UDK 903.28'13"634"

Documenta Praehistorica XXIX

The development of dairying in Europe: potential evidence from food residues on ceramics

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ABSTRACT – *Providing evidence of dairying is crucial to the understanding of the development and intensification of Neolithic farming practices in Europe, beyond the early stages of domestication. Until recently, research in this field had been limited to traditional archaeological methods, such as the study of pottery styles, faunal remains and specialised material artefacts. Although suggestive, these methods are unable to provide direct evidence of dairying. Advances in biomolecular methods now allow the identification of remnants of dairy products on ceramic vessels and the application of these methods to Neolithic ceramic assemblages across Europe is underway. There is no doubt that these new methods offer much scope for investigating hypotheses such as the 'secondary products revolution', but there are limitations. The cost of analyses prohibits indiscriminate sampling and differential survival is likely to prevent direct comparison of samples from different sites. Only by incorporating these techniques within the wider frameworks of archaeological research may theories be properly tested. Approaches to achieve this goal are discussed.*

IZVLEČEK – *Iskanje dokazov za mlekarstvo je ključnega pomena za razumevanje razvoja in intenziviranja kmetovanja v Evropi po začetnih stopnjah udomačitve. Do nedavnega so bile raziskave na tem področju omejene na tradicionalne arheološke metode, kot je raziskovanje stilov keramike, živalskih ostankov in specialnih predmetov. Čeprav mnogo povedo, pa te metode niso mogle zagotoviti neposrednih dokazov za mlekarstvo. Razvoj biomolekularnih metod danes omogoča določevanje ostankov mlečnih produktov na keramičnih posodah. Raziskave neolitske keramike po Evropi že potekajo. Nedvomno lahko z novimi metodami natančneje raziščemo hipoteze, kot je na primer 'sekundarna revolucija proizvodov', toda tudi tu so omejitve. Cena analiz onemogoča sistematično vzorčenje, diferencirani načini preživljanja pa bodo verjetno preprečili neposredno primerjavo vzorcev z različnih najdišč. Le če bomo vključili nove tehnike v širši okvir arheoloških raziskav, bomo lahko teorije primerno preverili. V članku razpravljamo o načinih za dosego tega cilja.*

KEY WORDS – *organic residue analysis; Neolithic ceramic; dairying; secondary products revolution*

INTRODUCTION

Identification of the original contents of archaeological pottery has fascinated archaeologists and scientists alike throughout the 20th century. In fact, it was Johannes Grüss who in 1933, first identified an amorphous black residue on a ceramic vessel from the Hallstatt period, as overcooked milk by conducting some basic chemical tests (*Grüss 1933*). Although these analyses may have lacked the necessary rigor, which is now demanded from archaeological scientific investigations, this early work helped pioneer a new approach to artifact analysis.

In the last decade, the development of biochemical techniques such as gas and liquid chromatography, mass spectrometry, immunology and stable isotopic analysis have provided much greater scope for the reliable identification of residues. Issues of contamination from the burial environment have been addressed by careful sampling methods (*Heron et al. 1991*), simulated degradation of replica pots have led to greater understanding of post-depositional processes (*Dudd et al. 1998; Craig et al. 2000*) and numerous procedural controls have been implemented to rule out contamination. Finally, a greater appreciation of the many and varied uses of archaeological pottery, including multiple inputs, re-use and a range of non-culinary uses, has tempered interpretations based on residue analysis alone.

Many studies involving residue analysis of ceramic artifacts have been undertaken, including the identification of tars, waxes and resins (e.g. *Heron & Pollard 1988*) and characterization of absorbed food residues on ceramics (*Heron & Evershed 1993;* for review). Lipids (fats) present within the fabric (rather than visible on the surface) of ceramics have been characterized by their fatty acid distributions (*Evans & Hill 1982; Rottländer 1986*), the presence of specific biomarkers (*Evershed et al 1991*; *Evershed et al. 1992*), and recently by the isotopic composition of individual compounds (*Evershed et al. 1997*; *Dudd & Evershed 1998*).

