GC–MS ANALYSIS AND FATTY ACID RATIOS OF ARCHAEOLOGICAL POTSHERDS FROM THE WESTERN GREAT BASIN OF NORTH AMERICA*

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The study of organic residues in archaeological pottery has focused on fatty acids due to their relative stability and longevity. However, even these compounds are subject to degradation, which makes assignment of residues to original foods problematic. This paper suggests that the use of ratios of fatty acids that degrade at roughly the same rate can be useful to identify very general categories of foods. It compares independent information on pot function based on ethnography and engineering/technological studies to that reconstructed based on extracted fatty acid ratios. The results support the notion that Great Basin pots were used primarily to boil seeds and that pot shape and pot function were related.

INTRODUCTION

Reconstruction of the types of foods that were cooked or stored in ceramic pots has been an important part of archaeological research over the last 30 years. An understanding of the function of prehistoric pots forms the foundations of important questions such as breadth of diet, the relationship between technology, form and function, and the origins of pottery (e.g., Brown 1989; Sassaman 1993; Crown and Wills 1995; Rice 1999; see also papers in Barnett and Hoopes 1995). There are many different approaches to help reconstruct the types of foods prepared in ancient pots. Engineering and economic analyses (e.g., Linton 1944; Rye 1976; Arnold 1985; Smith 1985; Bronitsky and Hamer 1986; Rice 1987; Brown 1989; Feathers 1989; Skibo *et al*. 1989; Juhl 1995), use wear studies (e.g., Hally 1983; Rice 1987; Shiffer 1989; Skibo 1992; Beck *et al*. 2002) and ethnographic analogy (e.g., Henrickson and McDonald 1983; Costin 2000; Hegmon 2000) are three common methods that have seen extensive application. While these methods have been successful in certain cases, they often provide only hypotheses about the types of foods that may have been cooked in a pot, rather than definitive evidence.

Residue analysis has the potential to be more precise. Over the last decade there has been a marked increase in the number of papers taking this approach (e.g., Evershed *et al*. 1994, 1997, 2003; Charters *et al*. 1997; Frankhauser 1997; Malainey *et al*. 1999a–c; Mottram *et al*. 1999; Stott *et al*. 1999; Eerkens 2002; Maniatis and Tsirtsoni 2002; Rafferty 2002). Despite difficulties related to preservation and extraction, these studies have demonstrated that a variety of compounds, including fatty acids, waxes, sterols, resins, tars, pitches and amino acids, can be preserved in prehistoric sherds and used to indicate the range of products cooked, stored or prepared in a pot (see Evershed 1993).
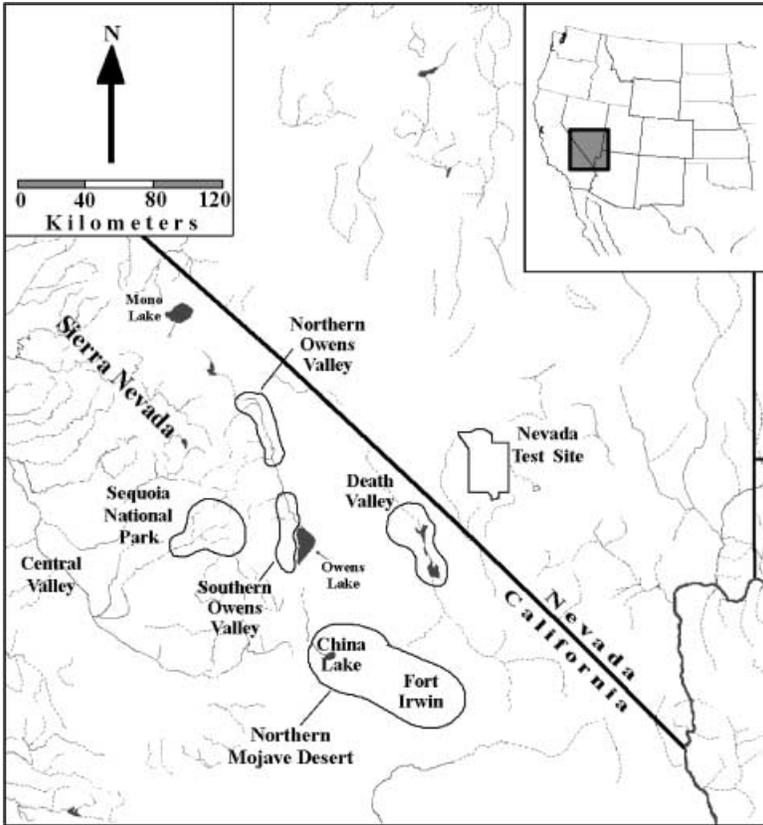
Figure 1   *A map of the study area.*

The Great Basin of North America (Fig. 1) is an ideal setting for the application of residue analysis. The porous, unglazed and unpainted nature of pots makes them good candidates for the absorption and retention of organic materials. Also, residues within sherds are more likely to be preserved due to the prevailing aridity of the region and the young age of the pottery, which is generally less than 600 years old (but see Eerkens *et al*. 1999). This paper presents the results of previous functional analyses on potsherds, including engineering and ethno-graphic studies, and compares them to the results of residue analyses on a sample of 75 sherds analysed using gas chromatography–mass spectrometry (GC–MS). Conclusions are then offered regarding the use of ceramics in the western Great Basin.

GREAT BASIN POTS AND PREVIOUS FUNCTIONAL STUDIES

Pots in the Great Basin were formed by the 'coil-and-scrape' method. Potters created a flat circular base about 8–20 cm in diameter, depending on the intended size of the pot, on to which coils of clay were stacked to form the body. The interior and exterior surfaces were finished by scraping with a brush, the fingers or some other implement to weld the coils together and to even out the surface. Leaving the exterior surface slightly rough with scraping marks would

have increased the surface area, giving pots a greater capacity to absorb heat. The paddle-and-anvil technique, widely used in extreme southern California (Kroeber and Harner 1954; Van Camp 1979), was not used in the Great Basin. Pots were fired in small brush fires with whatever fuels were conveniently available. The maximum temperatures of these fires were low (~600–800°C), and the firing technique often created an uncontrolled atmosphere. As a result, pots show considerable variation in surface colour and core structure even across the same vessel.

