REVIEWS

A new radiocarbon revolution and the dispersal of modern humans in Eurasia

Paul Mellars[1]

Radiocarbon dating has been fundamental to the study of human cultural and biological development over the past 50,000 yr. Two recent developments in the methodology of radiocarbon dating show that the speed of colonization of Europe by modern human populations was more rapid than previously believed, and that their period of coexistence with the preceding Neanderthal was shorter.

Radiocarbon dating, first developed by W. F. Libby in 1947, works on the assumption that the proportion of the radioactively unstable ^{14}C isotope to stable ^{12}C has remained effectively constant and homogeneous in the Earth's atmosphere over the past 50,000 yr (the effective limit of the method), and that the rate of decay of the ^{14}C isotope (with a half-life of approximately 5,730 yr) can be used as a measure of the age of all forms of once-living materials (principally plant and animal remains) that secured their original carbon content directly or indirectly from the contemporaneous atmosphere[1]. The degree of precision in dating declines with the increasing age of the samples, but even so, with the use of high-precision accelerator mass spectrometer techniques this method can produce dates with an accuracy of a few hundred years extending back to at least 45,000 yr before present (BP)[2]. Because this is better than the precision that can be obtained by almost any other dating methods in this time range (with the exception of some uranium decay methods, only applicable to carbonate formations[1]), radiocarbon continues to provide the central timescale for all of the current studies of the geographical dispersal and cultural development of early anatomically and behaviourally modern human populations (that is, *Homo sapiens*) after their initial dispersal from Africa between approximately 50,000 and 60,000 yr ago[3–7].

The application of radiocarbon dating to these crucial early phases in modern human development has, however, been critically dependent on two potential sources of error in the accuracy of radiocarbon age estimates. The first is the impact of even miniscule quantities of contamination by more recent, intrusive carbon into the dated samples (Fig. 1a). This can be illustrated by the fact that contamination by only 1% of modern carbon in a sample actually 40,000 yr in age would reduce the measured age of the sample by over 7,000 yr—an effect that doubles with every additional half-life (5,730 yr) in the age of the sample[1,8,9]. The second is the long-established recognition that the original proportion of ^{14}C to ^{12}C in the Earth's atmosphere has not remained constant over the past 50,000 yr, but has diverged sharply from present-day values, principally due to past variations in the intensity of the Earth's magnetic field and the shorter-term effects of sunspots on the amount of cosmic radiation reaching the upper atmosphere[1,10–17]. The combination of these two sources of potential error in radiocarbon dating has been a major complication for archaeologists and palaeoanthropologists attempting to unravel the true patterns of evolutionary and behavioural development during these early phases of modern human development[5,8,9].

Here I show that recent developments in the methodology of radiocarbon dating have had a dramatic impact on both of these sources of error. New developments in the preparation of bone samples would seem to have largely resolved the problem of modern contamination in the dating of these samples. And a spate of new data on the calibration of radiocarbon dates into 'absolute' calendar years show that the speed of dispersal of anatomically modern populations across Europe was much more rapid than previously believed.

New developments in radiocarbon dating

Two recent developments, in particular, have effectively revolutionized the application of radiocarbon dating to the study of modern human origins and dispersal in Eurasia. In the first place, recent developments in the pre-treatment of bone samples at the University of Oxford[8] have led to radical improvements in the procedures for the effective purification of bone collagen to eliminate contamination by more recent carbon—especially in the case of older bone samples, which have always provided the most widely available materials for dating from most early modern human sites[8,9,18]. The new techniques involve the 'ultrafiltration' of the prepared gelatin samples to separate out the smaller and lower molecular weight fractions, which seem to have been the major source of more recent organic contaminants (from percolating humic acids, organic salts, heavily degraded collagen, and so on) in the dated samples[8,18]. Recent applications of this procedure to a range of samples that had previously been processed by means of conventional pre-treatment techniques have led to dates that are frequently between 2,000 and 7,000 yr older than the original age estimates[18] (see Fig. 1b). For example, dating of a later Aurignacian bone point from Uphill quarry, Somerset, which had previously been dated to 28,080 ± 360 yr BP produced a revised date of 31,730 ± 250 yr BP, whereas the re-dating of a rhinoceros bone from the site of Kent's cavern, Devonshire, increased the measured age from 30,220 ± 460 to 37,200 ± 550 yr BP.

