4 When? Dating Methods and Chronology

All human beings experience time. An individual experiences a lifetime of perhaps 70 years or so. That person, through the memories of his or her parents and grandparents, may also indirectly experience earlier periods of time, back over one or two generations. The study of history gives one access – even less directly but often no less vividly – to hundreds of years of recorded time. But it is only archaeology, in particular prehistoric archaeology, that opens up the almost unimaginable vistas of thousands and even a few millions of years of past human existence.

In order to study the past it is not, rather surprisingly, always essential to know precisely how long ago in years a particular period or event occurred. As we saw in Chapter 1, C.J. Thomsen's great achievement in the 19th century was to establish a three-part organization of tools for the Old World into those of stone, bronze, and iron which stratigraphic excavation confirmed was a chronological sequence: stone artifacts came before bronze ones, and iron ones came after. Archaeologists could use this sequence to study, say, changes in tool technology from one stage of the sequence to the next, even without knowing how long each stage lasted or how many years ago such developments took place. This idea that something is older (or younger) relative to something else is the basis of ***relative dating***. The initial steps in most archaeological research today still depend crucially on relative dating, on the ordering of artifacts, deposits, societies, and events into sequences, earlier before later.

Ultimately, however, we want to know the full or absolute age in years before the present of the different parts of the sequence – we need methods of ***absolute dating*** (sometimes called chronometric dating). Absolute dates help us find out how quickly changes such as the introduction of agriculture occurred, and whether they occurred simultaneously or at different times in different regions of the world. Before World War II for much of archaeology virtually the only reliable absolute dates were historical ones – Tutankhamun reigned in the 14th century BC, Caesar invaded Britain in 55 BC. Only in the last 50 years have independent means of absolute dating become available, transforming archaeology in the process.

Measuring Time

How do we detect the passage of time? In our own lives, we observe its passing through the alternating darkness and light of nights and days, and then through the annual cycle of the seasons. In fact, until the development of modern astronomy and nuclear physics, these were the only ways of observing time, other than by the human lifespan. As we shall see, some dating methods still rely on the annual passage of the seasons. Increasingly, however, dating methods in archaeology have come to rely on other physical processes, many of them not observable to the human eye. The most significant of these is the use of radioactive clocks.

Whatever the dating method, we need an agreed measure of time in order to construct a chronology. Most human measuring systems reckon on the basis of years. Thus even age measurements such as radioactive clocks that are independent of annual cycles need to be converted into years. Often when there are dating errors it is the conversion into years rather than the dating method itself that is at fault.

In general the two biggest problems with archaeological dating methods are not the techniques themselves but (1) security of context: i.e. ensuring that the sample we are using does indeed relate securely to the context we are trying to date; and (2) contamination of the sample with more recent (or sometimes older) material. There is also the problem of precision: that many dating methods provide results which form an age-bracket which can stretch over several centuries or even millennia. Misunderstandings can arise when archaeologists have too high an expectation of the precision available from the method which they are using.

Our timescale in years must date from or to a fixed point in time. In the Christian world, this is by convention taken as the birth of Christ, supposedly in the year

AD 1 (there is no year 0), with years counted back before Christ (BC) and forward after Christ (AD or *Anno Domini*, Latin for "In the Year of Our Lord"). In the Muslim world the basic fixed point is the date of the Prophet's departure from Mecca, the Hegira (reckoned at AD 622 in the Christian calendar), whereas many Buddhists take theirs from the date of the Gautama Buddha's death – thus they celebrated his 2500th anniversary in AD 1957. As a result of these differences many scholars use the terms "Before the Common Era" (BCE) and "in the Common Era" (CE) instead of BC and AD to avoid cultural insensitivity.

Scientists who derive dates from radioactive methods, wanting a neutral international system without allegiance to any of the above calendars, have chosen to count years back from the present (BP). But since scientists too require a firm fixed point, they take BP to mean "before 1950" (the approximate year of Libby's establishment of the first radioactive method, radiocarbon). This may be convenient for scientists, but can be confusing for everyone else (a date of 400 BP is not 400 years ago but AD 1550, currently about 450 years ago). It is therefore clearest to convert any BP date for the last few thousand years into the BC/AD system. For the Paleolithic period, however (stretching back two or three million years before 10,000 BC), archaeologists use the terms "BP" and "years ago" interchangeably, since a difference of 50 years or so between them is irrelevant. For this remote epoch one is dating sites or events at best only to within several thousand years of their "true" date.

Discussion of the Paleolithic makes it evident that our whole conception and interpretation of time and its measurement needs to be adapted to the period being studied. If even the most precise dates for the Paleolithic give us glimpses of that epoch only at intervals of several thousand years, clearly archaeologists can never hope to reconstruct Paleolithic events in the manner of conventional history, peopled with individuals as, for instance, in ancient Egypt during the era of the pharaohs.

On the other hand, Paleolithic archaeologists can gain insights into some of the broad long-term changes that shaped the way modern humans evolved – insights that are denied archaeologists working with shorter periods of time, where in any case there may be too much "detail" for the broader pattern to be easily discernible.

The way in which archaeologists carry out their research is therefore very much dependent on the precision of dating – the sharpness of focus – obtainable for the period of time in question.

RELATIVE DATING

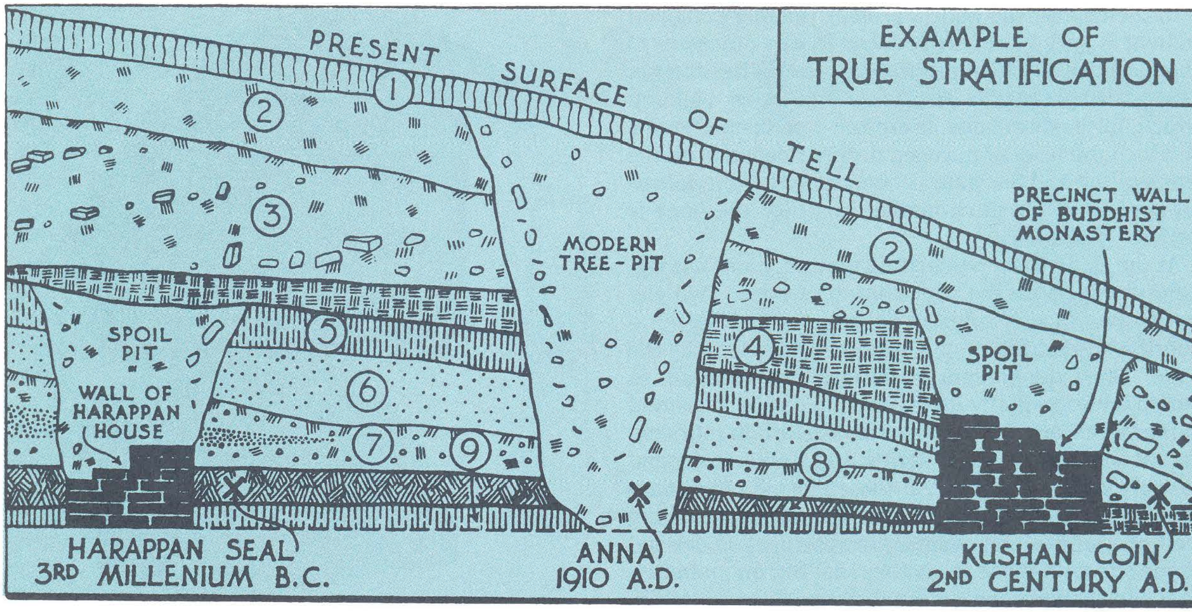
The first, and in some ways the most important, step in much archaeological research involves ordering things into sequences. The things to be put into sequence can be archaeological deposits in a stratigraphic excavation. Or they can be artifacts as in a typological sequence. Changes in the earth's climate also give rise to local, regional, and global environmental sequences – the most notable being the sequence of global fluctuations during the Ice Age. All these sequences can be used for relative dating.

STRATIGRAPHY

Stratigraphy, as we saw in Chapter 3, is the study of stratification – the laying down or depositing of strata or layers (also called deposits) one above the other. From the point of view of relative dating, the important principle is that the underlying layer was deposited first and therefore earlier than the overlying layer. Thus a succession of layers should provide a relative chronological sequence, from earliest (bottom) to latest (top).

Good stratigraphic excavation at an archaeological site is designed to obtain such a sequence. Part of this work involves detecting whether there has been any human or natural disturbance of the layers since they were originally deposited. In Chapter 2 we discussed some of these cultural and natural formation processes – such as rubbish pits dug down by later occupants of a site into earlier layers, animals burrowing holes, and floods washing layers away and redepositing them elsewhere in a secondary context. Armed with carefully observed stratigraphic information, the archaeologist can hope to construct a reliable relative chronological sequence for the deposition of the different layers.

But of course what we mostly want to date are not so much the layers or deposits themselves as the humanly generated materials within them – artifacts, structures,



Mortimer Wheeler's drawing of a section across a mound or tell in the Indus Valley (modern Pakistan). Pit disturbance makes dating difficult, but the Harappan seal, for example (age known from similar seals found elsewhere), lies in an undisturbed context in layer 8, and can therefore help date that layer and the wall against which the layer abuts.

organic remains – which ultimately (when systematically studied) reveal past human activities at the site. Here the idea of ***association***, touched on in Chapter 2, is important. When we say that two objects were found in association within the same archaeological deposit, we generally mean that they became buried at the same time. Provided that the deposit is a sealed one, without stratigraphic intrusions from another deposit, the associated objects can be said to be no later (no more recent) than the deposit itself. A sequence of sealed deposits thus gives a sequence – and relative chronology – for the time of burial of the objects found associated in those deposits.

This is a crucial concept to grasp, because if one of those objects can later be given an absolute date – say a piece of charcoal that can be dated by radiocarbon in the laboratory – then it is possible to assign that absolute date not only to the charcoal but to the sealed deposit and the other objects associated with it as well. A series of such dates from different deposits will give an absolute chronology for the whole sequence. It is this interconnecting of stratigraphic sequences with absolute dating methods that provides the most reliable basis for dating archaeological sites and their contents. The section on radiocarbon dating (see below) illustrates this for the site of Gatecliff Shelter, Nevada.

But there is another important point to consider. So far we have dated, relatively and with luck absolutely, the time of burial of the deposits and their associated material. As we have observed, however, what we want ultimately to reconstruct and date are the past human activities and behavior that those deposits and materials represent. If a deposit is a rubbish pit with pottery in it, the deposit itself is of interest as an example of human activity, and the date for it is the date of human use of the pit. This will also be the date of final burial of the pottery – but it will *not* be the date of human use of that pottery, which could have been in circulation tens or hundreds of years earlier, before being discarded, perhaps buried in another deposit and then dug up with other rubbish to be thrown into the pit. It is necessary therefore always to be clear about which activity one is trying to date, or can reliably date in the circumstances. The cultural formation processes discussed in Chapter 2 all have to be taken into account in any assessment of this question.

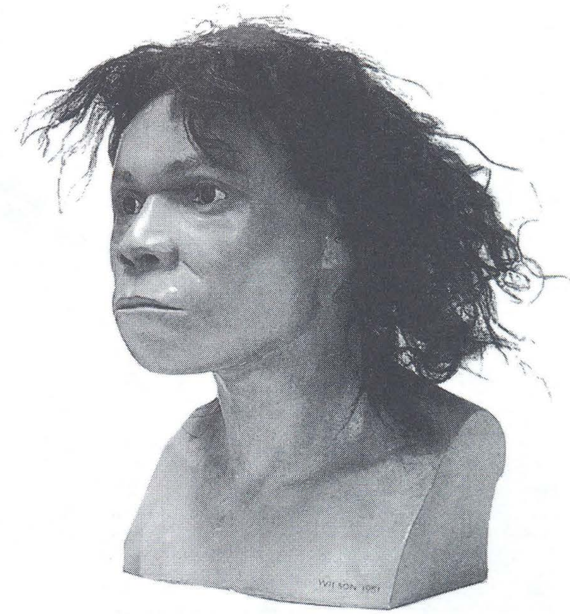
Bone Age

A useful method of assessing whether several bones found in association in the same stratigraphic deposit are in fact of the same relative age is chemical dating by studying nitrogen, fluorine, and uranium content.

In the deposit the bone's protein (mainly collagen) content is very gradually reduced by the processes of chemical decay. The most useful index for the amount of protein present is the bone's nitrogen content, which, for modern bone, is around 4 percent. The rate at which the level of nitrogen declines depends on the temperature and the water, chemical, and bacteriological content of the environment in which the bone is buried.

At the same time, percolating ground water has significant effects on the composition of bone. Two elements present in solution in the ground water – fluorine and uranium – are absorbed gradually by the bone. Thus, the content of fluorine and uranium in buried bone gradually increases, and can be measured in the laboratory. Like the rate of decrease in nitrogen, the rates of increase in fluorine and uranium depend strongly on local factors. All these rates of change are thus too variable to form the basis of an absolute dating method, nor can one compare relative ages so derived at one site with those at another site. But on an individual site chemical dating can distinguish bones of different age found in apparent stratigraphic association.

The most famous application of the method was in the case of the Piltdown forgery. In the early 1900s, pieces of human skull, an ape-like jawbone, and some teeth were found in a Lower Paleolithic gravel pit in Sussex, southern England. The discoveries led to claims that the "missing link" between apes and humans had been found. Piltdown Man (*Eoanthropus dawsoni*) had an important place in textbooks until 1953, when it was exposed as a complete hoax. Fluorine, uranium, and nitrogen dating at the British Museum (Natural History) showed that the skull was human but of relatively recent age (it was subsequently dated at about 620 years old); the jawbone came from an orang-utan and was a modern "plant." Both the skull and the jawbone had been treated with pigment (potassium dichromate) to make them look old and associated. Today, many suspect that Charles Dawson, the discoverer, was the hoaxer.



Piltdown Man: a reconstruction made shortly before the remains were discovered to be a hoax. Fluorine, uranium, and nitrogen dating of the skull, jawbone, and teeth proved that they were of different relative ages, and not associated.

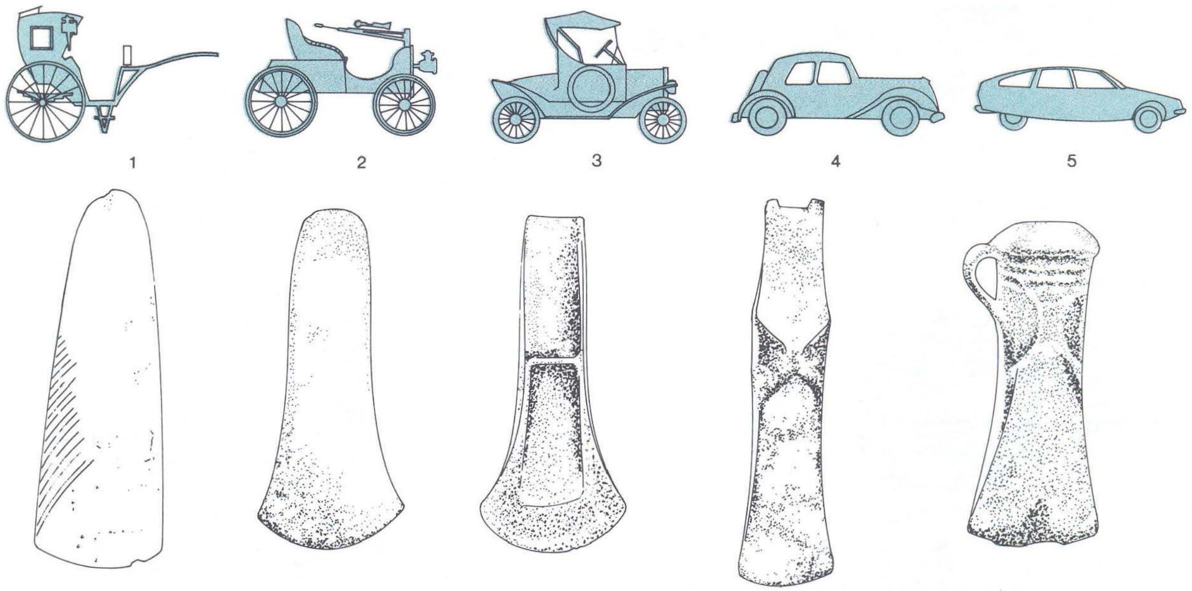
TYPOLOGICAL SEQUENCES

When we look at the artifacts, buildings, and indeed any of the human creations around us, most of us can mentally arrange some of them into a rough chronological sequence. One kind of aircraft looks older than another, one set of clothes looks more "old-fashioned" than the next. How do archaeologists exploit this ability for relative dating?