In keeping with Grüss's pioneering work of the 1930s, it is the identification of milk residues that has returned to become a focus for more recent studies and with good reason. Not only does milk contain a unique range of lipids and proteins, which are suspended in solution and free to adsorb to the ceramic surface, but also, residue analysis may provide the only way to unequivocally identify the use of this important and versatile product in prehistory. Many of these studies have centered around defining the development of dairying in the European Neolithic. Whether dairying was a principal component of a neat package of innovations that spread widely across Europe in 3rd millennium BC (*Sherratt 1981; 1983; Harrison 1985*) – the so-called secondary products revolution – or was present earlier in the Neolithic, perhaps on a smaller scale (e.g. *Bogucki 1984a; 1984b; Chapman 1982*), remains unresolved. Until the appearance of pictorial tablets depicting milking scenes (*Green 1980*), evidence for dairying is restricted to interpretations of archaeozoological data (e.g. *Bogucki 1984a; Milisauskas & Kruk; 1989; Greenfield 1988; 1991; Harrison 1985; Legge 1981a; Legge 1981b*) or from distinctive vessel forms (*Sherratt 1981; Bogucki 1984b*).

Clearly, residue analysis offers new research opportunities to tackle this problem, but how should these methodologies be effectively applied? This paper will review the archaeological issues surrounding the development of dairying and examine the potential of new methods for residue analysis of milk, before considering the role that residue analysis can play in the investigation of the origins of dairying in Europe.

THE DEVELOPMENT OF DAIRYING IN EUROPE: GENERAL PERSPECTIVES

The identification of dairying as an economic activity poses a number of challenges to archaeological researchers. As evidence of exploitation of domestic ruminants can be found in faunal assemblages from sites across Europe, often dating to the earliest phases of the Neolithic, it is reasonable to assume that milk was available for human consumption from these animals at this time. Dairying is not a specific technology nor is it necessarily limited to specific strains of livestock (*Sherrat 1997. 206*). Whether or not the inhabitants of Early Neolithic Europe had the necessary genetic adaptation to digest the lactose in fresh milk (*Sherratt 1981*) is ambiguous from modern phylogenetic data (*Akoi 1986; Holden & Mace 1997; Bodmer & Cavalli-Sforza 1976.279*) and is largely irrelevant considering the wide range of low lactose, easily stored products that can be made from milk. Therefore the key archaeological issue is not to provide evidence for the utilization of dairy products, but rather the scale of production and the significance of this activity in prehistoric economies.

The intensification of dairying in the 3rd millennium BC in many parts of Europe was first proposed over 20 years ago (*Sherratt 1981*) as a component of the secondary product complex, an economic package that had far reaching social and cultural implications and represented a unilinear progression of farming practice. Although initially implied, rather tentatively (see *Chapman 1981*), by the appearance of new ceramic vessels associated with the manipulations of liquids, weight has been given to this hypothesis by analysis of post Neolithic faunal assemblages'; e.g. from Britain (*Legge 1981a*), Spain (*Harrison 1985*) and the Balkans (*Greenfield 1988*). In these cases, a cattle-based dairy economy optimized for maximum production with the potential for exchange is implied, as kill-off patterns, dominated by juveniles and/or adult female bones, compare favorably with those obtained from modern herds optimized for milk production (produced by *Payne 1973*).

However, similar evidence for an optimized dairy economy can be found at earlier Neolithic sites; for example, Boguki has argued that the mortality profiles of linear pottery (LBK) faunal assemblages from temperate Europe are not inconsistent with Payne's models (*1984a*) and evidence from the Early Neolithic layers of Arene Cadide, in the West Mediterranean, shows that sheep kill off patterns also fit well with the optimized milk production strategies (*Rowly-Conwy 2000*). Legge has also noted female bias in adult cattle at Neolithic 'ceremonial' sites in the UK and at other Neolithic sites in Switzerland (*1981b*).

Using faunal kill-off patterns to define the scale and specifics of prehistoric animal husbandry practices has been criticized. Besides problems inherent with preservation and recovery of animal bones, ancient livestock may have different productivity compared to their modern counterparts (*Halstead 1998*). In addition, Halstead demonstrates, with reference to modern pastoralism in Northern Greece, that the decision to utilize livestock for meat or milk and when to cull is dependent on a range of economic and environmental factors, which may fluctuate from season to season (*Halstead op. cit.*). Furthermore, high juvenile culling need not indicate a dairy economy but could imply also as a mechanism to preserve fodder (*McCormick 1998*); indeed, the presence of calves may be a prerequisite of early cattle dairying in order to assist milk 'let down' (*McCormick 1992*). Equally, high frequencies of adult females in the animal assemblage, rather than indicating an optimized dairy strategy may reflect a sexual bias in maturity rates and thus meat productivity (*McCormick op. cit*).