The second breakthrough has emerged from recent research into the fluctuation patterns of the original ^{14}C content of the Earth's atmosphere over the past 50,000 yr[10–17]. The most significant and internally consistent results have come from the dating of a series of 280 stratified radiocarbon samples recovered from a long sequence of deep-sea sediments in the Cariaco Basin near Venezuela, dated in 'calendrical' terms by reference to closely matching patterns of oxygen isotope ($^{18}O/^{16}O$) fluctuations in the independently dated Greenland Ice Sheet Project 2 (GISP2) ice-core records from central

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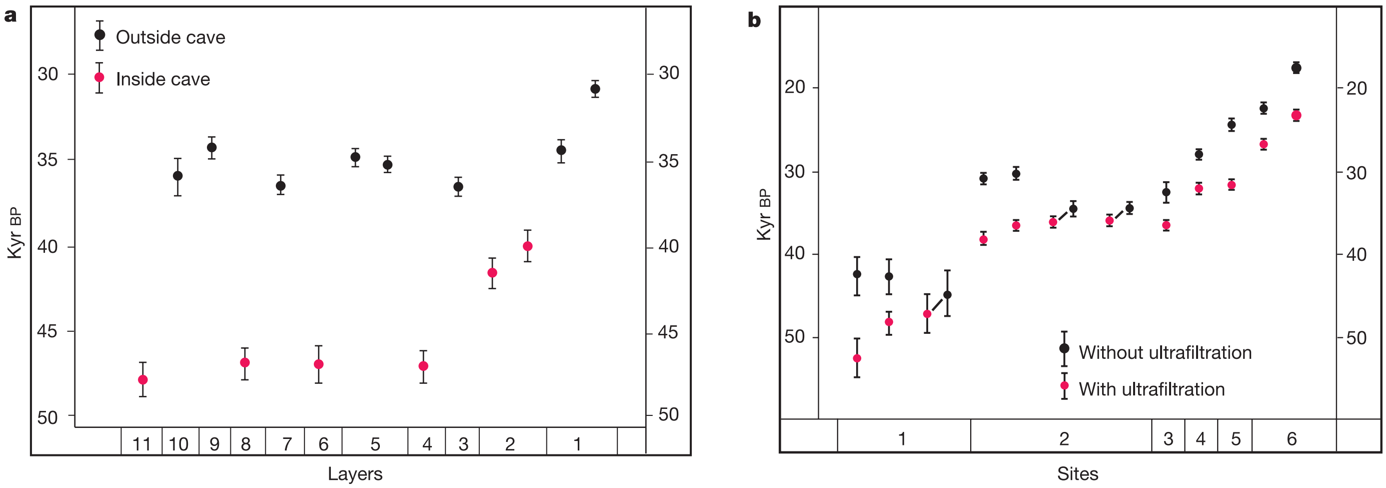

Figure 1 | Contamination effects in radiocarbon dating. a, Contamination effects on radiocarbon samples from the Sesselfelsgrotte cave (south Germany). The graph compares dates for successive levels based on bone samples collected from the exterior versus interior areas of the cave, dated by the Groningen radiocarbon accelerator laboratory. The samples from the unprotected exterior part of the cave have clearly been heavily affected by continuous percolation of groundwater containing humic acids and other organic contaminants from the present surface. The effects of the contamination are equivalent to approximately 1% of contamination by modern carbon in all of these samples. Data from ref. 48. **b**, The effects of ultrafiltration preparation techniques on the dating of bone samples. The graph compares dates on the same bone samples made respectively with and without the use of ultrafiltration pre-treatment techniques at the Oxford radiocarbon laboratory[8,18]. The sites are: 1, Pinhole cave (Derbyshire); 2, Kent's cavern (Devonshire); 3, Brixham cave (Devon); 4, Uphill cave (Somerset); 5, Hyaena den (Somerset); 6, Paviland cave (Swansea). Data reproduced with permission from Jacobi, Higham and Bronk Ramsey (ref. 18).