As we saw in Chapter 3, the form of an artifact such as a pot can be defined by its specific attributes of material, shape, and decoration. Several pots with the same attributes constitute a pot type, and typology groups artifacts into such types. Underlying the notion of relative dating through typology are two other ideas.

The first is that the products of a given period and place have a recognizable style: through their distinctive shape and decoration they are in some sense characteristic of the society that produced them. This point is further discussed in Chapters 5 and 10. The archaeologist or anthropologist can often recognize and classify individual artifacts by their style, and hence assign them to a particular place in a typological sequence.

The second idea is that the change in style (shape and decoration) of artifacts is often quite gradual, or evolutionary. Indeed, this idea came from the Darwinian theory of the evolution of species, and was embraced by 19th-century archaeologists, who realized that here was a very convenient rule, that "like goes with like." In other words, particular artifacts (e.g. bronze daggers) produced at about the same time are often alike, whereas those produced several centuries



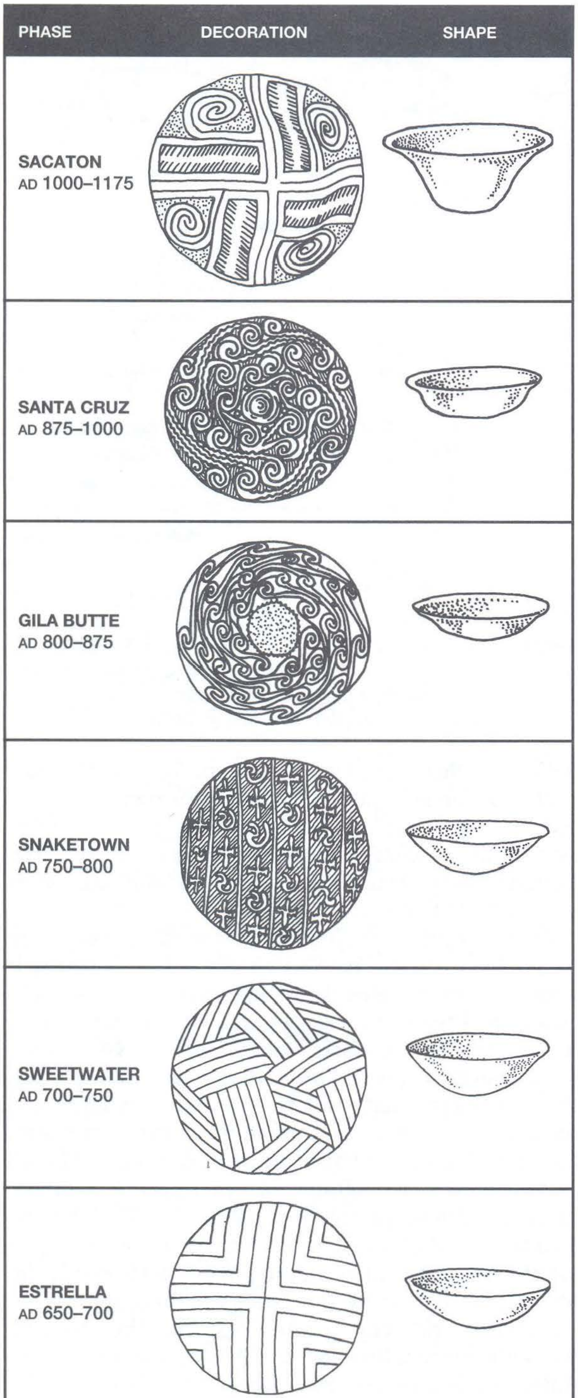
The arrangement of artifact types in a sequence is based on two simple ideas: first, that products of a given period and place have a distinctive style or design; and second, that changes in style are gradual, or evolutionary. Gradual changes in design are evident in the history of the automobile (top) and of the prehistoric European axe (above: (1) stone; (2–5) bronze). However, the rate of change (a century for the automobile, millennia for the axe) has to be deduced from absolute dating methods.

apart will be different as a result of centuries of change. It follows, then, that when one is faced with a series of daggers of unknown date, it is logical first to arrange them in a sequence in such a way that the most closely similar are located beside each other. This is then likely to be the true chronological sequence, because it best reflects the principle that "like goes with like."

Such arguments were developed by many archaeologists, who found that relative chronologies could be established for different classes of artifacts from different regions. The great master of the "typological method" was the 19th-century Swedish scholar Oscar Montelius, who formulated local relative chronologies for many of the regions of Bronze Age Europe, drawing upon bronze tool and weapon forms. These regional sequences could in many cases be confirmed in their outlines by stratigraphic excavations where it was indeed found that the simpler forms were the earliest.

Montelius went on to use the same arguments also in spatial terms to show how the artifact types in one region influenced those in adjacent areas. In this way, making certain assumptions about the direction of influence, he established a relative chronology of tool and weapon forms for the whole of Europe in the Bronze Age. (The assumption about the direction of influence – the famous principle that progress originated in the Near East and spread out from there – has been challenged and in part overthrown by more recent work. But in other respects the Montelius system for the European Bronze Age, as refined by the German prehistorian Paul Reinecke and others, is effectively still in use.)

For many purposes, it remains true that the best way to assign a relative date to an artifact is to match it with an artifact already recognized within a well-established typological system. In Europe, this is true for Bronze Age artifacts, but it applies, very much more widely, at a world level. In the Paleolithic period, the first approximate (relative) dating of a layer will often come from an examination of the stone tools found within it: hand-axes imply Lower (or to a lesser extent Middle) Paleolithic; blades Upper Paleolithic. In later periods, pottery typologies usually form the backbone of the chronological system. Good examples are the detailed studies on the pottery of Greece in the Mycenaean period by the Danish archaeologist Arne Furumark and his successors, and the ceramic sequence established for the Pueblo Indians of the American Southwest. But nearly every area has its own well-established ceramic succession. If this is tied into a stratigraphic sequence of deposits that can be dated by radiocarbon or other absolute means, then



Pottery typology, as exemplified by this 500-year sequence of Hohokam bowl styles from the American Southwest.

the artifacts in the typological sequence can themselves be assigned absolute dates in years.

It is also worth noting that different types of artifact change in style (decoration and shape) at different rates, and therefore vary in the chronological distinctions that they indicate. For example, the changes in decoration of the painted Mycenaean pottery mentioned above may have occurred at intervals of 20 years or so, whereas other types of decorated pottery often lasted more than a century. Undecorated pottery could keep much the same shape for several centuries. By and large, with pottery, surface decoration changes more rapidly than shape and is therefore the most chronologically sensitive attribute to use for a typological sequence. The shape of a vessel or container may in any case be most strongly influenced by a practical requirement, such as water storage, which need not alter for hundreds of years.

Other artifacts, such as metal weapons or tools, can change in style quite rapidly, and so may be useful chronological indicators. By contrast stone tools, such as hand-axes, are often notoriously slow to change in form and therefore rarely make sensitive indicators of the passage of time.

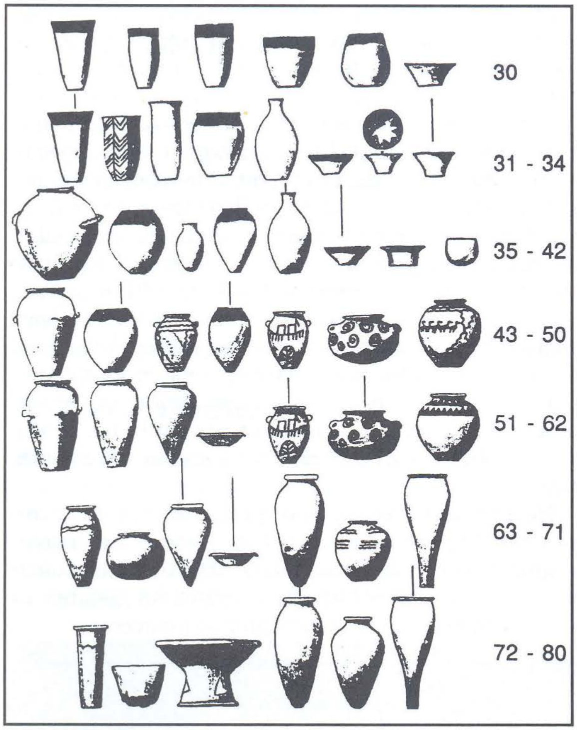
Seriation

The insights of the principle that "like goes with like" have been developed further to deal with associations of finds (assemblages), rather than with the forms of single objects taken in isolation. This technique of seriation allows assemblages of artifacts to be arranged in a succession, or serial order, which is then taken to indicate their ordering in time: it is thus an exercise in relative chronology.

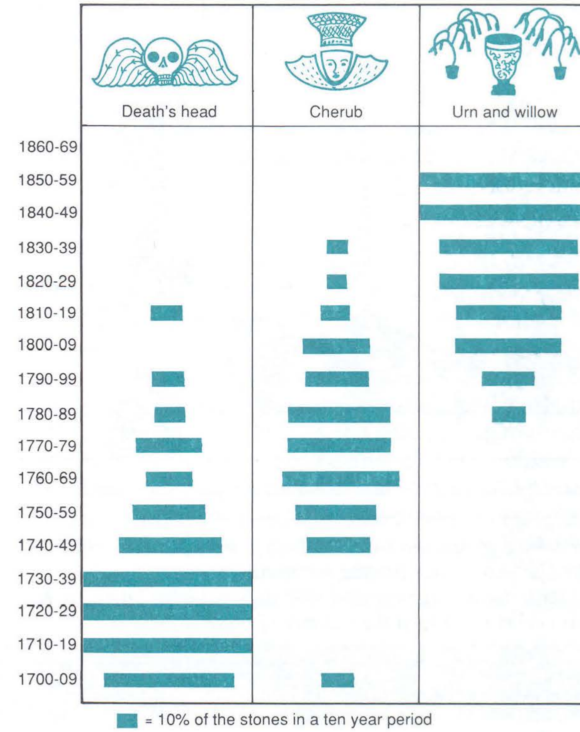
Two versions of the technique have been applied: ***contextual seriation*** and ***frequency seriation***.

Contextual Seriation. Here it is the duration of different artifact styles (shape and decoration) that governs the seriation. The pioneer of the method was Flinders Petrie. Working at Diospolis Parva in Upper Egypt at the very end of the 19th century, he excavated several predynastic graves that could be neither stratigraphically linked to each other nor tied into the historical king-lists of the subsequent dynastic period. Petrie wanted to put the graves into chronological order, so he began by making an inventory of their contents. Each grave was allocated a separate slip of paper listing its artifact types.

Petrie then placed the separate slips parallel to each other, one above the other in a column, and kept rearranging their position up or down the column. He



Contextual seriation: Flinders Petrie's own serial ordering of predynastic Egyptian pottery from the site of Diospolis Parva. Starting at the top, seven successive stages are identified, each linked to the one before and after by at least one similar shape. At the left of the five lower rows are the "wavy-handled" pots, arranged by Petrie in a sequence of "degradation" – his clue to the order of the whole series. Subsequent research in Egypt has largely supported Petrie's relative chronological sequence.

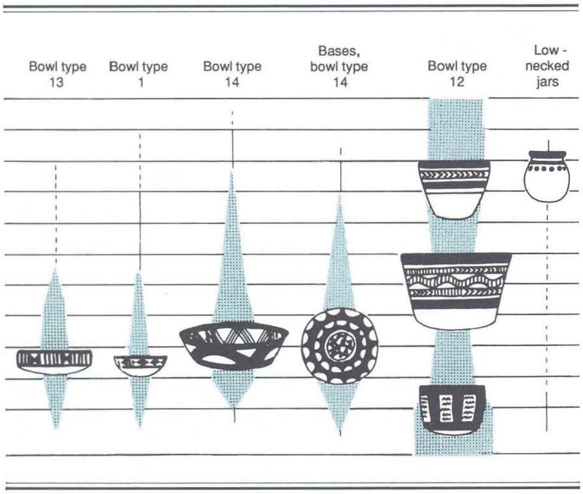


Frequency seriation: changes in the popularity (or frequency) of three tombstone designs in central Connecticut cemeteries, from 1700 to 1860. Rises and falls in popularity have produced the characteristic battleship-shaped curve for the fluctuating fortunes of each design. As elsewhere in New England, the Death's head design (peak popularity 1710–1739) was gradually replaced by the Cherub (peak 1760–1789) which in turn was replaced by the Urn and willow tree (peak 1840–1859).

believed that the best arrangement would be the one where the greatest number of individual types had the shortest duration across the various slips. In this way he arrived at a sequence of assemblages – and thus of graves – arranged in what he thought was their relative chronological order. Subsequent work in Egypt has largely vindicated Petrie and shown that his serial ordering of the graves does in fact generally reflect their true chronological sequence.

Frequency Seriation. A similar problem – the lack of any external chronological information – was faced by American archaeologists working at Maya sites in the Yucatán in the 1940s. Their material, however, consisted of ceramic collections which had been recovered without stratigraphic context. In this particular case, there was a need to place the ceramic assemblages in serial order so as to construct a relative chronology of the buildings and monuments with which they were associated.

The solution was frequency seriation, which relies principally on measuring changes in the proportional abundance, or frequency, of a ceramic style. The two basic assumptions behind the method were set out in a classic paper by W.S. Robinson and another by G.W. Brainerd, both published in *American Antiquity* in 1951. First, they assumed that pottery styles gradually become more popular, reach a peak popularity and then fade away (a phenomenon that diagrammatically produces a shape like a battleship as viewed from above – hence the common term for them, ***battleship curves***). Secondly, they argued that at a given time period, a pot style popular at one site would similarly be popular at another. Thus if the style in question



Frequency seriation: Frank Hole's ordering of bowl types representing Susiana Black-on-Buff pottery from sites in the Deh Luran Plain, Iran. The battleship curves are again evident, indicating rises and falls in popularity. Stratigraphic excavation confirmed the validity of these sequences.

represented 18 percent of the total pottery found at site A at a particular period, the pottery from site B for the same period would have a similar proportion or frequency of that style.

