

Chemical paleodietary reconstruction: Human populations at late prehistoric sites in the Lluta Valley of northern Chile

Reconstrucción química de paleodietas: Poblaciones humanas de sitios prehistóricos tardíos en el Valle de Lluta, norte de Chile

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ABSTRACT

We employed a trace element technique using bone barium and strontium content, supplemented by stable isotope ratios of carbon, nitrogen and strontium to reconstruct human paleodiet of the Molle Pampa Este (MPE) and Molle Pampa Medio (MPM) population subgroups. Samples were collected from the Lluta Valley in archaeological sites near Arica in northern Chile. These methods currently applied to ecological studies have proved to be useful in addressing processes of culture change, particularly when sources of archaeological data are scanty. Our results indicate that the principal components in the diet of Molle Pampa populations were terrestrial plants and marine meat resources with only a minor contribution from terrestrial meat sources. No statistically valid differences in diet between the two subgroups could be demonstrated. These results seem to indicate a homogeneous social group rather than the interaction of populations with different cultural backgrounds sharing the coastal section of the Lluta valley, in an ideal multiethnic occupation of this, culturally, peripheral valley.

Key words: paleodiet, Chile, stable isotopes, prehistoric populations.

RESUMEN

Se utiliza la técnica de identificación de elementos traza al contenido de bario y estroncio en huesos humanos, complementado con el análisis de la razón de isótopos estables de carbono, nitrógeno y estroncio para reconstruir paleodietas de poblaciones humanas de los sitios arqueológicos habitacionales Molle Pampa Este (MPE) y Molle Pampa Medio (MPM) en el valle de Lluta, cerca de Arica, en el extremo norte de Chile. El método, aplicado normalmente a estudios ecológicos, ha demostrado ser útil para documentar procesos de cambio cultural, especialmente cuando se dispone de una estrecha variedad de otros datos arqueológicos.

Los resultados indican que los principales componentes dietéticos provinieron de plantas terrestres y carne de animales marinos, con una pequeña contribución de recursos proteicos de animales terrestres. Los análisis no muestran diferencias dietéticas estadísticamente significativas entre los dos subgrupos. Estos resultados parecen indicar la existencia de grupos sociales homogéneos y no la interacción de poblaciones con tradiciones culturales distintas compartiendo la sección baja del valle de Lluta, bajo un régimen de ocupación multiétnica.

Palabras clave: paleodieta, Chile, isótopos estables, poblaciones prehistóricas.

INTRODUCTION

During the past several decades the measurement of stable isotope ratios have proved to be very effective for the identification and quantification of a modern ecosystem's specific features. Examples of such features include the regional sources of certain biologically important molecules such as carbon dioxide or nitrogenous com-

pounds, differing consumptions of nutrients by catchment area's fauna and others. Some of these features are dependent upon variables such as temperature or rainfall. This makes it possible in some instances to predict the time, nature and degree of these variables in the past when differences in such features between the present and the prehistoric are identified. For example, past climates can sometimes be assessed by

exploiting differences in an area's vegetational coverage as recorded by measured changes in isotope ratios of accumulated soil organic matter at different depths. The use of oxygen isotope ratios of coral reefs to predict past ocean temperatures is another well-known example. Finally, the differing isotope ratios of various food sources can be traced through food chains, leading to prediction of the quantitative contribution each regional source makes to an area's faunal consumers.

Specifically, Tieszen & Pfau (1995) found that the soil organic matter (SOM) of a now forested hilly area adjacent to a native prairie in eastern South Dakota (United States) revealed a $^{13}\text{C}/^{12}\text{C}$ ratio markedly depleted in ^{13}C characteristic of forest vegetation, but that earlier (deeper) soils showed more positive values until they reached levels much more enriched in ^{13}C , equal to those of the adjacent prairie. This suggested that, with cessation of fires following European settlement, forest expanded into the prairie site. A similar process was demonstrated at a Black Hills site in western South Dakota (Pentico & Tieszen 1991). Studying another South Dakota prairie site, Tieszen et al. (1983) identified an area dominated by a community of photosynthetic C_3 grasses and another nearby area harboring primarily C_4 grasses. Measurement of these same carbon isotope ratios of bison feces collected at different times of the year led to reconstruction of selective seasonal feeding patterns. Extending this approach further, measurement of carbon isotope ratios in the organic portion (collagen) of archaeological and modern bison bones made it clear that the vegetation shifted substantially in the direction of temperate climate (C_3) plants over a past period that has also been identified as an interval of reduced average temperature ("Little Ice Age") by radiocarbon techniques (Pease & Tieszen 1987).¹

Stable isotopes of strontium measurements permitted Gosz et al. (1983) to demonstrate that the vegetation's $^{87}\text{Sr}/^{86}\text{Sr}$ ratio from a site's elevated altitude had been reduced from its high expected value by fallout from wind-deposited lowland dust that had a low strontium isotope ratio.

They suggest other applications of such ratios to study stream detritus turnover, aquatic invertebrate nutrition and biologic transfer to migrating populations.

Useful reviews of the basic principles involved in stable isotope ratios can be found in articles by Tieszen & Archer (1990) and by Peterson & Fry (1987). The latter includes case examples that include identification of the slow contribution made to atmospheric carbon dioxide by the burning of terrestrial vegetation (low carbon isotope ratio) from forest clearance before 1960 and by burning similarly ^{13}C -depleted fossil fuels since then in rapidly increasing amounts. The result is the current status of atmospheric carbon dioxide whose carbon isotope ratio has been lowered by an average of 2‰, a value large enough to require correction of measured values from ancient specimens. Differences in germline carbon isotope discrimination values of samples from globally-distributed alfalfa plants were found to correlate with their water use efficiency rates, a feature of commercial interest (Johnson & Tieszen 1994). Moreover, the methods for identification of trace elements and stable isotopes may be useful in paleoecological reconstruction as well as in modern ecological studies, particularly in stress environments where the changeable interaction between trophic level of the ecosystem could be diachronically scrutinized by analyzing the carcasses of dead animals (Ludwickson & Tieszen 1995-1996).

