Change of diet in Northern Europe's Mesolithic – Neolithic transition: a new critique

The study of the proportions of stable isotopes of carbon and nitrogen which survive in ancient human and animal bones offers highly suggestive indications of ancient diets. Among the most remarkable results from such investigations is the dramatic change in diet which is thought to have occurred between the Mesolithic and the Neolithic when people turned from maritime to terrestrial food, from fish to meat and vegetables. The three contributions which follow challenge, modify, enhance or reflect on this model. In a pivotal critique of the evidence from Britain and Denmark, Milner et al. present a range of explanations for the signals of a maritime or terrestrial emphasis in diet and conclude that the change need not have been either rapid or total. Lidén et al. show that, in southern Sweden, the preferences for fish over meat were related less to period or culture, but (reasonably enough) to location: fish-eaters live by the sea. Finally Robert Hedges takes up the question of partial marine diets and how to detect them, developing the idea that marine diets might give a fainter signal in people who were only getting small amounts of protein. Perhaps there were many such people in the new order of the Neolithic …

Keywords: Northern Europe, Mesolithic, Neolithic, stable isotopes, diet

Something fishy in the Neolithic? A re-evaluation of stable isotope analysis of Mesolithic and Neolithic coastal populations

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Introduction

The case for a rapid abandonment of marine resources along the coastlines of Northwest Europe at the Mesolithic-Neolithic transition (*c.* 4000 cal BC) has recently gained momentum with a series of palaeodietary stable-isotope investigations on human bone (Richards & Hedges

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1999a, 1999b; Schulting & Richards 2002a, 2002b; Richards 2003; Richards, Price & Koch 2003; Richards, Schulting & Hedges 2003). When Tauber (1981) first announced the results of isotope analysis of human skeletons in Denmark over 20 years ago, his results had little impact on wider archaeological interpretation. The sample size of human skeletons was small, chronologically dispersed, and confined to Denmark. It was possible to argue that the apparently dramatic change in his data, from Mesolithic individuals who ate mostly marine protein to Early Neolithic individuals who ate none, would be moderated by larger and more geographically varied samples, not least because most of his Neolithic samples were inland and most of his Mesolithic ones coastal. The more recent work, however, seems to confirm the original pattern with a larger sample of material, not only in Denmark, but more widely in Britain, as well as France (Shulting & Richards 2001) and Portugal (Lubell *et al.* 1994).

Moreover, the newer generation of results uses stable isotopes of nitrogen as well as carbon. The carbon in marine organisms is obtained from seawater, which is enriched in ^{13}C relative to ^{12}C, whereas the heavier isotope of nitrogen, ^{15}N, is progressively enriched relative to ^{14}N as organisms occupy higher trophic levels in food chains, whether they are marine or terrestrial. Cod, for example, are secondary carnivores, whereas cattle are herbivores, with corresponding differences in their nitrogen isotope composition. The fact that two independent parameters apparently point in the same direction seems to confirm the reliability of the results.

The shift from Mesolithic diets dominated by marine protein to Neolithic diets in which marine protein is absent appears to be abrupt, widespread and sudden. Some commentators have used the isotope results to suggest that Neolithic peoples did not simply ignore marine resources in favour of the new agricultural economy, but actively rejected them as part of a new web of food taboos, religious beliefs and myths about the sea (Richards 2003; Thomas 2003). Others have urged caution (Bailey & Milner 2002; Lidén *et al.* 2003; cf. Parkington 1991 and Sealy & van der Merwe 1992), drawing attention to potential biases and untested assumptions in the isotope technique and contradictions with other sources of palaeodietary information.

Our aim in this paper is to take a critical look at the isotope results in relation to other sources of evidence and to reconcile the apparent differences between them, with particular emphasis on coastal sites in Britain and southern Scandinavia. Our starting point is the clear contradiction between archaeological sources of information retrieved from early Neolithic sites, which show substantial evidence for the continuation of marine subsistence activities, and the current interpretations of isotope data, which claim proof of the abandonment of marine subsistence in the Neolithic. We consider three issues:

1. Archaeological evidence for palaeodiet
2. Sample bias in the human skeletons used for isotope analysis
3. The interpretation of stable isotope data

The archaeological evidence

Denmark has one of the richest late Mesolithic and Neolithic archaeological records in coastal western Europe, thanks to isostatic uplift of the ancient shoreline in the north of the country. The Mesolithic Ertebølle culture, 5400–3900 cal BC, is famous for its large number of coastal sites and shell mounds with their abundant evidence of fishing, shell-gathering and sea-mammal hunting (Andersen 1993, 2000). More recently, underwater excavations on the now submerged Ertebølle shoreline in the south have revealed coastal sites with spectacular conditions of organic preservation including evidence of wooden fish traps, fish spears and boats (Malm 1995).