Using these two assumptions, Robinson and Brainerd were able to put the assemblages into a sequence so that those with the most similar percentages of certain pot styles were always together. The chronological validity of the method has since been demonstrated by American archaeologists such as James A. Ford working in the American Southeast and Frank Hole in Iran.

Both Ford and Hole studied ceramic assemblages mainly derived from stratigraphic excavations. They were therefore able to compare the sequences obtained using the method of frequency seriation with the true stratigraphic sequences they discovered in their excavations. In both instances there were no serious contradictions.

Nevertheless it should always be borne in mind that seriation by itself does not tell us which end of a given sequence is first and which last – the true chronology has to be determined by other means, for instance by links with excavated stratigraphic sequences.

LINGUISTIC DATING

For completeness, it is appropriate to mention here an interesting approach to questions of chronology, in this case applied not to artifacts but to ***language*** change, as studied by comparisons in the vocabularies of related languages. Earlier claims suggested that here might be some sort of absolute dating method; these have been widely (and rightly) rejected. However, the method remains of real interest from the standpoint of relative chronology. (And see also box, Language Families and Language Change, p. 467.)

The basic principle is straightforward. If you take two groups of people, speaking the same language, and separate them so that there is no further contact between them, both groups will no doubt continue to speak the same tongue. But in each population, with the passage of time, changes will occur; new words will be invented and introduced whereas others will fall out of use. So, after a few centuries, the two independent groups will no longer be speaking quite the same language; after a few thousand years, the language of one group will probably be almost unintelligible to the other.

The field of ***lexicostatistics*** sets out to study such changes of vocabulary. A popular method has been to choose a list of either 100 or 200 common vocabulary terms and to see how many of these, in the two languages being compared, share a common root-word. The positive score, out of 100 or 200, gives some measure of how far the two languages have diverged since the time when they were one.

The rather suspect discipline of ***glottochronology*** would claim to go further, and use a formula to pronounce, from this measure of similarity and dissimilarity, how long ago in years it is since the two languages under consideration diverged. The American scholar, Morris Swadesh, the principal exponent of the method, concluded that two related languages would retain a common vocabulary of 86 percent of the original after a period of separation of 1000 years. In reality, however, there is no basis for assuming a constant and quantifiable rate of change in this way: many factors influence linguistic change (the existence of literacy among them).

The method is complicated by various other factors, such as the existence of loan-words (borrowed from elsewhere, and not part of the common heritage) in both of the languages under study. But the underlying idea that two languages with a very high score for the common vocabulary are more recently related than those with a low score is itself reasonable, and the approach cannot be excluded from a discussion of methods of relative dating.

CLIMATE AND CHRONOLOGY

So far we have been discussing sequences that can be established stratigraphically for individual sites, or typologically for artifacts. In addition, there is a major class of sequences, based on changes in the earth's climate, that has proved useful for relative dating on a local, regional, and even global scale. Some of these environmental sequences can also be dated by various absolute methods. (The impact of climatic and environmental fluctuations on human life is discussed in detail in Chapter 6.)

Pleistocene Chronology

The idea of a great Ice Age (the Pleistocene epoch), that occurred in the distant past, has been with us since the 19th century. As world temperatures fell, ice sheets – or glaciers – expanded, mantling large parts of the earth's surface and lowering world sea levels (the lost water being quite literally locked up in the ice). Early geologists and paleoclimatologists, studying the clear traces in geological deposits, soon realized that the Ice Age was not one long unbroken spell of colder climate. Instead it had witnessed what they identified as four major ***glacials***, or periods of glacial advance (labeled, from earliest to latest, Günz, Mindel, Riss, and Würm in continental Europe; in North America different names were chosen – Wisconsin, for example, being the equivalent of Würm). Punctuating these cold periods were warmer interludes known as ***interglacials***. More minor fluctuations within these major phases were called ***stadials*** and ***interstadials***. Until the arrival after World War II of absolute dating methods such as those based on radioactive clocks, archaeologists depended very largely for their dating of the long Paleolithic period on attempts to correlate archaeological sites with this glacial sequence. Far away from the ice sheets, in regions such as Africa, strenuous efforts were made to link sites with fluctuations in rainfall

YEARS AGO	CLIMATE cool warm	GEOLOGICAL PERIODS	GEOLOGICAL EPOCHS	GLACIALS (EUROPE)	GLACIALS (N.AMERICA)	ARCHAEOLOGICAL STAGES
			HOLOCENE			
10,000						
			UPPER PLEISTOCENE	Würm (Weichsel)	Wisconsin	UPPER PALEOLITHIC
100,000						MIDDLE PALEOLITHIC
				Riss (Saale)	Illinoian	
			MIDDLE PLEISTOCENE	Mindel (Elster)	Kansan	
		QUATERNARY				
780,000				Günz (Menapian)	Nebraskan	LOWER PALEOLITHIC
			LOWER PLEISTOCENE			
	(uncertain)					
1,700,000						
		TERTIARY				

Table summarizing the main climatic changes, glacial terminology, and archaeological stages of the Pleistocene epoch.

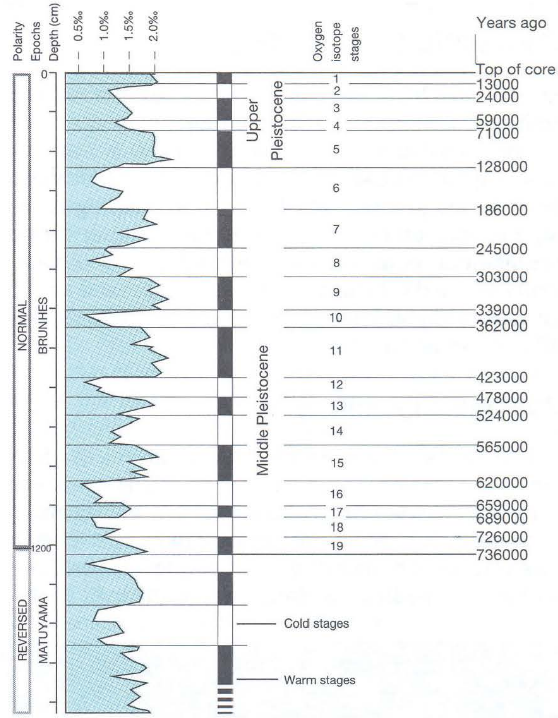
(*pluvials* and *interpluvials*); the hope was that the fluctuations might somehow themselves be tied in with the glacial sequence.

In recent decades, however, scientists have come to recognize that fluctuations in climate during the Ice Age were much more complex than originally supposed. From the beginning of the Pleistocene, about 1.7 million years ago, down to about 780,000 years ago (the end of the Lower Pleistocene), there were perhaps ten cold periods separated by warmer interludes. Another eight or nine distinct periods of cold climate may have characterized the Middle and Upper Pleistocene, from 780,000 to 10,000 years ago. (The period of warmer climate known as the Holocene covers the last 10,000 years.) Archaeologists no longer rely on complex glacial advances and retreats as the basis for dating the Paleolithic. However, fluctuations in Pleistocene and Holocene climate as recorded in deep-sea cores, ice cores, and sediments containing pollen are of considerable value for dating purposes.

Deep-Sea Cores and Ice Cores

As indicated in Chapter 6, the most coherent record of climatic changes on a worldwide scale is now provided by deep-sea cores, drilled from the ocean bed. These cores contain shells of microscopic marine organisms known as ***foraminifera***, laid down on the ocean floor through the slow continuous progress of sedimentation. Variations in the ratio of two oxygen isotopes in the calcium carbonate of these shells give a sensitive indicator of sea temperature at the time the organisms were alive. We now have an accurate temperature sequence stretching back 2.3 million years which reflects climate change on a global scale. Thus the cold episodes in the deep-sea cores relate to glacial periods of ice advance, and the warm episodes to interglacial or interstadial periods of ice retreat. The deep-sea core oxygen isotope record is a framework for a relative chronology for the Pleistocene.

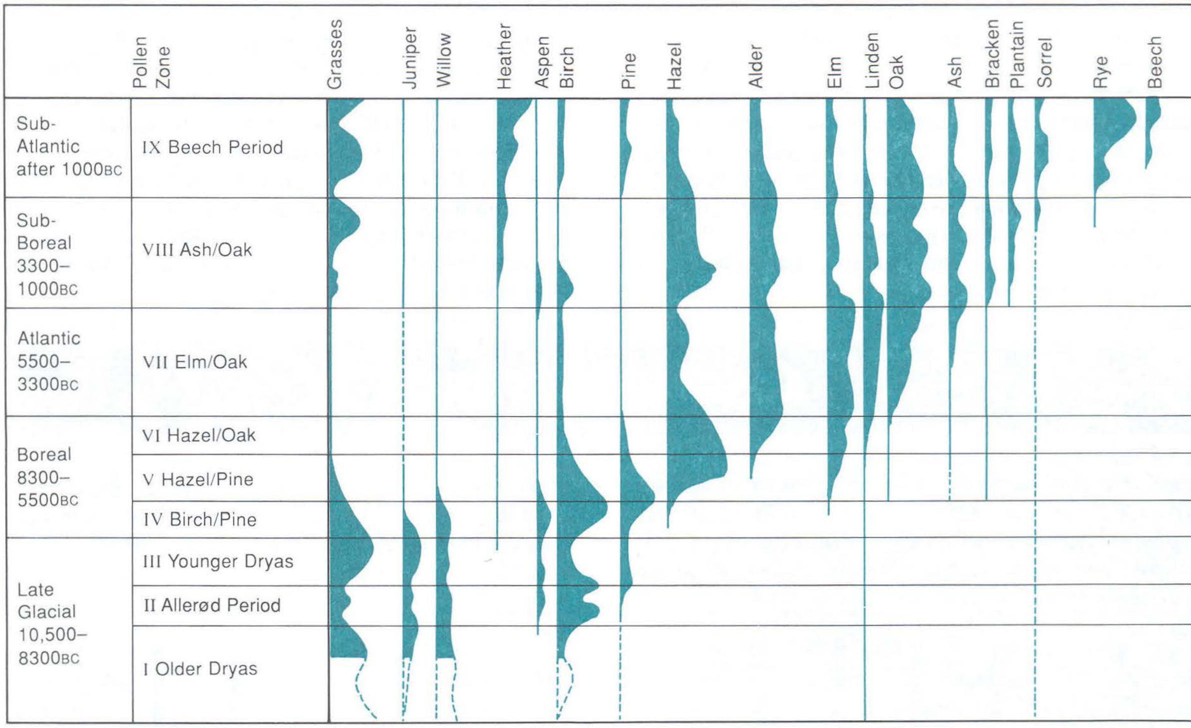
This chronology is invaluable for reconstructing a record of past environmental change, as will be discussed in Chapter 6. Radiocarbon and uranium-series dating (see below) can also be applied to the foraminiferan shells to provide absolute dates for the sequence. In addition, the phenomenon of geomagnetic reversals (reversals in the earth's magnetic field), discussed in a later section of this chapter, can be used to link the sequence to Paleolithic sites in the East African Rift Valley. Such reversals are recorded in both the cores and in the rock strata at the archaeological sites with evidence of early humans (see box, pp. 148–49, Dating Our African Ancestors).



Climatic variations during the Pleistocene as recorded in the differing amounts of the oxygen isotope 18O (tinted area) in the deep-sea core V 28-238, from the Pacific Ocean.

Ice Cores. As with deep-sea cores, cores extracted from the polar ice of the Arctic and Antarctic have been made to yield impressive sequences revealing climatic oscillations. Here again these are most useful for reconstructing ancient environments (Chapter 6), but they have relevance for dating as well.

The layers of compacted ice form annual deposits for the last 2000–3000 years that can be counted – thus giving an absolute chronology for this part of the sequence. As we shall see in the box on Dating the Thera Eruption (pp. 160–61), this has proved useful as one possible means of cross-checking the date of that volcanic explosion, which some scholars believe severely disrupted the Minoan civilization of Crete. For earlier time periods, however – at greater depths – the annual stratification is no longer visible, and dating of the ice cores is much less certain. The Vostok core in Antarctica reached a depth of about 2200 m (7200 ft), and spans a time-range estimated at 160,000 years, an age exceeded in the northern hemisphere by the two Greenland ice cores: GRIP and GISP2. Good correlations have been made with climatic oscillations deduced from the study of the deep-sea cores.



Idealized diagram illustrating the Holocene (postglacial) pollen zone sequence in Jutland, Denmark. Each pollen zone is characterized by rises and falls in pollen of certain plant species, e.g. birch and pine in zone IV, beech in zone IX. Dates are given in uncalibrated radiocarbon years BC *(see p. 141).*

Pollen Dating

All flowering plants produce the almost indestructible grains called pollen, and their preservation in bogs and lake sediments has allowed pollen experts (palynologists) to construct detailed sequences of past vegetation and climate. These sequences are an immense help in understanding ancient environments, as we shall discuss in Chapter 6. But they have also been – and to a limited extent still are – important as a method of relative dating.

The best-known pollen sequences are those developed for the Holocene (postglacial) of northern Europe, where an elaborate succession of so-called ***pollen zones*** covers the last 10,000 years. By studying pollen samples from a particular site, that site can often be fitted into a broader pollen zone sequence and thus assigned a relative date. Isolated artifacts and finds such as bog-bodies discovered in contexts where pollen is preserved can also very usefully be dated in the same way. However, it is important to remember that the pollen zones are not uniform across large areas. In any one local region, such as the Somerset Levels of southern England, it is best to work with a specialist who can build up a sequence of pollen zones for that region. The sites and finds in the vicinity can then be linked to it. If tree-ring or radiocarbon dates are available for all or part of the sequence, one has the makings of an absolute chronology for the region.

Thanks to the durability of pollen grains, they can yield environmental evidence even as far back as 3 million years ago for sites in East Africa (Chapter 6). Different interglacial periods in areas such as northern Europe have also been shown to have characteristic pollen sequences, which means that the pollen evidence at an individual site in the area can sometimes be matched to a particular interglacial – a useful dating mechanism given that radiocarbon does not operate at these early time periods.