It is clear then, from even these several examples, that applications of elemental isotope ratios to biological and ecosystem questions are limited only by the imagination of the investigator. This article deals with the use of stable isotope ratios, supplemented by trace element analysis, to reconstruction of the diet of several ancient populations in an effort to understand better the relationship between these groups.

Isotopic data has provided strong evidence in support of very diverse subsistence strategies for cultures occupying very similar geographic and presumably climatic areas. Particularly, trace mineral analysis of prehistoric human bones has supplied information useful in establishing the na-

ture of a population's diet and, indirectly, of certain social correlates such as socio-economic stratification (Brown 1973, Gilbert 1975, 1977, Blakely & Beck 1981, Price & Kavanah 1982, Connor & Slaughter 1984, Price et al. 1985, Decker 1986², Hastorf 1990).

Although some limitations have recently been recognized in this method of analysis (Radosevich 1989)³, there is no reason to overlook the value of these kinds of studies where conditions are appropriate for their application. Many different types of studies have demonstrated that diagenetic changes occur frequently in interred bone but most of these observations are qualitative, and have not been shown to define the fundamental question: does the antemortem, biogenetic skeletal patterns of the trace mineral of interest remain in a retrievable state? (Nelson et al. 1983, Price 1989, Sillen 1986, 1988⁴, Sillen et al. 1989). These methods have been shown to be applicable to certain very arid sites including the one herein reported (Aufderheide & Allison 1995a,b).

18°30' latitude south (Fig. 1 & Fig. 2). Most of the archaeological sites known are located on the slopes and terraces of the north and south walls of the valley. In general, prehistoric populations placed their residences and cemeteries 30 - 50+ meters above the flood plain. The location of prehistoric settlement may also have prevented contamination of the water and maximized the availability of the valley's rare fertile

MATERIALS AND METHODS

The site and specimens

The Molle Pampa site lies in the Lluta valley 22.5 km from its mouth at an altitude of 500 meters (m), adjacent to the city of Arica in extreme northern Chile at about

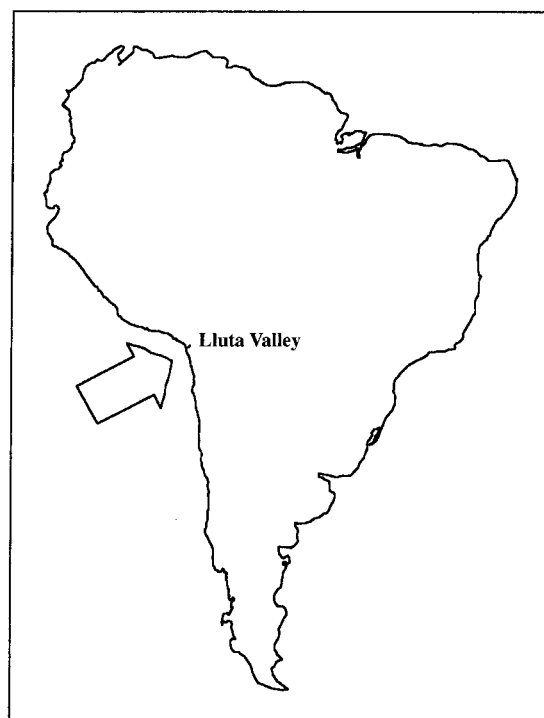


Fig. 1: Lluta Valley.
El Valle de Lluta.

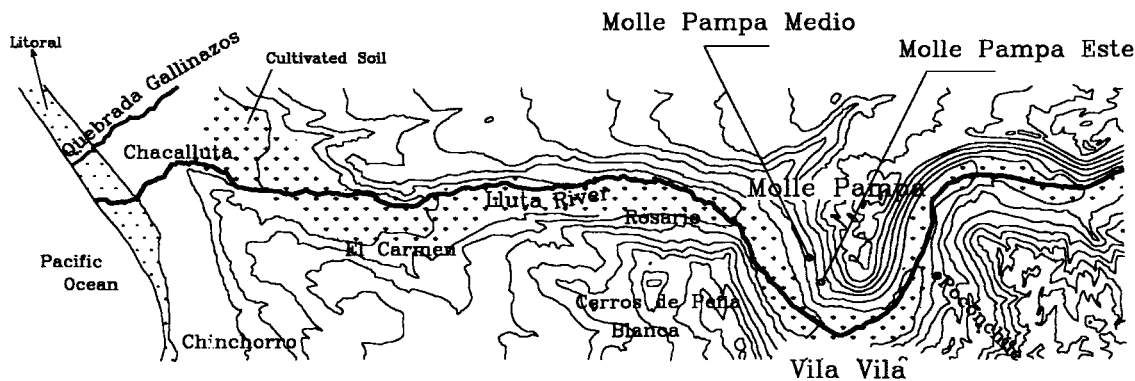


Fig. 2: Site locations.
Ubicación de los sitios.

land (Fig. 2). Since those locations have not been inhabited in historic times, the archaeological sites have not been obliterated by colonial and modern occupation. Prehistoric settlements have never been subject to farming, thus there is no severe post-occupational alteration of site stratigraphy. Tombs, however, because of their visibility, have been heavily looted. Despite this problem, it is still possible to generate useful mortuary data. Looters look for particular objects without using sifters or other devices, leaving behind broken and unnoted artifacts that are reburied by sand afterwards. The archaeological lower-coastal section of the Lluta Valley is an ideal setting to address issues of stylistics variability, local social processes, verticality, and colonization. First, sites in the valley display a range of ceramic styles, including several highland styles, some associated with ethnohistorically known altiplano polities. Second, a sequence of settlement allows us to distinguish «the local», identify potential «intrusions» of colonist, and most importantly, examine the diachronic processes associated with the appearance of highland-style materials. Consequently, this study was carried out to determine whether two subgroups of the Molle Pampa population could be differentiated on the basis of their diet as reconstituted chemically. This is an independent line of evidence in understanding the mechanisms of interaction between local and highland communities in the late prehistory of northern Chile (Santoro 1995). Variations in food consumption determined by means of trace elements and stable isotope ratios provide information about the variability observed in pottery styles, currently used as symbols for ethnic and social identity, or political affiliation (see Moseley 1992). We thought that chemical dietary reconstruction might be useful in identifying patterns of food consumption more directly related with cultural and social boundaries and even ethnicity, a thorny issue in Andean archaeology.