However, there has long been evidence for the continuation of all types of marine subsistence activity in early Neolithic deposits associated with the TRB culture, and this is reinforced by recent excavations. Neolithic shell mounds of substantial thickness and extent, often stratified above Ertebølle shell layers, are present at Norsminde, Bjørnsholm and Visborg, the latter two being amongst the biggest shell mounds in Denmark (Andersen 1989, 1993, 2000). Krabbesholm, currently under excavation, is another large mound, which is mainly of Early Neolithic date. At Norsminde, analysis of the marine molluscs shows that the rate of accumulation of shells was just as high throughout the Neolithic period as in the preceding Mesolithic, and that the pressure of human exploitation on the shell beds was, if anything, somewhat greater than in the Mesolithic (Bailey & Milner in press). Other such sites with Early Neolithic deposits and evidence of marine activities, notably seal-hunting, are Sebber, Dyrholm II, Havnø (Madsen *et al.* 1900), Sølager and Hesselø (Skaarup 1973), Lyø, Langø, Munkholm, Bramsnæs Vig, Frennemark, Lindø, Ørum Aa, Øsløs, Anholt and Aalborg (Andersen 1991; Degerbøl 1933; Møhl 1971). Whale bone has also been found at Lindø (Degerbøl 1933). Fish bones are less well represented in these Neolithic middens than in earlier deposits, although they are certainly present, notably at Bjørnsholm (Andersen 1991), and Pedersen (1995: 83) has described fish traps or structures from twelve coastal sites either from underwater or waterlogged conditions, of which five are dated to the Early Neolithic.

In Denmark, there is good evidence for continuity in coastal site occupation from the Mesolithic into the Neolithic which intuitively contradicts any suggested abrupt and radical change in the subsistence bone. However, several authors have suggested that these Neolithic coastal sites were the task-specific camps of farmers, used for fishing, shell-gathering or sea-mammal hunting as the case might be, and that the main settlements were now located inland (Bailey 1982; Rowley-Conwy 1983; Johansen 1997). If that is correct, it seems likely that much of the food collected there would have been removed for consumption at settlement sites elsewhere. Sea mammals are bulky animals and their hunters are likely to have butchered the carcasses on the spot and discarded the less desirable parts before moving elsewhere. Similarly, molluscs are much easier to transport after removal of the shells (Bird & Bliege Bird 1997). With fish, on the other hand, unless they are very large animals, preliminary processing makes little difference to ease of transport, so that fish bones are less likely to be represented in specialist coastal camps than other resources. Soils at inland Neolithic sites are not conducive to bone preservation, but if our hypothesis is correct, some evidence of fish consumption should eventually be forthcoming from hinterland sites.

Whatever the precise function of these Early Neolithic coastal sites, the evidence of marine subsistence, covering the full range of resources, is not in doubt. Conversely, there is considerable evidence for the hunting of land mammals during the Ertebølle period. Many shell mounds contain bone remains of wild cattle, red deer, roe deer and boar, especially on the Jutland Peninsula with its larger area of land and higher animal biomass, and evidence for the use of the bow and arrow. On the Jutland Peninsula, there is also evidence of inland hunting at the site of Ringkloster (Andersen 1998), and extensive flint scatters in the hinterland, mostly surface finds without stratigraphic context or associated organic materials, but including diagnostic artefacts of the Ertebølle period. Inland sites are also present in the Åmose bog region of central Zealand.

In Britain, the evidence for marine exploitation is less, because far more of the prehistoric British coastline is now submerged. The well-known Mesolithic shell middens on the uplifted shorelines of Scotland (Bonsall 1996; Coles 1971; Hardy & Wickham-Jones 2002; Mellars 1987), show little evidence of continuity into the ensuing Neolithic period. There are, however, some substantial oyster shell mounds known from the River Forth estuary, which indicate continuous occupation between about 5000 and 3000 cal BC, including deposits with typical Neolithic ceramics and domestic animals (Sloan 1984, 1989). Similar substantial oyster mounds of Neolithic and later date are present on the west and north coast of Ireland (Burenhult 1984; Milner & Woodman unpublished data). Fishing is also well represented at Neolithic sites in the Orkneys (Childe 1931; Wheeler 1979).

The notion that the Mesolithic–Neolithic transition is characterised by a shift from diets dominated by marine protein to diets in which it is absent looks like an oversimplification or an over-exaggeration in relation to this substantial and widely distributed body of archaeological evidence. We are well aware that dietary reconstructions from food remains in archaeological deposits are subject to biases and uncertainties of their own, but the fact that marine foods persist in Neolithic deposits at a time when the isotope data suggest otherwise, and that there is a continuity of occupation at productive coastal locations through that transition indicates that we must look more widely for sources of error. Either the isotope analysis is sampling a different subset of individuals from those who consumed the marine foods represented in Neolithic deposits, or the results of stable isotope analyses have been imprecisely interpreted.

Sample bias

One reason for the difference between isotope and archaeological results may be that these are measuring different phenomena. The archaeological data refer to generalised dietary tendencies over long periods in specific local environments or site catchments. The isotope data from human bone is often cited to provide information on the dominant protein intake by an individual during the last 10 years of his/her life. To put matters into perspective, let us consider how many individuals are represented by the isotope data (summarised in Figure 1) in relation to the size of the regional populations that might have occupied Britain and Scandinavia over the relevant period.

