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Australian Archaeology

Bone chemistry and palaeodiet: Bioarchaeological research at Roonka Flat, lower Murray River, South Australia 1983 - 1999.

F. Donald Pate

The predominance of stone and bone in prehistoric archaeological deposits has resulted in the development of a range of methods to extract information from these important cultural resources. Since the development of radiocarbon dating in the late 1940s, a variety of analytical techniques derived from chemistry have been applied to archaeological research problems. Many of these methods have been employed in the analysis of archaeological skeletal remains, both human and faunal. In addition to providing information about chronology, chemical analyses of bones and teeth offer independent scientific methods to address past diet, climate and ecology that supplement conventional approaches (Price 1989; Schoeninger and Moore 1992; MacFadden and Bryant 1994; Pate 1994, 1997a; Bocherens et al. 1999).

During the 1970s and early 1980s a variety of analytical techniques derived from chemistry emerged in the archaeological literature as a means to reconstruct past dietary patterns. The inorganic and organic chemical constituents of bone provide a record of long-term dietary intake. Elements and amino acids liberated by the digestion of foods are incorporated into the inorganic hydroxyapatite, $Ca_5(PO_4)_3OH$, organic collagen, and non-collagenous protein components of bone throughout a vertebrate's lifetime. In contrast, the chemical composition of teeth reflect the early stages of life during dental development. In some cases, chemical concentrations in bones and teeth can be related quantitatively to the chemical composition of past diet. Thus, chemical analyses of archaeological teeth and bones have the potential to provide information about juvenile and long-term dietary patterns, respectively, in both humans and associated fauna.

Elemental analyses of inorganic hydroxyapatite focused primarily on strontium (Sr), barium (Ba) and magnesium (Mg). The concentrations of these alkaline earth metals in bone and tooth mineral reflect percentages of meat vs. plant foods and marine vs. terrestrial foods in the diet (Boaz and Hampel 1978; Sillen and Kavanagh 1982; Connor and Slaughter 1984; Klepinger 1984). In addition, strontium isotope ratios ($^{87}Sr/^{86}Sr$) in bones and teeth were employed to distinguish marine vs. terrestrial inputs to prehistoric human diets (Ericson 1985). Many of these early elemental studies addressed relationships between dietary variability and mortuary variability as a means to assess past social differentiation (Brown 1974; Gilbert 1977; Lambert et al. 1979; Schoeninger 1979; Blakely and Beck 1981; Pate 1984).

Stable carbon ($^{13}C/^{12}C$), nitrogen ($^{15}N/^{14}N$) and sulfur ($^{34}S/^{32}S$) isotope ratios in the collagen and non-collagenous protein components of bones and teeth record the relative amounts of marine vs. terrestrial foods and C_3 vs. C_4 plants in individual diets (Schoeninger and DeNiro 1984; Peterson and Fry 1987). Stable carbon and oxygen ($^{18}O/^{16}O$) isotope ratios in the inorganic carbonate and phosphate portions of bone and tooth apatite can supplement these organic analyses (Krueger and Sullivan 1984; Sponheimer and Lee-Thorp 1999).

Initial archaeological applications involved stable carbon isotopes in bone collagen. These studies addressed the relative contribution of photosynthetically distinct plants, e.g. corn (C_4) vs. wheat (C_3), to prehistoric human diets (van der Merwe and Vogel 1978; Bender et al. 1981; van der Merwe 1982). Subsequent research involved stable carbon and nitrogen isotope analyses of prehistoric human bone collagen to infer relative consumption of marine vs. terrestrial foods (Norr, 1981, 1982; Chisholm et al. 1982; 1983; Schoeninger et al. 1983; Hobson and Collier 1984). More recently, stable oxygen isotopes have been employed to provide information about trophic level and diets based on browsing vs. grazing (Kohn et al. 1996; Wright and Schwarcz 1999).

Beacause of the substantial difficulties associated with quantitative inferences regarding prehistoric human dietary composition from archaeological food remains and artefacts, chemical palaeodietary techniques involving analyses of human and faunal bones and teeth received great attention following their introduction in various parts of the world and became widespread in the archaeological and physical anthropological literature during the 1990s.

Bone chemistry and palaeodiet: Australian research

Bone chemistry palaeodietary methods were introduced to Australian archaeology via North America in the early 1980s (Pate 1997a). Pate (1984) employed strontium concentrations in the inorganic component of prehistoric human bone to address relationships between Holocene dietary variability and mortuary variability at the inland riverine Roonka Flat site near Blanchetown, South Australia. Hobson and Collier (1984) used bone collagen stable carbon isotopes to address marine vs. terrestrial dietary composition at two Holocene Aboriginal sites, coastal Broadbeach near Surfers Paradise in southeastern Queensland, and Swanport located south of Roonka Flat on the lower Murray River of South Australia.

Following their initial paper, Hobson and Collier produced only one additional Australian based publication in the bone chemistry palaeodietary area. This paper (Collier and Hobson 1987) supplemented the earlier publication by providing baseline stable carbon isotope data for a range of potential marine and terrestrial plant and animal foods from the Broadbeach region. These faunal and floral reference samples were used to estimate mean marine protein dietary composition for the prehistoric human sample. A mean bone collagen stable carbon isotope value of -16.6 ± 1.2‰ (n = 10) for the coastal Broadbeach sample suggested a 46% marine dietary protein contribution. In contrast, a value of -19.6 ± 1.6‰ (n = 8) for the inland riverine Swanport sample indicated limited access to marine and C_4-based terrestrial foods.

Unfortunately, the Broadbeach skeletal population was reburied prior to the completion of more extensive chemical analyses (Meehan 1984; Webb 1987) and no further chemical analyses of the Swanport sample have been completed. Thus,

Department of Archaeology, Flinders University, GPO Box 2100, Adelaide, SA 5001, Australia

there is only limited information regarding stable carbon isotope variability within the Broadbeach and Swanport burial populations and stable nitrogen isotope analyses were not performed. Furthermore, the sample sizes employed in the initial analyses were not large enough to address dietary differences associated with age, sex and mortuary variability.