Bone samples were obtained at Museo Arqueológico San Miguel de Azapa of University of Tarapacá in Arica, Chile.

These represent random collections of bones from disarticulated skeletals scattered through two subareas within the site: Molle Pampa Este (MPE) and Molle Pampa Medio (MPM). Some were surface finds. The sites are composed of a residential area and three and two funerary areas respectively, located on the northern slope of the Lluta valley, at about 100 m above the current bed of the river. Archaeological excavation at domestic structures determined that MPE was mostly occupied during the Late Period (A.D. 1400-1500), while MPM was exclusively occupied in the Late Intermediate Period (ca. A.D. 1100-1400).

Chemical analysis

Many of these bones demonstrated fragmentation and frequent areas that had been bleached white, suggesting prolonged sun exposure. They were examined carefully and a total of 19 (10 from MPE and 9 from MPM) adult-size specimens were selected for trace element analysis and isotope ratio studies on the basis of their grossly apparent better preservation.

Following mechanical removal of surface bone until all discoloration was removed, seven random samples were dried for 48 hours at 100°C, cooled in a desiccator and weighed. They were then ashed in a muffle furnace at 450°C for 48 hours, cooled and weighed again. The fraction of aerosolized organic matter was calculated from the weight loss. Appropriate-sized samples were then sent to Augustana College Biology Department in Sioux Falls, South Dakota and analyzed by Drs. Michael Chapman and Larry Tieszen by ion ratio mass spectrometry for ratios of carbon and nitrogen stable isotopes in both collagen and apatite fractions of the bones using methods described earlier (Tieszen & Chapman 1995). Similar samples were forwarded to the Laboratory of Archaeological Chemistry in the Department of Anthropology at the University of Wisconsin in Madison, Wisconsin for trace element analysis by inductively coupled plasma technique under the direction of Dr. Douglas Price (for methods, see Burton & Price 1990). The strontium isotope ratios

TABLE 1

Determination of collagen content of representative bone samples

Determinación del contenido de colágeno de las muestras representativas de hueso

| | Before Ashing | | | | After Ashing | | | | | |
|-----------------|-----------------|------------------------|---------------------------------|-----------------------------|-------------------------------------|-----------------------------|---------------------------------|--|------------------------|-----------|
| | Crucible Number | Empty Crucible (grams) | Crucible + Sample (grams) (wet) | Wt. of Sample (grams) (wet) | Wt. Crucible + Sample (grams) (dry) | Sample Weight (grams) (dry) | Wt. of Crucible + Spec. (grams) | Wt. Loss of Spec = Organic Wt. (grams) | % Bone Organic Content | Bone Type |
| CH-MPE 17-1-2 | 1 | 13.3481 | 14.0017 | 0.6689 | 13.9730 | 0.6249 | 13.7209 | 0.2521 | .403 | Rib |
| CH-MPM-425-U-60 | 2 | 15.3898 | 16.1786 | 0.7888 | 16.1371 | 0.7473 | 15.8811 | 0.2561 | .343 | Tibia |
| CH-MPM-425-U-65 | 3 | 12.5582 | 12.9310 | 0.3728 | 12.9105 | 0.3523 | 12.7823 | 0.1282 | .364 | Rib |
| CH-MPM-36-U-1 | 4 | 13.0755 | 14.2293 | 1.1538 | 14.1671 | 1.0916 | 13.8184 | 0.3487 | .319 | Rib |
| CH-MPE-73-U-Z | 5 | 13.5825 | 14.6090 | 1.0265 | 14.5499 | 0.9674 | 14.2514 | 0.2985 | .309 | Femur |
| CH-MPE-55-U-1 | 6 | 14.9100 | 15.6996 | 0.7896 | 15.6588 | 0.7488 | 15.3643 | 0.2945 | .393 | Rib |
| CH-MPE-25-U-1 | 7 | 12.6538 | 13.1288 | 0.4750 | 13.1039 | 0.4501 | 12.9445 | 0.1594 | .354 | Rib |

were analysed by Geochron Laboratories, Cambridge, Massachusetts, USA.

RESULTS AND DISCUSSION

The analytical results are itemized in Tables 1, 2 and 3. Summary values are listed in Tables 4 and 5, together with results of evaluation for possible statistically valid differences (as measured by Student t-test) between MPE and MPM sites.

THE TRACE ELEMENT STUDIES

Validation of samples

Table 1 documents the results of ashing seven random specimens from those selected for study. This reveals that the organic content of bone ranges from 0.309 to 0.403 with a mean value of 0.360 ± 0.04 (S.D.) (normal = 0.360). Table 2 indicates bone calcium values are all within normal limits (360,000-4000,000 ppm). Calcium/phosphorus ratios are also within normal limits (2.15 ± 0.04). Three manganese values, often used to assess the possibility of contamination from groundwater (diagenesis) (Price 1989:135), are above 50 ppm (normal 2-10 ppm), but subsequent calculations carried out both including and excluding these values did not reveal any significant differences in group values nor in tests for statistical significance, so values reported here include these specimens. Since neither rainfall nor groundwater is present at this site, the presence of occasional manganese (Mn) elevations is probably the result of water from decaying soft tissue. The normal critical values such as calcium and phosphorus as well as low barium levels suggest that diagenesis does not appear to have altered the elements of interest. While diagenetic effects invalidate the use of skeletal trace element studies at many sites (Sillen 1989, Rodosevich 1989), the absence of ground water is probably responsible for the earlier successful validation of such studies in this area (Aufderheide & Allison 1995a, 1995b).