Greenland[16]; from a similar sequence of datings from deep-sea sediments adjacent to the Iberian coast[17]; from a series of 152 paired radiocarbon and high-precision uranium/thorium (U/Th) measurements on a number of fossil coral formations from the tropical Atlantic and Pacific[15]; and from a sequence of similar, combined ^{14}C and U/Th dating of a long cave stalagmite formation from the island of Socotra off the Arabian coast[17]. The results of these different measurements have recently been compared to give a "best-estimation" comparison between measured radiocarbon ages and 'absolute' calendar ages over the past 50,000 yr, in the recently published NotCal04 calibration study presented at the 2003 radiocarbon calibration conference in Wellington, New Zealand[17] (Fig. 2).

Although the results of the separate calibration records differ in certain respects, two significant patterns have emerged from these correlations. First, as noted above, we can now see that radiocarbon dates diverge sharply from true ages in the time range from about 10,000 to 45,000 yr BP, apparently due principally to the effects of the major Laschamp and Lake Mono geomagnetic excursion events at around 41,000 and 28,000 calendar years ago, respectively, which sharply increased the amount of cosmic radiation reaching the Earth's upper atmosphere and accordingly increased the ^{14}C content of the atmosphere[13,14,16,19]. The new calibration curves (Fig. 2) show that a measured radiocarbon date of 40,000 yr BP translates into an actual (calendrical) date of approximately 43,000 yr BP, whereas a radiocarbon date of 35,000 yr BP translates into a calendrical age of about 40,500 yr BP. The systematic displacement of radiocarbon ages from true calendrical ages has obvious implications for any comparison between dates for archaeological or geological sites produced by means of radiocarbon as compared to other dating methods, such as uranium/thorium or thermoluminescence[1]. The new calibration curves also reveal that the observed pattern of deviations between radiocarbon ages and real ages within this time range follows a relatively simple, smooth pattern, apparently without any of the sudden and aberrant oscillations in the atmospheric ^{14}C content that had been claimed from some earlier attempts at calibration based on studies of stratified lake sediments at Lake Suigetsu in Japan[11] and studies of a cave stalagmite formation in the Bahamas[12] (Fig. 2). This is clearly a highly important discovery, as the occurrence of erratic oscillations of this kind would inevitably lead to equally erratic fluctuations in measured radiocarbon ages, and in some cases to possible major 'plateaux' or even substantial reversals in the recorded patterns of radiocarbon dates.

There is another important methodological implication of this new radiocarbon calibration. As seen in Fig. 2, the effect of the new calibration is to reveal a rapid change in measured radiocarbon ages over the period between about 40,000 and 35,000 radiocarbon years ago, due to the rapid changes in the atmospheric ^{14}C content over this time range. In practice, this means that the radiocarbon dates that cover an apparent (that is, measured) period of 5,000 yr in reality cover an actual time range of only around 3,000 yr. In practical terms this means that the relative precision and chronological resolution of radiocarbon measurements over this time range is significantly greater than that in other, adjacent parts of the radiocarbon time-scale, where the atmospheric radiocarbon content followed a more regular, linear pattern. Thus, what had previously seemed to be a

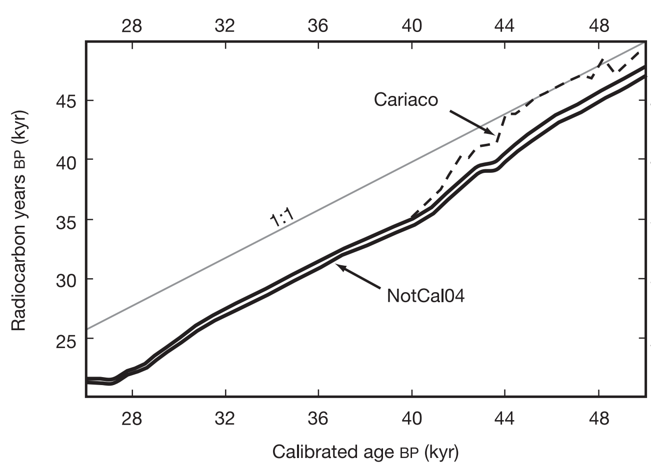

Figure 2 | Radiocarbon calibration curves for the 25,000–50,000-yr time range. The graph shows the recent NotCal04 "best estimation" calibration curve of ref. 17 (adjacent black lines) and the alternative calibration in the 40,000–50,000-yr range based on the recent Cariaco Basin data[16].

'nightmare' period for the application of radiocarbon dating in early prehistory now emerges as the period when the method is apparently performing at its best. Combined with the improvements in the methods for the pre-treatment and purification of bone samples, this is good news indeed.