Pate's initial palaeodietary research at Roonka Flat resulted in a M.A. degree awarded by Brown University (Pate, 1984). Following the completion of the MA thesis, Pate continued bone chemistry palaeodietary research in the lower Murray River Basin of South Australia in relation to Ph.D. (Pate 1989) and post-doctoral (Pate and Schoeninger 1993) studies at Brown, Harvard and the Australian National Universities. Pate took up the foundation lectureship in Archaeology at Flinders University, Adelaide, South Australia in 1990 and established bone chemistry and bioarchaeology as areas of research strength.

Bone chemistry research at Roonka Flat

Excavations directed by Graeme Pretty, Division of Anthropology, South Australian Museum, at the Roonka Flat archaeological site (Figure 1) between 1968 and 1977 produced one of the largest well provenanced prehistoric Aboriginal skeletal populations in Australia (Pretty 1977, 1986). The mortuary variability and elaborate grave goods observed at this hunter-gatherer site suggested the possibility of a non-egalitarian social organisation. During this time period, hunter-gatherer diversity and social complexity were a focus of archaeological and anthropological research (cf. Lee and DeVore 1968; Struever 1968; Bettinger and King 1971; King 1976, 1978). Consequently, the Roonka Flat site received a great deal of attention from archaeologists in Australia and abroad.

In relation to hunter-gatherer lifeways, the Roonka Flat site is located in a region with reliable water and food resources. The Murray-Darling is the largest permanent riverine system in the arid Australian continent. Settlements in the lower Murray River region in the vicinity of Roonka Flat provided access to a range of plant and animal foods derived from the river and surrounding semi-arid plains. Prehistoric Aboriginal sites along the river are numerous and include stratified rockshelters, open habitation sites, rock art, scarred trees, middens, and cemeteries. Aboriginal oral tradition and European historic records provide evidence for densely populated Aboriginal settlements throughout the lower Murray River region of South Australia in both prehistoric and post-contact periods (Eyre 1845; Pretty 1977, 1986).

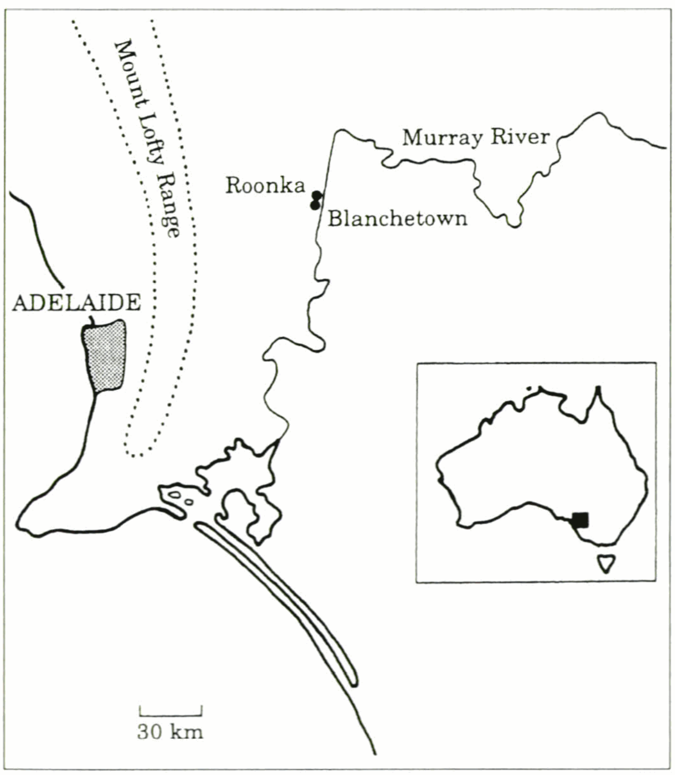


Figure 1 Location of the Roonka Flat archaeological site, South Australia

Prehistoric Aboriginal burials are common in the soft Holocene sand dunes and flats bordering the Murray-Darling Rivers. Cemetery sites in the riverine region become larger and more dense after 5000 BP (Pardoe 1988, 1994, 1995). The occurrence of these large cemeteries throughout the riverine zone provides additional archaeological evidence for semi-sedentary and sedentary hunter-gatherer settltements during the late Holocene. As at other archaeological sites located within the sandy deposits bordering the Murray River, modern erosion exposed prehistoric human burials and associated cultural materials and threatened to destroy the site. Consequently, the South Australian Museum mounted a rescue excavation to save these cultural resources.

Research at Roonka Flat involved a large multi-disciplinary team that focused on chronology, subsistence, palaeoecology, mortuary variability, social complexity and physical anthropology including palaeopathology (Pretty 1977, 1986, 1988; Prokopec 1979; Prescott 1983; Pate 1984, 1990, 1997a, 1998a, 1998b; Smith et al. 1988; Pretty and Kricun 1989; Boyd and Pretty 1989; Prokopec and Pretty 1991; Pate et al. 1998a).

Over 200 individuals were recovered during the Roonka Flat excavations. Approximately 18% of the interments dated to the Early Holocene (10,000 - 5000 BP) with the remainder dating to the Late Holocene (5000 BP - AD 1840). A majority of the Early Holocene burials consisted of adult males associated with a distinct cemetery; whereas, Late Holocene interments included an entire age/sex cross-section of the population associated with habitation remains.

Modes of burial also changed through time. Early Holocene burials are dominated by individuals who were placed fully extended in shallow pits or slumped in deep, vertical shafts. Late Holocene interments occur in shallow pits in either a fully extended, recumbent-contracted or fully contracted (flexed) position with approximately 38% of individuals included in group burials consisting of 2 to 5 persons per grave pit. Grave goods are associated with most of the burials. These include a range of stone and bone tools, animal bone and tooth headbands, necklaces and pendants, animal bone clothing pins, animal skeletons, freshwater mussel and snail shells, vegetable mats, hearthstones and associated ash and burnt nuts, seeds, clay and bone, and various ochres. Contact period burials include items of European origin such as pearl and metal buttons and clay and metal pipe fragments (Pretty 1977; Pate 1984).