A number of ecological and economic arguments are often cited in relation to this debate. It is often implied that dairying must have been practiced as soon as domesticated ruminants were available, as it offers by far the most energy efficient use of uncultivatable land (*Holmes 1970; Ingold 1980.176; Legge 1981a*) and results in products that are suitable for storage, which gives them additional economic value (*Bogucki 1987*). Others point out that the large herds/flocks, implied by a strategy optimized for dairy production (*Dahl & Hjort 1976.220*), are labor intensive and economically untenable in landscapes without easily accessible pasture (*Halstead 1996*), such as the relatively narrow riverside environments inhabited by early Neolithic farmers of central Europe. Halstead argues that a mixed farming strategy, where small numbers of a variety of animals are kept for a mixture of products (e.g. meat, milk, wool), principally for domestic use, not only seems more economically plausible in such environments, but also is evident in the considerable heterogeneity that exists in Neolithic faunal assemblages (*Halstead 1996*). Even at sites which show other supposed indicators of dairying, such as high numbers of juveniles, other domesticates are always present (e.g. *Rowley-Conwy 2000*).

These arguments support the concept that a specialized dairy economy could only develop towards the end of the Neolithic, after substantial amounts of primary forest were cleared which, in turn, fits within the framework of a 'Secondary Products Revolution' (*Sherratt 1981; 1983*). However, this does not necessarily preclude the independent localized development of large-scale milk-based pastoralism at earlier periods in the Neolithic. For sedentary communities, provision of cultivated or collected fodders and stalling of animals could have compensated for limited pasture. Large-scale seasonal movement of animals to exploit fresh pastures offers an alternative strategy. For example, the lowland LBK communities of the Northern European plain seem to have focused their economic activities on cattle herding rather than grain cultivation (*Bogucki 1987*). Settlement patterns, here, suggest a high degree of residential mobility consistent with a mobile milk-based pastoralist economy; the presence of perforated ceramic sherds, putatively interpreted as cheese-strainers, recovered from many of these 'camps', have been taken as further evidence (*Boguki 1984a; 1984b*). The socio-economic relationship between these semi-mobile intensive dairy farmers and the sedentary grain cultivators of the loess is unclear but it is interesting to speculate upon the potential for exchange, further complicating economic inferences made from faunal analysis alone.

Whether economic factors favour dairying or meat production may be less significant than the cultural value that may be obtained from pastoralism. In addition to 'allocative' resources such as milk and meat, animals may provide an 'authoratative' resource in terms of their socio-political significance (*Hall 1986*). The requirements of animals for ritual use cannot be overlooked (*Keswani 1994*), and caution has to be taken when interpreting economic regimes from animal assemblages recovered from ceremonial centers (*Enwhistle & Grant 1989*). The association between cattle and power through conspicuous display, exchange transactions and redistribution is exemplified by the complex pastoralist societies of Southern and Eastern Africa (*Reid 1996*). In particular, mobile pastoralism is likely to enhance social intercourse between neighboring households and villages through contact and exchange. Thus, the social, ideological and political demand for large herds or flocks may provide the impetus for a specialized economy, such as dairying, and may explain the resulting economic risks. Similarly, the existence of taboos may prevent dairy consumption, irrespective of the economic benefits.

Defining the scale of dairying is complicated by these cultural, economic and ecological factors. The available evidence neither demonstrates or disproves a unilinear progression from small-scale household dairying as part of a mixed economic strategy to the development of a large milk-based pastoral sector in the 3rd millennium BC, as originally proposed by Sherratt (*1981; 1983*). What role, then, can the identification of milk residues play in the study of prehistoric dairy economies?

METHODOLOGIES FOR THE IDENTIFICATION OF MILK RESIDUES ON CERAMICS

Milk is unique to mammals and is only produced by the lactating mammary gland. It contains the necessary nutrients to support the infant during development and thus has a distinctive range of proteins, lipids and sugars, which are dissolved or suspended in solution. During the processing of raw milk into different dairy products, the relative amounts of these biomolecules will change and some molecules may become chemically altered. Residue analysis has focused on the detection of the lipid and protein components of milk because lactose, the principal sugar in milk, is thought to be lost rapidly to bio-degradation and leaching in the burial environment.