Palaeoanthropological implications

The central question is exactly what implications do these new developments in radiocarbon dating have for our understanding of the patterns of human development during the critical 50,000–35,000 yr BP time range when we know that anatomically and behaviourally modern populations were expanding across western Eurasia from their original African homeland[3–7,20,21].

Overall, perhaps the most significant impact of this new radiocarbon calibration lies in its implications for the relative speed with which anatomically and behaviourally modern human populations expanded across Eurasia, and the extent to which they overlapped with the preceding Neanderthal populations within the different regions. On the basis of discoveries of fossilized human skeletal remains and a number of long stratified archaeological sequences in Israel and Lebanon it has been recognized that populations of anatomically and behaviourally modern humans, equipped with typically Upper Palaeolithic technology, had appeared in the near eastern region by at least 45,000 yr BP (in uncalibrated radiocarbon terms), and had apparently spread to parts of southeastern Europe shortly after this time[4,5,20,22,23]. However, the dispersal of these populations across the remaining areas of central and western Europe seemed, on the basis of the 'raw' radiocarbon dates, to have taken a period of at least a further 7,000 yr, between approximately 43,000 and 36,000 yr in uncalibrated radiocarbon terms. This implies an overall rate of dispersal of these populations of around 0.3 $km\,yr^{-1}$. In the light of the new calibration data (Fig. 2) we can now see that this period compresses to an actual time span of only about 5,000 yr (from about 46,000 to 41,000 yr BP in calibrated terms), implying a substantially faster rate of dispersal across this region (see Fig. 3). If we were to adopt the newly published Cariaco Basin calibration curve (Fig. 2), the result would be an even faster migration rate of around 0.4 $km\,yr^{-1}$. This rate of dispersal is broadly similar to the later dispersal of early agricultural communities across the same geographical range, between about 10,000 and 6,000 (calibrated) years BP[24]. It is equally interesting to see that the two dispersals seem to have followed closely similar geographical routes: one along the Mediterranean coast from Israel to northern Spain and the other along the Danube valley from the Balkans to southern Germany and eventually western France[5,21–23] (Fig. 4). The rapid spread of the early modern human populations was probably facilitated by a major improvement in climatic conditions in Europe between about 43,000–41,000 yr (calibrated) BP (the period of the Hengelo interstadial), which would inevitably have made a process of population expansion from southeast to northwest across Europe easier to achieve[14,23,25,26]. Climatic modelling studies suggest that both summer and winter temperature isotherms shifted by around 1,000 km westwards during this interval[27], closely paralleling the westwards expansion of the earliest anatomically modern populations from central Europe to western France.

The same chronological pattern points to a substantially shorter period of chronological and demographic overlap between the earliest intrusive populations of anatomically and behaviourally modern humans and the last survivors of the preceding Neanderthal populations within the different regions of Europe. Although this has often been estimated in the region of approximately 10,000 yr within Europe as a whole[3,28,29], we can now see from the new calibrated