Group values and comparisons

Strontium (Sr) is the principal trace element employed to estimate the vegetal fraction of the diet. Soil Sr content reflects the nature of its source rocks and thus is site-specific. Plant roots absorb Sr without fractionation. The mammalian intestine absorbs Sr, but with only about 1/5 the avidity that it shows for calcium (Ca). After circulation in the blood, virtually all Sr is stored in bone where it can replace Ca in the hydroxyapatite crystal. Essentially no Sr is present in muscle or other soft tissues. Hence, an herbivore's bones will contain abundant quantities of Sr while those of a carnivore contain little or none. Skeletal tissue of an omnivore such as a human will reveal an intermediate amount. Comparison of a quantitated value to that of an herbivore from the same site produces an approximation of the vegetal fraction of the human diet (Aufderheide 1989).

In this study the mean Sr value (expressed as Sr/Ca x 1000) for all 19 tested specimens from both MPE and MPM groups is 0.66 ± 0.15 . No difference in the Sr/Ca between MPE and MPM can be demonstrated by Student's t-test. Comparing this to the Sr/Ca value found in herbivores (llamas, 1.54 ± 0.23 , n = 10) in an earlier study from this area (Aufderheide & Allison 1995b) would suggest that the human diet of MPE and MPM groups consisted of about $0.66/1.54 = 0.43$, or 43% derived from vegetal sources. However, that same earlier study also revealed that strontium could be acquired at this near coastal site not only from terrestrial plants, but from marine resources as well. Before comparisons with a terrestrial herbivore value can be made, the total bone strontium at coastal sites must be separated into that derived from terrestrial plants and that from sea foods. This can be done by measuring the strontium isotope ratios of an herbivore and a human bone from the site, and then relating only the terrestrial fraction of total strontium in the human bone to the total strontium value of the herbivore (Sealy et al. 1991).

Such a separation is based on the observation that the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of terrestrial

TABLE 2

Trace element analysis by inductively coupled plasma method

Análisis de elementos traza a través del método inductivo de plasma acoplado

| Spec. No. | N | Site | ID | ppm ¹ Al | Ppm Ba | Ppm Ca | ppm Fe | ppm K | ppm Mg | ppm Mn | ppm Na | ppm P | ppm Sr | ppm Zn | ppm Pb | Ca:P | Sr:Ca | Ba:Sr | Log Ba:Sr |
|-----------|------|------|---------------|------------------------|-----------|-----------|-----------|----------|-----------|-----------|-----------|----------|-----------|-----------|-----------|------|-------|-------|--------------|
| 5 | 4985 | MPE | 25-U-1 | 125 | < 5 | 381217 | 67 | 370 | 4726 | 17.5 | 8430 | 177815 | 291 | 125 | 39 | 2.14 | .76 | <.02 | -1.76 |
| 6 | 4986 | MPE | 59-U-2 #948 | 188 | < 5 | 388470 | 23 | 612 | 5297 | 1.4 | 3385 | 175089 | 183 | 139 | 79 | 2.22 | .47 | <.03 | -1.52 |
| 7 | 4987 | MPE | 73-U-2 #949 | 192 | < 5 | 384660 | 3 | 1276 | 5125 | -.6 | 10539 | 179075 | 312 | 123 | 31 | 2.15 | .81 | <.02 | -1.76 |
| 8 | 4988 | MPE | 3-U-1 #950 | 197 | < 5 | 383116 | 53 | 887 | 4863 | 1.3 | 7695 | 179662 | 260 | 141 | 78 | 2.13 | .68 | <.02 | -1.76 |
| 9 | 4989 | MPE | 3-U-3 #942 | 204 | < 5 | 392470 | 19 | 272 | 4795 | -.1 | 5327 | 181185 | 246 | 142 | 33 | 2.17 | .63 | <.02 | -1.76 |
| 10 | 4990 | MPE | 43-U-1 | 185 | < 5 | 378483 | 15 | 465 | 6265 | 59.5 | 7507 | 177918 | 241 | 144 | 52 | 2.23 | .64 | <.02 | -1.76 |
| 11 | 4991 | MPE | 66-U-1 | 183 | < 5 | 380926 | 38 | 318 | 4015 | 1.4 | 5170 | 177891 | 224 | 145 | 34 | 2.14 | .59 | <.02 | -1.76 |
| 12 | 4992 | MPE | 73-U-1 | 217 | < 5 | 381304 | 152 | 531 | 4455 | 6.6 | 13489 | 183263 | 240 | 170 | 55 | 2.08 | .63 | <.02 | -1.76 |
| 13 | 4993 | MPE | 55-U-1 | 198 | < 5 | 384360 | 79 | 862 | 4860 | .1 | 8342 | 180633 | 231 | 150 | 88 | 2.13 | .60 | <.02 | -1.76 |
| 14 | 4994 | MPE | 17-1-2 | 228 | < 5 | 383846 | 188 | 571 | 4616 | .7 | 11539 | 183623 | 204 | 172 | 97 | 2.09 | .53 | <.02 | -1.76 |
| 15 | 4995 | MPM | 425-U-59 #458 | 199 | < 5 | 397104 | 15 | 1247 | 4784 | 1.4 | 8827 | 183598 | 256 | 129 | 84 | 2.16 | .65 | <.02 | -1.76 |
| 16 | 4996 | MPM | 423-U-63 #460 | 216 | 5.1 | 396448 | 13 | 653 | 5656 | .3 | 7567 | 185122 | 395 | 135 | 101 | 2.14 | 1.00 | <.01 | -2.00 |
| 17 | 4997 | MPM | 36-U-1 | 214 | < 5 | 381068 | 52 | 1714 | 8216 | 579.1 | 10366 | 176991 | 395 | 179 | 52 | 2.15 | 1.03 | <.01 | -2.00 |
| 18 | 4998 | MPM | 33(36) U-4 | 216 | < 5 | 384883 | 38 | 1370 | 4896 | 7.5 | 6996 | 176160 | 237 | 152 | 147 | 2.18 | .62 | <.02 | -1.76 |
| 19 | 4999 | MPM | 36(33) U-3 | 163 | < 5 | 383672 | 1 | 281 | 4700 | .1 | 7730 | 177912 | 216 | 114 | 90 | 2.16 | .56 | <.02 | -1.76 |
| 20 | 5000 | MPM | 27-1-1 | 189 | < 5 | 387016 | 110 | 482 | 4922 | 79.7 | 8067 | 180916 | 255 | 267 | 83 | 2.14 | .66 | <.02 | -1.76 |
| 21 | 5001 | MPM | 425-U-65 | 173 | < 5 | 381123 | 57 | 977 | 4338 | 8.2 | 7855 | 177495 | 214 | 122 | 69 | 2.15 | .56 | <.02 | -1.76 |
| 22 | 5002 | MPM | 33-U-1 #938 | 188 | < 5 | 386274 | 9 | 2203 | 5159 | 6.3 | 10877 | 172790 | 242 | 120 | 66 | 2.24 | .63 | <.02 | -1.76 |
| 23 | 5003 | MPM | 425-U-60 | 168 | < 5 | 373055 | 19 | 747 | 4549 | 2.7 | 8275 | 175540 | 181 | 105 | 77 | 2.13 | .49 | <.03 | -1.52 |

