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The Impact on Archaeology of Radiocarbon Dating by Accelerator Mass Spectrometry [and Discussion]

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The impact on archaeology of radiocarbon dating by accelerator mass spectrometry

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Radiocarbon dating by accelerator mass spectrometry (AMS) differs fundamentally from conventional ^{14}C dating because it is based on direct determination of the ratio of ^{14}C:^{12}C atoms rather than on counting the radioactivity of ^{14}C. It is therefore possible to measure much lower levels of ^{14}C in a sample much more rapidly than the conventional technique allows. Consequently, minimum sample size is reduced approximately 1000-fold (from *ca.* 1 g to *ca.* 1 mg) and the datable time span of the method can, theoretically, be doubled (from *ca.* 40 ka to *ca.* 80 ka). As yet, extension of the time span has not been achieved, because of the effects of sample contamination, but the great reduction in sample size is already having a major impact on archaeology by extending the range of organic remains that can be dated, and, especially, by allowing the archaeologist and the radiocarbon chemist to adopt more selective sampling strategies. This greater selectivity, in the field and the laboratory, is the most important archaeological attribute of AMS ^{14}C dating. It allows on-site chronological consistency to be tested by multiple sampling; archaeological materials to be dated that contain too little C, or are too rare or valuable, to be dated by the conventional method; and the validity of a date to be tested by isolating and independently dating particular fractions in chemically complex samples.

AMS laboratories have only been processing archaeological samples since 1982, but already several, notably those at Oxford, Toronto, and Tucson, Arizona, have made substantial contributions to archaeological dating. The Oxford laboratory has, since 1983, processed *ca.* 1200 samples and published over 500 archaeological dates. Particular attention is therefore paid in this paper to the archaeological significance of the dates obtained at Oxford. The AMS ^{14}C technique can contribute to archaeological dating in two complementary ways: (i) by testing prevailing assumptions about the antiquity of indirectly dated objects and materials, i.e. verification or falsification dating; and (ii) by dating new or existing archaeological sequences in greater detail than can be achieved by the conventional ^{14}C technique, i.e. the building of new and more detailed chronologies. In this paper, recent archaeological applications of the new technique are reviewed under these two headings: verification dating applied to the origin and spread of anatomically modern humans in Europe and the Americas, to putative evidence for early (pre-Neolithic) agriculture in Israel and Egypt, and to the dating of rare Palaeolithic and later artefacts; and the building of new and more-detailed chronologies illustrated by reference to Upper Palaeolithic sequences in Europe, Mesolithic–Neolithic sequences in Southwest Asia, and Neolithic–Bronze Age chronologies in Britain. It is concluded that the development and application of the AMS technique represents a revolution in ^{14}C dating that will have a profound impact on many aspects of archaeological research.

1. Introduction

In recent decades, archaeology has come increasingly to rely on a wide range of scientific techniques to aid it in its task of probing the human past. The subject has scientific roots that reach back to the mid-nineteenth century, when French geologists first showed that stone tools and extinct Pleistocene animals were of the same antiquity, and thus demonstrated to sceptical scientific colleagues that 'antediluvian' humans had existed during the Ice Age (Daniel 1981). Archaeology developed as an academic subject, however, largely in association with the study of classics and ancient history. It therefore came to be regarded as one of the humanities, and the scientific promise of its early alliance with geology was not realized. The divorce of humanistic archaeology from its potential scientific base lasted well into the twentieth century, but it has been followed, in the second half of the century, by a rapprochement of science and archaeology. In Britain, this was formally recognized in 1976 when, as a result of a joint initiative by the British Academy and the Royal Society, the Science-based Archaeology Committee (SBAC) of the Science Research Council (now the SERC) was set up.

Techniques of absolute dating have received the highest level of research-grant support from the SBAC: 53% by value over the six-year period 1978–1984 (Hart 1985). By far the largest project that the SBAC has supported has been the setting up and development of the Oxford Radiocarbon Accelerator Unit, which reflects the potential value to the archaeological community of ^{14}C dating by accelerator mass spectrometry (AMS). The scientific value of a facility, such as the Oxford Unit, dedicated to archaeological dating, is already becoming apparent, as the technique itself is refined and applied selectively to the resolution of dating problems across a range of archaeological topics and time periods. In this paper, the impact on archaeology of ^{14}C dating by AMS is assessed, by reviewing its present achievements and outlining some of its potential future applications.

The archaeological value of AMS ^{14}C dating is best considered first in the wider context of what has, by comparison with the new technique, come to be referred to as conventional ^{14}C dating. The original technique, and its application to archaeology, was pioneered by Willard Libby at the Institute of Nuclear Studies of the University of Chicago in the late 1940s (Libby 1952). Since then it has developed into the single most important contribution the physical sciences have made to archaeology, as the speed and extent of its adoption worldwide indicates. Today there are over 100 ^{14}C laboratories in existence. Most are in western Europe and North America, but others have been established in Asia, Africa, Australasia and South America (Clark 1980); and a total of about 50000 natural ^{14}C measurements have so far been published, approximately half of which are archaeological dates. Conventional ^{14}C dating has transformed understanding of later human prehistory in many parts of the World because it can provide chronological control over most of the past 50 ka, the period during which anatomically modern man, *Homo sapiens sapiens*, effectively colonized all habitable parts of the Earth. It has also contributed substantially to the investigation of such major questions as when and where agriculture originated and urban civilization began.

The widespread application in archaeology of conventional ^{14}C dating brought about what can in retrospect be regarded as the first radiocarbon revolution. The technique does, however, suffer from two main limitations, both of which can, theoretically, be overcome by AMS ^{14}C dating. They are (i) that minimum sample size is relatively large (approximately 1 g of elemental carbon), and (ii) that ages greater than approximately 40 ka cannot be determined within an acceptable range of probability without excessively long periods of time being devoted to measuring the radioactivity of each sample (a standard deviation of $\pm 1\%$ requires at least 10^4 counts, which, for a 5 g C sample that is 40 ka old at a measurement efficiency of 65% would take 20 days of continuous counting (by liquid scintillation spectrometry), and even then the stability of the system might change sufficiently to invalidate the result (R. Burleigh, personal communication 1986). Both of these limitations can be overcome by the use of AMS, because this technique allows ^{14}C atoms to be separated from ^{12}C atoms by their different atomic mass, and it is therefore possible to measure much lower levels of ^{14}C in a sample of comparable age and to do so rapidly (*ca.* 10^4 counts in a 30 min measurement). As a result, minimum sample size is reduced approximately a 1000-fold compared with the conventional technique (from *ca.* 1 g to *ca.* 1 mg), and the time span of the method can, theoretically, be doubled (from *ca.* 40 ka to *ca.* 80 ka). As yet, extension of the age range has not been achieved, because of the effects of sample contamination, but the dramatic reduction in sample size that AMS affords constitutes a major breakthrough in ^{14}C dating that is already having a conspicuous impact on archaeology.

2. Archaeologically significant attributes of AMS radiocarbon dating

In this section, the attributes of ^{14}C dating that are of greatest significance for archaeology are outlined, as a prelude to consideration of the archaeological applications of the technique.

Sample size

The 1000-fold reduction in sample size that the AMS technique allows is its most important attribute for archaeology. The need of conventional ^{14}C dating for relatively large samples has two main disadvantages: (i) it limits the range of archaeologically significant materials that can be dated to those that are present in comparatively large concentrations and/or are in the form of quite large (macroscopic) fragments, typically of bone, shell or charcoal; and (ii) it often results in uncertainty about the temporal relation of a sample that is not directly datable, because it is too small or too precious to be sacrificed (e.g. a few charred cereal grains or a miniature bone artefact), to the context with which it is presumed to be associated and which can be dated (e.g. a stratigraphic layer containing charcoal fragments). The tendency of small organic items, such as seeds, to undergo post-depositional stratigraphic movement exacerbates this problem of contextual uncertainty and reduces confidence in the archaeological significance of many conventional ^{14}C dates; indeed it has led to highly misleading interpretations of some apparently revolutionary archaeological discoveries.

In the four decades during which conventional ^{14}C dates have been produced, minimum sample sizes have been substantially reduced. It is interesting to look back to the first statement ever issued about the sample sizes that were regarded as acceptable for ^{14}C dating. It is contained in a letter dated February 1950 and signed by members of the 'Committee on Carbon 14' of the American Anthropological Association and the Geological Society of America. The Chairman of the Committee was Robert Braidwood, and the copy of the letter in my possession (Braidwood *et al.* 1950) was sent to Frederick Zeuner at the Institute of Archaeology in London, who included, in the third (1952) edition of his book *Dating the past*, a discussion of the then new radiocarbon method. In the letter, five types of sample are specified, with the amounts required ranging from 200 g for 'vegetable' and 'epidermal animal' remains to no less than

2.2 kg (or 5 lb) for 'teeth or ivory' (table 1)! This pioneering pronouncement also contains the interesting statement 'Please note that *bone* is *not* listed – it does not seem promising', a negative directive that, fortunately, proved unfounded.

If the sample sizes specified in this first systematic trial of the new technique are compared with those currently regarded as acceptable for conventional ^{14}C dating, it is seen that sample sizes for charcoal and wood and for shell have been reduced at least tenfold and sevenfold

TABLE 1. REDUCTION OF MINIMUM SAMPLE SIZES FOR ^{14}C DATING: 1950–1985

(Sources: Braidwood *et al.* 1950; R. Burleigh, personal communication 1986; Gowlett 1985, and personal communication 1986.)