In the Late Holocene sample, mortuary differentiation on the basis of role or division of labor was addressed. The types of artefacts included as grave goods varied with sex. Ochre, bone projectile points, and stone tools were associated primarily with males; whereas, vegetable mats placed beneath the bodies were confined to female and subadult burials. Animal bones and mussel shells were associated with both males and females. The association of bone projectile points and stone tools with the male activities of hunting and tool manufacture/maintenance and vegetable mats with the gathering activities of females and subadults is suggested by these differences in grave goods. In addition, there is differentiation based on quantity of grave goods. The majority of the more elaborate graves with greater amounts of grave goods are those of older males.

Bone strontium

As strontium concentrations are higher in plants and freshwater molluscs in comparison to terrestrial animal tissues and these differences are passed up the food chain to consumers, bone strontium concentrations were used to address relative consumption of these food types by prehistoric humans buried at Roonka Flat (Pate 1984).

Bone strontium concentrations indicated a differential access to food resources based upon male age and sex. In the Early Holocene sample, bone strontium content decreased with increasing male age indicating that older Aboriginal males had a greater access to terrestrial protein than younger males. Because only several females were buried at Roonka Flat during the Early Holocene, comparisons with females could not be made. In the Late Holocene sample, bone strontium content increased with increasing male age indicating that older Aboriginal males had diets consisting of greater amounts of vegetable foods and/or freshwater molluscs relative to younger males. Female bone strontium content was variable, but there was no correlation with age. In general, female bone strontium concentrations were lower than those of males indicating that females had greater access to terrestrial protein than males.

Pate (1984:ii) concluded that distinctions in mortuary treatment and diet at Roonka Flat during the Holocene were based solely on differences of age and sex, and thus did not provide evidence for a non-egalitarian form of social organisation.

Subsequent research at Roonka Flat (Pate and Brown 1985; Pate and Hutton 1988; Pate et al. 1989; Pate 1990; Pate et al. 1991) suggested that the bone strontium variability observed previously in prehistoric Aboriginal remains recovered from the site (Pate 1984) could not be related to past dietary differences. An examination of the chemical dynamics of the Roonka Flat burial environment including multi-elemental analyses of soils (Fig. 2) and associated human bones indicated that a variety of post-mortem chemical changes (diagenesis) had occurred in the interred bone that obscurred any elemental dietary signatures that existed during life.

Research addressing post-mortem diagenesis at other prehistoric cemetery sites reached similar conclusions regarding the instability of bone strontium and other elemental constituents of bone in a range of burial environments (Radosevich 1989a, 1989b, 1993; Whitmer et al. 1989; Sandford 1992; Sighinolfi et al. 1993). A variety of mechanisms that altered *in vivo* elemental concentrations in bone were identified. These post-mortem diagenetic mechanisms include dissolution, precipitation, mineral replacement, recrystallization, crystal growth, and ionic substitution. Due to the complex interactions of these various mechanisms, it was concluded that in many cases it was not possible to distinguish biological and post-mortem diagenetic components in interrred bone.

Figure 2 Graeme Pretty (background) and John Hutton collecting soil samples at Roonka Flat, South Australia, 1986. Photo: Donald Pate

Because of the limitations associated with the use of elemental concentrations in bone apatite as a means to reconstruct past diet, most archaeologists and physical anthropologists involved with chemical palaeodietary applications now employ stable isotope analyses of collagen and non-collagenous proteins in bones and teeth. However, in most cases, the biological decomposition of collagen limits organic palaeodietary determinations to Late Pleistocene and Holocene materials (Tuross et al. 1988; Bocherens et al. 1991). To overcome this temporal limitation, collagen data are often supplemented by carbon and oxygen isotope analyses of bone carbonate and bone phosphate. Although bone and tooth mineral are physically preserved for much longer periods, post-mortem chemical changes may also alter carbonate stable isotope values (Lee-Thorp et al. 1989; Lee-Thorp and van der Merwe 1991; Krueger 1991). In contrast to bone carbonate, stable oxygen isotope ratios in bone phosphate are more resilient to post-mortem alteration. Because tooth enamel is non-porous and has a larger apatite crystal size, it should be more resistent to post-mortem alteration than bone mineral (Quade et al. 1992).

Bone collagen stable isotopes

Stable isotope palaeodietary applications at Roonka Flat involved analysis of bone collagen from a range of modern marine and terrestrial fauna in order to provide baseline stable carbon and nitrogen isotope values (Figs 3 and 4) that could be used to infer prehistoric human dietary composition (Pate and

Schoeninger 1993; Pate 1997a; Pate et. al. 1998a). Once these baseline values were established analysis of the Roonka Flat prehistoric human sample proceeded. Bone collagen stable carbon and nitrogen isotopes values were employed to address 1) relative access to foods from coastal, riverine and arid interior habitats and 2) dietary variability within the population. Due to poor collagen preservation in the Early Holocene sample (Pate 1997b, 1998c), dietary inferences were restricted to the Late Holocene sample.