Identification of milk lipids

Lipids can be extracted from archaeological ceramics with organic solvents and analysed by high temperature gas chromatography or gas chromatography/mass spectrometry (*see Heron & Evershed 1993; for review*). Fresh milk contains a characteristic distribution of lipids, a range of fatty acids with carbon chain lengths of between 4 and 20 including branched chain and monounsaturated species and a complex range of triacyglycerol (TAG) species (*Mottram & Evershed 2001*). However over time many of the shorter chain fatty acids, which are characteristic of milk, are lost and the TAG distribution is altered to more closely resemble animal adipose fat rather than milk fat (*Dudd & Evershed 1998*). Therefore although lipid yields from archaeological pottery are generally high, there are no single lipid compounds that are unique to milk.

Dudd & Evershed (*1998*) overcame this problem by measuring the stable carbon isotope ratio (^{12}C:^{13}C) of the most prominent unsaturated fatty acids (with carbon chain lengths of 16 [$C_{16:0}$] and of 18 [$C_{18:0}$]) using gas chromatography combustion isotope ratio mass spectrometry (GC-C-IRMS). The relative proportion of light (^{12}C) and heavy (^{13}C) carbon atom in these molecules reflects the source of carbon from which the molecule was synthesised. The ratio between these two carbon molecules – the carbon isotope ratio, ($\delta^{13}C$), expressed in parts per thousand relative to an international standard – in the $C_{16:0}$ and $C_{18:0}$ fatty acids is different in various animal products. Fats from non-ruminant animals have similar isotope values for both acids, but in ruminants the $C_{18:0}$ fatty acid contains less ^{13}C than the $C_{16:0}$, it is therefore said to be isotopically “lighter” or “depleted”; significantly this difference is even more pronounced in ruminant milk fats. The absolute isotope ratios of these fatty acids in milk are a function of the animal’s diet, but in all cases the $C_{18:0}$ fatty acid in ruminant milks is between 3–5‰ depleted in the heavier (^{13}C) stable carbon isotope compared to the $C_{16:0}$.

This new approach has a number of methodological advantages. The $C_{16:0}$ and $C_{18:0}$ fatty acids are the most commonly encountered fats on archaeological pottery. They can be easily extracted and analysed and have been shown to be derived from pottery usage rather than the depositional matrix (*Heron et al., 1991*). Furthermore, as the absolute isotopic measurements made on these fats are direct indicators of animal diet, information concerning types of pasture and fodder provision may be obtained and directly related to husbandry strategy (i.e. milk/meat exploitation). However, there are problems of interpretation of the isotopic values derived from only two fatty acids. Both are present at variable concentrations in most animal and vegetable products; consequently, multiple inputs in pottery will result in a mixed isotope signal, which may be hard to interpret. This problem can be overcome by taking into account other diagnostic lipids in the pottery (*Dudd & Evershed op. cit.).*

Identification of milk proteins

A number of proteins are unique to milk; these include whey proteins and caseins (α–, β–, γ–casein). Of these, α-casein is the most attractive for study; not only is it the most abundant protein in milk (13.7 g l^{-1} in bovine milk; *Jenness 1970*) but also it is thermostable (*Wells 1908*). Its stability is demonstrated by the fact that bovine α-casein can be detected in baby vomit (*Sato 1992*) and in milk that has been heated at 75°C for 2 days; once complexed with ceramic it can survive an order of magnitude longer (Tab. 1). The immunological methods em-

Sample	Treatment	DACIA response[1] (ng g^{-1} sample)
Simulated pot[5] (Bovine milk)	None	>500
	Buried 2 years in controlled plots[6]	100–500
	Heated 75°C, 2 days, anoxic, 95% humidity	100–500
Bovine Milk[2]	No Treatment	>500
	Heated 75°C, 2 days, anoxic, 95% humidity	n.d.
Ethnographic Milk Pot[7]	None	>500
	5 day continuous leaching experiment[3]	>500
Blank ceramics	None	n.d.
	Buried 2 years in controlled plots	n.d.
Simulated pots[5] (Bovine adipose)	None	n.d.
	Buried 2 years in controlled plots	n.d.
Soil samples[4]		n.d.