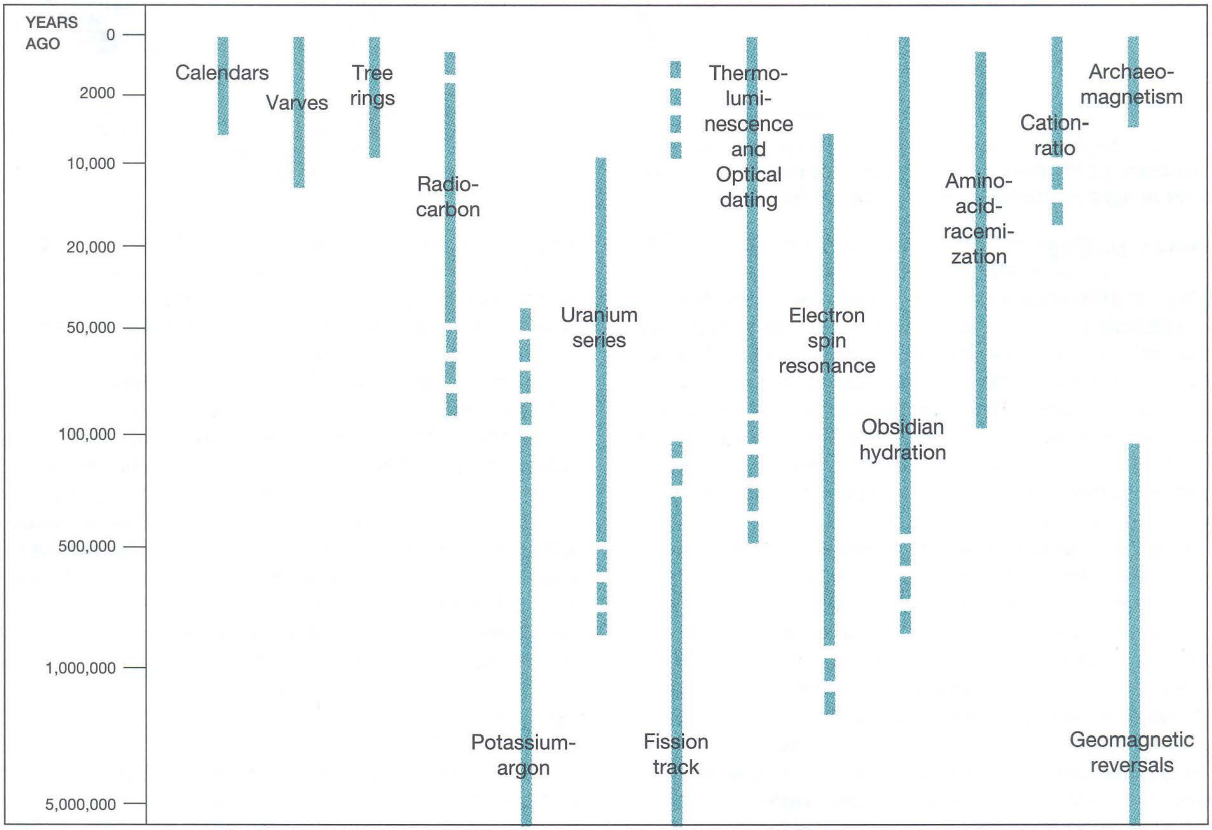
Faunal Dating

There is a further method of relative dating relevant for the Pleistocene epoch, though this one is not based on the sedimentary processes that lie behind the methods already discussed. This is the old-established technique of faunal dating, which relies on the fact that many mammal species have evolved considerably over the last few million years, new forms emerging and old ones dying out. The changes in each species have been charted to create a rough sequence, for instance of elephants or pigs. In theory, if a similar sequence of pig species is found at two different sites, those sites can be assigned the same relative age. In practice the method is very imprecise for many reasons, including the fact that species extinct in one area may have continued much longer in another.

Nevertheless, its imprecision does not rule out faunal dating altogether as a useful method for the Pleistocene, where an accuracy even only to within the nearest quarter million years can be of value. For instance, faunal dating has proved important in the correlation of the early human sites that have been discovered in East and South Africa. And in Britain, associated mammalian fauna suggested that the human tibia and a tooth found at Boxgrove, southern England, are about 500,000 years old and are thus Britain's oldest human fossils.

ABSOLUTE DATING

Despite the great utility of methods of relative dating, archaeologists ultimately want to know how old sequences, sites, and artifacts are in calendar years. To achieve this they need to use the methods of absolute dating described in the following sections – from traditional historical methods to those which are based on the great variety of modern scientific techniques now available.



Chronological table summarizing the spans of time for which different absolute dating methods are applicable.

CALENDARS AND HISTORICAL CHRONOLOGIES

Until the development of the first scientific dating techniques around the beginning of this century, dating in archaeology depended almost entirely on historical methods. That is to say, it relied on archaeological connections with chronologies and calendars that people in ancient times had themselves established. Such dating methods are still of immense value today.

In the ancient world, literate societies recorded their own history in written documents. The Romans recorded events in terms of the year of rule of their consuls and emperors, although they sometimes referred events back to the foundation of the city of Rome itself. The Greeks reckoned from the date of the first Olympic Games, today usually set in the year 776 BC. In Egypt, the Near East, and ancient China history was recorded in terms of the successive kings, who were organized in groups of "dynasties." As we shall see, there were also very precise calendrical systems in Mesoamerica.

Archaeologists have to bear in mind three main points when working with early historical chronologies. First, the chronological system requires careful reconstruction, and any list of rulers or kings needs to be reasonably complete. Second, the list, although it may reliably record the number of years in each reign, has still to be linked with our own calendar if it is not to remain merely a "floating chronology." Third, the artifacts, features, or structures to be dated at a particular site have somehow to be related to the historical chronology, perhaps by their association with an inscription referring to the ruler of the time.

These points can be well illustrated by the Egyptian and Maya chronologies. Egyptian history is arranged in terms of 31 dynasties, themselves organized into the Old, Middle, and New Kingdoms. The modern view is a synthesis based on several documents including the so-called Turin Royal Canon. This synthesis gives an estimate of the number of years in each reign, right down to the conquest of Egypt by Alexander the Great, which can be set firmly, using information from Greek historians, in the year 332 BC. So the Egyptian dynasties can be dated by working backward from there, although the exact length of every reign is not known. This system can be confirmed and refined using astronomy. Egyptian historical records describe observations of certain astronomical events that can be dated, quite independently, using current astronomical knowledge and knowledge of where in Egypt the ancient observations were carried out.

Egyptian dates are generally considered to be very reliable after 664 BC. For the New Kingdom (*c.* 1550–1070 BC), the margin of error may be one or two decades, and by the time one goes back to the beginning of the First Dynasty, around 3000 BC, the accumulated errors might amount to some 200 years or so.

Of the calendrical systems of Mesoamerica, the Maya calendar was the most elaborate (see box overleaf). It does not depend, as do those of Europe and the Near East, on a record of dynasties and rulers. Other areas of Mesoamerica had their own calendrical systems which operated on similar principles.

ANCIENT EGYPTIAN CHRONOLOGY

EARLY DYNASTIC (Archaic) (3000–2575 BC)
Dynasties 1–3

OLD KINGDOM (2575–2134 BC)
Dynasties 4–8

FIRST INTERMEDIATE PERIOD (2134–2040 BC)
Dynasties 9–11

MIDDLE KINGDOM (2040–1640 BC)
Dynasties 11–14

SECOND INTERMEDIATE PERIOD (1640–1532 BC)
Dynasties 15–17

NEW KINGDOM (1550–1070 BC)
Dynasties 18–20

THIRD INTERMEDIATE PERIOD (1070–712 BC)
Dynasties 21–25

LATE PERIOD (712–332 BC)
Dynasties 25–31

A historical chronology for ancient Egypt. The broad terminology is generally agreed by Egyptologists, but the precise dating of the earlier periods is disputed. Overlapping dates between dynasties/kingdoms (e.g. First Intermediate period and Middle Kingdom) indicate that separate rulers were accepted in different parts of the country.

THE MAYA CALENDAR

The Maya calendar was one of great precision, used for recording dates in inscriptions on stone columns or stelae erected at Maya cities during the Classic period (AD 300–900). The elucidation of the calendar, and the more recent decipherment of the Maya glyphs, mean that a well-dated Maya history is now emerging in a way which seemed impossible a few decades ago.

To understand the Maya calendar it is necessary to comprehend the Maya numerical system, and to recognize the various glyphs or signs by which the various days (each of which had a name, like our Monday, Tuesday, etc.) were distinguished. In addition, it is necessary to follow how the calendar itself was constructed.

The Maya numerals are relatively straightforward. A stylized shell meant zero, a dot "one," and a horizontal bar "five."

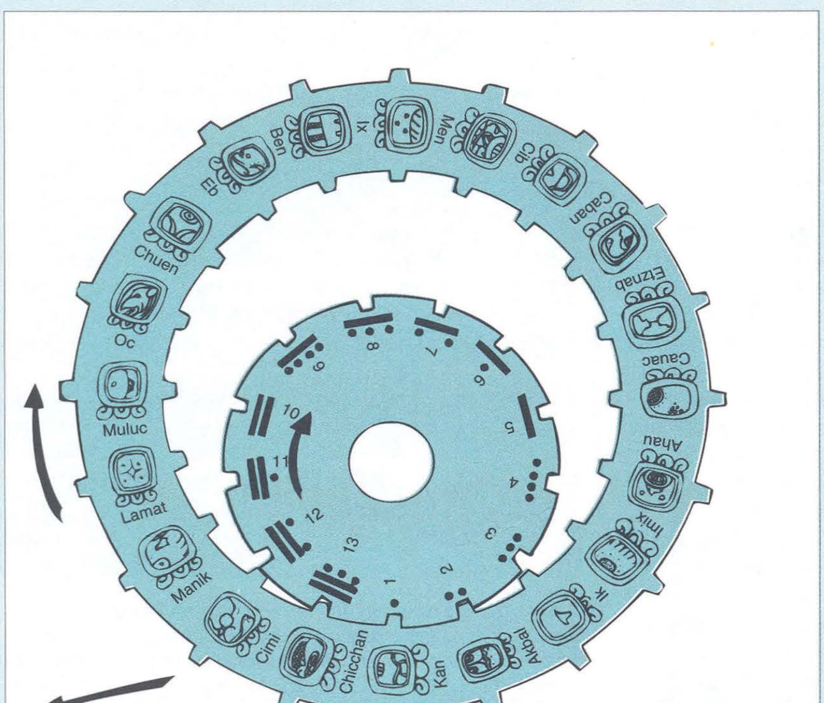
The Maya used two calendrical systems: the Calendar Round and the Long Count.

The **Calendar Round** was used for most everyday purposes. It involved two methods of counting. The first is the Sacred Round of 260 days, which is still used in some parts of the Maya highlands. We should imagine two interlocking cog wheels, one with numbers from 1 to 13, the other with 20 named days. Day 1 (to use our terminology) will be 1 Imix, day 2 is 2 Ik, day 3 is 3 Akbal, and so on until day 13, which is 13 Ben. But then day 14 is 1 Ix, and so the system continues. The sequence coincides again after 260 days and the new Sacred Round begins with 1 Imix once more.

In conjunction with this, the solar year was recorded, consisting of 18 named months, each of 20 days, plus a terminal period of 5 days. The Maya New Year began with 1 Pop (Pop being the name of the month); the next day was 2 Pop, and so on.

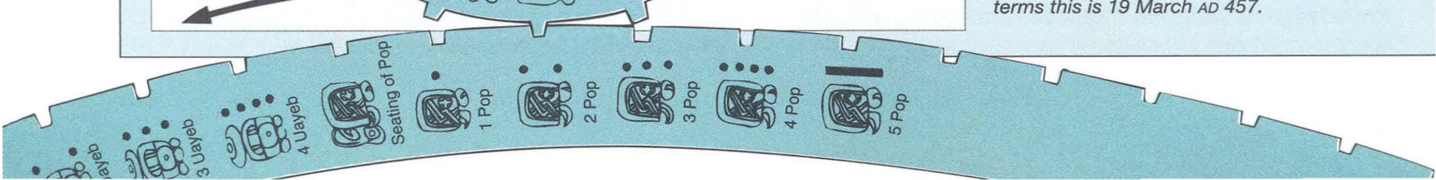
These two cycles proceeded simultaneously, so that a given day would be designated in both (e.g. 1 Kan 2 Pop). A specific combination of that kind could occur only once in every 52 years. This calendar was therefore sufficient for most daily purposes, and the 52-year cycle had symbolic significance for the Maya.

The **Long Count** was used for historical dates. Like any unique calendrical system, it needed to have a starting or zero date, and for the Maya this was 13 August 3113 BC (according to a commonly agreed correlation with the Christian calendar). A Long Count date takes the form of five numbers (e.g. in our own numerical notation 8.16.5.12.7). The first figure records the number elapsed of the largest unit, the *baktun* (of 144,000 days or about 400 years). The second is the *katun* (7200



The Calendar Round (left) can be visualized as a set of interlocking cog wheels. The 260-day cycle is created by the interlocking of the two wheels shown above. Meshing with this is the 365-day cycle (part of which is shown below). The specific conjoining of day names given here (1 Kan 2 Pop) cannot return until 52 years (18,980 days) have passed.

The Long Count (right) was used to record historical dates. Here, in Burial 48 at the city of Tikal, the date given – reading from top to bottom – is 9.1.1.10.10 4 Oc, or 9 baktuns, 1 katun, 1 tun, 10 uinals, and 10 kins, with the day name 4 Oc at the bottom. In modern terms this is 19 March AD 457.



days or 20 years), the third a *tun* of 360 days, the fourth a *uinal* of 20 days, and finally the *kin*, the single day.

A positional notation was used, starting at the top with the number of *baktuns*, and proceeding downwards through the lower units. Usually, each number was followed by the glyph for the unit in question (e.g. 8 *baktuns*) so that dates on the stelae can be readily recognized.

The earliest date yet noted on a stela in the Maya area proper is on Stela 29 at Tikal, and reads 8.12.14.8.15. In other words:

8 *baktuns*	1,152,000 days
12 *katuns*	86,400 days
14 *tuns*	5,040 days
8 *uinals*	160 days
15 *kins*	15 days
	or 1,243,615 days

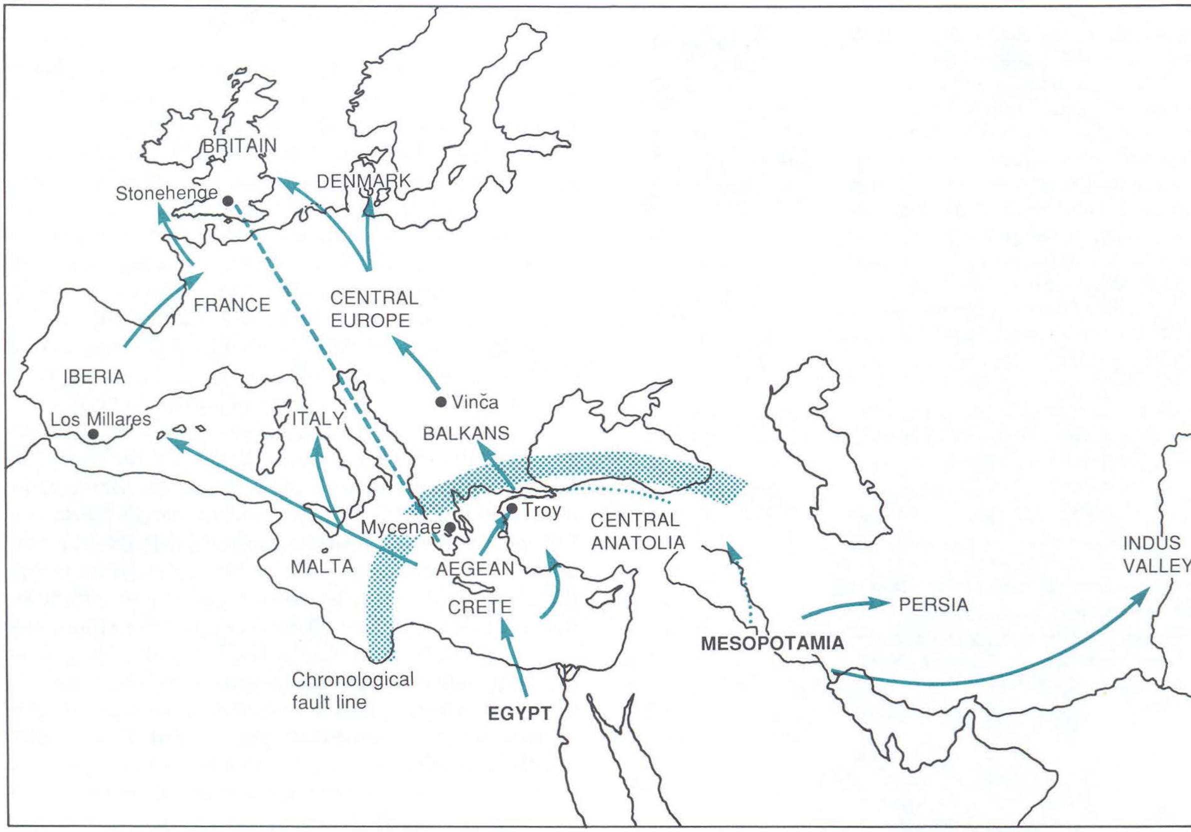
since the zero date in 3113 BC. This is the equivalent of 6 July AD 292. According to the Maya, the end of the present world will come about on 23 December 2012.