1950 Libby counter		*ca.* 1960– conventional counter		1980 small counter		1985 accelerator	
sample	amount / g	sample	amount / g	sample	amount / mg	sample	amount / mg
'epidermal animal remains': hair, horn, etc.	200	—	—	—	—	—	—
'vegetable remains':		charcoal	5–10	charcoal	20–400	charcoal	5–50
charred wood, etc.	200	wood	10–20	wood	40–800	wood	20–50
shell	700	shell	50–100	shell	150–800	shell	50–100
antler (no bone)	500	bone	100–500	bone	2000–15000	bone	200–5000
teeth and ivory	2200		100–500		2000–15000		200–5000

respectively (table 1). Still more substantial reductions were achieved recently by laboratories with 'small-counter' facilities, such as the Atomic Energy Research Establishment's laboratory at Harwell in Britain, and the Brookhaven National Laboratory in the U.S.A. (table 1). However, the number of archaeological dates produced by small-counter laboratories remains small compared with the continuing output of conventional ^{14}C dates, and their potential contribution to archaeology may now be superseded by the even greater archaeological promise of AMS ^{14}C dating, especially because AMS offers still greater reductions in sample size and shorter measurement times (Mook 1984) compared with conventional ^{14}C dating (table 1).

Sample materials

The main types of organic material commonly submitted for ^{14}C dating are charcoal, wood, bone, antler and shell. Few other materials are frequently recovered archaeologically in sufficient quantity and concentration to allow conventional dates to be obtained, although occasionally other organic remains, such as fibre, hair, and other soft plant or animal tissues, survive as a result of waterlogging, freezing or desiccation in sufficient quantity to make conventional dating possible. Peat samples are often dated for palaeoecological purposes and they sometimes provide archaeologically significant contextual information.

Experimental dating by conventional means of other archaeologically significant carbonaceous materials has also been carried out. These include ivory, iron, paper, parchment, leather, cloth, organic temper on pottery, and even soot from cave ceilings, but none of these materials is both commonly recovered archaeologically and routinely dated by ^{14}C laboratories. However, with the great reduction in sample size that AMS provides, dating of these materials becomes more feasible; and the technique can be extended to still more elusive or refractory materials, such as single cereal grains; disarticulated insect remains; organic residues on the surface or in the interstices of pottery sherds, stone tools including grinding stones, and bronze- and iron-working slag; some of the pigments used in rock and cave paintings; and sediments that contain small quantities of finely disseminated carbonaceous components. One of the most remarkable examples of the potential of the AMS ^{14}C technique for dating traces of organic material is the recent demonstration that blood residues on prehistoric stone tools can be directly dated (Nelson *et al.* 1986*a*). This opens up the archaeologically revolutionary possibility of determining the actual time of use of such tools, and by biochemical analysis of the residues themselves it may be possible to identify the animal species (including humans) from which the blood derived (Loy 1983).

Sample selection

Not only does the capacity of AMS to analyse very small samples greatly extend the range of materials that can be dated, but, even more importantly, it offers the archaeologist and the radiocarbon chemist the opportunity to be much more selective at all stages in the dating process, from research design through field sampling to choice of the samples, and fractions thereof, to be dated. It also allows the validity of a controversial date to be checked by carrying out multiple measurements on a single sample.

Enhanced selectivity at the level of field sampling functions in three main ways: (i) by including in the range of dateable samples materials that contain too little carbon to be dated by the conventional method; (ii) by promoting the possibility of multiple sampling, especially of stratigraphic and other contexts of archaeologically significant finds, so that on-site chronological consistency can be checked; and (iii) by allowing archaeological objects that were previously regarded as too rare and valuable to be wholly or partially sacrificed for a conventional ^{14}C date to be sampled and dated.

At the level of laboratory sampling, the AMS technique enhances the potential for isolating and independently dating particular fractions from a chemically complex sample (see, for example, Batten *et al.* 1986). This allows the validity of a date to be tested, because a given field sample may contain carbon atoms from different sources, each of which has its own radiocarbon age, for example humic-acid and organic-residue fractions present in some wood, charcoal and peat samples; specific amino acids in bone; and lipids and other fractions in sediments. Indeed, the greatly increased capacity for selectivity in sampling, in the field and in the laboratory, that follows from a 1000-fold reduction in sample size that the technique allows, is, from an archaeological point of view, its most important attribute. It is already being applied to archaeological sampling, with interesting and controversial results, some of which are reviewed below in §3.

Datable time span

The fourth attribute of AMS ^{14}C dating that has major archaeological significance is its capacity greatly to increase the time span within which dating of acceptable accuracy is possible. Theoretically, the AMS technique is capable of at least doubling the present time span of most conventional ^{14}C dating by extending it from *ca.* 40 ka to *ca.* 80 ka; but, in practice, as-yet unresolved problems of sample contamination have prevented any extension of dating beyond the limit of *ca.* 40 ka.

At the Oxford Unit, the laboratory contamination associated with the ion source remains the main impediment to such an extension, but this is expected to be considerably reduced by the development of a CO_2 source and of automatic sample changing (R. E. M. Hedges, this symposium). Field or context contamination originating outside the laboratory is less easily eliminated because it arises in many different ways during the excavation, handling and storage of samples before they reach the laboratory. For example, a bone sample must contain more than 5% of the modern level of collagen if the possibility of contamination is not to invalidate the result. Much contamination can, however, be eliminated by chemically meticulous pretreatment of samples. At present such pretreatment is required to yield at least 2 mg of pure carbon for the preparation of a datable target. Within these constraints, dating accuracies to one standard deviation have now been achieved at Oxford of *ca.* ±80 years within the past 9 ka, of *ca.* ±150 years for samples older than 12 ka, and *ca.* ±250 years for samples older than 20 ka. From *ca.* 20 ka, accuracy continues to decrease exponentially to the present age limit of *ca.* 40 ka.

3. Archaeological applications of AMS radiocarbon dating

The review, in the previous section, of the archaeologically significant attributes of AMS dating shows that at present the main value of the technique for archaeology lies in the possibility of greatly enhanced selectivity in sampling, which is itself a function of reduced sample size, rather than in increasing the datable time span. The latter objective may be attained within a decade if problems of sample contamination can be overcome, but the present impact of the technique on archaeology is a result of the ability it confers on the archaeologist and the radiocarbon chemist to be highly selective in choosing which samples, and which fractions of them, should be dated.

The technique has only recently begun to be applied to archaeological dating, but it is already apparent that it can contribute in two complementary ways to the solution of chronological questions: it can be used (i) to test prevailing assumptions about the antiquity of indirectly dated objects and materials, and (ii) to date new or existing archaeological sequences in greater detail than the conventional ^{14}C technique allows. The first type of contribution can be referred to as verification or falsification dating; the second can be described as the building of new and more detailed chronologies. In the remainder of this section, some of the main contributions that AMS dating has so far made to these two aspects of chronology are reviewed. Attention is focused particularly on the dating achievements of the Oxford Unit because it is, to a greater extent than other AMS ^{14}C laboratories, dedicated to archaeological dating, and because it has published more results.

Several AMS laboratories outside Britain that undertake ^{14}C dating are, however, beginning to make important contributions to archaeological dating. They include the Laboratory of Isotope Geochemistry at the University of Arizona, Tucson, U.S.A. (Donahue *et al.* 1984); the Isotrace Laboratory at the University of Toronto, Canada; the Institüt für Mittelenergiephysik of the Federal Institute of Technology (ETH), Zürich, Switzerland (Bill *et al.* 1984); and the joint dating facility of Simon Fraser and McMaster Universities, Canada (Nelson *et al.* 1984, 1986*a*, *b*). At the Tucson laboratory, between a quarter and a third of the dates produced are archaeological (approximately 150 dates in 1984 out of a total that year of about 500 dates); at Toronto about half of the laboratory's capacity is devoted to ^{14}C dating, of which about 15% is archaeological (at present 50–60 dates annually); and at Zürich and Simon Fraser–

McMaster fewer of the dates produced are archaeological. Several other laboratories have undertaken some AMS ^{14}C dating of archaeological samples, for example those at the University of Rochester, New York, U.S.A.; Atomic Energy of Canada, Chalk River, Ontario; the Rijksuniversiteit, Utrecht, Netherlands; and the Centre des Faibles Radioactivités, Centre National de la Recherche Scientifique, Gif-sur-Yvette, France; but their output of archaeological dates is as yet very small. The Oxford Unit, which started to produce ^{14}C dates routinely in 1983, and which has since then devoted approximately 85% of its dating capacity to archaeology, has so far processed about 1200 samples and published over 500 dates in the lists that have begun to appear regularly in the journal *Archaeometry* (Gillespie *et al.* 1984, 1985; Gowlett *et al.* 1986*a*, *b*, 1987). The Unit is now producing 350–400 dates per year, the great majority of which are archaeological. It is therefore appropriate that this review of the initial impact of AMS dating on archaeology should pay particular attention to the results obtained at Oxford.