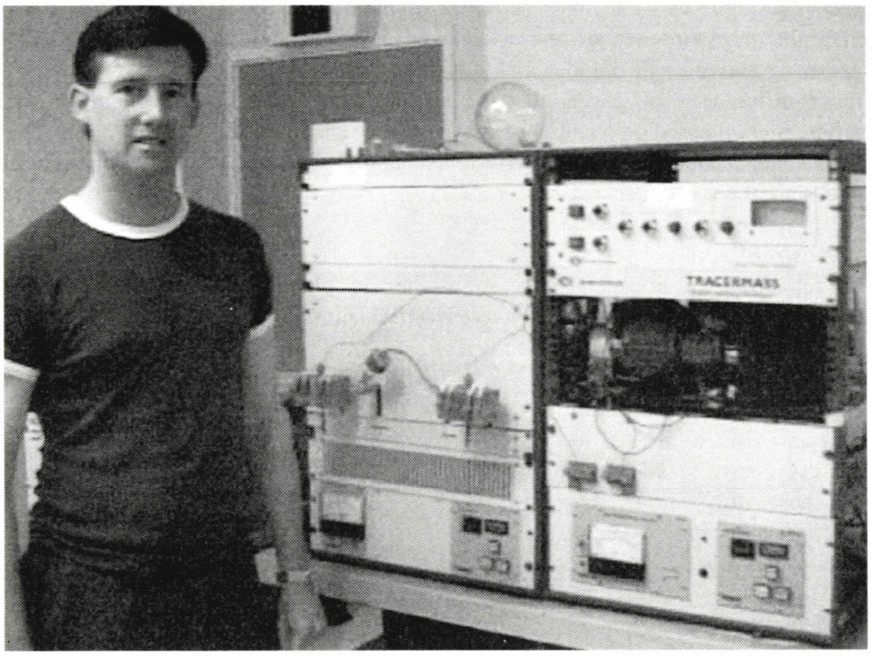


Figure 3 Donald Pate with the Europa Scientific mass spectrometer used to derermine bone collagen stable carbon and nitrogen isotape values, CSIRO Division of Land and Water, Adelaide, South Australia. Photo: Tim Owen

As the Roonka Flat site is located in an inland riverine environment dominated by plants employing the C_3 photosynthetic pathway, bone collagen stable carbon isotope values could be used to assess the relative quantities of local C_3-based foods and marine/inland C_4-based foods in prehistoric Aboriginal diets (Pate 1995a, 1995b). Plant and animal foods obtained from the Murray River are included in the C_3 terrestrial category. The mean bone collagen stable carbon isotope value (-20.1 ● 1.2‰, n = 32) for the Roonka Flat human sample indicated that Aboriginal diets consisted of at least 90% C_3-based terrestrial and freshwater foods. Thus, stable carbon isotope values suggested that there was minimal movement of people and/or food between the inland riverine area and the southeastern coastal and arid interior regions of South Australia during the late Holocene.

The addition of bone collagen stable nitrogen isotope data (Pate 1997a, 1998a, 1998b) provided more precise dietary discrimination suggesting a focus on local terrestrial mammals such as kangaroos, wombats, and dingoes supplemented by freshwater fish, mussels, and crustaceans. A plot of mean stable carbon vs. nitrogen isotope values for Roonka Flat humans and potential dietary items suggested that these riverine hunter-gatherers obtained 40-50% of their dietary protein from the meat of local terrestrial herbivores, 30-40% from freshwater fish and shellfish and 10-15% from terrestrial carnivores, i.e. dingoes. Marine foods, arid-land terrestrial mammals, and aquatic and terrestrial vegetable foods made only minimal contributions to the dietary protein intake of these Indigenous riverine inhabitants. Faunal remains from lower Murray rockshelters also indicated diets based on terrestrial mammals and freshwater fish and shellfish during the Late Holocene (Hale and Tindale 1930; Mulvaney 1960; Mulvaney et al. 1964; Smith 1978, 1982; Paton 1983).

Figure 4 Amy Roberts and Donald Pate in the mass spectrometry laboratory, CSIRO Division of Land and Water, Adelaide, South Australia. Photo: Tim Owen

While adult males and females had similar mean bone collagen stable nitrogen isotope values (male: 13.3 ± 1.2‰, n = 14; female: 13.2 ± 1.4‰, n = 11), on average males had mean stable carbon isotope values (-19.7 ● 1.0‰, n = 14) that were 0.7‰ more positive than females. Subadults (less than 15 years old), had mean stable nitrogen isotope values that were approximately 0.6‰ more positive than adults; whereas, stable carbon isotope values were similar in adult females and subadults. The observed $\delta^{15}N$-enrichment in Roonka Flat subadults may be an artefact of milk-based diets from childhood (Fogel et al. 1989; Tuross and Fogel 1994). In addition, subadults had diets more similar to those of adult females than adult males, including greater quantities of ^{13}C-depleted foods such as aquatic and terrestrial plants and freshwater shellfish. Thus, stable isotope dietary reconstructions for children suggest that they spent greater amounts of time with adult females than they did with adult males. Furthermore, dietary differences between adult males and adult females indicate that food sharing, if practiced, did not result in an equal distribution of various food types.

With regard to sedentism and territoriality, the stable nitrogen isotope data also indicated limited movement of food and people between the riverine environment and adjacent arid interior and coastal habitats. Other archaeological and physical anthropological data provide independent support for the stable isotope findings. Palaeopathological analyses, determinations of biological distance from cranial non-metric traits, surveys of cemetery and site distributions and numbers, and mortuary analyses have all provided evidence for increased sedentism and territoriality along the lower Murray River during the Late Holocene (Pretty 1977, 1986; Prokopec 1979; Pate 1984, 1995a, 1995b; 1997a; Webb 1984, 1989, 1995; Pardoe 1988, 1990, 1994, 1995; Pretty and Kricun 1989).

Discussion

Bone chemistry research at Roonka Flat played a primary role in the development of elemental and isotopic palaeodietary methods in Australia. In addition, a small number of stable isotope palaeodietary research projects have also been conducted in the Pacific (e.g. McGovern and Quinn 1996; Ambrose et al. 1997; Pate et al. 1999).

Stable isotope analyses of human and faunal bones and teeth are emerging as valuable alternative means for the reconstruction of past human dietary composition, territorial boundaries and social landscapes. In relation to pre-contact sites, stable isotope techniques provide quantitative dietary data that cannot be obtained using conventional archaeological and physical anthropological methods. For historical periods, stable isotope data provide a valuable supplement to information obtained from written records, archaeological excavations and physical anthropology.

Furthermore, stable isotope analyses of bones and teeth from archaeological and palaeontological sites are now employed to infer changes in past plant and animal distributions and climatic conditions. Recent Australian applications in these areas include the research of Ayliffe and Chivas (1990) with oxygen and Noble (1995), Anson (1997), Grocke (1997), Grocke et al. (1997), Pate et al. (1998b), Roberts (1998), Roberts et al. (1999) and Pate and Noble (2000) with carbon and/or nitrogen. Thus, stable isotope data are complementing standard palaeoecological methods by providing independent means to address various research questions.