Using a Historical Chronology

It is relatively easy for the archaeologist to use a historical chronology when abundant artifacts are found that can be related closely to it. Thus, at major Maya sites such as Tikal or Copán there are numerous stelae with calendrical inscriptions that can often be used to date the buildings with which they are associated. The artifacts associated with the buildings can in turn be dated: for instance, if a pottery typology has been worked out, the finding of known types of pottery in such historically dated contexts allows the pottery typology itself to be dated. Contexts and buildings on other sites lacking inscriptions can be dated approximately through the occurrence of similar pot types.

Sometimes artifacts themselves carry dates, or the names of rulers that can be dated. This is the case with many Classic Maya ceramics that bear hieroglyphic inscriptions. For the Roman and medieval periods of Europe, coins offer a similar opportunity, as they normally carry the name of the issuing ruler, and inscriptions or records elsewhere usually allow the ruler to be dated. To date a coin or an artifact is not the same thing as to date the context in which it is found. The date of the coin indicates the year in which it was made. Its inclusion within a sealed archaeological deposit establishes simply a ***terminus post quem*** ("date after which"): in other words, the deposit can be no earlier than the date on the coin – but it could be later than that date.

A well-established historical chronology in one country may be used to date events in neighboring and more far-flung lands that lack their own historical records but are mentioned in the histories of the literate homeland. Similarly, archaeologists can use exports and imports of objects to extend chronological linkages by means of ***cross-dating***. For instance, Flinders Petrie, in his excavations in 1891–92 at Tell el-Amarna, capital of the heretic pharaoh Akhenaten (now dated in the Egyptian historical chronology to about 1353–1335 BC), discovered pottery that he recognized to be of Aegean origin: Mycenaean pottery in fact. Within the typological system of Mycenaean pottery later established by the Swedish scholar Arne Furumark it can be termed Late Helladic IIIA2 (one of the divisions in a relative chronology). Its presence in a well-dated Egyptian context establishes a ***terminus ante quem*** ("date before which") for the manufacture in Greece of that pottery: it cannot be more recent than the Amarna context. Likewise, actual Egyptian objects, some with inscriptions allowing them to be accurately dated in Egyptian terms, occur at various Aegean sites, thereby helping to date the contexts in which they are



European chronology. Until the 1960s, prehistoric Europe was largely dated by supposed typological links between neighboring lands that rested ultimately on the historical chronology of ancient Egypt. Calibrated radiocarbon dates (p. 141) have shown many of these links to be false ones. Egypt and the Aegean can still be cross-dated by direct exports and imports, but the "fault line" indicates how links have been severed with regions to the north and west, where dates have been pushed back by several centuries.

found. It is this linkage from A to B (Aegean to Egypt), and conversely from B to A, that has given rise to the term cross-dating.

Until 20 or 30 years ago, much of European prehistory was based on this method of dating, with successive links established between neighboring lands. Even the remotest parts of Europe were dated in absolute years BC using a system that rested ultimately on the Egyptian chronology. But the calibration of radiocarbon dates (see below) has brought about the collapse of this precarious chronological edifice.

It is now clear that although the links between Egypt and the Aegean were valid, being based on actual imports and exports, those between the Aegean and the rest of Europe were not. The entire chronology of prehistoric Europe was constructed on false assumptions whose rectification produced (so far as Europe is concerned) what has come to be called the Second Radiocarbon Revolution (see map).

Dating by historical methods remains the most important procedure for the archaeologist in countries with a reliable calendar supported by a significant degree of literacy. Where there are serious uncertainties over the calendar, or over its correlation with the modern calendrical system, the correlations can often be checked, at least in outline, by the other absolute dating methods to be described below.

Outside the historic and literate lands, however, cross-dating and broad typological comparisons have been almost entirely superseded by the various scientifically based dating methods described below. So that now, all the world's cultures can be assigned absolute dates.

ANNUAL CYCLES: VARVES AND TREE-RINGS

Before the advent of radioactive methods after World War II, the counting of varves and tree-rings provided the most accurate means of absolute dating – but only in two regions of the world: Scandinavia for varves and the American Southwest for tree-rings. Today, while varves remain of restricted use, tree-rings have come to rival radiocarbon as the main method of dating for the last few thousand years in many parts of Europe, North America, and Japan, thanks to painstaking scientific work.

Any absolute dating method depends on the existence of a regular, time-dependent process. The most obvious of these is the system by which we order our modern calendar: the rotation of the earth around the sun once each year. Because this yearly cycle produces regular annual fluctuations in climate, it has an impact on features of the environment which can in certain cases be measured to create a chronology (as well as forming a record of environmental change: see Chapter 6).

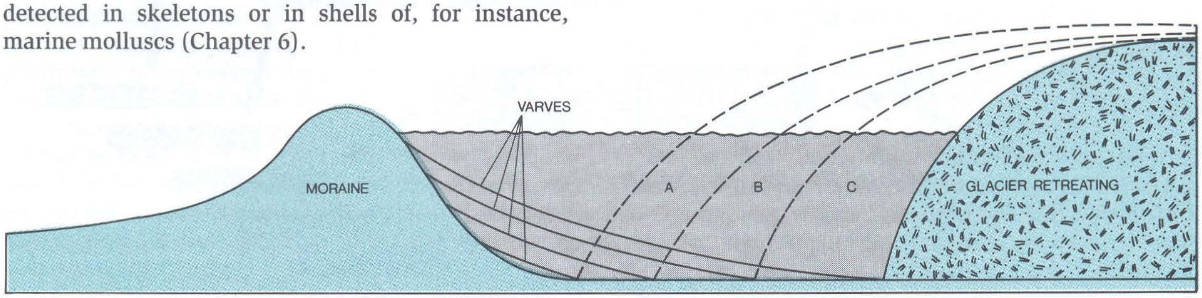
Evidence of these annual fluctuations is widespread. For example, the changes in temperature in polar regions result in annual variations in the thickness of polar ice, which scientists can study from cores drilled through the ice (see section above, Climate and Chronology). Similarly, in lands bordering the polar regions, the melting of the ice sheets each year when temperatures rise leads to the formation of annual deposits of sediment, called ***varves***, which can be counted. The growth of most species of plant varies annually, which makes possible the principle of ***tree-ring dating*** (dendrochronology). And growth in many animal species also varies during the year, so that annual variations in tissue deposits can sometimes be detected in skeletons or in shells of, for instance, marine molluscs (Chapter 6).

As with a historical king-list, for absolute dating purposes the sequence needs to be a long one (with no gaps), linked somehow to the present day, and capable of being related to the structures or artifacts one actually wants to date. Annual growth rings on molluscs found at a site can provide good evidence for season of occupation, for example (Chapter 7), but the ring sequence is much too short to form an absolute chronology. Varves and tree-rings, on the other hand, can be counted to produce unbroken sequences stretching back many thousands of years.

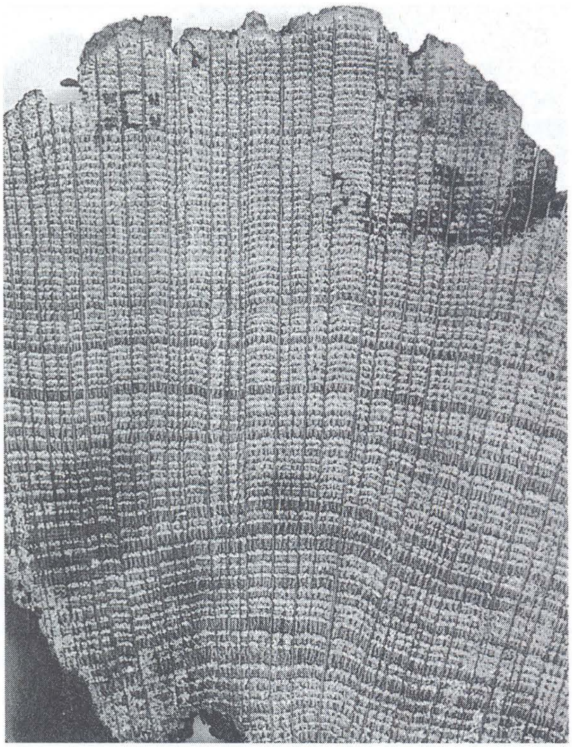
Varves and Lake Sediments

In 1878, the Swedish geologist Baron Gerard de Geer noticed that certain deposits of clay were layered in a regular way. He realized that these layers ("varves" in Swedish) had been deposited in lakes around the edges of Scandinavian glaciers by the annual melting of the ice sheets, which had been steadily retreating since the end of the Pleistocene epoch, or last Ice Age. The layers varied in thickness from year to year, a thick layer resulting from a warm year with increased glacial melting, a thin layer indicating colder conditions. By measuring the successive thicknesses of a whole sequence, and comparing the pattern with varves in nearby areas, it proved possible to link long sequences together.

This was the first geochronological method to be developed. Considerable deposits were found, representing thousands of years, stretching (when linked together) from the present back to the beginning of the retreat of the glacial ice sheets in Scandinavia some



Varves are sediment layers that were deposited in lakes by melting glaciers. When the ice retreated to position A, the sediments contained in the melted waters settled to form the lowermost varve. In successive years (B, C, etc.), more sediments were deposited, each varve extending horizontally to the point where that winter halted the glacier's thaw and representing in thickness the amount of glacial discharge. When varves from several glacial lakes have been recorded they can be correlated, to create a master sequence for an area. Such sequences have been established in Scandinavia and North America.

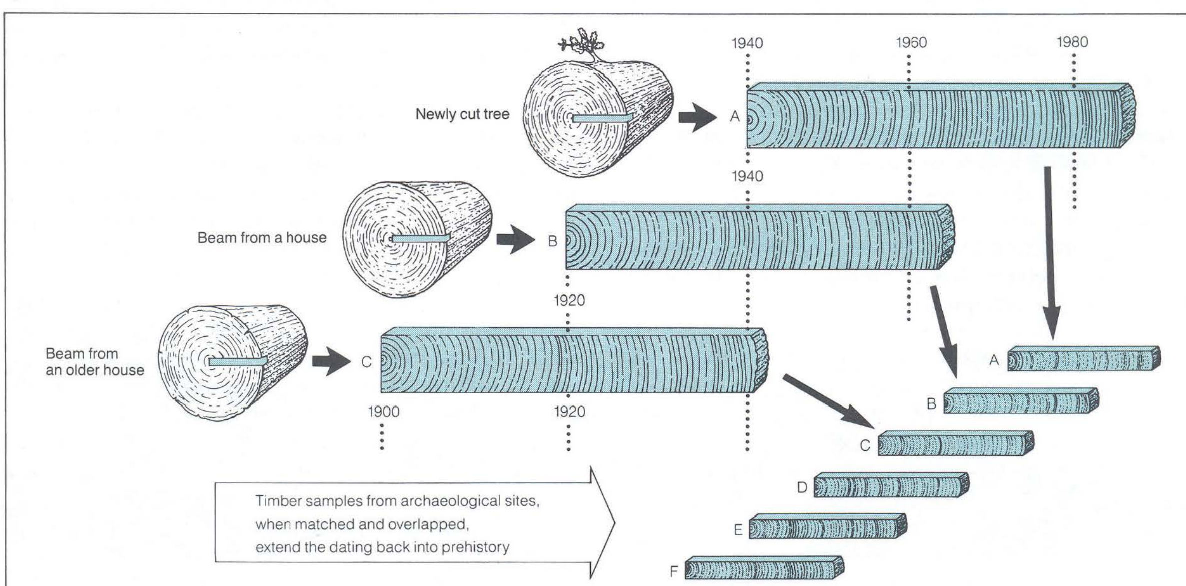


13,000 years ago. The method allowed, for the first time, a fairly reliable estimate for the date of the end of the last Ice Age, and hence made a contribution to archaeological chronology not only in Scandinavia but in many other parts of the world as well.

Comparable studies have been undertaken in North America, for instance in Wisconsin. But there are problems in correlating the North American and North European (Finnish and Swedish) data. For direct archaeological applications, radiocarbon dating and tree-ring work are in general much more useful. There has however been a significant advance using carbon samples taken from annually laminated sediments from the bottom of Lake Suigetsu in Japan, which can be dated (by direct counting of the annual layers) back to 45,000 years ago. This has, for the first time, permitted the calibration of the radiocarbon calendar back to this very early date.

Tree-Ring Dating

The modern technique of tree-ring dating (dendrochronology) was developed by an American astronomer, A.E. Douglass, in the early decades of this century – although many of the principles had been understood long before that. Working on well-preserved timbers in the arid American Southwest, by 1930



Tree-ring dating. (Top) Section across an Irish oak, the varying thickness of the annual growth rings clearly visible. The inner rings here date to the AD *1550s. (Above) Diagram to show how the annual growth rings can be counted, matched, and overlapped, to build up a master sequence for a particular region.*

Douglass could assign absolute dates to many of the major sites there, such as Mesa Verde and Pueblo Bonito. But it was not until the end of the 1930s that the technique was introduced to Europe, and only in the 1960s that the use of statistical procedures and computers laid the foundations for the establishment of the long tree-ring chronologies now so fundamental to modern archaeology. Today dendrochronology has two distinct archaeological uses: (1) as a successful means of calibrating or correcting radiocarbon dates (see below); and (2) as an independent method of absolute dating in its own right.

Basis of Method. Most trees produce a ring of new wood each year and these circles of growth can easily be seen in a cross-section of the trunk of a felled tree. These rings are not of uniform thickness. In an individual tree, they will vary for two reasons. First, the rings become narrower with the increasing age of the tree. Second, the amount a tree grows each year is affected by fluctuations in climate. In arid regions, rainfall above the average one year will produce a particularly thick annual ring. In more temperate regions, sunlight and temperature may be more critical than rainfall in affecting a tree's growth. Here, a sharp cold spell in spring may produce a narrow growth ring.

Dendrochronologists measure and plot these rings and produce a diagram indicating the thickness of successive rings in an individual tree. Trees of the same species growing in the same area will generally show the same pattern of rings so that the growth sequence can be matched between successively older timbers to build up a chronology for an area. (It is not necessary to fell trees in order to study the ring sequence: a usable sample can be extracted by boring without harming the tree.) By matching sequences of rings from living trees of different ages as well as from old timber, dendrochronologists can produce a long, continuous sequence extending back hundreds, even thousands, of years from the present. Thus, when an ancient timber of the same species (e.g. Douglas fir in the American Southwest or oak in Europe) is found, it should be possible to match its tree-ring sequence of, say, 100 years with the appropriate 100-year length of the master sequence or chronology. In this way, the felling date for that piece of timber can usually be dated to within a year.