1 DACIA using anti-bovine α-casein monoclonal antibody. Two separate extractions all s.d. <10%. Positive twice background values;
2 against 100 μl;
3 experiment performed by Carl Challinor, University of Bradford;
4 range of soil samples (clay, loam, sand);
5 simulated pot 'open' fired high porosity and 'kiln' fired low porosity (*Craig 2000*);
6 burial experiments repeated in two plots with measured hydrology, microbial biomass/activity, and pH. n.d. – not detected;
7 obtained from N.E. India used for c. 10 years for heating bovine milk discarded 1988.

Tab. 1. Identification of milk proteins on control samples using Digestion and Capture Immunoassay.

ployed for detecting milk proteins on ceramic involve using indirectly labeled antibodies, which will bind tightly to specific regions of the α-casein structure. The regions that are targeted by antibodies are unique to that particular protein, and can be even used to distinguish α-caseins that are derived from different species of animal. This is in part due to the random structure of the casein molecule, which facilitates the production of antibodies against its primary amino acid sequence (*Enamoto 1990*), and because of a number of amino acid substitutions that exist between α-caseins from different species.

However the application of immunological methods to archaeological materials poses a number of problems. Perhaps the greatest methodological challenge has been the removal of proteins, such as caseins, which have survived by strong association with the mineral (ceramic) surface (Tab. 1). Extraction with conventional solvents yields insufficient quantities of protein for analysis. An improved method has been developed (digestion and capture immunoassay: DACIA) to increase yields, this involves digesting the mineral surface with hydrofluoric acid and simultaneously capturing any released molecules for subsequent immunological detection. The sensitivity and specificity of this technique has been demonstrated by testing a range of simulated and ethnographic ceramics with known input (Tab. 1 and *Craig & Collins 2000*).

Another problem with immunological based approaches is the use of inappropriate methods, which result in non-specific cross-reactions with contaminants or compounds derived from the burial environment generating a positive response in the assay even when the target protein is absent. Such issues have been widely discussed in connection with earlier immunological studies of residues, notably those which have attempted to identify species of blood on stone tools (*Gurfinkel & Franklin 1988; Smith & Wilson 1992; Cattaneo et al. 1993; Manning 1994; Downs & Lowenstein 1995; Child & Pollard 1992; Leach & Mauldin 1996; Tuross et al. 1996; Leach 1998*). To address these criticisms, experimental design has to include an appropriate range of negative controls to confirm the specificity of the test; these may include blank ceramic, blank ceramics that have been exposed to the burial environment, ceramics with non-milk input also exposed to the burial environment, and soil samples (Tab. 1).

Preservation of organic residues on ceramics

The potential for preservation for the different classes of organic residues encountered on archaeological pottery is highly variable and dependent on a number of factors. These include mode of use, physical properties of the ceramic, depositional environment and post excavation treatment. Organic residues present within the porous matrix are likely to be protected from microbial degradation and are less susceptible to leaching. In addition, organic-mineral interactions at the ceramic surface stabilise organic structures and retard chemical and biological degradation mechanisms (*Evershed 1993; Heron & Evershed 1993; Craig et al. 2002*). Charring of residues may also provide a mechanism for protection (*Oudemans & Boon 1991*) but is likely to result in substantial structural modification preventing routine extraction and identification, especially using immunological methods.

The length of time in the depositional environment may not be as important as the nature of the environment itself (i.e. pH, redox potential, hydrology, microbial activity). Burial experiments have shown that whilst the majority of the protein component of absorbed milk residues is lost within the first few months of burial probably by leaching, subsequent degradation of the remaining fraction is greatly reduced (*Craig 2000*). Lipids, which are hydrophobic and less susceptible to leaching, may stay at high concentrations in sherds for thousands of years (e.g. *Charters et al. 1993*). They are also more resistent to structural modification than proteins. Immunological methods rely on the preservation of large, hydrophilic protein subunits (polypeptides), which undergo side chain modification and hydrolysis (chain splitting). Lipids are therefore likely to survive over longer timescales and in a wider range of environmental conditions than proteins (e.g. *Regert et al. 1998*).