¹ppm = parts per million

soils varies according to the age of its source rocks, while that of the well-mixed ocean water is universally 0.7091; this latter value labels marine meat. Thus, the difference between the terrestrial ratio (commonly determined by measuring the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in an herbivore's bone from the same site) and 0.7091 represents the full range from a purely terrestrial Sr source (at the site being studied) to a purely marine Sr source. Then the measured ratio in a human bone will produce an intermediate value, indicating what fraction of the total Sr in that human bone was derived from terrestrial sources. Correction of the total human bone Sr/Ca value by that terrestrial fraction will then produce a terrestrial Sr/Ca value that can be compared with that of the herbivore (Aufderheide 1989).

Such measurements revealed a $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratio value of 0.707840 ± 0.000010 (2 S.D.) for the MPE group and 0.707525 ± 0.000011 for the MPM group. Using the mean of these values (0.7076) and measuring it against the previously-determined value found in herbivores (llamas: 0.7071) and the universal marine value (0.7091), it is evident that the intermediate value for MPE and MPM of 0.7076 represents (0.70910-0.70765) of the total (0.70910-0.70710) range = 0.75. Thus 75% of the total bone strontium content is of vegetal origin. Since the total Sr/Ca = 0.66, then vegetal Sr/Ca = $(0.66) * (0.75) = 0.50$. When this is compared with the Sr/Ca value of the herbivore (1.54), then $0.50 : 1.54 = 0.33$. Thus only 33% of the diet of the MPE and MPM groups is of vegetal origin. If, instead of pooling the two group's values, the MPE and MPM values are estimated individually, based on their individual Sr/Ca and Sr isotope ratio values, the vegetal dietary fraction estimates are 27% for the MPE group and 36% for the MPM group (not a statistically valid difference). This approach tends to underestimate the dietary vegetal fraction when maize is a significant dietary constituent. This is the result of nonhomogeneous distribution of Sr in the maize plant (Aufderheide & Allison 1995:459, Table 2a), resulting in a low Sr content in maize kernels. In contrast to most other edible plants, therefore,

maize makes a lesser contribution to the bone Sr pool. At inland sites the C4 signal in isotope studies can often be employed to estimate dietary maize, but this is obscured at coastal sites by the C4 signal of marine meat. At this site, correction for the contribution of maize to the vegetal fraction was carried out by measurement of $\delta^{13}\text{C}$ in both collagen and apatite (see below).

Another possible method to assess the diet's terrestrial/marine meat fraction by trace element analysis is the measurement of the bone barium content, usually expressed as the barium/strontium ratio. This is based on the assumption that these elements are equally actively absorbed from the soil by plants (though strontium is preferentially absorbed from the intestine) and that both are stored in bone, not muscle. Marine foods, however, are depleted in barium because sea water's high sulfur content will render the barium insoluble in the form of barium sulfate (Burton & Price 1990). The extremely low barium values found in both the MPE and MPM bones (Tables 2 and 5) are characteristic of a predominantly marine diet. Here, too, however, interpretative caution must be observed, because Burton and Price (1990) point out that even terrestrial diets sometimes generate a marine pattern at desert sites. The reason for this appears to be the observation that some desert soils may be enriched in strontium but also contain enough sulfur to «fix» its barium in an insoluble state much as sea water does (Sealy et al. 1991). Since the specimens for MPE and MPM are from a desert site, the certainty of their apparent marine pattern of values remains unresolved by this method alone (but see isotope values below).

THE ISOTOPE STUDIES

Plants use two different pathways to create sugars. In the first step of the Calvin pathway a three-carbon compound is created, so the group of plants using this pathway are called C_3 plants; they represent trees, shrubs and many grasses that thrive in a cooler, temperate climate. The alternative enzymatic pathway (Hatch-Slack) produces