Due to the central role of stable isotope data from modern fauna in providing baseline values for inferences about past diet, climate and ecology, improved faunal data bases for various ecosystems and geographic regions of Australia are required before widespread applications of stable isotope methods can be realised. In addition, the future success of isotopic applications involving pre-contact human bone samples in Australia will depend on a significant improvement of the existing skeletal collections available for study. Large, well-provenanced skeletal samples representing a variety of ecological zones in different regions of the continent are required (Pate 1997a). A range of bioarchaeological research areas will benefit from better skeletal samples. In addition, applications of bioarchaeological data to general archaeological research problems will be facilitated by improved skeletal collections.

Pate's research group is currently investigating the potential of stable isotope data as a means to determine the geographical origin of non-provenanced skeletal remains held by the South Australian Museum. If successful, the technique will be applied to other museum collections in Australia and abroad. The provision of geographical locality for un-provenanced skeletal remains will benefit bioarchaeological research by improving skeletal samples and at the same time provide Indigenous communities with better information regarding the nature of these collections.

As Indigenous Australians learn more about the benefits of bioarchaeological research, they are placing greater value on the results of this research and its direct application to community health programs, native title claims and improved information about the diversity of past lifeways. The improving relations between archaeologists and Indigenous communities in Australia including the direct involvement of Aboriginal and Torres Strait Islander peoples in archaeological research is paving the way for a productive future that will benefit archaeologists, Indigenous peoples and the general Australian public. Bioarchaeological research has the potential to make a significant contribution to this process of reconciliation.

References

Ambrose, S.H., Butler, B.M., Hanson, D.B., Hunter-Anderson, R.L. and Krueger, H.W. 1997 Stable isotopic analysis of human diet in the Marianas archipelago, western Pacific. *American Journal of Physical Anthropology* 104:343-361.

Anson, T.J. 1997 The Effect of Climate on Stable Nitrogen Isotope Enrichment in Modern South Australian Mammals. Unpublished M.A. thesis, Flinders University, Adelaide, South Australia.

Ayliffe, L. and Chivas, A. 1990 Oxygen isotope composition of the bone phosphate of Australian kangaroos- potential as a paleoenvironmental recorder. *Geochimica et Cosmochimica Acta* 54:2603-2609.

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

Bettinger, R.L. and King, T.F. 1971 Interaction and political organization: A theoretical framework for archaeology in Owens Valley, California. *University of California, Los Angeles, Archaeological Survey Annual Report*, 13.

Blakely, R.L. and Beck, L.A. 1981 Trace elements, nutritional status and social stratification at Etowah, Georgia. *Annals of the New York Academy of Science* 376:417-431.

Boaz, N.T. and Hampel, J. 1978 Strontium content of fossil tooth enamel and diet of early hominids. *Journal of Paleontology* 52: 928-933.

Bocherens, H., Fizet, M., Mariotti, A., Lange-Badre, B., Vandermeersch, B., Borel, J.P.and Bellon, G. 1991 Isotopic biogeochemistry (^{13}C, ^{15}N) of fossil vertebrate collagen: Application to the study of a past food web including Neandertal Man. *Journal of Human Evolution* 20:481-492.

Bocherens H., van Klinken G.J. and Pollard A.M. (Editors) 1999 Proceedings of the 5th Advanced Seminar on Paleodiet. *Journal of Archaeological Science* 26:593-728.

Boyd, W.E. and Pretty, G.L. 1989 Some prospects for archaeological palaeobotany in Australia: an example from South Australia. *Australian Archaeology* 28:40-52.

Brown, A.B. 1974 Bone strontium as a dietary indicator in human skeletal populations. *Contributions to Geology* 13:47-48.

Bunn, S.E. and Boon, P.I. 1993 What sources of organic carbon drive food webs in billabongs?: A study based on stable isotope analysis. *Oecologia* 96:85-94.

Chisholm, B.S., Nelson, D.E., and Schwarcz, H.P. 1982 Stable-carbon isotope ratios as a measure of marine versus terrestrial protein in ancient diets. *Science* 216:1131-1132.

Chisholm, B.S., Nelson, D.E., and Schwarcz, H.P. 1983 Marine and terrestrial protein in prehistoric diets on the British Columbia coast. *Current Anthropology* 24:396-398.

Collier, S. and Hobson, K.A. 1987 The importance of marine protein in the diet of coastal Australian Aborigines. *Current Anthropology* 28:559-564.

Connor, M. and Slaughter, D. 1984 Diachronic study of Inuit diets utilizing trace element analysis. *Arctic Anthropology* 21:123-134.

Ericson, J.E. 1985 Strontium isotope characterization in the study of prehistoric human ecology. *Journal of Human Evolution* 14:503-514.

Fogel, M.L., Tuross, N. and Owsley, D.W. 1989 Nitrogen isotope tracers of human lactation in modern and archaeological populations. *Annual Report of the Director of the Geophysical Laboratory, Carnegie Institution*, pp. 111-117. Carnegie Institution, Washington, D.C.

Gilbert, R.I. 1977 Application of trace element research to problems in archaeology. In R.L. Blakely (ed.) *Biocultural Adaptation in Prehistoric America*, pp. 85-100. Athens: University of Georgia Press.

Grocke, D.R. 1997. Distribution of C^3 and C^4 plants in the Late Pleistocene of South Australia recorded by isotope biogeochemistry of collagen in megafauna. *Australian Journal of Botany* 45:607-617.

Grocke, D.R., Bocherens, H. and Mariotti, A. 1997 Annual rainfall and nitrogen-isotope correlation in macropod collagen: application as a palaeoprecipitation indicator. *Earth and Planetary Science Letters* 153:279-285.

Hale, H.M. and Tindale, N.B. 1930 Notes on some human remains in the lower Murray Valley, South Australia. *Records of the South Australian Museum* 4:145-218.

Hobson, K.A., and Collier S. 1984 Marine and terrestrial protein in Australian Aboriginal diets. *Current Anthropology* 25:238-240.

King, T.F. 1976 Political Differentiation among Hunter-Gatherers: An Archaeological Test. Unpublished Ph.D. thesis, University of California, Riverside.