***Applications*: (1) The Long Master Sequences and Radiocarbon.** Perhaps the greatest contribution so far of dendrochronology to archaeological dating has been the development of long tree-ring sequences, against which it has proved possible to check and calibrate radiocarbon dates. The pioneering research was done in Arizona on a remarkable species, the California bristlecone pine (*Pinus aristata*), some of which are up to 4900 years old – the oldest living things on earth. By matching samples from these living trees with rings from dead pines preserved in the region's arid environment, the scientists – led by E. Schulman and later C. Wesley Ferguson – built up an unbroken sequence back from the present as far as 6700 BC. Just how this sequence has been used for calibration work will be discussed in the section on radiocarbon below.

The research in the American Southwest has now been complemented by studies in Europe of tree-rings of oak, often well preserved in waterlogged deposits. Two separate oak sequences in Northern Ireland and western Germany both now stretch back unbroken into the distant past, as far as *c.* 5300 BC in the Irish case and *c.* 8500 BC in the German. The scientists who did the work – Michael Baillie in Belfast, the late Bernd Becker in Stuttgart, Marco Spurk from Hohenheim, and their colleagues – have also succeeded in matching the two separate sequences, thus creating a reliable central and west European absolute chronology against which to calibrate radiocarbon dates, as well as to use in direct tree-ring dating.

***Applications*: (2) Direct Tree-Ring Dating.** Where people in the past used timber from a species, such as oak, that today forms one of the dendrochronological sequences, one can obtain an archaeologically useful absolute date by matching the preserved timber with part of the master sequence. This is now feasible in many parts of the world outside the tropics.

Results are particularly impressive in the American Southwest, where the technique is longest established and wood is well preserved. Here Pueblo Indians built their dwellings from trees such as the Douglas fir and piñon pine that have yielded excellent ring sequences. Dendrochronology has become the principal dating method for the Pueblo villages, the earliest dates for which belong to the 1st century BC, although the main period of building came a millennium later.

One brief example from the Southwest will serve to highlight the precision and implications of the method. In his pioneer work, A.E. Douglass had established that Betatakin, a cliff dwelling in northwest Arizona, dated from around AD 1270. Returning to the site in the 1960s, Jeffrey Dean collected 292 tree-ring samples and used them to document not just the founding of the settlement in AD 1267, but its expansion room by room, year by year until it reached a peak in the mid-1280s, before being abandoned shortly thereafter. Estimates of numbers of occupants per room also made

Tree-ring dating of the late Bronze Age settlement of Cortaillod-Est, Switzerland, is remarkably precise. Founded in 1010 BC *with a nucleus of four houses (phase 1), the village was enlarged four times, and a fence added in 985* BC.

it possible to calculate the rate of expansion of Betatakin's population to a maximum of about 125 people. Dendrochronology can thus lead on to wider considerations beyond questions of dating.

In central and western Europe, the oak master sequences now allow the equally precise dating of the development of Neolithic and Bronze Age lake villages such as Cortaillod Est in Switzerland. In the German Rhineland, close to the village of Kückhoven, recently discovered timbers from the wooden supporting frame of a well have provided three tree-ring dates of 5090 BC, 5067 BC, and 5055 BC (see illus. p. 264). The timbers were associated with sherds of the *Linearbandkeramik* culture and thus provide an absolute date for the early practice of agriculture in western Europe. The earliest tree-ring date for the English Neolithic is from the Sweet Track in the Somerset Levels: a plank walkway constructed across a swamp during the winter of 3807/3806 BC, or shortly after (see box, pp. 330–31).

Sometimes local chronologies remain "floating" – their short-term sequences have not been tied into the main master sequences. In many parts of the world, however, master sequences are gradually being extended and floating chronologies fitted into them. In the Aegean area, for example, a master sequence is now available back to early medieval times (the Byzantine period), with earlier floating sequence stretching back in some cases to 7200 BC. In future, the link between them will no doubt be found. Considerable progress is being made toward establishing a long tree-ring chronology for Anatolia by Peter Kuniholm of Cornell.

Limiting Factors. Unlike radiocarbon, dendrochronology is not a worldwide dating method because of two basic limitations:

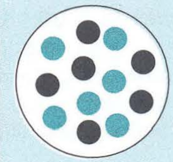
1 it applies only to trees in regions outside the tropics where pronounced differences between the seasons produce clearly defined annual rings;
2 for a direct tree-ring date it is restricted to wood from those species that (a) have yielded a master sequence back from the present and (b) people actually used in the past, and where (c) the sample affords a sufficiently long record to give a unique match.

In addition, there are important questions of interpretation to consider. A tree-ring date refers to the date of felling of the tree. This is determined by matching the tree-ring sample ending with the outermost rings (the sapwood) to a regional sequence. Where most or all of the sapwood is missing, the felling date cannot be identified. But even with an accurate felling date, the archaeologist has to make a judgment – based on context and formation processes – about how soon after felling the timber entered the archaeological deposit. Timbers may be older or younger than the structures into which they were finally incorporated, depending on whether they were reused from somewhere else, or used to make a repair in a long-established structure. As always, the best solution is to take multiple samples, and to check the evidence carefully on-site. Despite these qualifications, dendrochronology looks set to become the major dating technique alongside radiocarbon for the last 8000 years in temperate and arid lands.

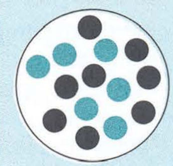
RADIOACTIVE CLOCKS

Many of the most important developments in absolute dating since World War II have come from the use of what one might call "radioactive clocks," based on that widespread and regular feature in the natural world, radioactive decay (see box). The best known of these

THE PRINCIPLES OF RADIOACTIVE DECAY



Carbon-12 atom



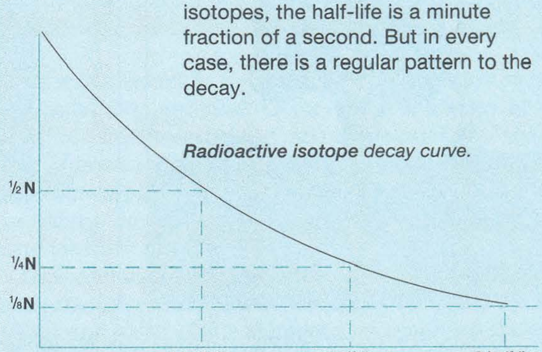
Carbon-14 atom

Neutron

Proton

Like most elements occurring in nature, carbon exists in more than one isotopic form. It has three isotopes: ^{12}C, ^{13}C, and ^{14}C – the numbers correspond to the atomic weights of these isotopes. In any sample of carbon 98.9 percent of atoms are of ^{12}C type and have six protons and six neutrons in the nucleus, and 1.1 percent are of the ^{13}C type with six protons and seven neutrons. Only one atom in a million millions of atoms of carbon will be that of the isotope ^{14}C with eight neutrons in the nucleus. This isotope of carbon is produced in the upper atmosphere by cosmic rays bombarding nitrogen (^{14}N) and it contains an excess of neutrons, making it unstable. It decays by the emission of weak beta radiation back to its precursor isotope of nitrogen – ^{14}N – with seven protons and seven neutrons in a nucleus. Like all types of radioactive decay the process takes place at a constant rate, independent of all environmental conditions.

The time taken for half of the atoms of a radioactive isotope to decay is called its half-life. In other words, after one half-life, there will be half of the atoms left; after two half-lives, one-quarter of the original quantity of isotope remains, and so on. In the case of ^{14}C, the half-life is now agreed to be 5730 years. For ^{238}U, it is 4500 million years. For certain other isotopes, the half-life is a minute fraction of a second. But in every case, there is a regular pattern to the decay.



Radioactive isotope decay curve.

methods is radiocarbon, today the main dating tool for the last 50,000 years or so. The main radioactive methods for periods before the timespan of radiocarbon are potassium-argon, uranium-series dating, and fission-track dating. Thermoluminescence (TL) overlaps with radiocarbon in the time period for which it is useful, but also has potential for dating earlier epochs – as do optical dating and electron spin resonance – all trapped electron dating methods that rely indirectly on radioactive decay. In the following sections we will discuss each method in turn.

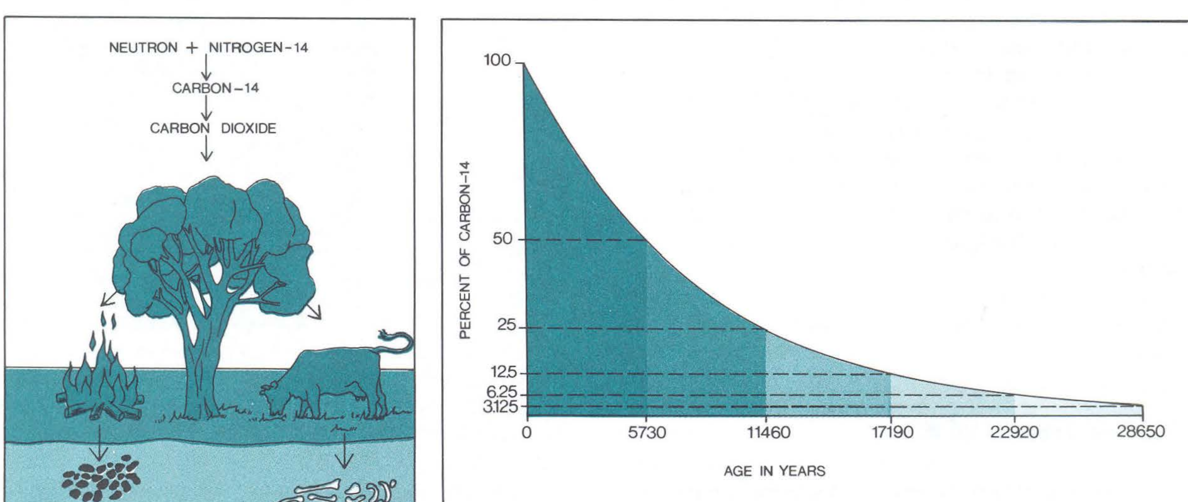
Radiocarbon Dating

Radiocarbon is the single most useful method of dating for the archaeologist. As we shall see, it has its limitations, both in terms of accuracy, and for the time range where it is useful. Archaeologists themselves are also the cause of major errors, thanks to poor sampling procedures and careless interpretation. Nevertheless, radiocarbon has transformed our understanding of the past, helping archaeologists to establish for the first time a reliable chronology of world cultures.

History and Basis of Method. In 1949, the American chemist Willard Libby published the first radiocarbon dates. During World War II he had been one of several scientists studying cosmic radiation, the sub-atomic particles that constantly bombard the earth, producing high-energy neutrons. These neutrons react with nitrogen atoms in the atmosphere to produce atoms of carbon-14 (^{14}C), or radiocarbon, which are unstable because they have eight neutrons in the nucleus instead of the usual six as for ordinary carbon (^{12}C) (see box, p. 137). This instability leads to radioactive decay of ^{14}C at a regular rate. Libby estimated that it took 5568 years for half the ^{14}C in any sample to decay – its half-life – although modern research indicates that the more accurate figure is 5730 years (for consistency laboratories still use 5568 years for the half-life; the difference no longer matters now that we have a correctly calibrated radiocarbon timescale: see below).

Libby realized that the decay of radiocarbon at a constant rate should be balanced by its constant production through cosmic radiation, and that therefore the proportion of ^{14}C in the atmosphere should remain the same throughout time. Furthermore, this steady atmospheric concentration of radiocarbon is passed on uniformly to all living things through carbon dioxide. Plants take up carbon dioxide during photosynthesis, they are eaten by herbivorous animals, which in turn are eaten by carnivores. Only when a plant or animal dies does the uptake of ^{14}C cease, and the steady concentration of ^{14}C begin to decline through radioactive decay. Thus, knowing the decay rate or half-life of ^{14}C, Libby recognized that the age of dead plant or animal tissue could be calculated by measuring the amount of radiocarbon left in a sample.

Libby's great practical achievement was to devise an accurate means of measurement. (The traces of ^{14}C are



(Left) Radiocarbon (carbon-14) is produced in the atmosphere and absorbed by plants through carbon dioxide, and by animals through feeding off plants or other animals. Uptake of ^{14}C ceases when the plant or animal dies. (Right) After death, the amount of ^{14}C decays at a known rate (50 percent after 5730 years, etc.). Measurement of the amount left in a sample gives the date.

THE PUBLICATION OF RADIOCARBON RESULTS

Radiocarbon laboratories provide an estimate of age based on their measurement of the amount of radiocarbon activity in a sample. The level of activity is converted to an age expressed in number of years between the death of an organism and the present. To avoid confusion caused by the fact that the "present" advances each year, radiocarbon laboratories have adopted AD 1950 as their "present" and all radiocarbon dates are quoted in years BP or years "before the present," meaning before 1950. Thus, in scientific publications, radiocarbon dates are given in the form:

3700 ± 100 BP (P-685)

The first figure is the year BP (i.e. before AD 1950). Next is the associated probable error known as the standard deviation (see below). Finally, in parentheses is the laboratory analysis number. Each laboratory has its own letter code (e.g. P for Philadelphia and Q for Cambridge, England).

As discussed in the main text, various factors prevent the precise measurement of radiocarbon activity in a sample and, consequently, there is a statistical error or standard deviation (which may not have been realistically calculated: see main text) associated with all radiocarbon dates. Thus, when a radiocarbon date is quoted as 3700 ±100 BP this means that there should be a 68 percent probability – two chances in three – that the correct estimate of age in radiocarbon years lies between 3800 and 3600 BP. Since there is also a one-in-three chance that the correct age does *not* fall within this range, archaeologists are advised to convert the date range to two standard deviations, i.e. to double the size of the standard deviation, so that there should be a 95 percent chance that the age estimate will be bracketed. For example, for an age estimate of 3700 ±100 BP there is a 95 percent chance that the radiocarbon age of the sample will lie between 3900 (3700 +200) and 3500 (3700 -200) BP. Obviously, the larger the standard deviation, the less precise (and for those dealing with later prehistory or historical times, the less useful) the date. For example, the 95 percent probability range of a date of 3700 ±150 BP brackets the period 4000 to 3400 BP, which is 200 years more than a date quoted at ±100 radiocarbon years.

The forms of the dates given above are laboratory determinations. They represent the uncalibrated age estimate of the sample and are based on the assumption, now known to be erroneous, that the levels of radiocarbon produced in the atmosphere have been constant through time. Thus, whenever possible the radiocarbon age should be calibrated to actual calendar years. To make clear whether or not a date has been calibrated, archaeologists often follow one of two conventions in their publications:

	Uncalibrated date	Calibrated date
"Scientific"	BP	Cal BC/AD
"Historical"	bc/ad	BC/AD

The "scientific" convention (used and promoted by the radiocarbon laboratories) has the merit of being very clear, but has the inconvenience of not providing for the discussion of an uncalibrated date in years bc or ad. The "historical" convention is less cumbersome and is for this reason preferred by many archaeologists. However, the style for distinguishing dates by simply using lower case letters (bc/ad) and upper case ones (BC/AD) is vulnerable to editorial inconsistency and to printing errors. Moreover, it is important (and difficult) to remember that an uncalibrated date of say 3500 bc is not linked to any system of reckoning in calendar years, nor is it a century older than a date of 3400 bc.