In Scotland, the entire Mesolithic human bone assemblage consists of incomplete and partial remains of seven individuals from the Oronsay shell middens dating to the fifth millennium cal BC (Meiklejohn & Denston 1987). Four bones have been analysed by stable isotope analysis and dated by AMS, representing a minimum of three individuals (Richards & Mellars 1998; Richards & Sheridan 2000). In the rest of Britain, eleven further measurements have been made on disarticulated humans, mainly from coastal cave sites in Wales, representing perhaps ten individuals (Schulting & Richards 2002b), of which only three actually date from the sixth to the fourth millennium cal BC. Overall, only seven individuals from the whole of Britain date to the two-thousand-year period prior to the transition to agriculture. For the Neolithic, stable isotope analysis has been performed on 67 bone samples from 22 coastal sites from the fourth millennium cal BC, including chambered tombs, causewayed enclosures (Scott 1961; Whittle & Wysocki 1998) and interments in caves (Schulting & Richards 2000, 2002a, 2002b). It is hard to assess the minimum number of individuals (MNI) represented. At Carding Mill Bay, the eleven measurements may represent four individuals (Schulting & Richards 2002a), or perhaps only two (Connock *et al.* 1992).

In Southern Scandinavia, with its greater variety of burial practices and the 'cemeteries' of Vedbæk Bøgebakken and Skateholm, there are stable isotope measurements and radiocarbon dates from eighteen individuals in Ertebølle contexts at fourteen sites.

From Early Neolithic funnel beaker (TRB) contexts, only six individuals have been analysed, and these include three from the Store Åmose bog on Zealand, over 25 km from the coast (Richards & Koch 2001). A further four individuals, previously considered to be Late Ertebølle, may also date to the Early Neolithic.

We can arrive at some very conservative estimates of total population size for Mesolithic Britain by using a population density of 0.1 individuals per km^2 (at the low end of the range for ethnographically known hunter-gatherers), and a total land area of 150 000 km^2, giving a total standing population of 15 000. If we assume a generational turnover of 25 years, and a time depth of 2000 years, we arrive at a total estimate of the number of people who lived in late Mesolithic Britain of 1 200 000. Let us call it 1 million for the sake of simplicity. The seven individuals for which we have isotope information thus represent 0.000007 per cent of the total potential population. For Denmark, the position is slightly better, with 18 individuals and a smaller land area, though one that arguably was able to support higher population densities because of the high proportion of productive coastline. For the Neolithic, we have at most ten individuals in Denmark and about double that number in Britain, perhaps in relation to higher population densities associated with an agricultural economy and a shorter time span. These population estimates are only an illustrative guide, but give some idea of orders of magnitude. No doubt it could be argued that most archaeological data represent a tiny fraction of the totality of past human activity, and that confidence in patterning depends on consistent results from diverse contexts. However, the limited sample size urges caution in interpretation.

In Figure 1, we show all the available radiocarbon dates, calibrated and corrected for the marine reservoir effect (see Figure 1 caption), plotted against the $\delta^{13}C$ values for all measured bone samples in the UK and Southern Scandinavia dating to 2000 years either side of the transition II. In neither Britain nor Scandinavia is the evidence for a rapid transition compelling. In both, there appears to be a narrowing of the dietary range from the Mesolithic to the Neolithic, but with considerable overlap at the Mesolithic–Neolithic transition. In Britain (Figure 1a), the Mesolithic data cover a wide range of marine and terrestrial diets, and suggest that terrestrial resources were as important on the coast for some individuals as marine (Schulting & Richards 2002a, 2002b).

Similarly, in Denmark (Figure 1b), there is considerable dietary variation throughout the Mesolithic (Fischer 2002), with some evidence of heavy marine exploitation in the latest phase. However, in the Early Neolithic period, individuals with both extreme marine and extreme terrestrial isotope values are present, although there is disagreement over their date. The key site is Dragsholm, which has played a prominent role in the argument for a rapid