King, T.F. 1978 Don't that beat the band? Non-egalitarian political organization in prehistoric central California. In C. Redman et al. (eds) *Social Archaeology: Beyond Subsistence and Dating*, pp. 225-248. New York: Academic Press.

Klepinger, L.L. 1984 Nutritional assessment from bone. *Annual Review of Anthropology* 13:75-96.

Kohn, M.J., Schoeninger, M.J. and Valley, J.W. 1996 Herbivore tooth oxygen isotope compositions: effects of diet and physiology. *Geochimica et Cosmochimica Acta* 60:3889-3896.

Krueger, H.W. 1991 Exchange of carbon with biological apatite. *Journal of Archaeological Science* 18:355-361.

Krueger, H.W. and Sullivan, C.H. 1984 Models for carbon isotope fractionation between diet and bone. In J.R. Turnlund and P.E. Johnson (eds) *Stable Isotopes in Nutrition*, pp. 205-220. Washington, D.C: American Chemical Society.

Lambert, J.B., Szpunar, C.B. and Buikstra, J.E. 1979 Chemical analysis of excavated human bone from Middle and Late Woodland sites. *Archaeometry* 21:115-129.

Lee, R.B. and DeVore, I. (eds) 1968 *Man the Hunter*. Chicago: Aldine.

Lee-Thorp, J.A. and van der Merwe, N.J. 1991 Aspects of the chemistry of modern and fossil biological apatites. *Journal of Archaeological Science* 18:343-354.

Lee-Thorp, J.A., Sealy J.C. and van der Merwe, N.J. 1989 Stable carbon isotope ratio differences between bone collagen and bone apatite, and their relationship to diet. *Journal of Archaeological Science* 16:585-599.

MacFadden, B.J. and Bryant, J.D. (eds) 1994 Stable isotope and trace element geochemistry of vertebrate fossils: interpreting ancient diets and climates. *Palaeogeography, Palaeoclimatology, Palaeoecology.* 107:199-329.

McGovern-Wilson, R.J. and Quinn, C. 1996 Stable isotope analysis of ten individuals from Afetna, Saipan, Northern Mariana Islands. *Journal of Archaeological Science* 23:59-65.

Meehan, B. 1984 Aboriginal skeletal remains. *Australian Archaeology* 19:122-127.

Mulvaney, D.J. 1960 Archaeological excavations at Fromm's Landing on the lower Murray River, South Australia. *Proceedings of the Royal Society of Victoria* 72:53-85.

Mulvaney, D.J., Lawton, G.H. and Twidale, C.R. 1964 Archaeological excavation of rockshelter No. 6, Fromm's Landing, South Australia. *Proceedings of the Royal Society of Victoria* 77:479-516.

Noble, A.H. 1995 An Analysis of Stable Carbon Isotope Variation within Animal Bone Collagen along the Eastern Border of South Australia. Unpublished B.A. Honours thesis, Department of Archaeology, Flinders University, Adelaide, South Australia.

Norr, L., 1981 Prehistoric Costa Rican diet as determined from stable carbon isotope ratios in bone collagen. *American Journal of Physical Anthropology* 54:258-259.

Norr, L. 1982 A new chemical analysis for the determination of a marine fauna component in prehistoric diets. *American Journal of Physical Anthropology* 57:214.

Pardoe, C. 1988 The cemetery as symbol. The distribution of Aboriginal burial grounds in southeastern Australia. *Archaeology in Oceania* 23:1-16.

Pardoe, C. 1990 The demographic basis of human evolution in southeastern Australia. In B. Meehan and N. White (eds) Hunter-Gatherer Demography, pp. 59-70. Sydney: University of Sydney. *Oceania Monograph* 39.

Pardoe, C. 1994 Bioscapes: The evolutionary landscape of Australia. *Archaeology in Oceania* 29:182-190.

Pardoe, C. 1995 Riverine, biological and cultural evolution in southeastern Australia. *Antiquity* 69:696-713.

Pate, F.D. 1984 Mortuary Practices and Paleodiet as Archaeological Signatures of Social Organization and Status at Roonka on the lower Murray River of South Australia. Unpublished M.A. thesis, Department of Anthropology, Brown University, Providence, Rhode Island.

Pate, F.D. 1989 Postmortem Chemical Changes in Buried Bone: An Investigation of Environmental Formation Processes at the Roonka Archaeological Site, South Australia. Ph.D. thesis, Department of Anthropology, Brown University, Providence, Rhode Island.

Pate, F.D. 1990 Postmortem Chemical Changes in Buried Bone: An Investigation of Environmental Formation Processes at the Roonka Archaeological Site, South Australia. Ann Arbor: University Microfilms International.

Pate, F.D. 1994 Bone chemistry and paleodiet. *Journal of Archaeological Method Theory* 1:161-209.

Pate, F.D. 1995a Stable carbon isotope assessment of hunter-gatherer mobility in prehistoric South Australia. *Journal of Archaeological Science* 22:81-87.

Pate, F.D. 1995b Palaeodietary inferences from bone collagen stable carbon isotopes at Roonka Flat, South Australia. *Australian Archaeology* 40:57.

Pate, F.D. 1997a Bone chemistry and paleodiet: Reconstructing prehistoric subsistence-settlement systems in Australia. *Journal of Anthropological Archaeology* 16:103-120.

Pate, F.D. 1997b Bone collagen diagenesis at Roonka Flat, South Australia: Implications for isotopic analysis. *Archaeology in Oceania* 32:170-175.

Pate, F.D. 1998a Bone collagen stable nitrogen and carbon isotopes as indicators of prehistoric diet and landscape use in southeastern South Australia. *Australian Archaeology* 46: 23-29.

Pate, F.D. 1998b Stable carbon and nitrogen isotope evidence for prehistoric hunter-gatherer diet in the lower Murray River Basin, South Australia. *Archaeology in Oceania* 33:92-99.

Pate, F.D. 1998c Bone collagen preservation at the Roonka Flat Aboriginal burial ground: A natural laboratory. *Journal of Field Archaeology* 25:203-217.