Although pots were occasionally embellished with fingernail incisions or punctate holes, the majority (~90%) were left undecorated. Moreover, when they were decorated, the style was surprisingly homogenous over a large geographical region, usually consisting of a single row of haphazardly spaced marks on the exterior of the pot, just below or occasionally on the lip. Given the lack of decoration, the weight and susceptibility to breakage, it is not surprising that pots were not widely exchanged (Eerkens *et al*. 2002). This is quite unlike other goods such as obsidian and shell beads that were distributed widely over California and the Great Basin (e.g., Davis 1961; Bennyhoff and Hughes 1987). Certainly, pots *could* have served as vehicles to transport other goods (i.e., be moved as a by-product of exchange for other goods). However, empirical evidence suggests that pots were produced primarily for local consumption (Eerkens *et al*. 2002). Village- and/or individual-level production seems to have been the norm.

Engineering studies

Pot forms in the western Great Basin are not very diverse. The dominant type is a V-shaped straight-sided vessel, usually between 20 and 40 cm in height and mouth diameter. A slightly smaller and more hemispherical bowl that occasionally displays recurved rims is also present, especially in the southern and eastern parts of the study area. Both forms have relatively open mouths that allow heat to escape through the mouth and provide easy access to the contents. Also, both display thin walls between 5 and 7 mm that facilitate transfer of heat, although pots get thinner through time (Eerkens 2003a). These characteristics, along with the presence of rough exterior surfaces that increase the surface area, and mineral temper that facilitates heat transfer, suggest that pots were designed to withstand repeated cycles of heating and cooling. Together, the data suggest that pots, especially the V-shaped form, were ideally suited for high-temperature boiling activities (for a more extensive discussion, see Eerkens 2001, 2003b). Burning marks on the exterior and carbonized food residues on the interior support this notion that pots were used to boil foods over open fires.

As others have argued, high-temperature boiling is particularly effective in the preparation of seeds and other carbohydrate-rich foods (Linton 1944; Braun 1983; Stahl 1989; Crown and Wills 1995; Wandsnider 1997). Complex carbohydrates in seeds can be reduced to a more easily digested gelatinized gruel by boiling in water over high-temperature fires. Other products are typically prepared in alternative manners. For example, meats are better prepared by long-term simmering, and roots and tubers are optimally prepared through steaming and roasting. Technological studies suggest that pots used for such boiling activities often have wide, open and flaring mouths to allow heat to escape through the orifice, while pots used for simmering have constricted openings to conserve heat within the vessel (Arnold 1985; Smith 1985; Juhl 1995). Pots with restricted orifices used in high-temperature boiling build up heat within the neck, causing explosive overboiling of the contents or even breakage of the vessel across the neck. Thus, pots used to cook seeds should have direct rims and wide mouths, while those used to cook meats should be incurved or recurved, with more narrow mouths.

Table 1 *Ethnographic accounts of food preparation and the use of pottery*

Group	Region	Foods cooked in pots	Foods not cooked in pots	Reference
Western Mono	Western Sierra Nevada	Greens, deer meat, acorn mush (rarely)	Small rodents, fish, manzanita, grasshopper	Gayton (1948)
Owens Valley Paiute	Owens Valley	Seeds, piñon, berries, acorn, rabbit, water fowl, sheep, pandora moth, brine fly	Fish, deer, rodents	Steward (1933)
Western Shoshoni	Western Nevada	Seeds, roots, animal internal organs	Meat flesh, piñon, acorn	Steward (1941)
Tubatulabal	Southern Sierra Nevada	Seeds, piñon, elderberry, yucca, buckeye, acorn, meat flesh	Small game, fish, freshwater mussel, roots	Voegelin (1938)
Western Shoshoni	Inyo County	Seeds, rabbit	Piñon, blue dick, Joshua tree seeds	Irwin (1980)

Together, these results suggest that boiling of seed and other carbohydrate-rich plant resources was an important function of western Great Basin pots, especially in the V-shaped forms. Residues from these resources should be prevalent in such pots. Recurved bowls, on the other hand, are predicted to have been used more for lower-temperature simmering for meat products.

Ethnographic analogy

With the exception of work by Gayton (1929), ethnographic descriptions of pottery use in the western Great Basin are not extensive. In fact, some descriptions of pottery are at odds with what is known from prehistoric contexts. For example, Driver (1937) describes pots in the Owens Valley as being painted with black-on-white designs, yet not a single painted pot is known from the region. This is probably the result of access to metal pots, which prompted the Paiute and Shoshone peoples to drop pottery from the material culture repertoire. As a result, by the 1930s many informants had little or no direct experience with pottery-making, and the validity of ethnographic analogy for prehistoric contexts should be regarded with caution. At the same time, if we assume that metal pots replaced earthenware ones, an examination of the foods that were cooked in the former in ethnographic times may provide some indication for the range of foods cooked in the latter in prehistoric times.

Table 1 presents the results of a survey of ethnographic data from the western Great Basin on foods for which specific preparation techniques are described. The table demonstrates that a wide range of foods were cooked in pots and that the types of foods varied from group to group. Overall, plants are more commonly represented in the positive side and meats, with the exception of rabbit, more commonly in the negative side. If we add up all the occurrences of plant and animal products in each category (cooked in pot versus not cooked in pot), we find that while 70% (16 of 23) of plant products were cooked in pots, only 47% (9 of 19) of meat products were. However, a chi-square test suggests that this difference is not significant at the 5% level ($p = 0.23$). Roots are also notably absent from the positive side.

Overall, seeds are nearly ubiquitously mentioned as having been, and rodents having not been, prepared in pots. While the ethnographic data do not suggest a single and consistent use for pots, they do provide some useful comparative data for a residue study. In particular, if we

trust the data we should see a range of products with a strong presence of plants, especially seeds, relative to meats.

<div align="center">RESIDUE ANALYSIS</div>

The basic assumption of most residue studies is that different plants and animals produce different types and quantities of organic compounds. Pots have a 'clean slate' of organic residues after being fired and begin to absorb compounds during use. Organic materials from foods, especially fats and oils, essentially clog the porous spaces or vugs within the fabric of the pot during the first several uses, where they are sealed and preserved. Residue profiles are not subsequently contaminated by the influx of materials from the surrounding soil (Deal and Silk 1988; Heron *et al*. 1991). Thus, it is generally believed that preserved residues represent the first few uses of a pot.