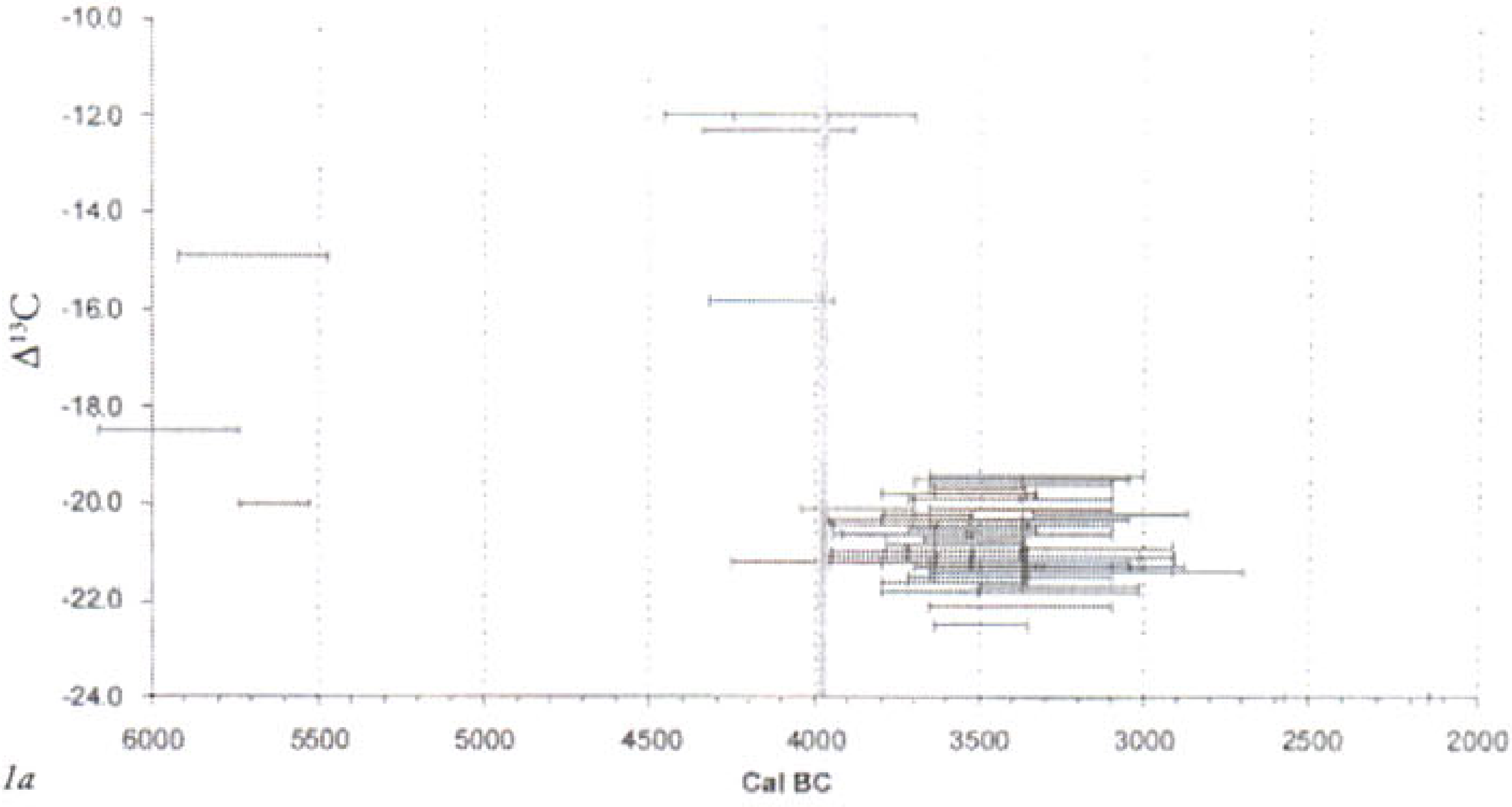

Figure 1a

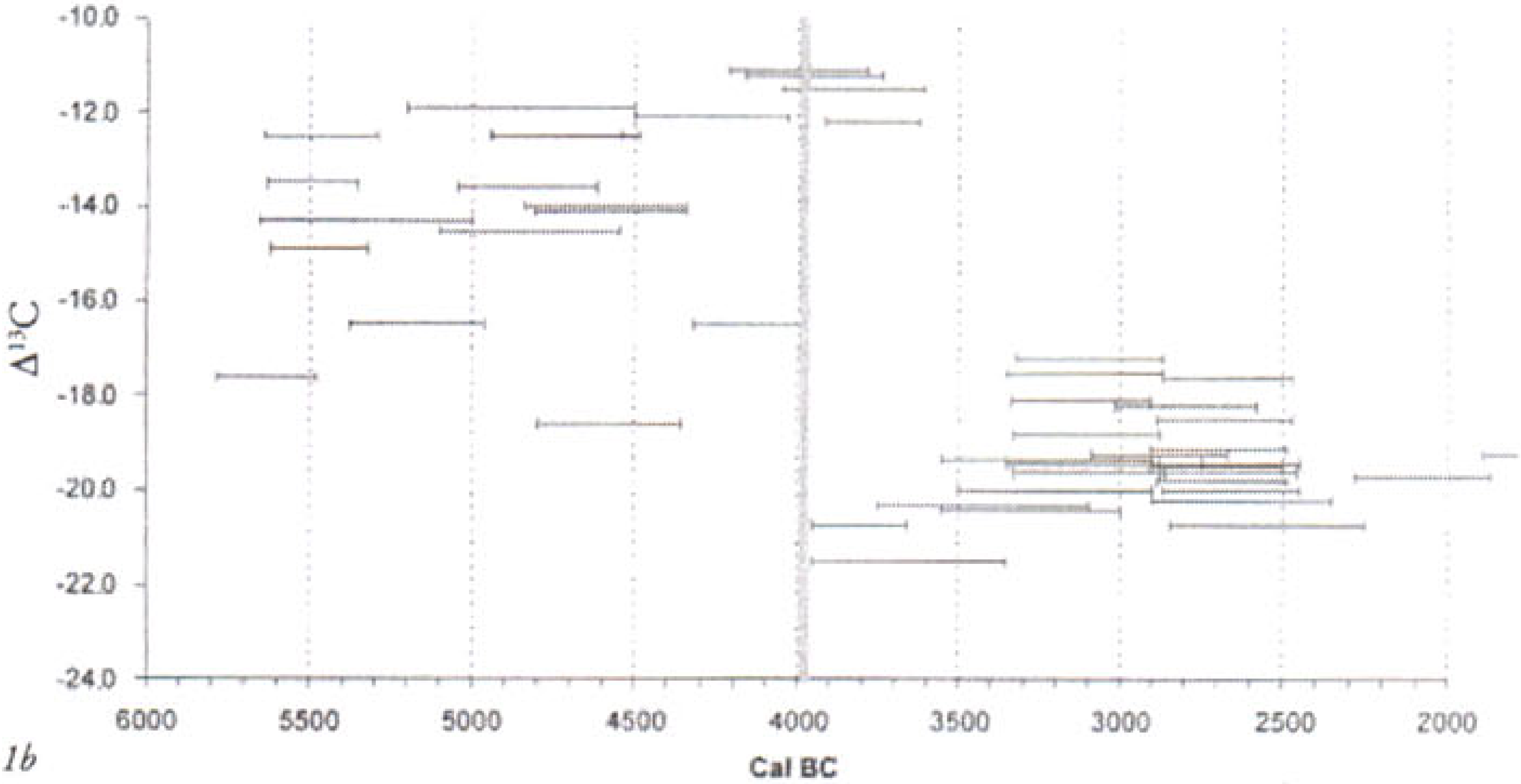

Figure 1b

Figure 1a & 1b: Plots of $\delta^{13}C$ values against calibrated radiocarbon dates (2σ) for humans from coastal sites in Britain and Southern Scandinavia from 6000-2000 cal BC.

The vertical bar marks the approximate date of the transition to agriculture in the UK and Southern Scandinavia. Carbon derived from marine sources is often depleted in ^{14}C compared to atmospheric carbon, producing apparent radiocarbon dates that are too old relative to dates obtained from terrestrial materials (Stuiver & Braziunas 1993). To account for this effect, dates have been re-calibrated using OxCal v.3.8 (Bronk-Ramsey 2002) using a mixed marine/terrestrial curve. A further correction (ΔR) is applied to account for regional variation in the marine reservoir effect (ΔR). For the UK sites a ΔR value of -33 ± 90 years is used (the average value for British coastal waters, see Barrett et al. 2000). For Southern Scandinavia a ΔR of value of 0 is used as there is considerable regional variation. For example, at some sites, particularly those in the Limfjord region, the marine reservoir effect may be as great as 750–900 years (Heier-Nielsen et al. 1995) making these dates too old, in other areas such as the central Baltic it is almost insignificant (Eriksson et al. 2003). The percentage of marine carbon in individual samples is estimated ($\pm 10\%$) by comparing the $\delta^{13}C$ value against known dietary end-members (defined by 100% marine and 100% terrestrial organisms). For the UK sites dietary end-members as defined by Barrett et al. (2000) are used. For the Southern Scandinavian sites, the terrestrial and marine end-members are defined by measurements made on red deer ($\delta^{13}C = -21‰$; $n=5$) and grey seal ($\delta^{13}C = -11‰$; $n=2$) from the Norsminde shell midden. However, it should be noted that estimating the end-members and local marine reservoir effects produces considerable uncertainties in both the calibrated dates and the dietary interpretation, as discussed in the text. Dates generated by Tauber (1981) have been converted to conventional radiocarbon dates prior to calibration. Full details of all the samples calibrated are available at http://antiquity.ac.uk/ProjGall/milner change from marine to terrestrial resources at the Mesolithic–Neolithic transition (Tauber 