Verification dating

There is great scope for using AMS dating in archaeology to resolve chronological uncertainties and to test the validity of controversial hypotheses about the human past. The objectives of such research range from establishing the unknown or disputed age of single objects, such as artefacts in museum collections, to the resolution of major chronological problems, such as the timing of the earliest human occupation of the Americas, or the antiquity of cereal cultivation in Southwest Asia and other parts of the world. In this section, several examples of such exercises in verification dating are given to illustrate the potential archaeological value of this approach. They are selected to demonstrate, first, the capacity of AMS dating to clarify chronological confusion in two controversial phases of prehistory: early human migrations and early agriculture; and, second, to show how useful it is for establishing the age of ancient artefacts of particular value or rarity.

(*a*) *Early human migrations*

Two of the major controversies concerning the evolution and spread of anatomically modern humans relate to the origin of the modern populations of Eurasia, and to the question of when humans first occupied North and South America.

Disputes over the origin of the modern Eurasian populations of *Homo sapiens sapiens*, and their relation to the Upper Pleistocene fossil hominids of Neanderthal type, have long preoccupied palaeoanthropologists. The relevant time period of 30–50 ka BP stretches across the present upper limit of AMS dating of *ca.* 40 ka, but the technique has, nevertheless, already contributed to the resolution of some outstanding chronological uncertainties. It has done so through its capacity to date directly very small samples from fossil hominid bones that previously could only be dated indirectly or not at all. Thus the Oxford Unit has recently dated five samples from putatively Upper Pleistocene (Upper Palaeolithic) hominid bones excavated at four British cave sites (Badger Hole and Sun Hole, Somerset; Paviland Cave, Glamorgan; and Robin Hood's Cave, Derbyshire), with the result that only one of the specimens (an ulna from Sun Hole 2) was confirmed as genuinely Upper Pleistocene in age, and of the other four, two (a mandible from Badger Hole 1 and a humerus from Paviland 2) proved to be Mesolithic, and two (a cranial fragment from Badger Hole 3 and a mandible from Robin Hood's Cave) turned out to be even more recent (Gowlett *et al.* 1986*a*, *b*; Stringer 1986).

These examples demonstrate the potential value of the technique for resolving uncertainties about the ages of particular specimens of Upper Pleistocene fossil hominids, but, as Stringer (1986) argues, AMS dating could help to resolve the long-standing dispute over whether *Homo sapiens sapiens* evolved locally and gradually from more archaic predecessors in various parts of the World, including Neanderthals in Europe, or whether all living peoples derive from one founder population in one area (probably Africa). At present, application of the technique is effectively limited to Europe, because there the time period when the earliest modern humans may have co-existed with the last Neanderthals is 30–40 ka BP. By dating sufficiently well preserved hominid specimens from selected European sites in this time range, some of the fundamental questions about the origin of modern humans might be answered; but until the dating limit can be extended to 50 ka BP, the chronology of Upper Pleistocene hominid fossils from Asia, particularly southwestern Asia, which is crucial to a better understanding of Upper Pleistocene human evolution in Eurasia, will remain obscure and uncertain.

The timing of the earliest human occupation of the Americas is the second major palaeoanthropological controversy that has been subject to verification dating by the AMS technique. A programme of dating human and other remains from putatively early sites in North and South America has been undertaken by the Oxford Unit. In a recent review of the controversy and of the initial results, Gowlett (1986) stresses that it was regarded by the Unit as a particularly appropriate topic for the early stages of AMS dating because the chronological discrepancies between competing hypotheses were so great that high precision was not required to resolve them.

There is general agreement that the Americas were first entered via the Bering Strait route, probably not earlier than 30–40 ka BP. Beyond that there is little agreement, and Gowlett (1986) contrasts the two main hypotheses that have dominated the debate as follows.

1. That entry was delayed until about 12 ka ago, when an ice-free corridor opened between the two halves of the Canadian ice sheet and the first 'palaeoindian' migrants were able to move south from the Bering Strait landbridge to settle both North and South America very rapidly.

2. That the first occupation occurred before the last glacial maximum, more than 20 ka ago, possibly by way of the Pacific coast, with settlement concentrated within the American tropics during the glacial maximum, followed by rapid post-glacial expansion both north and south.

In devising a chronological test of these competing hypotheses, the central aim must clearly be to determine whether there is any irrefutable evidence for Pleistocene occupation before 12 ka BP. The most direct evidence would be in the form of human remains, but such finds are rare, and the dating of other organic materials from reputedly early sites in North and South America must be part of any coherent attempt to date the colonization process. Accordingly, the Oxford Unit concentrated on a highly controversial set of human skeletal remains from southern California, and on samples of other materials from selected sites in North and South America. The Californian skeletons, for which ages in excess of 40 ka have been claimed, mainly on the basis of amino-acid racemization dating (Bada & Helfman 1975), were dated by the AMS laboratories at Oxford, Tucson and Chalk River, with results that all fall within the Holocene, in an age range of 1–9 ka BP (Gillespie *et al.* 1985; Gowlett *et al.* 1987; Taylor *et al.* 1984, 1985). These results, together with several other AMS dates on possibly early North American human skeletons that have proved to be recent (Gowlett 1986), demonstrate that no human remains in the Americas have been shown to pre-date 11 ka BP.

This conclusion could be taken to support the 'late-entry' hypothesis, but lack of early dates on human skeletons does not prove an absence of human occupation before 11 ka BP. To take the process of hypothesis testing further, it is necessary to date other materials from a geographically wider selection of apparently early occupation sites. The Oxford Unit has dated samples of animal bone, charcoal, ivory and wood from three such sites: Meadowcroft Rock-shelter in Pennsylvania, Guitarrero Cave in Peru, and the Monte Verde site in Chile, with results that are in general consistent with early dates at those sites previously obtained by conventional ^{14}C dating (Gowlett 1986). This is most clearly exemplified by the results from Monte Verde where two AMS and two conventional ^{14}C dates on three types of material all date, at one standard deviation, to within a period of 1040 ^{14}C years, from a minimum of 11740 to a maximum of 12780 BP (table 2).

TABLE 2. AMS AND CONVENTIONAL ^{14}C DATES FOR THE MONTE VERDE SITE, CHILE

(Sources: Gillespie *et al.* 1985; Gowlett 1986.)

dating method	laboratory	sample	^{14}C age BP/years
conventional	TX-4437	wood	12650 ± 130
AMS	OxA-381	wood	12400 ± 150
AMS	OxA-105	ivory (amino acids from collagen)	12000 ± 250
conventional	TX-3760	bone	11990 ± 250

Another location associated with claims for early occupation of the Americas is the Old Crow Basin in the Canadian Yukon, where artefacts made from caribou antler and bone were found, as well as possibly Man-modified mammoth limb bones, three of which were dated by the conventional ^{14}C method to between *ca.* 26 ka and *ca.* 29 ka BP (Irving & Harington 1973). The use of AMS ^{14}C dating has now allowed collagen fractions from four artefacts to be dated, with the result that all four specimens have been shown to be of late Holocene age (less than 3070 BP) (Nelson *et al.* 1986*b*). In South America a very early occupation site with rock art, Boqueirao do Sitio da Pedra Furada in northeastern Brazil, has recently been reported that, on the basis of 17 conventional ^{14}C dates on charcoal samples from a stratified series of hearths, appears to indicate human occupation between 6160 ± 130 and 32160 ± 1000 BP (Guidon & Delibrias 1986). The apparently great antiquity of this site would, if confirmed, establish beyond doubt that humans were present in South America well before the last glacial maximum, and it is therefore a prime candidate for (chemically selective) verification dating of charcoal and other samples (if available) by the AMS ^{14}C technique.

Although more dates are needed on other apparently early sites before the controversy about the initial peopling of the Americas can be resolved, the overall pattern of reliable dates now argues against the 'late-entry' hypothesis and in favour of an initial occupation before the glacial maximum of 18 ka BP. In particular, it is difficult to equate an entry across the Bering Strait landbridge as late as 12 ka ago with the very strong evidence for contemporaneous occupation of the Monte Verde site at 42° S, 11000 km and 105° of latitude south of the Bering Strait.

AMS dating has thus already had a positive impact on two areas of particular interest in the investigation of early human migrations. It has the capacity to resolve many other chronological problems that arise as attempts are made to trace human dispersals which have taken place within the last 40 ka. One of the most challenging questions, which remains full of uncertainties, is the chronology of the initial colonization of Australia. It is assumed that humans first reached the continent from the Asian mainland by crossing the water barrier that apparently existed throughout the Pleistocene, even at times of lowered sea level, between the continental shelves of Sunda (Southeast Asia) and Sahul (Australia–New Guinea) (Birdsell 1977). Conventional ^{14}C dates attest to human occupation of southeastern and southwestern Australia by 40 ka BP (Jones 1979), but little is known in detail about the route(s) of entry and the course of colonization of the continent. Also, there are anatomically and chronologically controversial finds of human remains, such as those at Kow Swamp in Victoria and Lake Mungo in New South Wales (Thorne 1977), that deserve to be dated by the AMS technique. The peopling of the Pacific is another area of enquiry that, although it took place much more recently (Bellwood 1978), raises severe chronological problems, associated with a relative lack of conventionally datable organic samples, that AMS dating of very small samples could help to solve.