Archaeological residue studies have generally targeted the recovery of lipids, since they are stable and do not degrade as quickly as other compounds (Christie 1989; Evershed 1993). In general, lipid profiles are distinct between different plant and animal species. However, two processes act to obscure these differences in archaeological sherds. First, cooking exposes lipids to heat, which causes degradation. Of course, this is the goal of cooking in the first place; namely, to make foods easier to digest by breaking down complex compounds extra-somatically (e.g., see Wandsnider 1997). To get around this, archaeologists have generally relied on the lipid profiles of items cooked in test pots as fingerprints or signatures of different foods, rather than raw or unmodified foods (e.g., Skibo 1992; Charters *et al*. 1997; Evershed *et al*. 1997; Malainey *et al*. 1999c).

Secondly, although lipids are stable relative to other organic compounds such as DNA and proteins, oxidation and hydrolysis do contribute to their decomposition (Christie 1989; Frankel 1998). The extent of degradation in a sherd depends on the depositional context, how well lipids are sealed and the length of time since the pot was used. While hydrolysis is unlikely to be significant in the arid Great Basin, oxidation is a potential problem, although some suggest that the effects are minimal (e.g., Hill and Evans 1989; Malainey 1997, 109). Oxidation results in the breakdown of lipids into various by-products (Fritsch and Deatherage 1956; Frankel 1980, 1987, 1998; Porter *et al*. 1981; Hudlicky 1990, 222). The most common way to deal with oxidation in archaeological contexts is to examine the ratios of lipids to one another, rather than absolute values, an approach that has been followed here. However, not all lipids oxidize at the same rate. For example, unsaturated fats oxidize more quickly than saturated ones, the rate increasing over 10 times for each double bond present. For example, it is estimated that the rate of oxidation between C18:0, C18:1, C18:2 and C18:3 at 100°C is 1:100:1200:2500 (deMan 1992). Also, longer-chained compounds oxidize more quickly than shorter-chained compounds, although the difference is not as severe.

Thus, when using ratios of lipids to identify foods, a goal should be to examine the ratios of compounds that oxidize at similar rates. Unfortunately, compounds that degrade at similar rates tend to be related and serve similar biological functions in plants and animals, and consequently tend to be produced in similar amounts in different species (either high or low). As a result, the ratios of these compounds will not be dramatically different between species. The tension, then, is between using ratios of compounds that are more discriminatory between modern food types but degrade at different rates, and using ratios of compounds that have less discriminatory power but degrade at similar rates. Because the latter approach is more relevant in ancient contexts, I follow it as much as possible. Studies by Malainey *et al*. (1999b) suggest

that simulated long-term decomposition greatly effects fatty acid composition. An examination of their data, however, suggests that the ratios of similar compounds are relatively constant even after long-term decomposition. However, there are slight changes in these ratios, which I attempt to incorporate into the assignments of sherds to food classes below.

METHODS

Analyses were carried out on a 5890 Hewlett Packard Gas Chromatograph (GC) with splitless injection, coupled to a 5790 Hewlett Packard Mass Spectrometer (MS). A 30 m long fused silica wall-coated open-tube (WCOT) capillary column with an internal diameter of 0.25 mm was used (J and B DB5). Temperatures within the GC were raised from 100°C to 325°C at a rate of 12°C per minute, with the final 325°C temperature held for at least 8 min. Helium was used as the carrier gas.

Sherds were prepared by breaking off a 1 cm^2 piece and burring away the outer 1 mm of all exposed surfaces using an abrasive silicon carbide drill bit. This fragment was crushed into a powder in a small agate mortar and pestle, and 400 mg was transferred to a test tube. Then 200 ml of a 2:1 mixture of chloroform:methanol was added to the tube, gently agitated for 5 min and sonicated for 15–20 min. Following sonication, the test tube was placed in a centrifuge for 10 min to separate the solvent mixture from the inorganic clay particles. The solvent was then transferred to a second test tube and placed in a vacuum centrifuge. Finally, samples were derivatized to fatty acid methyl esters (FAMEs) by the addition of 100:l of methanolic HCl and placement in a heating block set at 60°C for 1 h. After heating, samples were dried within the vacuum centrifuge and stored in a freezer until ready for analysis, usually within 1–3 days. A solution containing known amounts of an internal standard and hexane (a solvent) was added to each sample prior to injection in the GC–MS.

Compounds were identified partially by their retention time within the GC, but mainly by their mass spectra. The National Institute of Standards and Technology (NIST) 98 Mass Spectral Library was used to match spectra in archaeological sherds to reference spectra. The NIST library contains over 100 000 standard reference spectra of high quality, including most FAMEs and sterols of interest. The amount of each organic compound present in a sample was computed using the Automated Mass Spectral Deconvolution and Identification System program developed at NIST. The quantity of a particular compound was estimated using this program by integrating and calculating the area under the GC total ion current peak associated with each compound.

Seventy-five archaeological sherds from the western Great Basin of North America were analysed. These sherds were found in a variety of contexts in six main areas, including Owens Valley, Death Valley, Sequoia National Park, the Nevada Test Site and the northern Mojave Desert. In addition, a number of food products mentioned as important sources of food in the ethnographic literature for the Great Basin were analysed. Foods were homogenized (i.e., crushed), brought to a boil and left to simmer for 1–2 h in small test pots. These pots were then broken, with a rim sherd treated in the manner described above. These samples, in addition to data presented by Malainey (1997; see also Malainey *et al*. 1999a), represent a reference collection of food types. If the organic residues of a sherd were intermediate between two classes of foods, it was classified as having potentially been used to prepare both.

Blanks (i.e., unused but refired pots) were run with each batch of sherds to control background levels of lipids, which are likely introduced through contact with human skin and/or laboratory equipment. Although every attempt was made to eliminate these lipids, low levels

were consistently observed. In practice, it appears that low levels of non-food lipids are often encountered in ceramic residue analysis, despite attempts to eliminate them. For example, Deal and Silk (1988), Malainey *et al*. (1999b,c) and Skibo (1992) all report low levels of fatty acids in blank control samples, and even biochemists find low levels of fatty acids in blank samples (e.g., Alexander and Justice 1985). Lipid levels in the blanks were averaged and subtracted from archaeological samples. When background contamination exceeded 5% of the total lipid content in any sherd, the sample was considered to have too weak a lipid signature and was removed from the analysis.

COMPOSITION OF FOODS

Analyses by Malainey (1997; see also Malainey *et al*. 1999a) show that it is possible to differentiate various food classes on the basis of the presence of different fatty acids. She uses principal components analysis (PCA) of various fatty acids expressed as percentages of total fatty acid content to distinguish plant from different animal products. Because different compounds degrade at different rates, I do not apply PCA in the same manner as she does. However, I do use her raw data on food composition, which, together with my own data on traditional Great Basin foods, forms the background database against which archaeological sherds were compared. As mentioned, I focus on classification using ratios of various fatty acids that degrade at similar rates. This approach gives slightly better resolution to the discrimination of various food types.