1981; Richards, Price & Koch 2003). Here there are two female skeletons, one of which has a marine isotopic signature, interred only two metres away from a male skeleton with a terrestrial signature and grave goods attributed to the TRB culture. Richards, Price and Koch (2003) maintain that the female burial with a marine diet is several generations older than the male, thus placing them either side of the Mesolithic–Neolithic boundary (Figure 2). However, the dates could equally well be argued to indicate contemporaneity, especially since we do not know the precise correction to be applied to the date of the female to allow for the marine reservoir effect. Indeed Fischer (2002) suggests that the three skeletons may represent *'a man and his wives'*.

This raises the possibility of another confounding variable, and that is intra-population dietary variation related to gender, age or status. These variations are widely reported in the ethnographic literature of hunter-gatherers (e.g. Meehan 1982; Moss 1993). Women, children and older individuals often have greater dependence on small and more easily accessible foods such as shellfish, plant food and small animals, while men hunt and eat more of the larger and less predictable resources like large mammals and fish. In the ranked hunter-gatherer societies of the North-west coast of North America, food taboos applied differentially to individuals of different status. Amongst the Tlingit, shellfish were taboo because of their association with sexuality and disease, but the rules were more relaxed for women than for men, and for people of low status who depended on shellfood than for people of high status who could afford to avoid it (Moss 1993). We might thus construct a variety of speculative scenarios in which Mesolithic burials are systematically biased towards individuals of high status with diets higher in marine protein than the norm, while high status in the Neolithic might have been associated with preferential access to the foods provided by the new agricultural economy. Equally, however, we accept that there might be no such bias, or none sufficient to account for the consistent change in Neolithic isotope values, and while we believe that the analysis of isotopes by gender and other indicators of status offers a potentially fruitful line of enquiry (e.g. Schulting & Richards 2002a), we do not pursue this theme further.