TABLE 3

Molle Pampa Site: stable isotope ratio analysis by ion ratio mass spectrometry

Sitios Molle Pampa: Análisis de la razón de isótopos estables a través de la razón de espectrometría de masa de iones

| Site | I.D. | Quality | Rank | % Yield | $\delta^{13}\text{C}$ | Collagen $\delta^{15}\text{N}$ | %N | %C | C:N | Apatite $\delta^{13}\text{C}$ | Δ Apatite & Collagen |
|---------|-----------|---------------------------------|---------|---------|-----------------------|-----------------------------------|-------|-------|------|----------------------------------|--------------------------------|
| CH-MPE | 73-U-Z | dense | 5 | 27.92 | -14.02 | 19.27 | 21.66 | 58.40 | 3.18 | -8.30 | 5.72 |
| CH-MPE* | 73-U-Z* | dense | 5 | 26.38 | -12.35 | 20.81 | 11.87 | 36.36 | 3.57 | -9.09 | 3.25 |
| CH-MPE | 3-U-1 | porous | 5 | 30.80 | -8.98 | 23.94 | 15.23 | 42.48 | 3.25 | -3.75 | 5.23 |
| CH-MPE | 3-U-3 | dense | 5 | 27.52 | -10.98 | 23.87 | 14.75 | 40.98 | 3.24 | -6.21 | 4.77 |
| CH-MPE | 43-U-1 | thin | 4 | 17.05 | -15.54 | 17.20 | 11.68 | 33.26 | 3.32 | -10.11 | 5.43 |
| CH-MPE | 66-U-1 | dense | 5 | 27.92 | -9.40 | 22.99 | 13.23 | 36.74 | 3.24 | -4.37 | 5.03 |
| CH-MPE | 73-U-1 | porous | 5 | 25.26 | -9.54 | 23.11 | 21.32 | 58.04 | 3.21 | -5.67 | 3.87 |
| CH-MPE | 55-U-1 | porous | 5 | 33.57 | -9.47 | 22.27 | 14.64 | 42.65 | 3.40 | 0.005 | 9.47 |
| CH-MPE | 17-1-2 | porous | 5 | 33.28 | -10.87 | 20.37 | 14.00 | 39.02 | 3.25 | -7.58 | 3.28 |
| CH-MPM | 425-U-58 | dense | 5 | 34.24 | -14.94 | 16.41 | 11.20 | 31.92 | 3.32 | lost | N/A |
| CH-MPM | 425-U-59 | dense | 5 | 21.53 | -17.57 | 14.72 | 14.28 | 40.26 | 3.29 | -10.47 | 7.09 |
| CH-MPM | 423-U-63 | dense | 5 | 24.70 | -13.50 | 19.22 | 10.54 | 32.90 | 3.64 | -8.95 | 4.55 |
| CH-MPM* | 423-U-63* | dense | 5 | 26.66 | -13.30 | 19.37 | 13.09 | 36.75 | 3.27 | -8.25 | 5.05 |
| CH-MPM | 36-U-1 | thin | 4 | 13.61 | -12.22 | 21.28 | 13.76 | 39.52 | 3.35 | -7.13 | 5.09 |
| CH-MPM | 33-U-4 | porous | 5 | 25.30 | -10.57 | 22.72 | 13.07 | 39.64 | 3.54 | -7.46 | 3.11 |
| CH-MPM | 36-U-3 | dense | 5 | 29.52 | lost | 22.20 | N/A | N/A | N/A | -4.35 | N/A |
| CH-MPM | 27-1-1 | thin | 5 | 29.02 | -16.86 | 14.95 | 12.62 | 34.89 | 3.23 | lost | N/A |
| CH-MPM | 425-U-65 | porous | 5 | 27.04 | -9.59 | 22.29 | 11.26 | 32.40 | 3.36 | -3.85 | 5.74 |
| CH-MPM | 33-U-1 | dense | 5 | 25.55 | -10.36 | 20.44 | 17.26 | 48.37 | 3.27 | -5.06 | 5.30 |
| CH-MPM | 425-U-60 | dense | 5 | 24.35 | -9.73 | 23.09 | 13.73 | 37.91 | 3.22 | -3.80 | 5.93 |
| CH-MPE | 55-U-1 | $^{87}\text{Sr}/^{86}\text{Sr}$ | ratio = | .707840 | ± 000010 | (2 S.D.) | | | | | |
| CH-MPM | 36-U-3 | $^{87}\text{Sr}/^{86}\text{Sr}$ | ratio = | .707525 | ± 000010 | (2 S.D.) | | | | | |

^Rank is used to describe the condition of the pseudomorph.

Those with rank "5" are of the best quality while those with rank "1" did not produce usable pseudomorphs.

*Indicates that a repeat test was done on sample

Criteria include: Rank >1, % Yield ≥ 3.0 , %C $\geq 15\%$, C/N ≤ 3.6 and ≥ 2.9 .

This sample produced an odd result, however, no extra bone was left for a repeat analysis.

"lost" indicates that the samples were lost in processing and did not contain enough bone for a repeat analysis.

first a four-carbon compound and these plants are called C_4 plants; they are commonly found in warmer or tropical areas (though maize, a C_4 plant, is an exception). Isotope ratios of carbon, nitrogen and sulfur are expressed as the degree to which they differ from a known standard. The standard for carbon is a limestone ore called Peedee belemnite and the formula for the difference (delta or δ) is:

$$\delta^{13}\text{C} = \frac{\frac{^{13}\text{C}}{^{12}\text{C}}_{\text{sample}} - \frac{^{13}\text{C}}{^{12}\text{C}}_{\text{PDB standard}}}{\frac{^{13}\text{C}}{^{12}\text{C}}_{\text{PDB standard}}} \times 1000$$

The enzymes of both pathways tend to partially reject (i.e., discriminate against) the ^{13}C isotope, incorporating the heavier and slower ^{13}C atom, but to differing degrees. Hence the C_3 plants have a $\delta^{13}\text{C}$ value about -27‰ (parts per thousand or mil) while C_4 plants cluster around -12‰ . Specifically, in the region from which these studied bodies originated, Tieszen and Chapman found the $\delta^{13}\text{C}$ value of food resources to have a mean of -23.50 for C_3 terrestrial plants, -14.1 for C_4 terrestrial plants and -15.2 for marine fish (all corrected for modern industrial fossil fuel burning effects). These isotope "signatures" are carried into their final carbohydrate and protein products. Measured $\delta^{13}\text{C}$ values of these final products, therefore, can reveal the nutritional sources of which they were composed (Keegan 1989). The measurements are carried out on the protein (collagen) of bone matrix and on the bone mineral (hydroxyapatite or simply apatite) that includes carbonate formed from the carbonate and carbon dioxide that represent end products of energy metabolism of fat, carbohydrates and some protein.