Contamination of potsherds post-deposition and post-excavation is more of a problem for lipid residue analysis than for protein residue analysis. Although proteins are mobile in the burial environment and easily transferred during handling, contaminating proteins will not usually be detected due to the specificity of the immunological tests (of course, extra precautions would have to be taken if research is directed towards the detection of human proteins). Post-excavation contamination with lipids is particularly significant especially when no provision has been made for residue analysis prior to excavation and post-excavation analysis. Contamination with plasticizers, glues and skin lipids are commonly encountered and can interfere with analysis, especially if they are in high concentration. Washing and brushing of sherds is also likely to result in loss of information, although no systematic study of this has been carried out. It is recommended that newly excavated sherds, which have previously been selected for residue analysis, are as handled as little as possible, air-dried together with any adhering soil and wrapped in aluminium foil or acid-free tissue and then bagged.

The cost of analysis is likely to be a decisive factor when assessing the impact of residue analysis to archaeology. Generally, lipid analysis is expensive, especially when combined with isotopic measurements needed to identify dairy products, but provides more information into pottery use per analysis (e.g. analysis of other plant and animal lipids and contaminants). Protein analysis is cheaper but only a single compound can be detected per analysis (e.g. bovine milk protein). These factors will obviously affect the sampling strategy and ultimately the type of questions that can be addressed. Furthermore the costs associated with residue analysis highlight the need for these techniques to be utilised efficiently, for example to augment less expensive forms of pottery use analysis such as determination of the form/function relationship and use-wear analysis. One final but important consideration is the discrimination between food and non-food residues. For precisely the same reason that products such as milk and blood are the most prepossessing products for residue analysis, they also provide excellent products to seal pots that lack the required porosity. For example, Ethiopian potters use milk to seal ceramic vessels immediately after firing (*Rice 1987.163*). Discrimination between sealants and food residues is methodologically challenging but characteristics such as vessel permeability may be used to aid interpretations.

In conclusion, given the relative strengths and weaknesses of both approaches, there is clear advantage in combining the two different methods of residue analysis for the study of dairying. The two methods are entirely independent, in that they target different biomolecules using different analytical methods, and provide complementary information.

DEVELOPMENT OF DAIRYING IN EUROPE: THE POTENTIAL OF RESIDUE ANALYSIS

There is no doubt that the successful identification of milk residues on ceramics may contribute to the study of the origins and impacts of dairying, but at present only limited studies have been undertaken. Milk residues have been detected at a number of UK sites: milk proteins in Late Bronze Age/Early Iron sites in the Western Isles of Scotland (*Craig et al. 2000*), milk lipids in Iron Age and Early Medieval ceramics from Northamptonshire (*Dudd & Evershed 1998*) and Late Neolithic sherds from the Welsh borders (*Dudd et al. 1999*). These cases unequivocally demonstrate that milk was an element of the prehistoric economy. In the Western Isles, where faunal assemblages are exceptionally well preserved, the detection of milk residues supports the interpretation of a large developed dairy economy based on the high number of associated neonatal cattle bones, a feature of settlements in this area (*Parker Pearson et al.* 1996; 1999). However, without other palaeodietary indicators, differential preservation, contamination and multiple uses of ceramics (such as sealing) complicate a more quantitative approach to residue analysis, which aims to define the scale of animal husbandry practices. Furthermore, biases associated with small sample sizes (implicit considering the amount of ceramic generally recovered from sites and the costs of analysis) limits inter-site and temporal comparisons.

The analysis of specific ceramic artifacts

One way to overcome biases involved in sampling a random selection of domestic pottery is to target specific ceramic artifacts. Much debate involving an early or late origin for dairying has involved speculation of the techno-function of pottery shapes or specific ceramic artifacts. The appearances of new forms of Bronze Age and Copper age vessels across Europe, that have been associated with dairying (*Sherratt 1981; 1983*), provide obvious avenues for a targeted investigation. In central Europe, both cattle and new forms of drinking vessels were included in the graves of the Copper Age Baden culture (*Whittle 1996.123*). The increased significance of cattle and the appearance of these new vessel forms may point to the intensification of dairying and could be tested by residue analysis and compared with earlier late Neolithic vessels from the region. Similarly, a systematic study of the function of LBK ceramic sieves, interpreted as dairy-processing utensils (*Bogucki 1984a; 1984b*) provides a clear hypothesis to test using residue analysis. Identification of milk on these artifacts would imply the presence of a developed dairy economy, much earlier than originally hypothesized (*Sherratt 1981; 1983*). Nevertheless, clear distinctions should be made between regional specialization, i.e. by early Neolithic semi-mobile cattle herders of the Northern European plain, and the adoption of a wide spread dairy sector in the 3rd millennium BC.