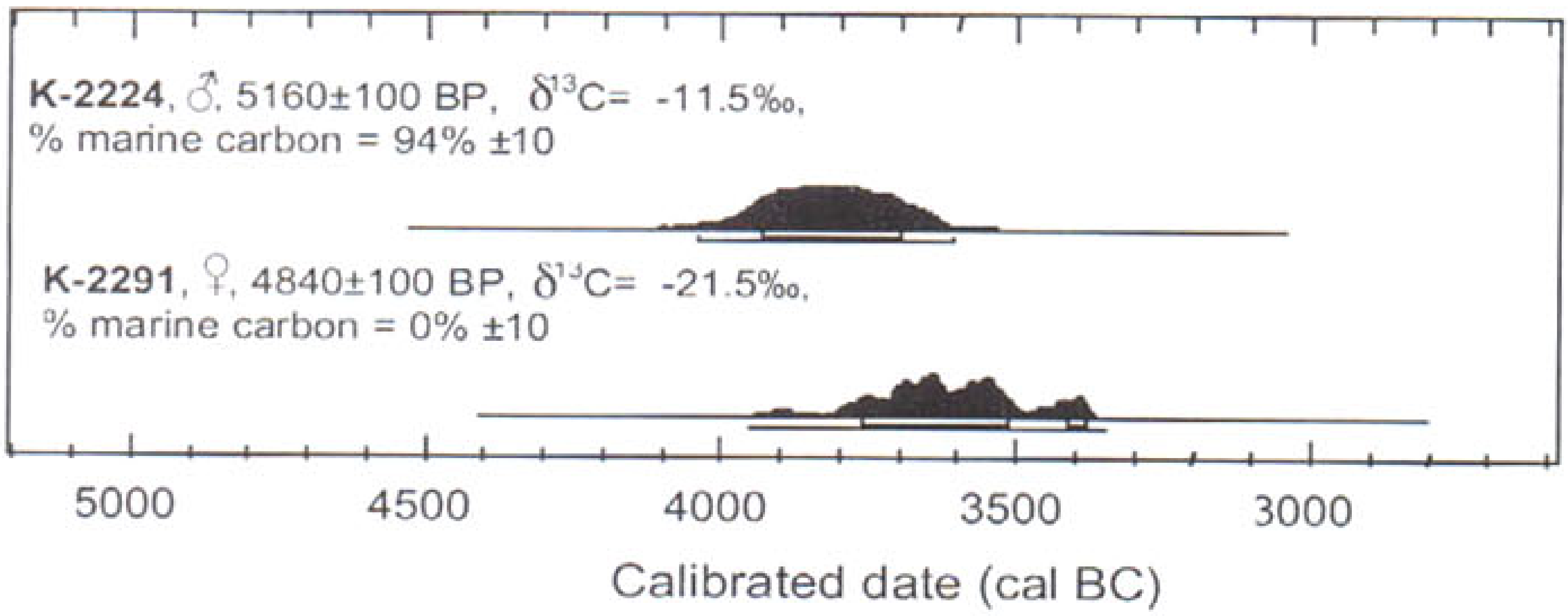

Figure 2: Re-calibrated radiocarbon dates of an adult male (K-2291) and adult female (K-2224) buried at Dragsholm. Both dates were re-calibrated as described in Figure 1 caption. The adult female burial (K-2224) had been converted to conventional radiocarbon date prior to calibration (see Richards et al., 2003). The third burial, an adult female, has not been dated.

Stable isotope values and human diets

Considering the continued evidence for marine food remains throughout the Neolithic, do the isotope data necessarily imply the complete abandonment of marine foods in this period? To address this question, we assess how stable isotope data have been interpreted. Estimating the proportion of marine foods in human diets from stable carbon and nitrogen isotope measurements is based on the following assumptions, outlined by Richards & Hedges (1999a):

1. Human bone collagen composition reflects the diet averaged over 5–10 years prior to death.
2. Stable isotope ratios in human bone collagen only reflect the protein portion of the diet, and therefore the lipid and carbohydrate components are effectively 'invisible'.
3. The offset between dietary protein and the consumer's bone collagen is 0–1 per mil for $\delta^{13}C$ and *c.* 3 per mil for $\delta^{15}N$.
4. Variations in the nutritional quality of the diet, and in particular the proportion of protein to carbohydrate, do not affect any of the above assumptions
5. The dietary end-members, i.e. the $\delta^{13}C$ and $\delta^{15}N$ values that correspond to the extremes of a purely marine and purely terrestrial diet, are approximately known.

The key question that we focus on here is how accurately isotope values can reconstruct the proportion of marine and terrestrial foods in a diet that combines both in varying proportions. In this respect, we have no reason to question assumptions (1) or (3), but the other assumptions require careful scrutiny. In order to correct radiocarbon dates, as in Figure 1, we can roughly estimate the percentage of marine carbon in a bone collagen sample by linear interpolation between maximum and minimum $\delta^{13}C$ values, defined by the known dietary end-members (assumption five). While this is adequate for correction of radiocarbon dates, absolute $\delta^{13}C$ measurements may not accurately correspond to direct consumption of marine foods, because the marine and terrestrial end-members may vary considerably, both temporally and spatially, depending on the broader isotope ecology.