For example, most leafy green products have much higher ratios of C16:1 to C18:1 than other products, especially seeds and berries. Similarly, the ratio of odd-chained fatty acids (C15:0 and C17:0) to C18:0 is higher for root products than meat and berry products. As shown in Figure 2, food products tend to fall into discrete parts of the graph when plotted using these two ratios. The ellipses in Figure 2 are not statistical confidence intervals, but merely subjective regions of the graph into which different food types fall.

Plotting the ratio of C16:0 to C18:0 against C12:0 to C14:0 serves to further isolate the different food types, especially fish and meat from other products. Figure 3 shows these values. An ellipse encompassing roots is not drawn because they are particularly variable on these two ratios; however, they occupy the upper half of the graph. In previous work (Eerkens 2001), I had suggested using the ratio of short-chain saturated fats to long-chain saturated fats [i.e., (C12:0 + C14:0)/(C20:0 + C22:0)]. While this ratio serves to separate fresh foods very well, in retrospect longer-chained compounds will degrade quite a bit faster than the shorter ones. Moreover, few ancient sherds retain these compounds in significant densities to make the comparison worthwhile.

Work by Malainey (1997; see also Malainey *et al*. 1999b) examining experimental long-term decomposition suggests that the ratio of C16:1 to C18:1 increases over time in most food samples, occasionally up to a factor of 5. This is probably due to the preferential decomposition of C18:1. On the other hand, (C15:0 + C17:0)/C18:0 remains fairly constant across the samples, increasing slightly in some cases and decreasing in others. This suggests that the ellipses drawn in Figure 2 should all shift to the right in degraded samples, as we would expect in archaeological sherds.

Similarly, the ratio of C16:0 to C18:0 consistently decreases with degradation in Malainey's work by an average factor of 2. Since she does not ubiquitously report C12:0 and C14:0, it is difficult to know how this ratio should change. However, given the relative stability of these compounds, we should not expect great change. Overall, this should move the ellipses in Figure 3 slightly to the right for degraded samples (note that the *x*-axis is not plotted on a log
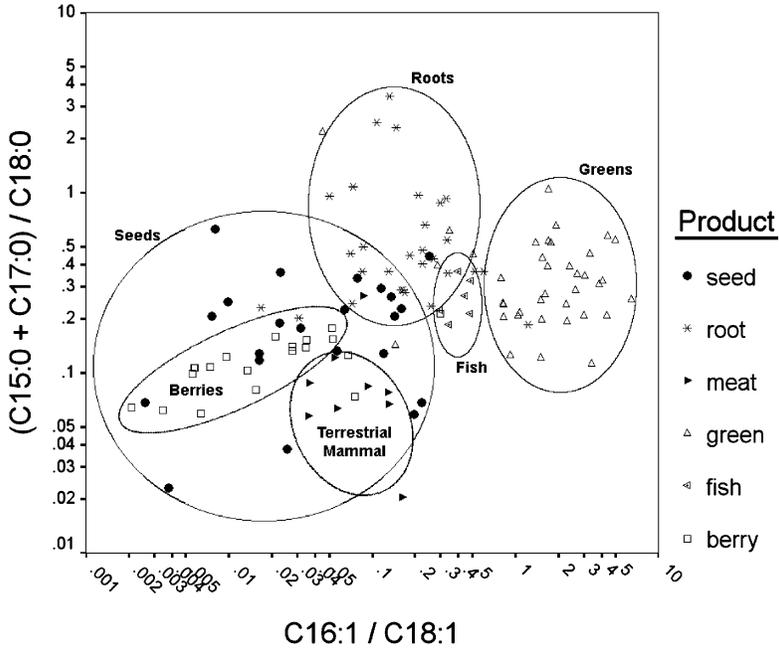
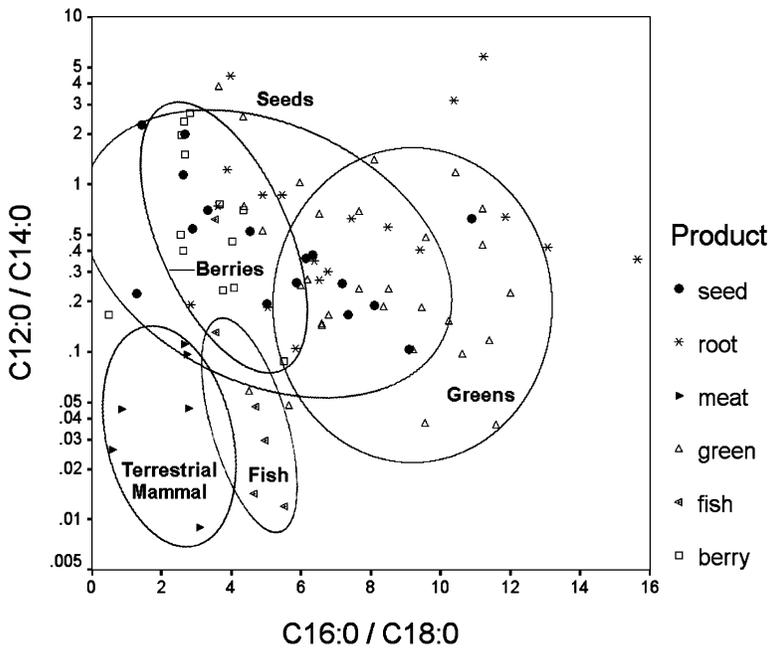Figure 2   *A biplot of two fatty acid ratios for modern food products.*

Figure 3   *A biplot of two additional fatty acid ratios for modern food products.*

Table 2 *Criteria used to distinguish food types based on fatty acid ratios*

Ratio	State	Terrestrial mammals	Fish	Roots	Greens	Seeds and nuts	Berries
$\dfrac{(C15:0 + C17:0)}{C18:0}$	Fresh	<0.2	0.2–0.5	>0.2	0.1–1.0	<0.6	<0.2
	Degraded	<0.2	0.2–0.5	>0.2	0.1–1.0	<0.6	<0.2
$\dfrac{C16:1}{C18:1}$	Fresh	0.02–0.2	0.2–0.5	0.05–0.7	>0.7	<0.3	<0.08
	Degraded	0.08–0.8	0.8–2.0	0.2–2.8	>2.8	<1.2	<0.32
$\dfrac{C16:0}{C18:0}$	Fresh	<3.5	4–6	3–12	5–12	0–9	2–6
	Degraded	<7	8–12	6–24	10–24	0–18	4–12
$\dfrac{C12:0}{C14:0}$	Fresh	<0.15	<0.15	>0.15	>0.05	>0.15	>0.15
	Degraded	<0.15	<0.15	>0.15	>0.05	>0.15	>0.15

scale, causing the ellipses to increasingly inflate in size towards the right of the graph). In the sections below, these transformations are accounted for and used to help interpret archaeological residues.