Pate, F.D. and Brown, K.A. 1985 The stability of bone strontium in the geochemical environment. *Journal of Human Evolution* 14:483-491.

Pate, F.D. and Hutton, J.T. 1988 The use of soil chemistry data to address postmortem diagenesis in bone mineral. *Journal of Archaeological Science* 15:729-739.

Pate, F.D. and Schoeninger, M.J. 1993 Stable carbon isotope ratios in bone collagen as indicators of marine and terrestrial dietary composition in southeastern South Australia: A preliminary report. In B.L. Fankhauser and J.R. Bird (eds) *Archaeometry: Current Australasian Research*, pp. 38-44. Canberra: Department of Prehistory, Research School of Pacific Studies, The Australian National University. *Occasional Papers in Prehistory* 22.

Pate, F.D. and Noble, A.H. 2000 Geographic distribution of C^3 and C^4 grasses recorded in bone collagen stable carbon isotope values of South Australian herbivores. *Australian Journal of Botany* 48(2):203-207.

Pate, F.D., Hutton, J.T. and Norrish, K. 1989 Ionic exchange between soil solution and bone: Toward a predictive model. *Applied Geochemistry* 4:303-316.

Pate, F.D., Hutton, J.T., Gould, R.A. and Pretty, G.L. 1991 Alterations of in vivo elemental dietary signatures in archaeological bone: Evidence from the Roonka Flat dune, South Australia. *Archaeology in Oceania* 26:58-69.

Pate, F.D., Pretty, G.L., Hunter, R., Tuniz, C. and Lawson, E.M. 1998a New radiocarbon dates for the Roonka Flat Aboriginal burial ground, South Australia. *Australian Archaeology* 46:36-37.

Pate, F.D., Anson, T.J., Schoeninger, M.J. and Noble, A.H. 1998b Bone collagen stable carbon and nitrogen isotope variability in modern South Australian mammals: A baseline for palaeoecological inferences. *Quaternary Australasia* 16:43-51.

Pate, F.D., Craib, J.L. and Heathcote, G.M. 1999 Stable isotopic analysis of prehistoric human diet in the Mariana Islands, Western Pacific. *Australian Archaeological Association Annual Conference Programme and Abstracts*: 10. Perth: University of Western Australia.

Paton, R.C. 1983 An Analysis of Aboriginal Subsistence in the lower Murray District, South Australia. Unpublished BA Honours thesis, The Australian National University.

Peterson, B.J. and Fry, B. 1987 Stable isotopes in ecosystem studies. *Annual Review of Ecology and Systematics* 18:293-320.

Prescott, J.R. 1983 TL dating of sands at Roonka, South Australia. *PACT Journal* 9:505-512.

Pretty, G.L. 1977 The cultural chronology of the Roonka Flat. In R.V.S. Wright (ed.) *Stone Tools as Cultural Markers*, pp. 288-331. Canberra: Australian Institute of Aboriginal Studies.

Pretty, G.L. 1986 Australian history at Roonka. *Journal of the Historical Society of South Australia* 14:107-122.

Pretty, G.L. 1988 Radiometric chronology and signifigance of the fossil hominid sequence from Roonka, South Australia. In J.R. Prescott (ed.) *Early Man in the Southern Hemisphere. Supplement to Archaeometry: Australasian Studies 1988*, pp. S32-S52. Adelaide: University of Adelaide.

Pretty, G.L., and Kricun, M.E. 1989 Prehistoric health status of the Roonka population. *World Archaeology* 21:198-224.

Price, T.D. (ed.) 1989 *The Chemistry of Prehistoric Human Bone*. Cambridge: Cambridge University Press.

Prokopec, M. 1979 Demographical and morphological aspects of the Roonka population. *Archaeology and Physical Anthropology in Oceania* 14:11-26.

Prokopec, M. and Pretty, G.L. 1991 Observations on health, genetics and culture from analysis of skeletal remains from Roonka, South Australia. In D.J. Ortner and A.C. Aufderheide (eds) *Human Paleopathology: Current Syntheses and Future Options*, pp. 151-158. Washington: Smithsonian Institution Press.

Quade, J., Cerling, T.E., Barry, J.C., Morgan, M.E., Pilbeam, D.R., Chivas, A.R., Lee-Thorp, J.A. and van der Merwe, N. 1992 A 16-Ma record of paleodiet using carbon and oxygen isotopes in fossil teeth from Pakistan. *Isotope Geoscience* 94:183-192.

Radosevich, S.C. 1989a Diet or Diagenesis?: An Evaluation of the Trace Element Analysis of Bone. Unpublished Ph.D. thesis, Department of Anthropology, University of Oregon.

Radosevich, S.C. 1989b Geochemical techniques applied to bone from south Asia and Alaska: Neither God's truth or hocus-pocus. *Wisconsin Journal of Archaeology* 2:93-102.

Radosevich, S.C. 1993 The six deadly sins of trace element analysis = a case of wishful thinking in science. In M.K. Sandford (ed.) *Investigations of Ancient Human Tissues: Chemical Analysis in Anthropology*, pp. 269-321. New York: Gordon and Breach.

Roberts, A.L. 1998 Digging Deeper: A Re-analysis of the Archaeology of Fromm's Landing, South Australia. Unpublished B.A. Honours thesis, Department of Archaeology, Flinders University, Adelaide, South Australia.

Roberts, A.L., Pate, F.D. and Hunter, R. 1999 Late Holocene climatic changes recorded in macropod bone collagen stable carbon and nitrogen isotopes at Fromm's Landing, South Australia. *Australian Archaeology* 49:48-49.

Sanford, M.K. 1992 A reconsideration of trace element analysis in prehistoric bone. In S.R. Saunders and M.A. Katzenberg (eds) *Skeletal Biology of Past Peoples: Research Methods*, pp. 79-103. New York: Wiley-Liss.

Schoeninger, M.J. 1979 Diet and status at Chalcatzingo: Some empirical and technical aspects of strontium analysis. *American Journal of Physical Anthropology* 51:295-310.