The C:N, % C and % N values for evaluating the quality of the tested samples, are within normal limits (thus validating their use for this purpose) and are listed in the legend for Table 3. The $\delta^{13}\text{C}$ values of the MPE and MPM studied groups in Tables 3 and 4 are closer to 12‰ (C_4) than 27‰ (C_3) and therefore suggest a C_4 pattern. This certainly could have been contributed by maize consumption. However, earlier studies from this area (Tieszen & Chapman

1995) indicate that the marine higher trophic level food sources in this region (marine fish, sea lions, sea birds, and shellfish) all contribute a $\delta^{13}\text{C}$ signal similar to that of C_4 plants, so that by itself the ^{13}C value from collagen can not distinguish between C_4 plants and upper trophic level marine foods. This could be resolved by estimating the dietary fraction represented by marine foods. Since we have measured values of $\delta^{13}\text{C}$ in bone collagen and also know the $\delta^{13}\text{C}$ value for terrestrial C_3 plants (-23.5‰) and for C_4 marine foods (-15.2‰) in this locale, we can predict what the bone collagen value would be on a pure C_3 plant diet and also what it would be on a pure C_4 marine diet. The mean value for our studied population's mixed diet would then fall between these two extremes, approaching more closely to one or the other, depending on the fraction of the diet represented by C_4 marine foods. However, first we must correct the C_3 and C_4 plant values by a $+5\text{‰}$ figure produced by the multiple enzymes acting to transfer the food item into collagen protein; this figure is called a "fractionation" value. The $\delta^{13}\text{C}$ value for C_3 plants (-23.5‰) would be fractionated into a bone collagen value of -18.5‰ while the C_4 marine food value (-15.2‰) would be fractionated into a collagen value of -10.2‰ . The full range between these two extremes is 8.3‰ . Thus movement from the terrestrial plant C_3 value of -15.2‰ fully up to -10.2‰ would be caused by a 100% C_4 marine diet. Our studied population's collagen $\delta^{13}\text{C}$ value was 11.9‰ representing a shift from the C_3 -18.5‰ value toward the marine value of 6.6‰ which is 80% of the full 8.3‰ range. Thus the fraction of the bone collagen protein derived from marine foods is 80%.

The $\delta^{13}\text{C}$ apatite values can also be used in the same way if we correct the C_3 and C_4 values by $+9.4$ which is the fractionation value for bone apatite. Using the apatite values results in a similar but slightly higher value of 90.8% for the marine fraction.

An alternative way to estimate the marine protein fraction is to employ the $\delta^{15}\text{N}$ values. Tieszen & Chapman (1995) found that terrestrial plants in this area rarely reveal $\delta^{15}\text{N}$ values greater than $+8\text{‰}$, the mean

value being $+3.9 \pm 2.3$, while upper trophic level marine foods averages 24.9‰ (equivalent to 27.9‰ in the consumer because of a $+3\text{‰}$ fractionation factor for each trophic level). Thus, the 20.63:2.98 values of the MPE and MPM protein fractions of the diets represent about 73% (20.6 : 27.9) of that figure. This is an estimate of the marine dietary protein fraction. It remains important to remember that this is an estimate of the dietary protein portion only. The values for MPE and MPM are not significantly different so the groups can be pooled into a single population. Thus the three methods noted above for estimating the marine fraction of dietary protein ($\delta^{13}\text{C}$ values in collagen, $\delta^{13}\text{C}$ values in apatite and $\delta^{15}\text{N}$ values in collagen) produce estimates of 80%, 91% and 73% respectively. The final estimate of dietary protein derived from marine foods can be comfortably assumed to be the mean of these three values: 81%.

These isotope data, however, also contain some information about the vegetal/meat dietary fraction. Earlier interpretations had assumed that the carbon atoms of all ingested foods contributed equally and randomly to the collagen protein synthesis (linear mixing model). Recent experimental studies (Ambrose et al. 1997, Tieszen & Fagre 1993) have validated that model for $\delta^{13}\text{C}$ measurements on bone apatite, demonstrating a $+9.4\text{‰}$ fractionation value for the whole diet $\delta^{13}\text{C}$ value on that matrix resulting from the carbon in bone

carbonate consequent to energy metabolism. However, preformed amino acids from ingested proteins are commonly employed intact for protein synthesis (protein routing model). Thus, while some of the carbon in collagen may be derived from dietary carbohydrates manufactured into proteins by the liver, probably most collagen protein is synthesized using amino acids from protein in the diet when protein is as readily available as it was at this site. Carbon in bone mineral apatite, however, comes from circulating blood carbonate, derived from energy sources. In a carnivore both its collagenous carbon and the carbon in the meat it burns for energy (some of the latter from ^{13}C -depleted meat lipids) comes from meat while in herbivores the energy source is primarily carbohydrates in plants. The $\delta^{13}\text{C}$ values of apatite, therefore, will more closely approximate the $\delta^{13}\text{C}$ values of collagen in a carnivore than in an herbivore. In a human ingesting meat or plants, the ^{13}C patterns will behave similarly. Work by Hedges and Van Klinken (cited by Ambrose et al. 1997) suggests an alternative explanation for the apatite-collagen differences based on $\delta^{13}\text{C}$ -depleted methane production in ruminants (and consequent balancing enrichment of respired carbon dioxide). However, because most of the terrestrial meat consumed by the groups reported in this article would be herbivore ruminants (camelids) the differences in $\delta^{13}\text{C}$ of apatite and collagen