Table 2 gives the general criteria by which archaeological sherds were classified using the four ratios shown in Figures 2 and 3. When available, biomarkers such as the presence of cholesterol, citric acid and erucic acid (C22:1) were used to supplement this information. It proved impossible to separate seeds from berries using these criteria, since the ellipses including berries fall entirely within the seed ellipses. This is not surprising, as seeds and berries are structurally similar and serve the same biological purpose, and should have similar lipid compositions. As a result, I collapse these two categories in the analyses below.

Clearly, there is overlap in fatty acid ratios and there are outliers to nearly all the food classes, which suggests that the residues from a single potsherd may occasionally be misidentified. However, I argue that the criteria developed are useful at a more general level, and that analysis of large numbers of sherds should reveal the general or most common food products prepared in those pots.

A discriminant analysis of the data using the four ratios discussed above shows that 65% of the samples are correctly classified using the criterion established, the greatest overlap coming in berries and seeds. If we were to randomly assign products to classes, we would expect to correctly classify only 17% of the samples. If we collapse the seed and berry categories, 72% of the cases are correctly classified, with the greatest overlap occurring between seeds (now subsuming berries) and terrestrial mammal meats. This suggests that the use of these fatty acid ratios is a useful exploratory method for determining the function of ancient pots. Incidentally, meats and fishes are never misclassified as plant products, although the reverse is not true.

RESULTS

Fatty acids and other organic compounds were common in the majority of the archaeological sherds analysed. Of the 75 sherds selected for GC–MS study, only seven had such low concentrations of residues that quantitative analysis was not worthwhile (i.e., the average background was over 5% of total for this sample). These pots may not have been used for cooking or storing foods, the foods may not have been very high in fats or the fatty acids may have degraded prior to analysis.

Table 3 *Fatty acids encountered in western Great Basin potsherds*

Compound	Systematic name	Sherds containing compound (%)	Fraction of all fatty acids encountered (%)
C9:0	Nonanoic	7	0.2
C10:0	Decanoic	19	0.2
C11:0	Undecanoic	32	0.2
C12:0	Dodecanoic	80	4.6
C13:0	Tridecanoic	72	0.6
C14:0	Tetradecanoic	100	13.1
C14:1	Tetradecenoic	26	0.3
C15:0	Pentadecanoic	82	3.0
C15:0 br	Methyltetradecanoic	69	0.9
C16:0	Hexadecanoic	100	32.2
C16:1	Hexadecenoic	88	7.4
C17:0	Heptadecanoic	78	1.5
C17:0 br	Methylhexadecanoic	54	0.3
C18:0	Octadecanoic	100	11.8
C18:1	Octadecenoic	90	18.0
C18:2	Octadecadienoic	15	0.3
C19:0	Nonadecanoic	15	0.03
C20:0	Eicosanoic	34	0.4
C22:0	Docosanoic	19	0.1
C22:1	Docosenoic	6	0.04
C24:0	Tetracosanoic	25	0.06

Table 4 *Non-fatty acid lipids encountered in western Great Basin potsherds*

Compound	Sherds containing compound (%)	Average amount relative to total fatty acids* (%)
Citric acid	7	18.0
Short-chain n-alkane (C14–C19)	66	10.6
Long-chain n-alkane (C20+)	85	39.0
Short-chain dicarboxylic (C6–C10)	40	4.5
Long-chain dicarboxylic (C11+)	3	0.4
Epoxy fatty acids	22	1.9
Hydroxyalkanoic acids	6	1.3
Cholestane isomer	12	0.1
Pine resin	1	>100

*This figure represents the quantity of this compound divided by the total fatty acid quantity for those sherds in which this compound was found.

Nine fatty acids were regularly encountered in the remaining 68 sherds, including C12:0, C13:0, C14:0, C15:0 (including iso-, ante-iso- and other branched isomers), C16:0, C16:1, C17:0 (including iso-, ante-iso- and other branched isomers), C18:0 and C18:1. As shown in Table 3, these compounds were found in over three-quarters of all samples. Other fatty acids (Table 3) and organic compounds (Table 4) were less frequently observed. A number of additional compounds were encountered during the study, but could not be identified by either their mass
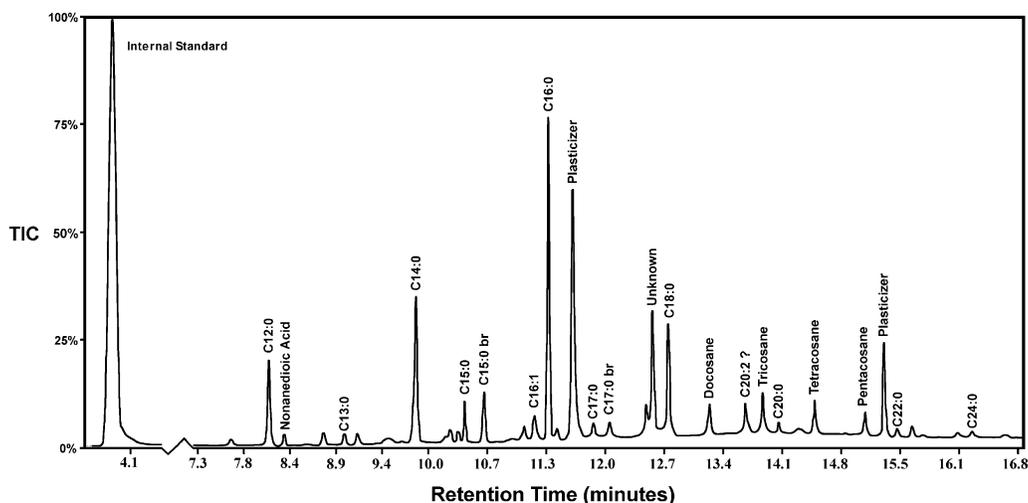
Figure 4   *A typical GC–MS chromatogram, plotting TIC against retention time.*

spectra or their retention time and are not considered further. Future research will attempt to identify their nature. Figure 4 shows a typical chromatogram, plotting total ion current (TIC) against time and labelling the more common compounds encountered.