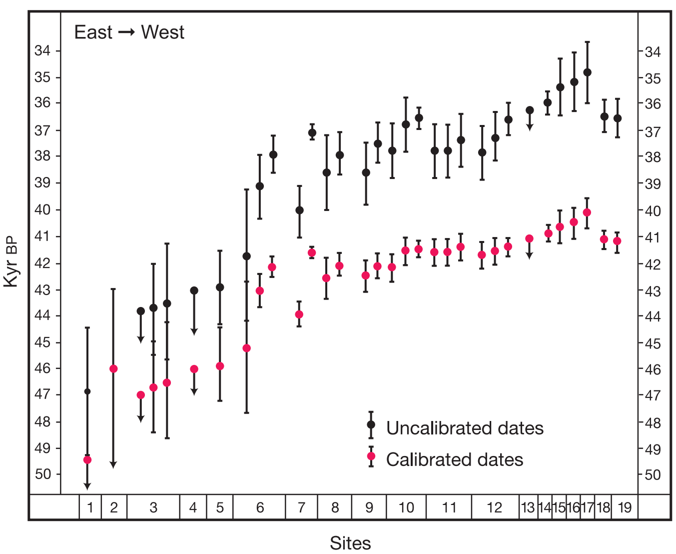

Figure 3 | Comparison of calibrated and uncalibrated radiocarbon dates for the dispersal of modern humans across Europe and the Near East. The numbers, arranged from east to west, refer to archaeological sites belonging to the Emiran, Ahmarian, Bacho-Kirian, Bohunician, Proto-Aurignacian and Aurignacian technologies in different regions, all believed to be the products of early anatomically modern populations[4,5,22,23]. Calibrated dates are based on the mid-points of the NotCal04 calibration shown in Fig. 2. Application of the Cariaco Basin calibration curve (Fig. 2) would yield substantially younger calibrated ages for the 40,000–50,000-yr range, and a correspondingly faster rate of dispersal across Europe. Owing to the slope of the calibration curves, the error bars (±1 s.d.) on the calibrated dates are smaller than those on the uncalibrated dates. Only the oldest radiocarbon measurements are plotted from each region, on the assumption that these are likely to be least affected by contamination with more recent carbon. The sites plotted are: 1, Boker Tachtit (Israel); 2, Ksar Akil (Lebanon); 3, Kebara (Israel); 4, Bacho Kiro (Bulgaria); 5, Bohunice (Czech Republic); 6, Willendorf (Austria); 7, Grotta Fumane (Italy); 8, El Paina (Italy); 9, Keilberg-Kirche (Germany); 10, Geissenklösterle (Germany); 11, L'Arbreda (Spain); 12, Abric Romaní (Spain); 13, Châtelperron (France); 14, La Rochette (France); 15, Abri Caminade (France); 16, Abri Castanet (France); 17, Roc de Combe (France); 18, Isturitz (France); 19, Cueva Morín (Spain) (refs 4, 28, 30, 33, 47, 49–56). The date range shown for Ksar Akil (site 2) is based on age/depth extrapolations from overlying radiocarbon measurements[55]. The currently controversial dates for El Castillo (Spain), with disputed archaeological and skeletal associations[56], have been omitted.

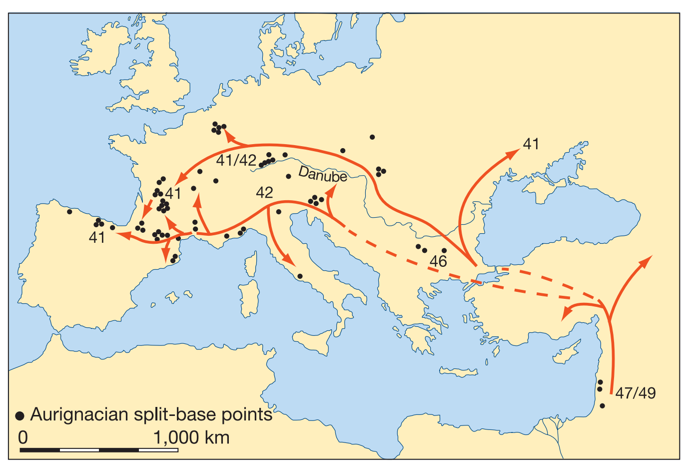

Figure 4 | Dispersal routes of modern human populations across Europe. The dates shown for each region (in thousands of yr BP; range 47,000–41,000) are based on the calibrated (that is, calendrical age) radiocarbon measurements plotted in Fig 3, derived from the NotCal04 calibration data shown in Fig. 2. The distribution of classical Aurignacian split-base bone/antler points is also shown for comparison, although these are not necessarily associated directly with the adjacent age estimates. Note the contrast between these dates and the uncalibrated radiocarbon ages plotted in ref. 5.

Figure 5 | Drawing of heads of cave lions in the Chauvet cave (south-east France). The drawings in the Chauvet cave were originally dated by radiocarbon dating of the charcoal used to produce the drawings to around 31,000–32,000 yr BP, but are now redated by the new NotCal04 calibration (Fig. 2) to around 36,000 yr BP in calendrical terms. Reproduced from Clottes (ref. 32) with permission (see Acknowledgements).

chronology that this must be shortened to at most about 6,000 yr (at least in the more central and northern parts of Europe), with periods of overlap within the individual regions of Europe (such as western France) of perhaps only 1,000–2,000 yr[28,30]. Evidently the native Neanderthal populations of Europe succumbed much more rapidly to competition from the expanding biologically and behaviourally modern populations than previous estimates have generally assumed.