(*b*) *Early agriculture*

The second field of archaeological enquiry to which verification dating by the AMS technique has already made a major contribution is that of plant and animal domestication and the beginnings of agriculture. The present and potential impact of the technique on this field of study has recently been reviewed (Harris 1986), and so it is only exemplified here. It is, however, a field on which AMS dating is likely to have an important impact because the main sources of direct evidence are the plant and animal remains themselves, which are usually fragmentary and often few in number.

The capacity to process samples of milligram size is particularly relevant to the dating of early plant remains, which most commonly occur as charred seeds and other small inflorescence fragments, and tend to be more stratigraphically mobile than bones and other larger and heavier materials such as mollusc shells. Problems of contextual integrity are therefore especially likely to bedevil interpretations of the age of plant remains that are based on indirect conventional ^{14}C dates obtained by dating organic materials – usually charcoal – from the stratigraphic context of the plant remains, rather than by dating the seeds or other plant fragments themselves. The possibility of directly dating samples as small as a single cereal grain allows the chronological uncertainties that often undermine confidence in interpretations of early agriculture to be resolved, and it also invites the archaeologist in future to employ more refined sampling strategies during excavation.

The main contribution so far made by AMS dating to the investigation of early agriculture has been the work of the Oxford Unit on seed and bone samples from sites in Southwest Asia and North Africa. This includes both the verification dating of existing controversial finds and the direct dating of newly excavated samples. Examples of the former include the dating of wheat grains recovered from pre-Neolithic levels at two sites in Israel (Nahal Oren and 'Ain Mallaha) and of a date-palm seed recovered from a late Palaeolithic site in Egypt (Wadi Kubbaniya). In each case the seeds were too few or too archaeobotanically valuable to date by the conventional ^{14}C method and so their reputed antiquity was subjected to the test of AMS dating.

The controversies surrounding these finds arose because they implied the possibility of pre-Neolithic cereal cultivation, for which there was (and still is) little or no other supporting evidence. Three charred grains of emmer wheat from the late Palaeolithic (Kebaran) levels at Nahal Oren were dated at Oxford (Gowlett *et al.* 1987). One of them, which dated to more than 33 ka (OxA-390), is typical of the seeds of wild emmer, *Triticum dicoccoides*, whereas the other two, which dated to 3100 ± 130 BP (OxA-395) and 2940 ± 120 BP (OxA-389), are typical of domestic emmer, *T. dicoccum*. The domesticated grains are clearly much younger than the late Palaeolithic levels from which they were recovered and therefore must be regarded as intrusive, thus refuting the possibility of pre-Neolithic cereal cultivation at the site. The wild-type seed is very much older than its stratigraphic and cultural context suggests, and is interpreted by Legge, in his recent detailed discussion of the samples (Legge 1986), as derived from ancient sediments redeposited at the site. Two charred grains of wheat, identified by Hillman as from free-threshing wheats of 'macaroni' and 'bread' type that are indicative of long-established agriculture, were recovered from the Mesolithic (Natufian) site of 'Ain Mallaha (Legge 1986). One of them was used to test their apparent Mesolithic age, and the date obtained on it at Oxford was 330 ± 100 BP (OxA-543) (Gowlett *et al.* 1987). So, again, the grain was shown to be intrusive and another putative piece of evidence for pre-Neolithic cereal cultivation was negated.

The finds of seeds at the late Paleolithic site of Wadi Kubbaniya were still more controversial. They were excavated by Wendorf and his colleagues from open sites on dunes that border a now-dry side valley that enters the Nile from the west 20 km north of Aswan in southern Egypt. They consisted mainly of barley grains with, in addition, some seeds identified as of chickpea, lentil and date palm, as well as a single inflorescence fragment of (einkorn) wheat. These finds led Wendorf and his colleagues to suggest that domestic crops might have been cultivated in the late Palaeolithic at Wadi Kubbaniya, because the seeds appeared to be securely associated with stratigraphic contexts dated by the conventional ^{14}C method, on charcoal samples, to between 8.5 and 17 ka BP. This hypothesis, which proposed that domestic cereals and pulses could have been cultivated in southern Egypt some 8 ka earlier than in Southwest Asia or anywhere else in the World, was advanced in several publications (Wendorf *et al.* 1979, 1980, 1982), although it was regarded with incredulity by most students of early agriculture.

In 1982, Wendorf submitted 172 of the barley grains to the Department of Human Environment at the Institute of Archaeology in London so that Hillman could check the accuracy of the original identification by examining them for the twist in the lateral grains that is diagnostic of domesticated, six-row barley. Hillman found that 49 of the grains unequivocally exhibited the diagnostic twist and were therefore derived from cultivated barley. Thus far, the archaeobotanical investigation appeared to support Wendorf's revolutionary hypotheses of late Paleaolithic agriculture. But Hillman's examination of the grains showed that they were not charred, as had been reported, but that their blackish colour had probably been caused by partial decomposition of the outer cell layers under temporarily wet conditions. Because uncharred grains could not have survived at the site if they had been deposited at the time of the late Palaeolithic occupation, Hillman suggested, in an unpublished report to the excavator (1982), that the barley grains must be intrusive and had been carried down, possibly by ants, through the dune to the level at which they were found. This conclusion was later reinforced by the results of electron spin resonance spectroscopy of some of the blackish grains which indicated a 'highest past temperature of exposure' insufficient to induce charring (Hillman *et al.* 1983, 1985).

The suggestion that the barley grains were intrusive was received with great scepticism by the excavators, who were confident of the stratigraphic integrity of the late Palaeolithic contexts from which the seeds came, as the following quotation shows (Wendorf *et al.* 1980, pp. 272, 273).

> First, let us state that there can be no question concerning the association of the grains with the occupation of Site E-78-4. The botanical samples were collected by hand from the exposed face of the stratigraphic trench at that site, and most of the pieces came from in or near the buried hearth exposed in the side of the trench.

There is no evidence of contamination by later materials and the nature of the deposits is such that contamination would be easily detected if it had occurred... The discovery of the wheat and barley at Site E-78-4 finally answers the question of what grains were utilized with the grinding-stones long known from several late Palaeolithic sites along the Nile.

And there the matter would have rested, unresolved, had not the possibility existed of dating some of the grains directly by AMS. Wendorf had by then proposed his revolutionary hypothesis of late Palaeolithic agriculture in several publications, but he nevertheless decided to submit some of the barley grains to the crucial test of direct dating. He therefore asked the Tucson laboratory to date six of the barley grains and three fragments of wood charcoal from the same stratigraphic context as the barley; and he also asked the Oxford laboratory to date one of the two date-palm seeds that had been recovered, as well as a charcoal sample. The results of this dating exercise are shown in table 3. Contamination of the barley grains by tracer ^{14}C

TABLE 3. AMS ^{14}C DATES ON PLANT REMAINS AND CHARCOAL SAMPLES FROM WADI KUBBANIYA, EGYPT

(Sources: Gillespie *et al.* 1984; Wendorf *et al.* 1984.)

laboratory	sample	^{14}C age BP/years
Tucson		
AA-96	charcoal, E-78-3, level 4	17450 ± 1000
AA-98	barley seed, E-78-3, AF-25, 10 cm	820 ± 500
AA-97	barley seed, E-78-3, AE-25, 25 cm	1090 ± 500
AA-226	barley seed, E-78-4, layer a, hearth	> modern
AA-225	barley seed, E-78-4, layer a, hearth	2670 ± 250
AA-227	barley seed, E-78-4, layer a, hearth	> modern
AA-228	barley seed, E-78-4, layer a, row K-5, 10 cm	4850 ± 200
AA-224A	charcoal, E-78-4, layer a	19060 ± 1000
AA-224B	charcoal, E-78-4, layer a	18020 ± 525
Oxford		
OxA-103	charcoal	17150 ± 300
OxA-101	acid- and alkali-insoluble material from date-palm seed	350 ± 200
OxA-102	humic acids from date-palm seed	modern

in the laboratory, or as a result of their preparation for scanning electron microscopy, is thought to have invalidated the results for five of the seeds, and the sixth gave the ^{14}C age of 4850 ± 200 BP (AA228), which showed it to be intrusive (Wendorf *et al.* 1984). The Oxford results show the date seed also to be intrusive, whereas the charcoal sample confirmed the late Palaeolithic age of the site (Gillespie *et al.* 1984). The AMS dates thus conclusively disproved the postulated antiquity of the barley and date seeds and effectively destroyed the hypothesis of late Palaeolithic cultivation at Wadi Kubbaniya. Only the reported finds of chickpea and lentil then remained as possible indicators of agriculture at the site, but Hillman showed them to have been wrongly identified and so the entire hypothesis was invalidated.

This example has been discussed in some detail because it demonstrates so convincingly the value of verification dating by AMS in investigations of plant and animal domestication and early agriculture. Had the technique not been available to date the seeds independently of the deposits in which they were found, the claim that cultivation was practised in the Nile Valley over 17 ka ago might soon have become accepted, at least in the secondary literature of popular archaeology. In fact, some of the plant remains recovered at Wadi Kubbaniya are of great archaeobotanical interest in themselves. For example, the reputed chickpeas turned out, when examined by Hillman, to be charred tubers of the sedge *Cyperus rotundus*, which may have been a staple source of starchy food for the late Palaeolithic inhabitants. Further study of these and other charred plant remains from Wadi Kubbaniya, including AMS dating of selected samples, is expected to provide a unique body of information on the exploitation of wild plants in that environment 18 ka ago (Hillman 1988).