As shown in Tables 3 and 4, polyunsaturated fats, very long-chain saturated fats (over 20) and sterols were uncommon. This result was expected, given the propensity for these compounds to oxidize. In fact, many of the dicarboxylic (dibasic–dioic dimethyl esters; grouped into short and long forms in Table 4) and epoxy acids encountered are likely to be the by-products of oxidation of unsaturated fatty acids (Frankel 1998; Hudlicky 1990, 226). For example, the most common dicarboxylic fatty acid, nonanedioic acid with nine carbon atoms, was found in 38% of all samples and probably represents the fragmentation (i.e., decomposition) of an unsaturated fat with a double bond at the ninth carbon position (Hudlicky 1990), such as C18:1ω9. Higher densities of these compounds, then, probably indicate the former presence of unsaturated fatty acids, most likely mono-unsaturated fats with a double bond at the ninth position in the carbon chain. Similarly, the cholestane isomer encountered probably represents the oxidative by-product of cholesterol or cholestanol.

The significance of some compounds listed in Table 4, such as straight-chain hydrocarbons (n-alkanes), is not known. These compounds were especially common in 15 sherds from Sequoia National Park and Death Valley. Straight-chain hydrocarbons occur naturally in many animals and plants, particularly in leaf waxes, and were present in many of the food samples prepared in test pots discussed previously. It is possible that their presence indicates the processing of certain types of food products that are high in n-alkanes or that conditions were particularly conducive to their preservation. Alternatively, it is also possible that alkanes represent the by-products of decomposition of long-chain waxes (Frankel 1998). Finally, it is also possible that cleaning and/or storage procedures in the curation facilities in these regions introduced n-alkanes into the artefacts. Resolution of this issue will be the subject of future research and n-alkanes are not considered further.

Figure 5 plots the archaeological sherds by the same two fatty acid ratios used in Figure 2. A small number lacked one or more of the fatty acids and could not be plotted. Overall, the
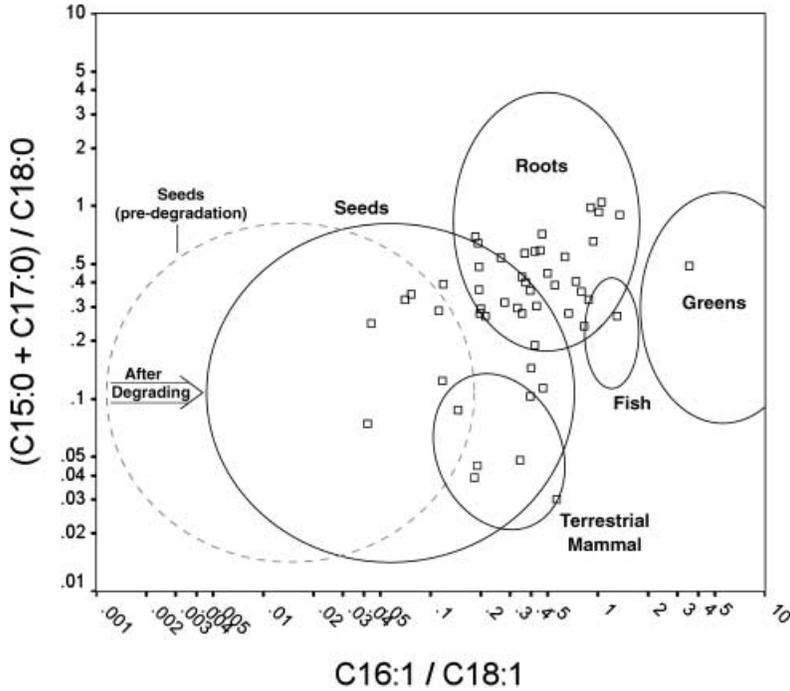
Figure 5   *Archaeological sherds plotted by two fatty acid ratios.*

ratios suggest that few greens and fish are represented in the sample of sherds. Also, few sam-ples fall within the projected range of terrestrial mammal meats. Instead, the majority fall within the seed and root ellipses—indeed, only three fall outside this range. Similarly, if we plot the sherds by the ratios presented in Figure 3 (see Fig. 6), it appears that again few sam-ples fall within the range of greens and fish. A slightly higher percentage falls in the range of terrestrial mammals; however, the majority again fall within the range of seeds and roots.

Using the discriminant function created earlier for modern foods, the data plotted in Figures 4 and 5 and the presence of various biomarkers (i.e., cholestanol, erucic acid etc.), archaeologi-cal sherds were classified as representing one of five different food types (root, green, seed/ berry, fish and meat) or as mixes of these types if they fell into intermediary areas. These results differ slightly from those that I presented in my Ph.D. dissertation (Eerkens 2001), as I have used different fatty acid ratios and have had a chance to analyse the data in a more detailed manner in this paper. Table 5 summarizes the results of this classification.

As the table shows, the residues from plants are most pronounced in western Great Basin potsherds, especially seeds (which subsumes the berry category). Seeds appear to be a com-ponent of 70% of the sherd samples, even more if they contribute to the more general category of 'plant' (with or without meat). Over half of these samples represent cases in which seeds alone appear to have been cooked in a pot.

Lipid ratios and biomarkers (i.e., cholestane) consistent with meats are present in 35% of the samples. However, in all but one sample, lipids representing meats comprise only a minor portion of the sample; for example, trace quantities of cholestane or slight overlap with ratio values for meats. Only one sherd appears to have been used for cooking meat alone. The lack
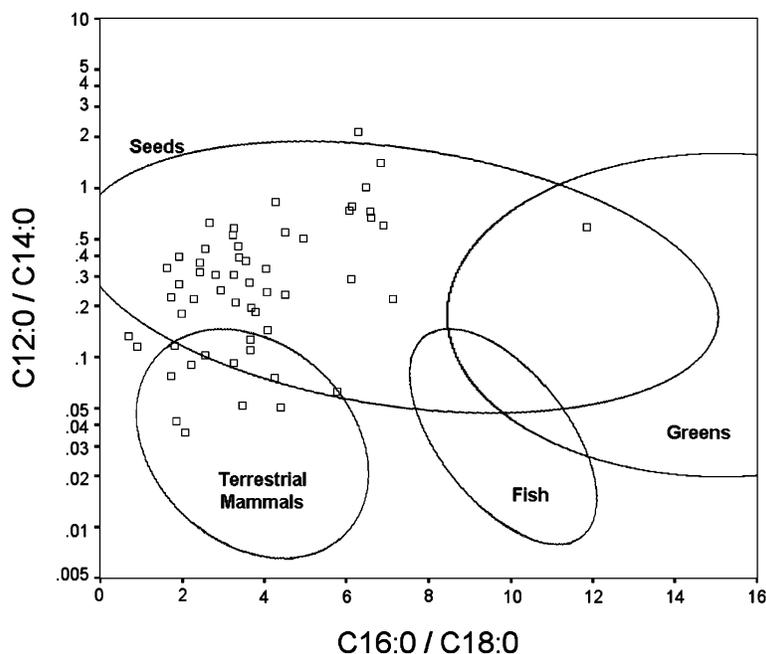
Figure 6   *Archaeological sherds plotted by two additional fatty acid ratios.*