We can now see from the new calibration data that some of the most striking cultural achievements of the new anatomically modern human populations in Europe appeared much earlier than the original radiocarbon dates had suggested. As Bard *et al.*[31] have pointed out, the spectacular cave art in the Chauvet cave[32] in southeastern France (Fig. 5) can now be seen to date from around 36,000 yr BP in real terms (as compared to about 31,000–32,000 yr BP in radiocarbon terms), whereas the equally dramatic eruption of elaborate bone, antler and ivory technology, and the associated proliferation of various forms of personal ornaments, appeared in association with the earliest Aurignacian populations in central and western Europe by at least 41,000 yr BP in calendar terms[5,33–35]. Whether or not these innovations coincided with the first appearance of fully structured language and associated complex social organization among the earliest biologically modern human populations in Europe is still disputed[35–38], but there can be little doubt that these new cultural and behavioural developments had a critical role in the rapid replacement of the European Neanderthals by the new, intrusive, biologically modern populations from an ultimately African source.

There are increasing indications that over many areas of Europe the final demise of the Neanderthal populations may have coincided with the sudden onset of very much colder and drier climatic conditions marked in the deep-sea records by the period of Heinrich event 4 (dated to about 35,000 yr BP in radiocarbon terms, or about 40,500 yr BP in calibrated terms), during which many icebergs broke off from the North Atlantic ice sheet and sharply depressed sea and land temperatures over large areas of Europe[26,39–41]. If, as most of the current evidence suggests, the new anatomically modern human populations were better equipped technologically and culturally to deal with these severe glacial conditions[30,35,41,42], then this could have delivered the *coup de grace* to the Neanderthals in many parts of western and central Europe, in their economic and demographic competition with the incoming modern groups[26,30]. Whether some of the Neanderthal groups may have survived longer in some of the more southerly areas of Europe, such as the Iberian peninsula or the Balkans, is more controversial[3,29,40,43–45], and once again depends heavily on the reliability of the available radiocarbon dates used to support these apparently late Neanderthal survival events.

Future prospects

Although these are all major breakthroughs, we should continue to be cautious about the current state of radiocarbon dating in human prehistory. Palaeolithic archaeology has inherited a massive legacy of published radiocarbon dates accumulated over the past 40 yr, a high proportion of which are almost certainly serious underestimates of the true ages of the samples, as a direct result of the major contamination effects discussed earlier[8–18] (Fig. 1). This is almost certainly the explanation for the long tail of dates for late Mousterian (that is Neanderthal) sites in Europe extending long after 35,000 yr BP[9,29], and the similar tail of Aurignacian dates extending after 30,000 yr BP—far into the range of the stratigraphically younger Gravettian sites[22,29,33]. This is also the explanation for the successive datings of the early anatomically modern human skeleton from the Paviland cave (Swansea) becoming progressively younger from (initially) around 18,000 yr BP to (currently) around 26,000 yr BP[46] and for the large differences in the measured ages of radiocarbon samples collected respectively from the interior versus exterior areas of cave sites such as the Grotta Fumane (Italy)[47], Sesselfelsgrotte (Germany)[48] and elsewhere. These show the dramatic effects of contamination by percolating groundwater in samples collected from the 'wet' versus 'dry' areas of these sites. The results of the long series of ^{14}C measurements from Sesselfelsgrotte provide, in effect, a 40,000-yr-long laboratory experiment in the effects of percolating groundwater on the contamination of radiocarbon samples, leading, in this case, to errors of between 5,000 and 12,000 yr in the measured ages of the samples collected from the exposed, exterior parts of the cave (see Fig. 1a). For the same reason we must be extremely cautious about accepting the published dates for critical discoveries such as the late Neanderthal fossils from the Zafarraya cave (Spain) or from Vindija (Croatia)—both dated to between about 31,000 and 28,000 yr BP—at face value[43–45].

We should bear in mind that all of the recent attempts at radiocarbon calibration within the 25,000–50,000-yr time range are still provisional, and potentially subject to a number of errors in both the radiocarbon and associated calendrical age estimates of the dated samples[13–17]. A final, definitive calibration curve for this time range will depend on the results of new calibration studies, at present being pursued in several different laboratories[17]. The full implications of these studies for the interpretation of the human archaeological and evolutionary record will need to be kept under active and vigilant review.

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