Defining specific dairying practices

At most sites residue analysis is confined to the analysis of undifferentiated pottery with unknown techno-function, often from domestic contexts. Identification of milk residues in these cases is of limited value to our wider understanding of the significance of dairying, unless this is integrated with other lines of enquiry. Assessment of settlement distribution and size, availability of surrounding resources combined with analysis of plant and animal remains and stable isotopes extracted from human bone can provide some scope for broadly determining the maximum scale of specific economic activities. Evidence for the scale and significance of dairying may also be obtained through a greater understanding of production and consumption practices. Associating vessel contents with broad classifications of ceramic typologies (e.g. storage vessels, cooking pots, serving wares), use-wear and depositional context provides one way of achieving this. Identification of vessels that have been dedicated for milk use, evident from the fatty acid isotopic signal, would also be useful in this respect. In addition, information concerning specific consumption practices, such as feasting, may be gained by relating food residues to distinctive pottery styles, methods of deposition and context.

Finding evidence for fodder provision is also crucial in defining specific animal husbandry practices. If dairying is suggested in marginal environments or at sites where surrounding pasture is limited, such as many Early Neolithic European settlements, then provision of fodders must be envisaged. Besides the economic implications, the deliberate provision of gathered and cultivated fodders implies a different relationship between humans and their livestock. Evidence of cattle byres (*Nielsen et al. 2000*) and twig foddering of sheep and goats (*Rasmussen 1993*) have been found at the earliest Neolithic settlement sites in Switzerland. Stable carbon and nitrogen isotopic analysis of animal bone collagen and of sectioned teeth can be used to reveal variations in cattle diets, including seasonal changes and weaning (*Balasse et al. 1997; 1999*). This approach may be particularly applicable to the identification of foddering regimes, such as the supplement of marine or C4 fodders like maize and millet, for specific practices when combined with direct isotopic measurements of ruminant adipose or milk fats in pots (*Craig et al., in prep*).

Dairy products have also been implicated as important commodities for exchange (*Bogucki 1987*). The identification of milk-containing vessels not produced locally, at sites with no other evidence of an indigenous dairy based economy, may be the only way of substantiating this interpretation. Similarly, targeting storage vessels, suitable for transport, may facilitate the identification of producer and consumer sites, especially if the products transported can be related to economic practices at specific sites. Finally, it is worth noting that identifying the original species of dairy products, using an immunological approach, is vital to the interpretation of dairying in the past. Although cattle, sheep and goats can all be exploited to obtain a product with similar nutritional properties, the archaeological implications of these activities are very different.

CONCLUSIONS

Dairying can only be placed in the proper economic, social and cultural context by knowing its scale and significance. Although the identification of milk residues provides unequivocal evidence of dairying, it provides little information relating to these aspects. Whilst, residue analysis of specific ceramic artifacts may be used to give weight to theories, such as the 'Secondary Products Revolution', it is hard to see how these methods can be used to track the supposed intensification of dairying through the Neolithic, when used in isolation. As Bogucki has pointed out, new ways of food production were not introduced uniformly throughout Europe (*1987*), hence it is vital that regional and site specific studies are undertaken. In this respect, it is crucial that residue analysis is integrated with other forms of cultural, dietary, economic and environmental evidence to look at specific animal husbandry practices. When used in this way, information additional to pottery use may be gained, such as the nature of exchange networks, seasonal mobility, consumption practices and strategies for fodder provision.

ACKNOWLEDGEMENTS

I thank Dr. Matthew Collins, Dr. Nicky Miner and Ms. Jennifer Hiller for help with all aspects of this manuscript and Dr. Mihael Budja for kindly inviting me to the seminars. The research was supported with grants form the UK National Environmental Research Council (GR3/12827).

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