Table 5   *Summary of results of GC–MS study*

Food type	Sherds (%)
Seeds only	35
Seeds with meat	23
Seeds and roots	10
Roots and greens	12
Roots with meat	4
Plants, no meat	1.4
Plants with meat	12
Meat	1.4

of significant levels of cholesterol and its degradative by-products underscores the limited role of fish and terrestrial mammal products in these pots. Fish and other plant products are almost absent from the sample as well, contributing to only 26% of the samples, with almost half of these comprising seed–root stews (or alternatively, where seeds and roots were prepared in separate but closely spaced cooking events). In short, stews or multipurpose pots combining various products are most common, although seeds are particularly well represented in such pots. The lack of fish is not surprising given that these sherds were collected from areas where fish are not especially bountiful and ethnographic data suggest that they were not of great importance in prehistoric diets. A single sample from the Nevada Test Site had high levels of pine resins, suggesting that pots were on occasion used to render pine pitch. This sherd has been discussed in depth elsewhere (Eerkens 2002).

High values of odd-chained, primarily C15:0 and C17:0, fatty acids are good indicators of the presence of ruminant animal meat. In Malainey's (1997) study, ratios of (C15:0 + C17:0) to (C12:0 + C14:0 + C16:0 + C18:0) greater than 0.04 are characteristic of ruminant animals (in her samples, deer and bison). Of the 26 archaeological samples containing meat residues, 16 (62%) have ratios greater than 0.04, suggesting that antelope, deer and mountain sheep, the main ruminant animals native to the study area, were probably cooked in these pots. Interestingly, however, these 16 samples do not have particularly high levels of branched odd-chained fatty acids, which are also common in ruminant animals. The remaining 10 samples have ratios less than 0.04, suggesting that other animals, such as rabbits, rodents and potentially birds, were more rarely cooked in pots when meat was included.

A COMPARISON OF THE TECHNOLOGICAL AND RESIDUE DATA

A comparison of the residue profiles against technological data from the sherds is also informative. Recall that engineering studies suggest that foods simmered at lower temperatures for long periods of time, such as meat (Stahl 1989; Reid 1990; Wandsnider 1997), are typically prepared in pots with constricted necks that conserve heat. On the other hand, seeds are optimally cooked by high-temperature and shorter-duration boiling in pots with wide-open and flaring mouths.

Fifty-two of the 68 sherds could be classified by rim form, coded as either incurved (slightly constricted), direct (not constricted) or recurved (constricted). Figure 7 shows these different forms. The most striking pattern is that almost all (90%) of the sherds used to cook seeds alone or with meat are direct. On the other hand, pots used to cook other products are more varied in rim design. Only 77% of the remaining 31 pots used to cook non-seed products have direct rims, while two are incurved and five are recurved. These patterns, although not significantly different in a χ^2 test ($p = 0.25$), do support the general notion that seed pots tend to have more open and accessible mouths. These patterns are also evident in average diameter
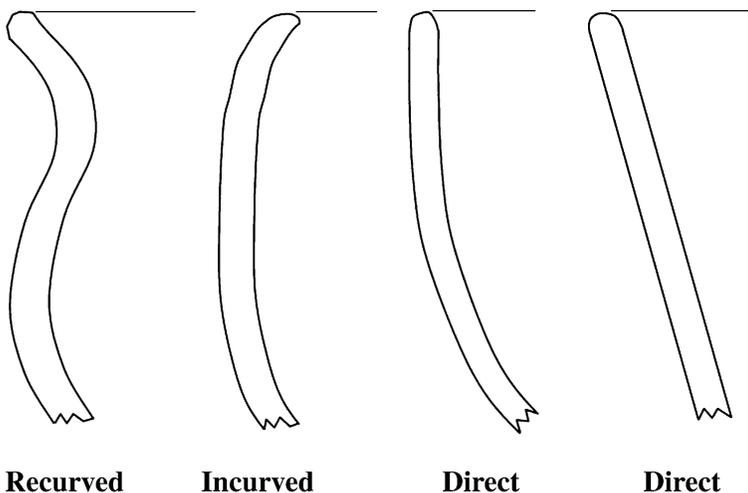

Recurved **Incurved** **Direct** **Direct**

Figure 7 *Rim forms typically encountered in the study.*

Table 6 *Attributes of rim sherds used to cook different products*

	Number	Direct rims (%)	Average month diameter (mm)	Average thickness (mm)	Decorated (%)
Seeds only, no meat	20	90	236	5.5	5
Seeds only, with meat	9	78	288	5.9	22
Plant mix, no meat	14	77	214	5.6	21
Plant mix, with meat	9	78	219	6.0	22

Note: Plant mixes include pots used to cook seeds with other plants, as well as those used for cooking non-seed products only.

measurements. Pots used to cook seeds, both with and without meat, tend to be larger at their mouths than those used to cook plant products only. Table 6 summarizes these results.

Differences in average thickness are also relatively informative. Pots used to cook seeds are thinner on average than those used to cook seeds and meats together and other plants without meat. This is consistent with the notion that seeds must be boiled at higher temperatures to achieve gelatinization. Thinner walls transfer heat more quickly and efficiently than thicker ones and conserve fuel. However, pots used to cook plants without meats are also relatively thin (5.6 mm). Finally, it is also interesting that meat pots are nearly twice as likely to be decorated. Four of the 17 pots used to cook meat are decorated (24%), while only four of the remaining 35 pots that do not include meat (11%) are similarly decorated.