In the investigation of early agriculture, AMS dating has so far been used more extensively to test the ages of plant than of animal remains, but the technique is equally applicable to the latter. The Oxford Unit has undertaken some verification dating related to animal domestication, for example by determining the age of a camel jawbone from a site in Israel that appeared to pre-date the earliest evidence for domestic camels in Southwest Asia, but that proved to be recent (210 ± 150 BP: OxA-135) and therefore intrusive (Gillespie *et al.* 1985); and of bones of domestic ass and horse from three Egyptian sites, one of which was shown to be intrusive (the Badari ass), whereas the other two have yielded the earliest direct dates so far for ass and horse in Southwest Asia–North Africa: the Tarkhan ass at 4390 ± 130 BP (OxA-566) and the Gaza horse at 3400 ± 120 BP (OxA-565) (Gowlett *et al.* 1987). The unit has also attempted to date a sample of canid bones from the middle Palaeolithic (Mousterian) site of Douara Cave in Syria that, had they proved to be datable and genuinely of Palaeolithic age, would have provided evidence either of the earliest domestic dogs known or of a previously unknown population of wild canids that might have contributed to the ancestry of domestic dogs. Unfortunately, however, none of the bones contained sufficient collagen to be dated.

There is great scope for AMS verification dating of plant and animal remains found at proven or postulated early agricultural sites in many areas outside Southwest Asia and North Africa, for example the plant remains recovered by MacNeish (1967) in the Tehuacan Valley, Mexico; by Lynch *et al.* (1985) at Guitarrero Cave in the Peruvian Andes; and by Gorman (1969) and Yen (1977) at Spirit Cave and other early sites in northwestern Thailand. An example from North America of verification dating is the recent determination of the ages of animal bones from Jaguar Cave in Idaho. This is not an early agricultural site, but the excavated remains included dog bones from a hearth dated to 10370 ± 350 BP that were believed to be the earliest known evidence of domestic dog (Kurtén & Anderson 1980; Lawrence 1968). Two of the dog bones have now been dated at Oxford and both are less than 3300 years old (Gowlett *et al.* 1987).

Enough has already been achieved, at Oxford and other laboratories, to show how valuable the technique is for exposing errors that arise from indirect dating of small, stratigraphically mobile organic remains such as seeds; errors that, if perpetuated, can lead to gross misinterpretations of the evidence relating to the origins of agriculture. The technique can also be used to try to determine the age of prehistoric field systems by dating very small sediment samples and reconstructing the sedimentary histories of the fields (Barham & Harris 1985; Harris 1986).

(*c*) *Dating rare artefacts*

There are many objects in museums and other collections that, although they may contain sufficient organic material for a conventional ^{14}C date, are too rare and valuable to be sacrificed for this purpose. The 1000-fold reduction in sample size of the AMS technique allows such artefacts to be directly dated with minimal destruction. The present and potential scope for dating rare artefacts from diverse areas and time periods appears almost unlimited, and it is sufficient here to illustrate that potential by brief reference to six examples of objects dated by the Oxford Unit.

1. An ivory gouge from the Chilean site of Monte Verde, that gave a date (on amino acids from the collagen in the ivory) of 12 ka ± 250 BP (OxA-105) (Gillespie *et al.* 1984).

2. A double-cut wooden dowel from Guitarrero Cave in Peru, that dated to 10 ka ± 200 BP (OxA-108) (Gillespie *et al.* 1984).

3. A decorated horse mandible from Kendrick's Cave in Wales, that is one of the very few Palaeolithic art objects from Britain and that was dated on amino acid from the bone collagen to 10 ka ± 200 BP (OxA-111) (Gillespie *et al.* 1985).

4. Three barbed points (one of bone and two of antler) from late glacial–early post-glacial deposits in eastern England that were dated to 10910 ± 150 BP, 10700 ± 160 BP and 9240 ± 160 BP (OxA-517, 518 and 500) (Cook & Barton 1986; Gowlett *et al.* 1986*a*).

5. Two finely decorated Islamic doors, the age of which needed to be authenticated, with minimal destruction, and that proved to be 580 ± 130 years old (OxA-112 and 113) (Gillespie *et al.* 1984).

6. A fragment of the Mappa Mundi that had been re-used as book-binding material and that gave a date of 850 ± 60 (OxA-421) calibrated to 1160–1200 A.D. (Gillespie *et al.* 1985).

AMS dating could be applied extensively to the authentication of paintings and other recent art objects, but of more direct relevance to archaeology is the possibility of dating rare finds of such objects from the prehistoric past. For example, one project of particular archaeological interest, which the Oxford Unit has undertaken, is the dating of Upper Palaeolithic mobiliary art, such as small bone and antler harpoons, rods and batons decorated with carved animal figures, from sites in the Pyrenees and Cantabria (Barrandiarán 1973), all of which date between 10 ka and 16 ka BP; and another example is the recent dating by AMS of two prehistoric duck decoys from a cache found in Lovelock Cave, Nevada (Tuohy & Napton 1986).

Building new and more detailed chronologies

The preceding discussion of verification dating by AMS demonstrates that it often also contributes to the building of new and more detailed chronologies for archaeological sites and sequences. The distinction between these two complementary aspects of AMS dating is somewhat artificial although conceptually useful. In this section, the value of the technique for refining and elaborating regional chronologies is exemplified by reference to three major areas of investigation: Upper Palaeolithic sequences in Europe, Mesolithic–Neolithic sequences in Southwest Asia, and Neolithic–Bronze-Age chronologies in Britain.

(*a*) *Upper Palaeolithic European sequences*

The Oxford Unit is currently engaged in several dating projects that will, collectively, contribute greatly to knowledge of the European Upper Palaeolithic. These projects focus at present on Upper Palaeolithic sites in Britain, France, Greece and Russia. Initial results from all these areas have recently been reported and discussed (Bailey *et al.* 1986; Gillespie *et al.* 1985; Gowlett & Hedges 1986*b*; Gowlett *et al.* 1986*a*, *b*, 1987; Jacobi 1986; Mellars & Bricker 1986; Mellars *et al.* 1987, Soffer 1986), and consequently only some general comments are offered here on the scope of AMS dating of the Upper Palaeolithic.

Most of the samples so far dated at Oxford are from cave sites in France and Britain. Part of the programme focuses on the earlier Upper Palaeolithic in France in the time range

23–30 ka BP, i.e. before the maximum of the last glaciation, and part on the later Upper Palaeolithic in Britain in the time range 10–13 ka BP, after the last glacial maximum. Additionally, a number of French rock-shelter sites with sequences that span the last glacial maximum are being dated to bridge the time gap, and several open sites in northern France have also been dated to facilitate comparison with sites in Britain. The result is expected to be a coherent geographical and temporal pattern of dates that establishes a new and more reliable chronological framework for the Northwest European Upper Palaeolithic.

As part of this programme, the Oxford Unit is attempting to assess the basic accuracy of the dates (that are too old to be compared with any known-age materials such as dendrochronologically dated wood) by undertaking a series of comparisons with conventional ^{14}C laboratories, particularly those, such as Groningen, that have specialized in dating beyond 30 ka (Gowlett and Hedges 1986*b*). The initial results are sufficiently encouraging to suggest that problems of sample contamination are not so great as severely to limit the scope of AMS dating of the European Upper Palaeolithic. The most suitable and widely available material for such dating is bone, because, except when collagen content is very low (less than 5% of modern), dates can be determined from total or even specific amino acids (particularly hydroxyproline) and problems of sample contamination thus greatly reduced. The small-sample capacity of AMS also allows series of intra-site dates to be obtained; this is especially valuable to the archaeologist trying to understand the characteristically complex stratigraphy of many Upper Palaeolithic caves and talus sites, such as those in northwestern Greece (Bailey *et al.* 1986), that have complex depositional histories.

The experience of the Oxford Unit thus far is that a series of determinations will nearly always date a site, even though some of the samples from it may present problems of contamination or prove to have been stratigraphically mobile; and there is no doubt that the technique is capable of distinguishing any samples in Palaeolithic contexts that are of Neolithic or more recent age. Overall then, it can be said that the Upper Palaeolithic dating programme is yielding new data of both theoretical and substantive archaeological significance, including not only valuable cultural information but also much new environmental evidence, particularly on Pleistocene mammalian extinctions and introductions (Burleigh 1986; Clutton-Brock & Burleigh 1983; Gowlett *et al.* 1986*a*).

(*b*) *Mesolithic–Neolithic Southwest Asian sequences*

As part of their programme of dating samples relevant to plant and animal domestication and early agriculture (Harris 1986), the Oxford Unit is helping to build a more detailed chronology of changes in prehistoric subsistence in Southwest Asia, focusing particularly on the Mesolithic–Neolithic transition and the emergence of agriculture.