Marine carbon can be incorporated into human bone collagen without *direct* consumption of marine foods. Marine detritus can enter the terrestrial food chain through the action of beach scavengers (Polis & Hurd 1996) or through anthropogenic practices, such as manuring and foddering with various marine products of which there is ample historical evidence (e.g. Brand 1883; Kemp 1801). However, it is the converse of this last point that may explain the discrepancy between the isotopic and other archaeological evidence, i.e. consumption of marine foods does *not* always result in a marine stable isotope value. Carbon from terrestrial organic detritus and dissolved inorganic carbon from the dissolution of pre-Quaternary carbonates in rocks and sediments can enter the marine food chain at various trophic levels, primarily via river systems (Riera & Richard 1996). The greatest effect is likely to be on 'stationary' marine organisms, such as molluscs, which are often collected from estuaries, and may have consumed significant amounts of terrestrial carbon. In fact, studies have demonstrated large variations (-14 to -23 per mil) in the $\delta^{13}C$ values of annelid worms caught in UK estuaries (Nithart 2000). Interpreting diets based on stable isotope measurement of humans exploiting lagoons and estuaries is therefore always likely to be difficult

Understanding the stable isotope ecology of 'open' seas is not always straightforward either. Here too, there exists variation in $\delta^{13}C$ values of marine organisms. Isotope measurements of seals and pelagic fish obtained from shallow seas such as the Baltic are significantly depleted in $\delta^{13}C$ compared to the same species from the Atlantic (e.g. Eriksson 2003; Barrett *et al.* 2002; Richards & Mellars 2000). At the site of Norsminde on Jutland in Denmark, similarly large differences in $\delta^{13}C$ have been observed in a number of seal bones, identified to a single species (Craig, unpublished data), perhaps indicating variations in the feeding grounds between individual animals. As salinity correlates with the $\delta^{13}C$ values of marine organisms (Eriksson & Lidén 2002), changes in salinity through time complicate dietary inferences. An extreme but relevant example is the Baltic, where intrusion of salt water effectively transformed a lacustrine environment to a brackish one between 6500 and 5300 cal BC (Emeis *et al.*, 2003) with the effect of increasing $\delta^{13}C$ values. In the millennia prior to the Mesolithic/Neolithic transition (3900 cal BC), salinity is estimated to have fluctuated rapidly and $\delta^{13}C$ values over this period may have varied by as much as 4 per mil before increasing steadily in the fourth millennium cal BC (Emeis *et al.*, 2003).

Therefore, palaeodietary interpretations of stable isotope values need to be put into the wider context of the changing isotope ecology, and not read off by simply equating diet with the estimated percentage of marine carbon in bone collagen based on $\delta^{13}C$ measurements. The only secure way to do this is to make extensive stable isotope measurements on organisms represented in archaeological deposits associated with the human bone, and in particular marine molluscs, fish and marine mammals. Unfortunately, in part due to the poor survival and recovery of bone, adequate measurements on associated marine fauna have only rarely been made and are seldom reported with the amalgamated human datasets. Without such data, we do not think it can be asserted with confidence that the low $\delta^{13}C$ values from Neolithic humans demonstrate the total absence of marine foods in their diets.

Finally, we consider the validity of assumptions (2) and (4), listed above. In a series of experiments on rats fed controlled diets, Ambrose and Norr (1993) concluded that dietary proteins were directly routed into bone collagen, thus supporting the validity of assumption (2) – the 'direct' model. However, this result was modulated by the percentage of protein in the diet. When the rats were fed low protein diets (c. five per cent protein), carbon from lipids and carbohydrates contributed 49–58 per cent of the carbon in their collagen, thus supporting the 'mixed' model. Using a similar approach, Tieszen and Farge (1993) showed that rats fed high starch diets assimilated carbon from this carbohydrate source into their bone collagen. Fogel & Tuross (2003) compared carbon isotope ratios of individual amino acids from the collagen of prehistoric human hunter-gatherers and maize agriculturalists with those obtained from herbivore bone collagen and modern plants. In the protein-rich hunter-gatherer diet, amino acids in human collagen were highly correlated with amino acids in herbivore collagen, supporting the direct model. In contrast, the bone collagen of the maize agriculturalists showed a closer correlation with total dietary carbon rather than with protein carbon alone, supporting the mixed model. In other words, when the amount of protein in the diet is low, carbon in collagen is derived from a mixture of dietary components including carbohydrate and lipid, as well as protein. Thus, a diet based on high proportions of plant foods, and with low proportions of animal protein, should generate a relatively depressed $\delta^{13}C$ value in bone collagen. This effect will be further exaggerated because the carbon in the carbohydrate component of a particular foodstuff is isotopically depleted in $\delta^{13}C$ relative to the protein component (Galimov 1985).

If the protein component of such a mixed diet were from marine sources, the marine signal would be significantly moderated. Preliminary models (produced by Hedges in the volume) show that a diet dominated by plant-food might include up to 20 per cent of marine protein without raising the $\delta^{13}C$ values of bone collagen above –21 per mil; this would standardly by interpreted as a diet dominated by terrestrial food. This model is particularly appropriate to grain agriculturalists with low protein diets, and thus of particular relevance to Neolithic farmers in coastal areas. Therefore, carbon isotope measurements indicating extreme terrestrial values in Figure 1 may be compatible with diets comprising up to 20 per cent of marine food and certainly do not demonstrate the complete abandonment of marine resources. Conversely, diets rich in protein but also incorporating terrestrial plants foods are likely to exaggerate the marine signal in bone collagen. We suggest that the relationship between the percentage of marine carbon in human bone collagen and the proportion of marine foods in the diet is non-linear, with a tendency to exaggerate the extremes, and that the apparently marked shift in isotope values at the Mesolithic–Neolithic transition could have been exaggerated by the introduction of cereal agriculture.