Together, these findings suggest that pots used to cook seeds were designed slightly differently than those for cooking meat stews, which were different again from those used with other plant products. Pots used for cooking seeds tend to have larger and unrestricted openings. This design provides ready access to the contents and allows water to evaporate from the surface. In turn, this prevents heat from building up in the neck, which could cause breakage. Their thin walls also transfer heat more efficiently from an exterior fuel source. Thus, these types of pots are well designed for high-temperature boiling, which helps to break down the complex carbohydrates in seeds and other plant products. On the other hand, meat pots are more often incurved and recurved than seed pots, which restricts the orifice relative to maximum body diameter. This design reduces evaporation and prevents loss of heat, making them better suited for the simmering and stewing activities usually associated with meat preparation (Reid 1990). At the same time, despite their tendency to have incurved or recurved rims, pots used to cook meat still have greater average orifice diameters, suggesting that larger pots were needed to boil meat. This may be a result of the larger size of most animals relative to plant products, and hence their requirement for larger pots. Alternatively, because meat was widely and freely shared in most California and Great Basin societies (Steward 1933, 1938), while plant resources were typically considered private property, it is possible that larger pots were used to produce larger meals when meats were boiled (i.e., to assure that there was enough for everyone). In the final analysis, it appears that pots were not all-purpose or generalized tools, but were constructed with specific uses in mind.

DISCUSSION AND CONCLUSIONS

Organic residues are clearly present in western Great Basin potsherds and are informative about prehistoric use. The fact that some sherds have no lipids and that others have a high

density of a wide range of different compounds suggests that the residues are not a product of archaeological processing. Instead, as I have discussed at length elsewhere (Eerkens 2001), they appear to represent the remains of foods that were cooked or stored within these vessels.

The residue analysis did not produce definitive answers about the exact species prepared in any particular pot. However, as a whole, the residues extracted from the sherds are informative about the range of food products that were cooked. Especially satisfying in this respect is the fact that the residue profiles are in line with what was predicted from engineering analyses and ethnographic reports. The strong showing of plants complements the engineering analyses and ethnographic reports that often describe pots as being used to prepare such products. However, unlike the ethnographic data, the results here underscore the fact that pottery was predominantly used to cook seeds. Occasionally, seeds were mixed with meat in stews (or were prepared shortly before or after cooking meat), but they were often boiled by themselves. Interestingly, while the ethnographic reports suggest that rabbits were the most common type of meat boiled in pots (see Table 1), the residue data suggest that ruminant animals such as sheep, antelope and deer were more common. Future work will attempt to examine this result in greater detail.

The residue analysis also complements previous archaeological work on Great Basin pots. For example, Dean and Heath (1990) examined the surfaces of 20 potsherds from western Utah for any adhering carbonized residues, using low-powered visual microscopes. They found 12 (60%) sherds with a blackened residue consisting of plant remains. Seeds, both burned and unburned, and other plant parts were common, including fragments of *Chenopodium* sp., *Poa* sp. (grass), juniper, ricegrass and *Allenrolfea* sp. (pickleweed), species all known as native food resources (Fowler 1986). Although their techniques were unlikely to have identified the presence of meat residues, their results demonstrate that seeds and plants were an important part of pottery use in the eastern Great Basin. A second study by Touhy (1990) examined pollen and phytolith accumulations in the blackened residues on two cook pots from north-central Nevada. Significant levels of festucoid grass phytoliths were recovered from both pots. In addition, one of the pots contained high levels of pine pollen and fragments of pine seeds and needles. Although Touhy could not rule out that the pollen and phytoliths were due to natural accumulation, for various reasons he felt that they reflected pot function. Again, although it was unlikely that meat would be detected, the study suggests that these pots were used to prepare plant products, most likely grass seeds and pine nuts in this case. Finally, a third study in the Little Boulder Basin of north-central Nevada found that brownware sherds are much more common around hearths that contain large numbers of charred seeds, suggesting their association with seed-processing activities (Bright *et al*. 2002).

All of this suggests that the origins of ceramics in California and the Great Basin had much to do with the use of plants, especially seeds (Eerkens 2004). Nearly three-quarters of the pots with significant levels of fatty acids examined displayed residues consistent with those of seeds or seeds mixed with other products. This result contrasts with other analyses of hunter–gatherer pottery in North America. For example, Malainey (1997; see also Malainey *et al*. 1999c) found that 62% (122 of 201) of sherds analysed from western Canada are attributable to meat alone (large herbivore or beaver). Other than corn, plants are evident in only 28% of their samples, and more than half of these were classified as mixtures of plant with fish or meat products. In short, plants alone account for only 13% of the total sample, compared to 74% in this study. Similarly, Reid's (1990) summary of ethnographic information on northwest Canadian and Alaskan pottery use suggests that pots were used exclusively for cooking meat or rendering oils or fat from animal bone or blubber (see also Stimmell and Stromberg

1986). Thus, the origin of pottery technologies among the hunter–gatherers of California and the Great Basin seems to stem from different needs than in other regions of North America.

In conclusion, it seems that GC–MS residue analysis, at least in the manner employed here, is not a panacea for pottery functional analysis. First, the specificity with which residues can be identified is not very detailed. Using fatty acid ratios, only general categories of food products can be identified, as opposed to individual genera or species. Secondly, I would argue that it is necessary to run a large sample of sherds to be confident about assigning them to certain food categories. Trends in the data can help an analyst lean towards certain uses for pots over others, but one-to-one assignments of sherds to food products with great confidence are not realistic. Thus, even in the discriminant analysis that I ran on fatty acid ratios from known food samples, only 65% could be correctly identified in relation to original food products. Finally, given these shortcomings, independent lines of evidence about pot function from sources such as engineering analysis, archaeological context and/or ethnographic analogy should be used wherever possible to augment residue analyses.

To increase the utility of residue analysis in California and the Great Basin in the future, it may be worthwhile to compliment fatty acid analysis with the extraction and analysis of other organic compounds such as such as amino acids, proteins, waxes and other organic compounds (e.g., Charters *et al*. 1977; Frankhauser 1997; Stott *et al*. 1999; Evershed *et al*. 2003). A wider range of compounds may allow us to be more accurate about the types of foods cooked in ancient pots. Future work could also examine the ratios of various stable isotopes, particularly carbon and nitrogen (e.g., Evershed *et al*. 1994, 2003; Mottram *et al*. 1999). On the basis of the results obtained here, this work should probably focus on plants as a source of these residues, especially seeds, and should include study of a wider range of native foods as a background database against which to compare ancient residues. Also, experimental research should seek to understand how stews composed of different foodstuffs affect overall organic residue signatures. These avenues may make residue work more accurate in our ability to discriminate between different sources of organic compounds.

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