The Unit has concentrated initially on dating the plant and animal remains from the Mesolithic (Natufian)–Aceramic Neolithic levels at the site of Tell Abu Hureyra in the Euphrates Valley in northern Syria. This large tell was excavated in 1972 and 1973 by Moore (1975, 1979) and exceptionally large assemblages of plant remains and animal bones were recovered. These constitute the most comprehensive record presently available of plant and animal exploitation from non-agricultural Mesolithic to agricultural Neolithic food economies (Hillman 1975; Hillman *et al.* 1988; Legge & Rowley-Conwy 1986, 1987). The Unit has so far published 29 dates on 18 samples of charred grains of (wild-type einkorn) wheat and charred bones of gazelle, sheep, cattle and wild ass (Gowlett *et al.* 1987; Moore *et al.* 1986). Of seven dates on wild wheat, six are clearly Mesolithic (Gowlett *et al.* 1987; Harris 1986; Hillman *et al.* 1986, figure 1) and it is only in the early Aceramic Neolithic that there is evidence for the cultivation of domesticated cereals (einkorn and emmer wheat, six-rowed hulled barley, and rye) (Hillman *et al.* 1986). The seventh wild-wheat data (6100 ± 120 BP; OxA-882) is later than any known prehistoric occupation at Abu Hureyra and implies that the grain is intrusive. Similarly, analysis of the ungulate remains shows that gazelle bones dominate the Mesolithic assemblage, and it is not until the later Aceramic Neolithic that domestic sheep and goat become numerically preponderant (Legge & Rowley-Conwy 1986, 1987). More AMS dates on the Abu Hureyra sequence will be run at Oxford, but preliminary analysis and dating of plant and animal remains from the site fails to support a hypothesis of pre-Neolithic agriculture and suggests instead that year-round sedentary occupation of the site developed during the Mesolithic, supported by the exploitation of a broad spectrum of wild plant foods (Hillman *et al.* 1986).

As the work of the Oxford Unit expands, other Southwest Asian sites that yield evidence of early plant and animal exploitation are being included in the dating programme. Among them are the Mesolithic (Natufian) sites of Hayonim in Israel (Bar-Yosef & Goren 1973), from which two samples of lupine seed have been dated and shown to be contemporaneous with the Natufian occupation, and Wadi Hammeh in Jordan (Edwards & Colledge 1985), from which three dates on charred wild-plant seeds have been obtained; the Aceramic Neolithic A site of Netiv Hagdud in Israel (Bar-Yosef *et al.* 1980), from which securely stratified grains of domesticated two-row barley have been dated; and a site at Wadi el Jilat in Jordan (Garrard *et al.* 1986), with a stone industry reminiscent of the Levantine Aceramic Neolithic B, from which two charcoal samples associated with the remains of domesticated wheat and barley, other small-seeded grasses, legumes, chenopods, and liliaceous plants were dated to 8810 ± 110 BP and 8520 ± 110 BP (OxA-526 and 527) (Gowlett *et al.* 1986*b*).

(*c*) *Neolithic–Bronze Age chronologies in Britain*

Despite the close and prolonged attention archaeologists have given to the study of the Neolithic and Bronze Age in Britain (Renfrew 1974), both periods still lack detailed regional chronologies. Although over 400 ^{14}C dates are currently available for the Neolithic, they provide relatively little detailed chronological information on site stratigraphies, artefact associations and inter-site relations (Darvill 1986); and Bronze Age chronologies have traditionally been based on typological sequences of metal objects and pottery rather than on ^{14}C dates. When it became technically possible to date within a standard deviation of ± 80 years, the Oxford Unit began a programme of Neolithic and Bronze Age dating. Its first contributions to this field of research have focused on three interrelated themes: (i) the dating of types of Neolithic monument, notably the long, parallel-sided earthwork enclosures known as cursuses, the chronological context of which is unknown; (ii) the duration of use of chambered tombs and other Neolithic monuments; and (iii) the direct dating of Bronze Age metalwork.

Very few conventional ^{14}C dates on cursus monuments exist at present, and the Oxford Unit has now dated five samples of cattle bone from the largest of these monuments, the Dorset cursus, and a human cranial fragment from the Dorchester-on-Thames Cursus (Bradley 1986*a*; Gowlett *et al.* 1986*a*). More samples will be dated, but the results available so far suggest that cursuses were constructed earlier in the Neolithic than was commonly supposed, probably during the same phase of monument building as long barrows and causewayed enclosures

(Bradley 1986*a*). The Unit has also begun to date samples from chambered tombs and other Neolithic monuments (other than the cursuses) in southern and eastern England, specifically at West Kennet Long Barrow in Wiltshire, Hazleton North Long Barrow and the Peak Camp in Gloucestershire, and the Giants' Hill 2 Long Barrow in Lincolnshire, with the aim of establishing internal chronologies for the sites. Thirtythree dates have so far been published for samples of human bone, tooth, cattle bone and charcoal from these four sites, with results that show in general that use of AMS dating does allow the complex history of some sites to be worked out, and, more specifically, that the tombs were used for burials over periods of at least several centuries (Darvill 1986; Evans & Simpson 1986; Gillespie *et al.* 1985; Gowlett *et al.* 1986*a–c*, 1987; Saville 1986; Saville *et al.* 1987). The Oxford Unit has as yet only experimented with the possibilities of dating Bronze Age metalwork, but it has shown, for example, that a small sample of wood from a haft fragment remaining in a socketed spearhead can be dated (Gillespie *et al.* 1985); and the prospects of using AMS dating to clarify Bronze Age chronology have been reviewed by Bradley (1986*b*) and by Needham (1986).

4. Conclusion

It is only four years since laboratories began to date archaeological samples by the AMS technique. In that time, sufficient progress has been made to demonstrate that it can be applied successfully to many different types of archaeological sample, context and problem. The present limitations of the technique, that regulate its application to archaeology, are also well known. They are, essentially: an error of ± 80 years in the last 10 ka, which increases exponentially up to the present dating limit of 40 ka, and a minimal sample size of 1 mg of elemental carbon. The most important attribute of the technique, compared with conventional ^{14}C dating, is much greater selectivity, in the field and laboratory, over the type of sample measured. This allows the archaeologist to obtain dates from a much wider range of sample materials, to work out the internal chronology of complex stratigraphies, and to date rare objects directly without destroying them. It also allows the radiocarbon chemist to reduce sample contamination by dating particular fractions, such as hydroxyproline from bone collagen, and to replicate measurements on a single sample.

Use of the technique for verification dating is introducing to archaeology a new method of hypothesis testing, allowing chronological questions about such complex and controversial phenomena as the early spread of *Homo sapiens sapiens* and the emergence of agriculture to be answered much more rigorously than is possible by the use of conventional ^{14}C dating. Verification dating of existing (and new) samples will continue to be an important function of AMS dating in archaeology, but, as the backlog of undated samples is reduced, the technique will come to be used increasingly for the building of new and more detailed intra-site and inter-site chronologies. The Oxford Unit has already added greatly to chronological knowledge of the European Upper Palaeolithic, of early plant and animal exploitation in Southwest Asia, and of later British prehistory, and AMS ^{14}C laboratories outside Britain are also beginning to make important contributions to archaeological dating. The ability to detect ^{14}C directly by AMS, rather than by the conventional method of measuring its radioactivity, is ushering in a revolution in radiocarbon dating that, as the technique comes to be widely applied, will have a profound impact on many different aspects of archaeological research.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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References

Bada, J. L. & Helfman, P. M. 1975 Amino acid racemization dating of fossil bones. *Wld Archaeol.* **7**, 160–173.

Bailey, G. N., Gamble, C. S., Higgs, H. P., Roubet, C., Webley, D. P., Gowlett, J. A. J., Sturdy, D. A. & Turner, C. 1986 Dating results from Palaeolithic sites and palaeoenvironments in Epirus (North-west Greece). In *Archaeological results from accelerator dating* (ed. J. A. J. Gowlett & R. E. M. Hedges), pp. 99–107. Oxford: University Committee for Archaeology Monogr. Ser. no. 11.

Barham, A. J. & Harris, D. R. 1985 Relict field systems in the Torres Strait region. In *Prehistoric intensive agriculture in the Tropics* (ed. I. S. Farrington), pp. 247–283. Oxford: BAR International Series 232.

Barrandiarán, I. 1973 *Arte mueble de Paleolitico Cantabrico.* Zaragoza: University of Zaragoza Archaeological Monogr. XIV.

Bar-Yosef, O., Gopher, A. & Goring-Morris, A. N. 1980 Netiv Hagdud: a 'Sultanian' mound in the lower Jordan Valley. *Paléorient* **6**, 201–206.

Bar-Yosef, O. & Goren, N. 1973 Natufian remains in Hayonim Cave. *Paléorient* **1**, 49–68.

Batten, R., Gillespie, R., Gowlett, J. A. J. & Hedges, R. E. M. 1986 The AMS dating of separate fractions in archaeology. *Radiocarbon* **28**, 177–185.

Bellwood, P. 1978 *Man's conquest of the Pacific. The prehistory of Southeast Asia and Oceania.* Auckland: Collins.

Bill, J., Keller, W. A., Erne, R., Bonani, G. & Wölfli, W. 1984 ^{14}C dating of small archaeological samples: Neolithic to Iron Age in the Central Alpine region. *Nucl. Instrum. Meth. Phys. Res.* **233**, 317–320.

Birdsell, J. H. 1977 The recalibration of a paradigm for the first peopling of Greater Australia. In *Sunda and Sahul. Prehistoric studies in Southeast Asia, Melanesia and Australia* (ed. J. Allen, J. Golson & R. Jones), pp. 113–167. London: Academic Press.

