studies on Sulphur Isotope Variation in Nature*, pp. 113–121. International Atomic Energy Agency, Vienna.

Kusakabe, M., Rafter, T.A., Stout, J.D. and Collie, T.W. 1976. Sulphur isotopic variations in nature. *New Zealand Journal of Science* 19: 433–440.

Leach, B.F. n.d. Fishing in prehistoric New Zealand. Unpublished manuscript, Museum of New Zealand Te Papa Tongarewa.

Leach, B.F. 1996. New Zealand and oceanic obsidians: an archaeological perspective using neutron activation analysis. *Journal of the Royal Society of New Zealand* 26 (1): 79–105.

Leach, B.F. and Manly, B. 1982. Minimum Mahalanobis distance functions and lithic source characterization by multi-element analysis. *New Zealand Journal of Archaeology* 4: 77–109.

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.

Leach, B.F., Quinn, C.J., Lyon, G.L., Haystead, A. and Myers, D.B. 2000. Evidence of prehistoric Lapita diet at Watom Island, Papua New Guinea, using stable isotopes. *New Zealand Journal of Archaeology* 20 (1998): 149–159.

Leach, F. and Ward, G. 1981. *Archaeology on Kapingamarangi Atoll, a Polynesian Outlier in the Eastern Caroline Islands.* Privately published by B.F.Leach.

Leach, B.F. and Warren, S.E. 1981. Neutron activation analysis of New Zealand and Oceanic obsidians: towards a simple screening technique. *In* B.F. Leach and J.M. Davidson (eds), *Archaeological Studies of Pacific Stone Resources*, pp. 151–166. British Archaeological Reports S104.

Leaver, A.G., Triffit, J.T., and Holbrook, I.B. 1975. Newer knowledge of non-collageous protein in dentine and cortical bone matrix. *Clinical Orthopedics and Related Research* 110: 269–292.

Lindeberg, S. and Vessby, B. 1995. Fatty acid composition of cholesterol esters and serum tocopherols in Melanesians apparently free from cardiovascular disease: the Kitava study. *Nutrition Metabolism and Cardiovascular Disease* 5: 45–53.

Lyon, G.L. and Hickman, R.W. 1993. The stable isotope composition of green-lipped mussels *Perna canaliculus*, Marlborough Sounds. Institute of Geological and Nuclear Sciences, Science Report 93/41

Marquez, M.R. 1990. FAO Species Catalogue. Vol. 11. *Sea Turtles of the World.* FAO Fisheries Synopsis No. 125 Vol. 11. FAO, Rome. 81 pp.

Mees, C.E.K. 1934. Scientific Thought and Social Reconstruction, *American Scientist* 22: 13–24.

Mekhitiyeva, V.L. and Pankina, R.G. 1968. Isotopic composition of sulfur in aquatic plants and dissolved sulfates. *Geochemistry* 5: 624–627.

Mekhitiyeva, V.L., Pankina, R.G. and Gavrilov, Y.Y. 1976. Distributions and isotopic compositions of forms of sulfur in water animals and plants. *Geochemistry International* 13: 82–87.

Mihalic, F. 1971. *The Jacaranda Dictionary and Grammar of Melanesian Pidgin.* The Jacaranda Press.

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): 145–158.

Minagawa, M. and Akazawa, T. 1989. Dietary patterns of Japanese Jomon hunter-gatherers: Stable nitrogen and carbon isotope analyses of human bones. *Proceedings of Symposium 3B Circum Pacific Prehistory Conference, Seattle, Washington*, 1–6 August 1989.

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.

Mizutani, Y. and Rafter, T.A. 1969. Oxygen isotopic composition of sulphates Part 5. Isotopic composition of sulphate in rainwater, Gracefield, New Zealand. *New Zealand Journal of Science* 12: 69–80.

Morrison, J. 1996. Isotopic sulphur determinations by continuous flow-IRMS (CF-IRMS). Unpublished manuscript, Micromass UK Ltd. Paper presented at the Association of Applied Biologists Meeting, University of Newcastle upon Tyne, July 1996.

Myers, D.B. Personal Communication, Wellcome Medical Research Institute, Otago Medical School.

Nielsen, O.V., Grandjean, P. and Bennike, P. 1982. Chemical analysis of archaeological bone samples: evidence for high lead exposure of the Faroe Islands. *Journal of Danish Archaeology* 1: 145–148.