Where the archaeologist is discussing absolute chronology generally – perhaps using radiocarbon alongside other methods of dating, including historical ones – it seems logical to employ the simple BC/AD system, provided an attempt has been made to calibrate any radiocarbon dates incorporated in the chronology, and that this is stated clearly at the outset.

minute to start with, and are reduced by half after 5730 years. After 23,000 years, therefore, only one sixteenth of the original tiny concentration of ^{14}C is available to be measured in the sample.) Libby discovered that each atom of ^{14}C decays by releasing beta particles, and he succeeded in counting these emissions using a Geiger counter. This is the basis of the conventional method still employed by many radiocarbon laboratories today. Samples usually consist of organic materials found on archaeological sites, such as charcoal, wood, seeds, and other plant remains, and human or animal bone. The accurate measurement of the ^{14}C activity of a sample is affected by counting errors, background cosmic radiation, and other factors that contribute an element of uncertainty to the measurements. This means that radiocarbon dates are invariably accompanied by an estimate of the probable error: the plus/minus term (standard deviation) attached to every radiocarbon date (see box above).

One advance on the conventional method came with the introduction in some laboratories in the late 1970s and early 1980s of special gas counters capable of taking measurements from very small samples. In the conventional method one needed some 5 g of pure

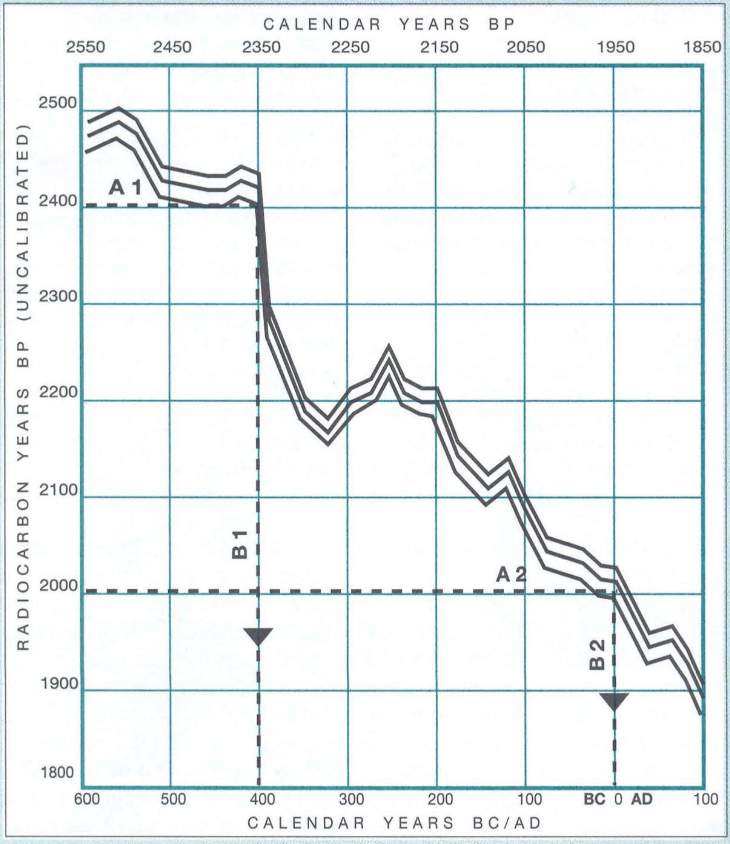
HOW TO CALIBRATE RADIOCARBON DATES

Radiocarbon laboratories will generally supply calibrated dates of their samples, but archaeologists may need to calibrate raw radiocarbon dates themselves, generally from a calibration graph.

The tree-ring calibration curve shown in the diagram (below) illustrates the relationship between radiocarbon years (BP) and tree-ring samples dated in actual calendar years (Cal BC/AD). The central line of the curve defines the mean estimate of age while the other two lines indicate the band width of the probable error at one standard deviation. In order to find the calibrated age range of a radiocarbon sample dated 2200 ±100 BP using this curve, the simplest method would be to draw two horizontal lines (A1 and A2) from the appropriate probability level on the "radiocarbon years" axis to the centre line of the calibration curve, and drop lines (B1 and B2) from these intercept points to the calendar axis. The calibrated date is then quoted as the range – or ranges – enclosed between the vertical lines (one of the problems of a wiggly calibration curve is that a single radiocarbon date will frequently calibrate to two or more possible calendar age ranges). In this instance the result would be an approximately 95 percent chance that the date of the sample falls between *c.* 405 Cal BC and 5 Cal BC.

Unfortunately, however, this does not truly reflect the information stored in the radiocarbon result. Since a radiocarbon measurement is an estimate of ^{14}C content based on a set of physical measurements, it has a known probability distribution of Gaussian or Normal form, as shown on the radiocarbon axis of the second diagram. Calibrating this probability distribution against the wiggly calibration curve is a complex process, and necessitates the use of a specialized form of statistics, termed Bayesian. This requires the use of a computer program, and is the only way to produce an accurate probability distribution of the resulting calendar age range. An effect of the wildly erratic calibration curve is to produce calendar age ranges with very irregular probability distributions, as clearly shown in this example (the tinted area under the calibration curve). This means that calibrated dates can no longer be expressed as a mean figure with ± error term. Calibrated dates are therefore expressed as possible age ranges, enclosing the most probable results at the required probability level. In this case there is a 95 percent probability that the dated event occurred between 550 Cal BC and 50 Cal AD.

It will be immediately apparent that a calibrated age range of 550 Cal BC to 50 Cal AD is too broad to be useful for most archaeological purposes. Fortunately there are two ways of narrowing the age range: high-precision dates and multiple dates. High-precision dates, obtainable so far from only a handful of the world's radiocarbon laboratories, can offer

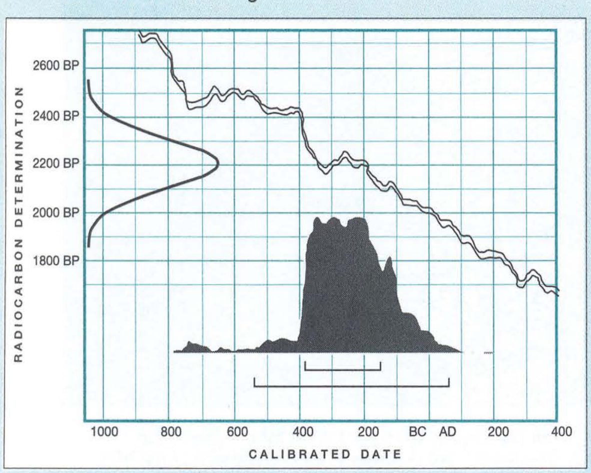


A section of the calibration curve from Stuiver and Pearson (1986) (left) to show the simple intercept method to obtain calibrated dates. Most archaeologists, however, need a more accurate assessment and the diagram (right) shows the probability distribution of the calendar date resulting from the Normal probability distribution of the radiocarbon measurement seen on the 'y'-axis.

dates quoted with a realistic error of ±20 years, which, after calibration, generally allows the sample to be dated within a century or less at the 95 percent probability level. Otherwise one can resort to multiple dates of the same sample to produce mean dates with a smaller standard deviation – hoping that the standard deviations of the dates have been realistically measured by the laboratory.

In the favorable but rare cases where the elapsed time between a series of datable events is known, it is possible to obtain a very precise date by wiggle matching. This is most frequently applied to radiocarbon dates from tree-rings. If high-precision measurements can be made of several radiocarbon samples with a known number of years between them, the resulting pattern of changes in radiocarbon content over time can be directly matched with the wiggles in the calibration curve, giving dates to within 10 or 20 years for the tree-rings included. Alternatively, where other information such as a set of radiocarbon figures linked by stratigraphy exists, it is now possible to use Bayesian statistics to combine all the known data. This was undertaken for the recent re-dating of Stonehenge.

Calibration programs and curves can be obtained directly from the *Radiocarbon* website at www.radiocarbon.org.



carbon after purification, which means an original sample of some 10–20 g of wood or charcoal, or 100–200 g of bone. The special equipment required only a few hundred milligrams (mg) of charcoal.

Several laboratories now use the accelerator mass spectrometry (AMS) method, which requires smaller samples still. AMS counts the atoms of ^{14}C directly, disregarding their radioactivity. The minimum sample size is reduced to as little as 5–10 mg – thus enabling precious organic materials, such as the Turin Shroud (see below), to be sampled and directly dated. Initially it was hoped that the datable timespan for radiocarbon using AMS could be pushed back from 50,000 to 80,000 years, although this is proving difficult to achieve, in part because of sample contamination.

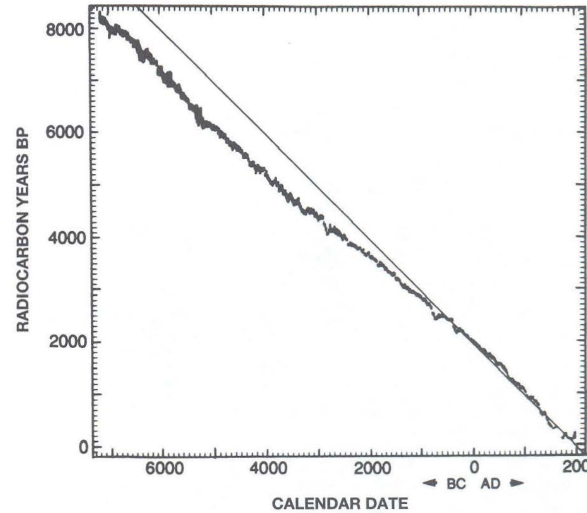
Calibration of Radiocarbon Dates. One of the basic assumptions of the radiocarbon method has turned out to be not quite correct. Libby assumed that the concentration of ^{14}C in the atmosphere has been constant through time; but we now know that it has varied, largely due to changes in the earth's magnetic field. The method that demonstrated the inaccuracy – tree-ring dating – has also provided the means of correcting or calibrating radiocarbon dates.

Radiocarbon dates obtained from tree-rings show that before about 1000 BC dates expressed in radiocarbon years are increasingly too young in relation to true calendar years. In other words, before 1000 BC trees (and all other living things) were exposed to greater concentrations of atmospheric ^{14}C than they are today. By obtaining radiocarbon dates systematically from the long tree-ring master sequences of bristlecone pine and oak (see above), scientists have been able to plot radiocarbon ages against tree-ring ages (in calendar years) to produce calibration curves back to around 8500 BC. The journal *Radiocarbon* publishes the most up-to-date curves which in principle permit the conversion of radiocarbon dates to calibrated dates. Very broadly, radiocarbon ages diverge increasingly from true ages before 1000 BC, so that by 5000 BC in calendar years the radiocarbon age is 900 years too young. Thus an age estimate in radiocarbon years of 4100 BC might well in fact when calibrated be somewhere near 5000 BC. It is this pushing back of many dates that has brought about the Second Radiocarbon Revolution (see above). Recently, comparison of ^{14}C dates and high precision uranium-series dates (see p. 146) from core samples of ancient coral reefs near Barbados has produced a calibration curve for radiocarbon from *c.* 9000 BP (the limit of tree-ring calibration) back to 40,000 BP. It has been found that between 18,000 and 40,000 BP, ^{14}C dates are about 3000 years too young.

The calibration curve (INTCAL98) recently produced by Minze Stuiver and co-workers combines the available data from tree-rings, uranium-thorium dated corals, and varve-counted marine sediment, to give a curve from 24,000 to 0 Cal BP. There are short-term wiggles in the curve, however, and occasionally, sections of the curve that run so flat that two samples with the same age in radiocarbon years might in reality be 400 years apart in calendar years, a problem that is particularly irksome for the period 800–400 BC in calendar years. To be accurate one needs to calibrate not merely the central radiocarbon date (e.g. 2200 BP) but its error estimate as well (2200 ± 100 BP), which will produce an *age range* in calendar years (see box, pp. 140–41). Some of the ranges will be narrower and more precise than others, depending on where on the curve the radiocarbon date with its error estimate falls.

An age range produced by visual calibration is limited as it contains no statement of probability – it cannot say whether the true age of a dated sample is more likely to be found in one part of the range than in another. To some extent this limitation is overcome by computer calibration. Several programs are now available which use a statistical methodology, termed Bayesian, to generate probability distributions of age estimations for single ^{14}C dates. Bayesian methods have been used, for instance at Stonehenge, to model complex archaeological event sequences by combining multiple related ^{14}C dates with associated chronological information such as that derived from stratigraphy.

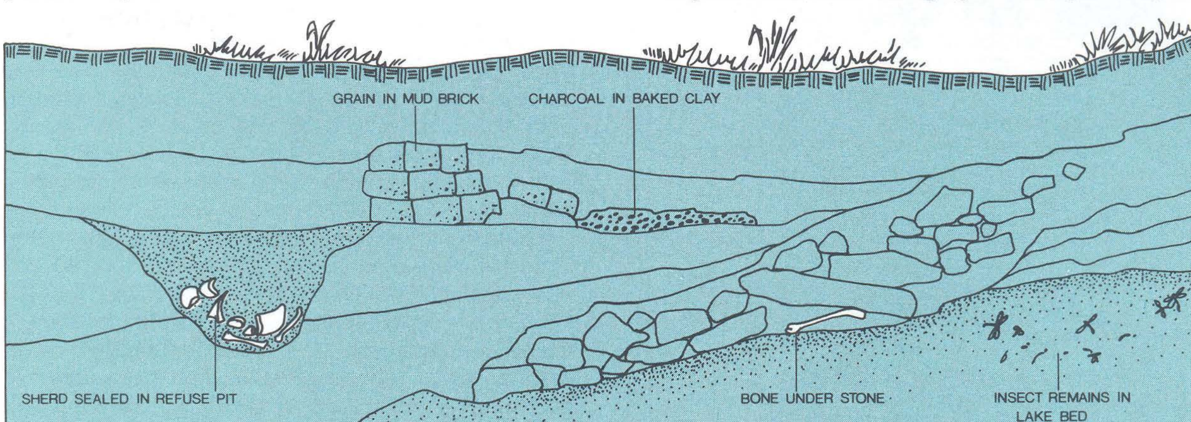
The crucial point is that in any publication it should be indicated whether or not the radiocarbon determination has been calibrated, and if it has been, by which particular system or curve.



Stuiver and Pearson's calibrated radiocarbon timescale based on Irish oak. The straight line indicates the ideal 1:1 radiocarbon / calendar age timescale.

Contamination and Interpretation of Radiocarbon Samples. Although radiocarbon dates have certain inescapable levels of error associated with them, erroneous results are as likely to derive from poor sampling and incorrect interpretation by the archaeologist as from inadequate laboratory procedures. The major sources of error in the field are as follows:

1 ***Contamination before sampling.*** Problems of contamination of the sample within the ground can be serious. For instance, groundwater on waterlogged sites can dissolve organic materials and also deposit them, thus changing the isotopic composi-



Samples for radiocarbon dating should be obtained, wherever possible, from the kind of contexts shown here – where the material to be dated has been sealed in an immobilizing matrix. The stratigraphic context of the sample must be clearly established by the excavator before the material is submitted to the laboratory for dating.

tion; the formation of mineral concretions around organic matter can bring calcium carbonate entirely lacking in radiocarbon, and thus fallaciously increase the apparent radiocarbon age of a specimen by effectively "diluting" the ^{14}C present. These matters can be tackled in the laboratory.