Schoeninger, M.J. and DeNiro, M.J. 1984 Nitrogen and carbon isotopic composition of bone collagen from marine and terrestrial animals. *Geochimica et Cosmochimica Acta* 48:625-639.

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

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

Sighinolfi, G.P., Sartono, S. and Artioli, G. 1993 Chemical and mineralogical studies on hominid remains from Sangiran, Central Java (Indonesia). *Journal of Human Evolution* 24:57-68.

Sillen, A. and Kavanagh, M. 1982 Strontium and paleodietary research: A review. *Yearbook of Physical Anthropology* 25:67-90.

Smith, M.A. 1978 A note on the fauna from Devon Downs shelter. *Australian Archaeology* 8:19-21.

Smith, M.A. 1982 Devon Downs reconsidered: Changes in site use at a lower Murray Valley rockshelter. *Archaeology in Oceania* 17:109-116.

Smith, P., Prokopec, M. and Pretty, G. 1988 Dentition of a prehistoric population from Roonka Flat, South Australia. *Archaeology in Oceania* 23:31-36.

Sponheimer, M. and Lee-Thorp, J.A. 1999 Oxygen isotope in enamel carbonate and their ecological signifigance. *Journal of Archaeological Science* 26:723-728.

Struever, S. 1968 Woodland subsistence systems in the lower Illinois Valley. In S.R. Binford and L.R. Binford (eds) *New Perspectives in Archaeology*, pp. 285-312. Chicago: Aldine.

Tuross, N. and Fogel, M.L. 1994 Stable isotope analysis and subsistence patterns at the Sully site. In D.W. Owsley and R.L. Jantz (eds) *Skeletal Biology in the Great Plains: Migration, Warfare, Health, and Subsistence*, pp. 283-290. Washington, D.C.: Smithsonian Institution Press.

Tuross, N., Fogel, M.L. and Hare, P.E. 1988 Variability in the preservation of the isotopic composition of collagen from fossil bone. *Geochimica et Cosmochimica Acta* 52:929-935.

van der Merwe, N.J. 1982 Carbon isotopes, photosynthesis and archaeology. *American Scientist* 70:596-606.

van der Merwe, N.J. and Vogel, J.C. 1978 ^{13}C concentration of human collagen as a measure of prehistoric diet in Woodland North America. *Nature* 276: 815-816.

Webb, S.G. 1984 Intensification, population and social change in southeastern Australia: The skeletal evidence. *Aboriginal History* 8:154-172.

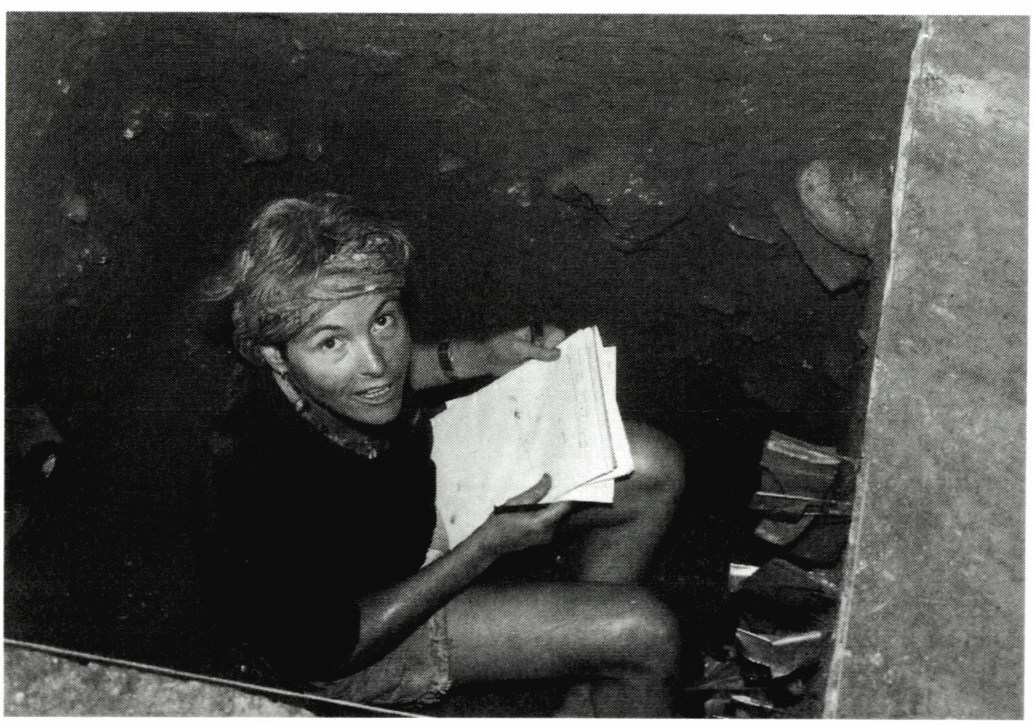
Webb, S.G. 1987 Reburying Australian skeletons. *Antiquity* 61:292-296.

Webb, S.G. 1989 *Prehistoric Stress in Australian Aborigines: A Palaeopathological Study of a Hunter-Gatherering Population*. Oxford: *British Archaeological Reports*, International Series 490.

Webb, S.G. 1995 *Palaeopathology of Aboriginal Australians: Health and Disease across a Hunter-Gatherer Continent.* Cambridge: Cambridge University Press.

Whitmer, A.M., Ramenofsky, A.F., Thomas, J., Thibodeaux, L.J., Field, S.D. and Miller, B.J. 1989 Stability or instability: The role of diffusion in trace element studies. In M.B. Schiffer (ed.) *Archaeological Method and Theory* 1, pp. 205-273. Tucson: University of Arizona Press.

Wright, L.E. and Schwarcz, H.P. 1999 Correspondence between stable carbon, oxygen and nitrogen isotopes in human tooth enamel and dentine: Infant diets at Kaminaljuyu. *Journal of Archaeological Science* 26:1159-1170.



Sue O'Connor in pursuit of the Pleistocene in the Aru Islands, Nabulai Lisa, 1998. Photo: courtesy of P. Veth