TABLE 4

Stable isotope ratios of carbon and nitrogen in bone: summary values

Razón de isótopos estables de carbono y nitrógeno en huesos: resumen de valores

| Parameter | MPE ¹ mean \pm S. D. ² (N) ³ | MPM mean \pm S. D. (N) | Student t-test |
|---|---|--------------------------|----------------|
| $\delta^{13}\text{C}$ (collagen) ⁴ | -11.00 ± 2.20 (8) | -12.80 ± 3.07 (9) | $P < .05$ |
| $\delta^{13}\text{C}$ (apatite) | -6.63 ± 2.30 (7) | -6.34 ± 2.46 (8) | $P > .05$ |
| $\Delta^{13}\text{C}$ (apatite-collagen) ⁵ | -5.20 ± 1.87 (8) | -5.29 ± 1.22 (7) | $P > .05$ |
| $\delta^{15}\text{N}$ (collagen) | $+21.72 \pm 2.34$ (8) | $+19.64 \pm 3.16$ (10) | $P > .05$ |

¹ MPE = Molle Pampa Este; MPM = Molle Pampa Medio.² Mean \pm S. D. = mean \pm standard deviation.³ N = number of specimens tested.⁴ Similarly for ^{15}N .⁵ $\Delta^{13}\text{C} = \delta^{13}\text{C}$ (apatite) - $\delta^{13}\text{C}$ (collagen). Also called " $\delta^{13}\text{C}$ spacing".

noted above would still be present, validating the following interpretation. The difference between collagen and apatite $\delta^{13}\text{C}$ values in the same individual commonly is called "spacing". In the MPE and MPM groups these measurements were made and appear in Tables 3 and 4 under the symbol $\Delta^{13}\text{C}$ (apatite and collagen). No statistically valid difference in these values between these two groups is evident. They can, therefore, be combined. The 15 measured samples average $\Delta 5.24 \pm 1.54\text{‰}$. Herbivores usually generate a "spacing" value of about 7‰ while carnivores approximate a difference of about 3‰ (Krueger & Sullivan 1984). The mean value of these two groups lies about halfway between these two extremes, suggesting a vegetal/meat fraction of about 0.50 or 50 percent. Lee-Thorp et al. (1989) identify other factors influencing the degree of "spacing", but we have less experience and laboratory support for this method of estimating the vegetal/meat ratios than we do with strontium. The trace element (strontium) approach had suggested a dietary vegetal fraction of about 33%, but for reasons given above this includes only a part of the maize dietary constituent. The $\Delta^{13}\text{C}$ spacing approach suggests about a 50% vegetal fraction. Since maize probably accounts for at least a part of this apparent discrepancy, it seems reasonable to estimate the dietary vegetal fraction at a value about midway between these two: 42%.

CALCULATION OF PRINCIPAL DIETARY COMPONENTS

Use of the Sr/Ca ratios (after correction of total Sr content by employing Sr isotope ratios and $\Delta^{13}\text{C}$ "spacing" measurements) indicated a vegetal dietary fraction of about 42%. This implies that 58% of the entire diet was acquired from meat. Carbon and nitrogen isotope ratio comparisons, however, demonstrated that 81% of that meat component was of marine origin. Therefore, $(0.58) * (0.81) = 0.47$, so 47% of the protein (meat) was composed of marine-derived foods. The remaining 19% of the meat, therefore, was acquired from terrestrial animals: $(0.58) * (1.9) = 0.11 = 11\%$. The final dietary components, then, were vegetal 42%, marine meat 47% and terrestrial meat 11%. Stated in more qualitative terms, the principal components of these two populations' diets are roughly equal contributions by terrestrial plants and marine meat resources with only a minor contribution from terrestrial meat resources.

INTEGRATION OF CHEMICAL AND ARCHAEOLOGICAL DIETARY STUDIES

These results challenged our initial impressions of these group's subsistence patterns since the bulk of macroscopic botanical and marine remains collected from the screen showed that Molle Pampa Este households yielded less marine resources,

TABLE 5

Bone trace element ratios: summary values (ppm)

Razón de elementos traza en hueso: resumen de valores (ppm)

| Parameter | MPE ¹ mean \pm S. D. ² (N) ³ | MPM mean \pm S. D. (N) | Student t-test |
|-----------|---|--------------------------|----------------|
| Sr/Ca | .63 \pm .10 (10) | .69 \pm .19 (9) | P > .05 |
| Ba/Sr | <.02 (log -1.76) | <.02 (log -1.76) | P > .05 |
| Ca/P | 2.14 \pm .04 (9) | 2.17 \pm .04 (7) | P > .05 |

¹ MPE = Molle Pampa Este; MPM = Molle Pampa Medio.

² Mean \pm S. D. = mean \pm standard deviation.

³ N = number of specimens tested.

particularly shells, than Molle Pampa Medio (Santoro 1995). It may be possible that fish were more customarily consumed in Molle Pampa Este than shellfish, whose remains are less evident in the archaeological record. Plant remains, especially maize, formed the bulk of the stratigraphic matrix and presented a staple, complemented with beans, pallares, potatoes, chuño, (deshidrated potatoe) yuca (manioc) (Dorsey-Vinton 1997), fruits, squash, and molle fruit (possibly consumed in a beverage). Marine resources, a minor component in the stratigraphy, included several kinds of shellfish, especially *Choromytilus* and *Donasium peruviana* (coquinas), as well as fish among which it was possible to identify *Trachurus murphyi* (jurel). The scarce remains of terrestrial animals matches the chemical dietary evidence. Although camelid dung was plentiful, it is possible that llama and alpaca were rarely butchered as they were a precious commodity in the system of llama cargo caravan, widely used along the Andes to transport goods from the lowland and highlands. It seems likely that some camelids were killed occasionally for domestic consumption and ceremonial purposes-offerings for house foundations and burial. Meat could also have been imported from the highlands in the form of charqui (deshidrated meat), (Santoro 1995). The chemical studies indicate that the quite accessible marine resources were exploited by both studied groups to a greater extent than the archaeological remains suggested.

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