Braidwood, R. J., Jacobsen, T., Parker-Brown, R. A. & Weinberg, S. S. 1950 Letter from the Subcommittee on the Near and Middle East – Committee on Carbon ^{14}C. Chicago: Oriental Institute, University of Chicago, 6 February 1950. Typescript: 2 pages.

Bradley, R. 1986*a* Radiocarbon and the cursus problem. In *Archaeological results from accelerator dating* (ed. J. A. J. Gowlett & R. E. M. Hedges), pp. 139–141. Oxford: University Committee for Archaeology Monogr. Ser. no. 11.

Bradley, R. 1986*b* Methodological issues in the study of Bronze Age chronology. In *Archaeological results from accelerator dating* (ed. J. A. J. Gowlett & R. E. M. Hedges), pp. 151–154. Oxford: University Committee for Archaeology Monogr. Ser. no. 11.

Burleigh, R. 1986 Complementarity of conventional and accelerator dating: examples in Pleistocene extinctions. In *Archaeological results from accelerator dating* (ed. J. A. J. Gowlett & R. E. M. Hedges), pp. 95–98. Oxford: University Committee for Archaeology Monogr. Ser. no. 11.

Clark, G. 1980 World prehistory and natural science. A. J. C. Jacobsen Memorial Lecture. *Historisk-filosofiske Meddelser* **50**, 1–40.

Clutton-Brock, J. & Burleigh, R. 1983 Some archaeological applications of the dating of animal bone by radiocarbon with particular reference to post-Pleistocene extinctions. *PACT Jl* **8**, 409–418.

Cook, J. & Barton, R. N. E. 1986 Dating late Devensian-early Flandrian barbed points. In *Archaeological results from accelerator dating* (ed. J. A. J. Gowlett & R. E. M. Hedges), pp. 87–89. Oxford: University Committee on Archaeology Monogr. Ser. no. 11.

Daniel, G. 1981 *A short history of archaeology*, pp. 51–55. London: Thames and Hudson.

Darvill, T. C. 1986 Prospects for dating Neolithic sites and monuments in the Cotswolds and adjacent areas. In *Archaeological results from accelerator dating* (ed. J. A. J. Gowlett & R. E. M. Hedges), pp. 119–124. Oxford: University Committee for Archaeology Monogr. Ser. no. 11.

Donahue, D. J., Jull, A. J. T. & Zabel, T. H. 1984 Results of radioisotope measurements at the NSF-University of Arizona tandem accelerator mass spectrometer facility. *Nucl. Instrum. Meth. Phys. Res.* **233**, 162–166.

Edwards, P. C. & Colledge, S. M. 1985 The Natufian settlement in the Wadi Hammeh (Area XX). In *Preliminary report on a sixth season of excavation by the University of Sydney at Pella in Jordan 1983/84* (ed. T. F. Potts, S. M. Colledge & P. C. Edwards), pp. 182–196. *A. Rep. Dep. Antiqu. Jordan*, **29**, 181–210.

Evans, J. G. & Simpson, D. D. A. 1986 Radiocarbon dates for the Giants' Hills 2 Long Barrow, Skendleby, Lincolnshire. In *Archaeological results from accelerator dating* (ed. J. A. J. Gowlett & R. E. M. Hedges), pp. 125–131. Oxford: University Committee for Archaeology Monogr. Ser. no. 11.

Garrard, A., Byrd, B. & Betts, A. 1986 Prehistoric environment and settlement in the Azraq Basin: an interim report on the 1984 excavation season. *Levant* **18**, 5–24.

Gillespie, R., Gowlett, J. A. J., Hall, E. T. & Hedges, R. E. M. 1984 Radiocarbon measurement by accelerator mass spectrometry: an early selection of dates. *Archaeometry* **26**, 15–20.

Gillespie, R., Gowlett, J. A. J., Hall, E. T., Hedges, R. E. M. & Perry, C. 1985 Radiocarbon dates from the Oxford AMS system: Archaeometry datelist 2. *Archaeometry* **27**, 237–246.

Gorman, C. F. 1969 Hoabinhian: a pebble-tool complex with early plant associations in Southeast Asia. *Science, Wash.* **163**, 671–673.

Gowlett, J. A. J. 1985 Notes to accompany Project Application Forms and Sample Forms. Oxford: Oxford Radiocarbon Accelerator Unit. Typescript: 2 pages.

Gowlett, J. A. J. 1986 Problems in dating the early human settlement of the Americas. In *Archaeological results from accelerator dating* (ed. J. A. J. Gowlett & R. E. M. Hedges), pp. 51–59. Oxford: University Committee for Archaeology Monogr. Ser. no. 11.

Gowlett, J. A. J., Hall, E. T., Hedges, R. E. M. & Perry, C. 1986*a* Radiocarbon dates from the Oxford AMS system: Archaeometry datelist 3. *Archaeometry* **28**, 116–125.

Gowlett, J. A. J., Hedges, R. E. M., Law, I. A. & Perry, C. 1986*b* Radiocarbon dates from the Oxford AMS system: Archaeometry datelist 4. *Archaeometry* **28**, 206–221.

Gowlett, J. A. J., Hall, E. T. & Hedges, R. E. M. 1986*c* The date of West Kennet Long Barrow (with comment by S. Piggott & R. J. C. Atkinson). *Antiquity* **60**, 143–144.

Gowlett, J. A. J., Hedges, R. E. M., Law, I. A. & Perry, C. 1987 Radiocarbon dates from the Oxford AMS system: Archaeometry datelist 5. *Archaeometry* **29**, 125–155.

Gowlett, J. A. J. & Hedges, R. E. M. (eds) 1986*a* *Archaeological results from accelerator dating*. Oxford: University Committee for Archaeology Monogr. Ser. no. 11.

Gowlett, J. A. J. & Hedges, R. E. M. 1986*b* Lessons of context and contamination in dating the Upper Palaeolithic. In *Archaeological results from accelerator dating* (ed. J. A. J. Gowlett & R. E. M. Hedges), pp. 63–71. Oxford: University Committee for Archaeology Monogr. Ser. no. 11.

Guidon, N. & Delibrias, G. 1986 Carbon-14 dates point to man in the Americas 32000 years ago. *Nature, Lond.* **321**, 769–771.

Harris, D. R. 1986 Plant and animal domestication and the origins of agriculture: the contribution of radiocarbon accelerator dating. In *Archaeological results from accelerator dating* (ed. J. A. J. Gowlett & R. E. M. Hedges), pp. 5–12. Oxford: University Committee for Archaeology Monogr. Ser. no. 11.

Hart, M. 1985 *Review of science-based archaeology 1985. The funding of research in science-based archaeology in universities and polytechnics*. Report of a Panel chaired by Professor M. Hart FRS. Swindon: Science and Engineering Research Council.

Hillman, G. C. 1975 The plant remains from Tell Abu Hureyra: a preliminary report, pp. 70–73. In Moore, A. M. T. The excavation of Tell Abu Hureyra in Syria: a preliminary report. *Proc. prehist. Soc.* **41**, 50–77.

Hillman, G. C. 1988 Late Palaeolithic riverine plant-food economy at Wadi Kubbaniya, Upper Egypt. In *Foraging and farming: the evolution of plant exploitation* (ed. D. R. Harris & G. C. Hillman). London: Allen and Unwin. (In the press.)

Hillman, G. C., Robins, G. V., Oduwole, D., Sales, K. D. & McNeil, D. A. C. 1983 Determination of thermal histories of archeological cereal grains with electron spin resonance spectroscopy. *Science, Wash.* **222**, 1235–1236.

Hillman, G. C., Robins, G. V., Oduwole, D., Sales, K. D. and McNeil, D. A. C. 1985 The use of electron spin resonance spectroscopy to determine the thermal histories of cereal grains. *J. archaeol. Sci.* **12**, 49–58.

Hillman, G. C., Colledge, S. M. & Harris, D. R. 1988 Archaeobotanical evidence for plant-food economy during the Epi-Palaeolithic period at Tell Abu Hureyra, Syria: dietary diversity, seasonality and modes of exploitation. Paper prepared in advance for the Symposium on Recent Advances in the Understanding of Plant Domestication and Early Agriculture, World Archaeological Congress, Southampton, September 1986; to be published in *Foraging and Farming: the evolution of plant exploitation* (ed. D. R. Harris & G. C. Hillman). London: Allen and Unwin.

Irving, W. N. & Harington, C. R. 1973 Upper Pleistocene radiocarbon-dated artefacts from the northern Yukon. *Science, Wash.* **179**, 335–340.

Jacobi, R. M. 1986 A.M.S. results from Cheddar Gorge – trodden and untrodden 'lifeways'. In *Archaeological results from accelerator dating* (ed. J. A. J. Gowlett & R. E. M. Hedges), pp. 81–86. Oxford: University Committee for Archaeology Monogr. Ser. no. 11.

Jones, R. 1979 The fifth continent: problems concerning the human colonization of Australia. *A. Rev. Anthropol.* **8**, 445–466.

Kurtén, B. & Anderson, E. 1980 *Pleistocene mammals of North America*. New York: Columbia University Press.

Lawrence, B. 1968 Antiquity of large dogs in North America. *Tebiwa* **11**, 43–49.