These considerations do not affect nitrogen values because lipids and carbohydrates contain no nitrogen, so that incorporation of this element into bone collagen is always from dietary protein. A reduction in the $\delta^{15}N$ values of Neolithic coastal populations compared to Mesolithic populations is observed, suggesting less consumption of marine foods in the Neolithic. However, the Neolithic values are not generally so light (i.e. less that 8 per mil) as to exclude the consumption of substantial amounts of marine food (e.g. 20 per cent). This last point is even more significant, if the diet includes marine foods occupying a low trophic level, such as the major edible molluscs, or is composed of higher trophic level marine foods mixed with substantial amounts of plant materials. Finally, it has been noted that in southern Britain the stable nitrogen isotope values of Early Neolithic individuals interred in inland chambered tombs, such as Hazleton and West Kennet, are significantly lighter than the contemporary tombs on the coast (Richards 2000). It is interesting to speculate whether these differences could be the result of the higher consumption of marine foods at coastal locations.

Conclusion

Measurements of stable isotope values in human bone collagen are a valuable additional tool in the interpretation of ancient diets, but they are not a panacea or a substitute for other sources of information. As with other sources of palaeodietary information, isotope measurements are subject to a number of significant uncertainties and potential biases, which require further experimental investigation, and their interpretation is further constrained by the small sample of human skeletons so far analysed.

We agree that the available isotope record indicates a consistent tendency towards a more dominant terrestrial signal in the diets of Neolithic individuals compared to their Mesolithic predecessors. However, we do not believe the evidence can be used to demonstrate a change as extreme or rapid as has been claimed, or to exclude the consumption of marine or terrestrial foods by Neolithic individuals, let alone whole populations. The inshore waters of Northwest Europe are some of the most productive in the world, with an abundance of fish, sea mammals and shellfish. The notion that generations of Neolithic farmers throughout large areas of coastal Europe deliberately turned their back on this marine cornucopia as part of some widespread new system of ideas and taboos would be remarkable, especially given the clear evidence of Neolithic seafaring and maritime contacts. Such a notion is not, in our view, supported by the isotope data, ignores a large amount of existing archaeological information, and is theoretically implausible. As Laderman (1981) has demonstrated in her analysis of Malay systems of food classification, these are inherently cultural and symbolic constructs, but they also operate on many different levels and tend to be reinforced by practical needs and experiences. Food prohibitions on fish apply to species of little significance as food, which are also potentially harmful, difficult to catch or of unusual appearance and colouring. Even in these cases, the taboo is not rigorously enforced (see also Moss 1993). Those fish species that are the most abundant, the most commonly available, the easiest to catch and the most important for daily subsistence are never proscribed.

More isotope measurements from larger samples of human skeletons would undoubtedly help, but human bone remains are not available in unlimited supply, and increasing the sample size will not resolve the inherent uncertainties in the technique. We also need more rigorous analyses of local isotope ecology and palaeoeconomic potential to place the isotope results in context.

Above all, we should remember that the traditional sources of palaeodietary information give us a generalised picture of subsistence within the catchment of an archaeological deposit. Isotope measurements, in contrast, tell us about the recent dietary history of specific individuals, whose personal 'food catchments' may have been very extensive or highly localised, and in all probability a very small and potentially biased subset of the general food economy. Isotope data reflect high resolution 'events', which are necessarily very rare compared to the general dietary behaviour of wider populations over large areas and long periods. The food remains from archaeological deposits are relatively low-resolution palimpsests, which rarely if ever tell us about the detail of individuals or individual groups, but probably have wider applicability than the dietary signals in individual human skeletons. In short, these two techniques measure palaeodiet at two such different scales of observation and resolution that to bring them into a coherent relationship according to a common scale of values is very difficult. Using one technique as a crosscheck on the other may be misleading.

In the decades since Eric Higgs poured cold water on claims of interdisciplinary research in archaeology as '*A horrid porridge … of disciplines, each one uncritically accepting or ignoring the work of others*' (Higgs 1968: 620), much of course has changed, but the concept of interdisciplinarity has lost none of its popularity. The risks of circular argument that can arise in such an intellectual environment have been well charted in the history of studies on plant and animal domestication. Zoologists drafted in to find the origin of domestication duly devised criteria that found it in the appropriate times and places because that is where they had been told to look by the archaeologists. The archaeologists in their turn duly quoted the zoologists' results as support for a pre-existing belief about the origins of agriculture, until a new generation of archaeozoologists appeared who were capable of critically evaluating both sides of the argument. The present application of stable isotope studies is at risk of repeating that history, with scientists tempted to exaggerate the power of their techniques to attract the attention of the archaeological community, and archaeologists unfamiliar with the science tempted to misuse its results in archaeological interpretation. As long as we continue to believe that the Neolithic Revolution was the defining moment in the origin of European civilisation, we will be tempted to find evidence in support of a Mesolithic–Neolithic transition that is short and sharp and that emphasises the differences on either side of the boundary. Critically examining the nature of that boundary should be part of the intellectual context in which the next generation of isotope analyses and palaeodietary interpretations are conducted.

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