Oser, B.L. (ed.) 1965. *Hawk's Physiological Chemistry*. McGraw-Hill Book Company.

Paijmans, K. 1976. Vegetation. *In* K. Paijmans (ed.), *New Guinea vegetation*, pp. 23–104. Commonwealth Scientific and Industrial Research Organisation and Australian National University Press, Canberra.

Pearcy, R.W. and Troughton, J. 1975. C4 photosynthesis in tree form *Euphorbia* species from Hawaiian rainforest sites. *Plant Physiology* 55: 1054–1056.

Peterson, B.J., Howarth, R.W. and Garritt, R.H. 1985. Multiple stable isotopes used to trace the flow of organic matter in estuarine food webs. *Science* 227: 1361–1363.

Peterson, B.J., Howarth, R.W. and Garritt, R.H. 1986. Sulfur and carbon isotopes as tracers of salt-marsh organic matter flow. *Ecology* 67 (4): 865–874.

Poulsen, J. 1987. *Early Tongan Prehistory*. 2 vols. Terra Australis 12. Department of Prehistory, Research School of Pacific Studies, Australian National University, Canberra.

Pietrusewsky, M. 1969. An osteological study of cranial and infracranial remains from Tonga. *Records of the Auckland Institute and Museum* 6 (4–6): 287–402.

Pietrusewsky, M. 1976. The physical anthropology of Nebira: a prehistoric site in Central Papua New Guinea. *In* Prehistoric Skeletal Remains from Papua New Guinea and the Marquesas Part One. *Asian and Pacific Archaeology Series* 7: 94–191. Social Sciences and Linguistics Institute, University of Hawaii, Honolulu.

Pietrusewsky, M. 1989. A Lapita-associated skeleton from Natunuku, Fiji. *Records of the Australian Museum* 41 (3): 297–325.

Pietrusewsky, M. and Batista, C. 1980. Human skeletal and dental remains from four sites on Tinian and Saipan, Commonwealth of the Northern Mariana Islands. Department of Anthropology, University of Hawaii at Manoa, Honolulu, Hawaii.

Pietrusewsky, M., Galipaud, J.-C. and Leach, F. 1998. A skeleton from the Lapita site of Koné, Foué Peninsula, New Caledonia. *New Zealand Journal of Archaeology* 18 (1996): 25–74.

Preston, T. and Owens, N.J.P. 1983. Interfacing an automatic elemental analyser with an isotope ratio mass spectrometer: the potential for fully automated total nitrogen and nitrogen-15 analysis. *Analyst* 108: 971–977.

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.

Rafter, T.A. 1967. Oxygen isotopic composition of sulphates. 1. A method for the extraction of oxygen and its quantitative conversion to carbon dioxide for isotope ratio measurements. *New Zealand Journal of Science* 10: 493–510.

Rawle, N.C. 1980. Predicting the weight of bone required for radiocarbon dating: The estimation of collagen content from hydroxyproline. Unpublished BA Hons Dissertation, Anthropology Department, University of Otago.

Rees, C.E., Jenkins, W.J. and Monster, J. 1978. The sulphur isotopic composition of ocean water sulphate. *Geochimica et Cosmochimica Acta* 42: 377–381.

Robinson, B.W. and Kusakabe, M. 1975. Quantitative preparation of sulfur dioxide, for 34S/32S analysis, from sulfides by combustion with cuprous oxide. *Analytical Chemistry* 47 (7): 1179–1181.

Ross, H.M. 1976. Bush fallow farming, diet and nutrition: a Melanesian example of successful adaptation. *In* E. Giles and J.S. Friedlaender (eds), *The Measures of Man: Methodologies in Biological Anthropology*, pp. 550–615. Peabody Museum Press, Cambridge Massachusetts.

Rundel, P.W. 1980. The ecological distribution of C4 and C3 grasses in the Hawaiian Islands. *Oecologia* (Berl.) 45: 354–359.

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

Schoeninger, M.J., DeNiro, M.J. and Tauber, H. 1983. Stable isotope ratios of bone collagen reflect marine and terrestrial components of prehistoric human diet. *Science* 220: 1381–1383.

Schoeninger, M.J. and Moore, K. 1992. Bone stable isotope studies in archaeology. *Journal of World Prehistory* 6 (2): 247–296.