Legge, A. J. 1986 Seeds of discontent: accelerator dates on some charred plant remains from the Kebaran and Natufian cultures. In *Archaeological results from accelerator dating* (ed. J. A. J. Gowlett & R. E. M. Hedges), pp. 13–21. Oxford: University Committee for Archaeology Monogr. Ser. no. 11.

Legge, A. J. & Rowley-Conwy, P. 1986 New Radiocarbon dates for early sheep at Tell Abu Hureyra, Syria. In *Archaeological results from accelerator dating* (ed. J. A. J. Gowlett & R. E. M. Hedges), pp. 23–25. Oxford: University Committee for Archaeology Monogr. Ser. no. 11.

Legge, A. J. & Rowley-Conwy, P. 1987 Steppe hunters and the rise of domestication: the evidence from Tell Abu Hureyra. *Scient. Am.* (In the press.)

Libby, W. F. 1952 *Radiocarbon dating*. Chicago: University of Chicago Press.

Loy, T. H. 1983 Prehistoric blood residues: detection on tool surfaces and identification of species of origin. *Science, Wash.* **320**, 1269–1271.

Lynch, T. F., Gillespie, R., Gowlett, J. A. J. & Hedges, R. E. M. 1985 Chronology of Guitarrero Cave, Peru. *Science, Wash.* **229**, 864–867.

MacNeish, R. S. 1967 A summary of subsistence. In *The prehistory of the Tehuacan Valley* (ed. D. S. Byers), vol. 1, *Environment and subsistence*, pp. 290–309. Austin: University of Texas Press.

Mellars, P. A. & Bricker, H. M. 1986 Radiocarbon accelerator dating in the earlier Upper Palaeolithic. In *Archaeological results from accelerator dating* (ed. J. A. J. Gowlett & R. E. M. Hedges), pp. 73–80. Oxford: University Committee for Archaeology Monogr. Ser. no. 11.

Mellars, P. A., Bricker, H. M., Gowlett, J. A. J. & Hedges, R. E. M. 1987 Radiocarbon accelerator dating of French Upper Palaeolithic sites. *Curr. Anthropol.* **28**, 128–133.

Mook, W. G. 1984 Archaeological and geological interest in applying ^{14}C AMS to small samples. *Nucl. Instrum. Meth. Phys. Res.* **233**, 297–302.

Moore, A. M. T. 1975 The excavation of Tell Abu Hureyra in Syria: a preliminary report. *Proc. prehist. Soc.* **41**, 50–77.

Moore, A. M. T. 1979 A pre-Neolithic farmers' village on the Euphrates. *Scient. Am.* **241**, 50–58.

Moore, A. M. T., Gowlett, J. A. J., Hedges, R. E. M., Hillman, G. C., Legge, A. J. & Rowley-Conwy, P. A. 1986 Radiocarbon accelerator (AMS) dates for the Epipalaeolithic settlement at Abu Hureyra, Syria. *Radiocarbon* **28**, 1068–1076.

Needham, S. P. 1986 Radiocarbon: a means to understanding the role of Bronze Age metalwork. In *Archaeological results from accelerator dating* (ed. J. A. J. Gowlett & R. E. M. Hedges), pp. 143–150. Oxford: University Committee for Archaeology Monogr. Ser. no. 11.

Nelson, D. E., Southon, J. R., Vogel, J. S. & Korteling, R. G. 1984 Progress in ^{14}C and ^{10}Be dating at SFU. *Nucl. Instrum. Meth. Phys. Res.* **233**, 139–143.

Nelson, D. E., Loy, T. H., Vogel, J. S. & Southon, J. R. 1986*a* Radiocarbon dating blood residues on prehistoric stone tools. *Radiocarbon* **28**, 170–174.

Nelson, D. E., Morlan, R. E., Vogel, J. S., Southon, J. R. & Harington, C. R. 1986*b* New dates on northern Yukon artefacts: Holocene not Upper Pleistocene. *Science, Wash.* **232**, 749–751.

Renfrew, A. C. (ed.) 1974 *British prehistory. A new outline*. London: Duckworth. (See chapters by C. Burgess, I. F. Smith & A. C. Renfrew.)

Saville, A. 1986 Radiocarbon dating of Hazleton North chambered tomb: a preliminary statement. In *Archaeological results from accelerator dating* (ed. J. A. J. Gowlett & R. E. M. Hedges), pp. 133–137. Oxford: University Committee for Archaeology Monogr. Ser. no. 11.

Saville, A., Gowlett, J. A. J. & Hedges, R. E. M. 1987 Radiocarbon dates from the Neolithic chambered tomb at Hazleton (Glos.): a chronology for collective burial. *Antiquity* **61**, 108–119.

Soffer, O. 1986 Radiocarbon accelerator dates for Upper Palaeolithic sites in European U.S.S.R. In *Archaeological results from accelerator dating* (ed. J. A. J. Gowlett & R. E. M. Hedges), pp. 109–115. Oxford: University Committee for Archaeology Monogr. Ser. no. 11.

Stringer, C. B. 1986 Direct dates for the fossil hominid record. In *Archaeological results from accelerator dating* (ed. J. A. J. Gowlett & R. E. M. Hedges), pp. 45–50. Oxford: University Committee for Archaeology Monogr. Ser. no. 11.

Taylor, R. E., Payen, L. A., Prior, C. A., Slota, P. J. Jr, Gillespie, R., Gowlett, J. A. J., Hedges, R. E. M., Jull, A. J. T., Zabel, T. H., Donahue, D. J. & Berger, R. 1985 Major revisions in the Pleistocene age assignments for North American human skeletons by $C\text{-}^{14}$ accelerator mass spectrometry: none older than 11000 $C\text{-}^{14}$ years B.P. *Am. Antiqu.* **50**, 136–140.

Taylor, R. E., Payen, L. A. & Slota, P. J. Jr 1984 Impact of $AMS^{14}C$ determinations on considerations of the antiquity of *Homo sapiens* in the western hemisphere. *Nucl. Instrum. Meth. Phys. Res.* **233**, 312–316.

Thorne, A. G. 1977 Mungo and Kow Swamp: morphological variation in Pleistocene Australians. *Mankind* **8**, 85–89.

Tuohy, D. R. & Napton, L. K. 1986 Duck decoys from Lovelock Cave, Nevada, dated by ^{14}C accelerator mass spectrometry. *Am. Antiqu.* **51**, 813–816.

Wendorf, F., Schild, R., el Hadidi, N., Close, A. E., Kobusiewicz, M., Wieckowska, H., Issawi, B. & Haas, H. 1979 Use of barley in the Egyptian Late Palaeolithic. *Science, Wash.* **205**, 1341–1347.

Wendorf, F., Schild, R. and Close, A. E. (eds) 1980 *Loaves and fishes: the prehistory of Wadi Kubbaniya*. Dallas: Southern Methodist University.

Wendorf, F., Schild, R. & Close, A. E. 1982 An ancient harvest on the Nile. *Science 82* **3** (9), 68–73.

Wendorf, F., Schild, R., Close, A. E., Donahue, D. J., Jull, A. J. T., Zabel, T. H., Wieckowska, H., Kobusiewicz, M., Issawi, B. & el Hadidi, N. 1984 New radiocarbon dates on the cereals from Wadi Kubbaniya. *Science, Wash.* **225**, 645–646.

Yen, D. E. 1977 Hoabinhian horticulture? The evidence and the questions from Northwest Thailand. In *Sunda and Sahul. Prehistoric studies in Southeast Asia, Melanesia and Australia* (ed. J. Allen, J. Golson & R. Jones), pp. 567–599. London: Academic Press.

Zeuner, F. E. 1952 *Dating the past. An introduction to Geochronology*, 3rd edition. London: Methuen.

Discussion

H. E. Gove. With only one facility in Great Britain available for AMS radiocarbon measurements, I would like to know how the priorities of measuring an obviously large number of important samples are established.

D. R. Harris. The Oxford Laboratory is supported largely by the Science and Engineering Research Council (SERC) and the arrangement is that 50% of its capacity should be under what we call the national facility programme. Under that programme any archaeologist or other academic in a British University or polytechnic interested in archaeologically relevant dates may apply to have samples dated. There is an application form and applications are considered by a body called the Programme Advisory Panel that is charged by SERC with the responsibility for adjudicating between claims and establishing orders of priority. One of the things we have done on that panel is to suggest to the archaeological community a number of themes that we consider should have high priority for dating. It is not just a matter of sitting back, receiving every application that comes to the panel, and accepting some and rejecting others. Rather it is a mixture of freedom for any eligible person to submit an application, and the panel also encouraging people to focus their applications on some of the major themes that we have identified. I have, in fact, illustrated some of those today, for instance early agriculture, early human migrations, Neolithic and Bronze Age chronologies in Britain, and so on. So far, the demand for scientifically acceptable dating projects has not outstripped the capacity of the laboratory, and if that capacity does increase as much as we hope it may, then it should still be possible to accommodate the increase in demand for AMS dates that we expect over the next few years.

P. Damon (*University of Arizona, Arizona, U.S.A.*). There is a recent report of a French group on Pleistocene occupation in Brazil. Has Professor Harris heard anything about that?

D. R. Harris. Only what I read in *The Times* the other day. I would be very interested to hear about it if anyone here has more information. The report claimed dates for human occupation of the order of 35000 years.

Note added in proof. A brief discussion of the dating of this site has now been included in the present paper (see p. 31).