Schwarcz, H.P. 1991. Some theoretical aspects of isotope paleodiet studies. *Journal of Archaeological Science* 18: 261–275.

Sealy, J.C. and van der Merwe, N.J. 1986. Isotope assessment and the seasonal mobility hypothesis in the southwestern cape of South Africa. *Current Anthropology* 27 (2): 135–150.

Sealy, J.C., van der Merwe, N.J., Lee Thorp, J.A. and Lanham, J.L. 1987. Nitrogen isotope ecology in Southern Africa: Implications for environmental and dietary tracing. *Geochimica et Cosmochimica Acta* 51: 2707–2717.

Seelenfreund, A. 2000. Easter Island burial practices. *In* C.M. Stephenson and W.S. Ayres (eds), *Easter Island Archaeology: Research on Early Rapa Nui Culture*, pp.81–101. The Easter Island Foundation, Los Osos, California.

Shaw, L. 2000a. The investigation of an ahu poe poe and two avanga on Easter Island. *In* C.M. Stephenson and W.S. Ayres (eds), *Easter Island Archaeology: Research on Early Rapa Nui Culture*, pp. 13–25. The Easter Island Foundation, Los Osos, California.

Shaw, L. 2000b. Human burials in the coastal caves of Easter Island. *In* C.M. Stephenson and W.S. Ayres (eds), *Easter Island Archaeology: Research on Early Rapa Nui Culture*, pp. 59–79. The Easter Island Foundation, Los Osos, California.

Smith, I.W.G. 1985. Sea mammal hunting and prehistoric subsistence in New Zealand. Unpublished PhD Thesis, Anthropology, University of Otago.

Smith, I.W.G. n.d. Nutritional perspectives on prehistoric marine fishing in New Zealand. *New Zealand Journal of Archaeology* 24 (in press).

Sutton, D.G. 1982. The Chatham Islands. *In* N. Prickett (ed.), *The First Thousand Years. Regional Perspectives in New Zealand Archaeology*, pp. 160–78. New Zealand Archaeological Association Monograph 13. Dunmore Press, Palmerston North.

Torrence, R. 1986. *Production and exchange of stone tools.* Cambridge University Press.

Torrence, R., Specht, J., Fullagar, R. and Bird, R. 1992. From Pleistocene to present: Obsidian sources in West New Britain, Papua New Guinea. *Records of the Australian Museum, Supplement* 15: 83–98.

Trotter, M. 1982. Canterbury and Marlborough. *In* N. Prickett (ed.), *The First Thousand Years. Regional Perspectives in New Zealand Archaeology*, pp. 83–102. New Zealand Archaeological Association Monograph 13. Dunmore Press, Palmerston North.

Trotter, M.M. and McCulloch, B. 1989. Historic records or archaeological facts? The Witchells Road Cemetery. *New Zealand Journal of Archaeology* 11: 5–21.

Troughton, J.H. and Card, K.A. 1972. Carbon isotope fractionation by plants. Report 380, Physics and Engineering Laboratory, Department of Scientific and Industrial Research. 50 pp.

Van der Merwe, N.J. and Vogel, J.C. 1978. ^{13}C content of human collagen as a measure of prehistoric diet in woodland North America. *Nature* 276: 815–816.

Van der Raaij, R.W., Gooley, W.D.J., Robinson, B.W. and Lyon, G.L. 1992. Stable isotope analysis of organic sulphur. *Department of Scientific and Industrial Research Physical Sciences Report* 47.

Visser, E. 1994. The prehistoric people from Sigatoka: an analysis of skeletal and dental traits as evidence of adaptation. Unpublished PhD thesis, University of Otago.

Vlieg, P. 1988. *Proximate composition of New Zealand marine finfish and shellfish.* Biotechnology Division, Department of Scientific and Industrial Research, Palmerston North.

Vogel, J.C. 1978. Isotopic assessment of the dietary habits of ungulates. *South African Journal of Science* 74: 298–301.

Vogel, J., Fuls, A. and Ellis, R. 1978. The geographic distribution of Kranz grasses in South Africa. *South African Journal of Science* 74: 209–215.

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

Whitehead, N.E., Devine, S.D. and Leach, B.F. 1986. Electron spin resonance dating of human teeth from the Namu burial ground, Taumako, Solomon Islands. *New Zealand Journal of Geology and Geophysics* 29: 359–361.

Received 23 July 2001
Accepted 5 March 2002