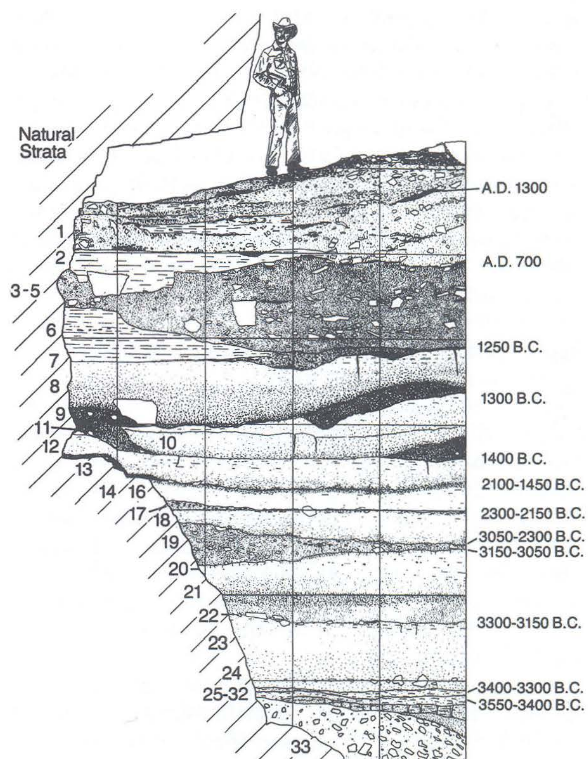
2 *Contamination during or after sampling.* All radiocarbon samples should be sealed within a clean container such as a plastic bag at the time of recovery. They should be labeled in detail at once on the outside of the container; cardboard labels inside can be a major source of contamination. The container should be placed inside another: one plastic bag, well sealed, inside another bag separately sealed can be a sound procedure for most materials. But wood or carbon samples that may preserve some tree-ring structure should be more carefully housed in a rigid container. Wherever possible exclude any modern carbon, such as paper, which can be disastrous. However, modern roots and earth cannot always be avoided: in such cases, it is better to include them, together with a note for the laboratory, where the problem can be tackled.

Application of any organic material later – such as glue or carbowax – is likewise disastrous (although the laboratory may be able to remedy it). So is continuing photosynthesis within the sample: for this reason, the relevant containers should be stored in the dark. A green mold is not uncommon in sample bags on some projects. It automatically indicates contamination of the sample.

3 *Context of deposition.* Most errors in radiocarbon dating arise because the excavator has not fully understood the formation processes of the context in question. Unless it is appreciated how the organic material found its way to the position where it was found, and how and when (in terms of the site) it came to be buried, then precise interpretation is impossible. The first rule of radiocarbon dating must be that the excavator should not submit a sample for dating unless he or she is sure of its archaeological context.

4 *Date of context.* Too often, it is assumed that a radiocarbon determination, e.g. on charcoal, will give a straightforward estimate for the date of the charcoal's burial context. However, if that charcoal derives from roof timbers that might themselves have been several centuries old when destroyed by fire, then one is dating some early construction, not the context of destruction. There are numerous examples of such difficulties, one of the most conspicuous being the reuse of such timbers or even of fossil wood (e.g. "bog oak") whose radiocarbon date could be centuries earlier than the context in question. For this reason, samples with a short life are often preferred, such as twigs of brushwood, or charred cereal grains that are not likely to be old at the time of burial.

A strategy for sampling will recall the wise dictum that "one date is no date": several are needed. The best dating procedure is to work toward an internal relative sequence – for instance, in the stratigraphic succession on a well-stratified site such as the Gatecliff Shelter, Monitor Valley, Nevada, excavated by David Hurst Thomas and his associates. If the samples can be arranged in relative sequence in this way with the lowest unit having the earliest date and so on, then there is an internal check on the coherence of the laboratory determinations and on the quality of field sampling. Some of the dates from such a sequence may come out older than expected. This is quite reasonable – as explained above, some of the material may have been



Master profile for Gatecliff Shelter, Nevada, produced by David Hurst Thomas, showing how dates derived from radiocarbon determinations are consistent with the stratigraphic succession.

"old" at the time of burial. But if they come out younger (i.e. more recent) than expected, then there is something wrong. Either some contamination has affected the samples, or the laboratory has made a serious error, or – as not infrequently happens – the stratigraphic interpretation is wrong.

Although many problems with radiocarbon dates may be attributed to the submitter, recent evidence suggests that radiocarbon laboratories themselves may be overestimating the precision of their own dates. In one comparative study, over 30 radiocarbon laboratories dated the same sample. While some estimated their errors within reasonable accuracy others did not, and one laboratory produced systematic errors of 200 years. In general, it was seen that although radiocarbon laboratories might quote levels of precision of ±50 years, in fact it was safer to assume that their actual errors were ±80 years or more. As the interlaboratory study comprised an anonymous sample of the world's radiocarbon laboratories, the archaeological community has no way of knowing how widespread the underestimation of errors is or how systematically biased in their radiocarbon dates some laboratories are. Archaeologists would be best advised to treat radiocarbon laboratories like purveyors of any other service and request evidence that they deliver both the accuracy and the precision they purport to offer. Many laboratories are aware of their past biases and now quote realistic statements of precision which need not be regarded as underestimates. Furthermore, often they may be approached to quote new and more realistic errors for their earlier dates.

Part of the Turin Shroud, bearing the image of a man's head. Radiocarbon AMS dating has given a calibrated age range for the cloth of AD *1260–1390.*

Applications: The Impact of Radiocarbon Dating. If we seek to answer the question "When?" in archaeology, radiocarbon has undoubtedly offered the most generally useful way of finding an answer. The greatest advantage is that the method can be used anywhere, whatever the climate, as long as there is material of organic (i.e. living) origin. Thus the method works as well in South America or Polynesia as it does in Egypt or Mesopotamia. And it can take us back 50,000 years – although at the other end of the timescale it is too imprecise to be of much use for the 400 years of the most recent past.

The use of the method on a single site has been illustrated by reference to the Gatecliff Shelter, Nevada. A recent interesting application is the dating of the newly discovered Upper Paleolithic paintings in the Chauvet Cave, southern France. Tiny samples from three paintings done with charcoal were dated, producing a series of results centered around 31,000 BP – far older than anticipated. Two different laboratories also dated samples of charcoal from the floor, and obtained results of around 29,000 BP, not significantly different from the paintings, and also around 24,000 BP. Torch-marks were analyzed, producing dates of around 26,500 BP. The surprisingly early dates for the paintings show the value of obtaining a series of dates – a single date coming out so early would probably have aroused skepticism. If these still controversial results are valid it seems there were several different phases of use of the cave, each separated by a few thousand years.

On a wider scale radiocarbon has been even more important in establishing for the first time broad chronologies for the world's cultures that previously lacked timescales (such as calendars) of their own. Calibration of radiocarbon has heightened, not diminished, this success. As we saw in the section above on Calendars and Historical Chronologies, calibration has helped assert the validity of an independent radiocarbon chronology for prehistoric Europe, free from false links with the Egyptian historical chronology.

Radiocarbon dating by the AMS technique is opening up new possibilities. Precious objects and works of art can now be dated because minute samples are all that is required. In 1988 AMS dating resolved the long-standing controversy over the age of the Turin Shroud, a piece of cloth with the image of a man's body on it that many genuinely believed to be the actual imprint of the body of Christ. Laboratories at Tucson, Oxford, and Zurich all placed it in the 14th century AD, not from the time of Christ at all, although this remains a matter of controversy. Likewise it is now possible to date a single grain of wheat or a fruit pip. An AMS reading on a grape pip from Hambledon Hill, southern Britain, shows that grapes – and probably vines as well – had reached this part of the world by 3500 BC in calendar years, over 3000 years earlier than had previously been supposed.

Radiocarbon looks set to maintain its position as the main dating tool back to 50,000 years ago for organic materials. For inorganic materials, however, thermoluminescence (p. 151) and other, new, techniques are very useful.

Potassium-Argon (and Argon-Argon) Dating

The potassium-argon (K-Ar) method is used by geologists to date rocks hundreds or even thousands of millions of years old. It is also one of the most appropriate techniques for dating early human (hominid) sites in Africa, which can be up to 5 million years old. It is restricted to volcanic rock no more recent than around 100,000 years.

Basis of Method. Potassium-argon dating, like radiocarbon dating, is based on the principle of radioactive decay: in this case, the steady but very slow decay of the radioactive isotope potassium-40 (^{40}K) to the inert gas argon-40 (^{40}Ar) in volcanic rock. Knowing the decay rate of ^{40}K – its half-life is around 1.3 billion years – a measure of the quantity of ^{40}Ar trapped within a 10 g rock sample gives an estimate of the date of the rock's formation.

A more sensitive variant of the method, which requires a smaller sample, sometimes a single crystal extracted from pumice (single crystal laser fusion), is known as laser-fusion argon-argon dating ($^{40}Ar/^{39}Ar$ dating). A stable isotope of potassium, ^{39}K, is converted to ^{39}Ar by neutron bombardment of the sample to be dated. Both argon isotopes are then measured by mass spectrometry after their release by laser fusion. As the $^{40}K/^{39}K$ ratio in a rock is constant, the age of the rock can be determined from its $^{40}Ar/^{39}Ar$ ratio. As with all radioactive methods, it is important to be clear about what sets the radioactive clock to zero. In this case, it is the formation of the rock through volcanic activity, which drives off any argon formerly present.

The dates obtained in the laboratory are in effect geological dates for rock samples. Happily, some of the most important areas for the study of the Lower Paleolithic, notably the Rift Valley in East Africa, are areas of volcanic activity. This means that archaeological remains often lie on geological strata formed by volcanic action, and hence suitable for K-Ar dating. In addition, they are often overlain by comparable volcanic rock, so that dates for these two geological strata provide a chronological sandwich, between the upper and lower slices of which the archaeological deposits are set. It has recently been shown, by argon-argon analysis of pumice from the eruption of Vesuvius in AD 79 (giving an age of 1925 ± 94 years), that the method has a good degree of precision even for quite recent eruptions.

Applications: Early Human Sites in East Africa. Olduvai Gorge in Tanzania is one of the most crucial sites for the study of hominid evolution, as it has yielded fossil remains of *Australopithecus* (*Paranthropus*) *boisei*, *Homo habilis*, and *Homo erectus* (see pp. 162–63) as well as large numbers of stone artifacts and bones. Being in the Rift Valley, Olduvai is a volcanic area, and its 2-million-year chronology has been well established by K-Ar dating and Ar-Ar dating of the relevant deposits of hardened volcanic ash (tuff) and other materials between which the archaeological remains are found (see box, pp. 148–49). The K-Ar method has also been immensely important in dating other early East African sites, such as Hadar in Ethiopia.

Limiting Factors. The results of K-Ar dating are generally accompanied by an error estimate, as in the case of other radioactivity-based methods. For example, the date of Tuff IB at Olduvai has been measured as 1.79 ± 0.03 million years. An error estimate of 30,000 years might at first seem a large one, but it is in fact only of the order of 2 percent of the total age. (Note that here, as in other cases, the estimate of error relates to the counting process in the laboratory, and does not seek to estimate also other sources of error arising from varying chemical conditions of deposition, or indeed from uncertainties of archaeological interpretation.)

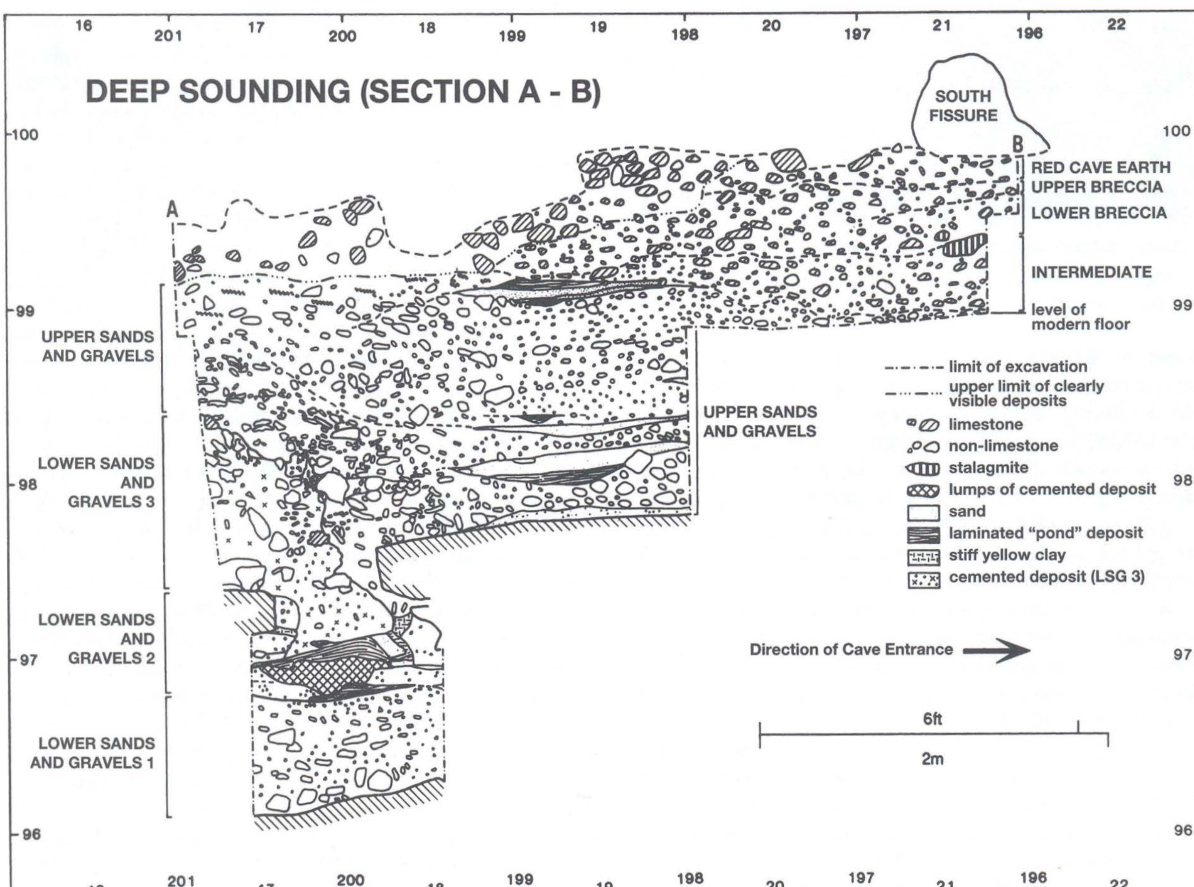
The principal limitations of the technique are that it can only be used to date sites buried by volcanic rock, and that it is rarely possible to achieve an accuracy of better than ± 10 percent. Potassium-argon dating has nevertheless proved a key tool in areas where suitable volcanic materials are present.

Uranium-Series Dating

This is a dating method based on the radioactive decay of isotopes of uranium. It has proved particularly useful for the period 500,000–50,000 years ago, which lies outside the time range of radiocarbon dating. In Europe, where there are few volcanic rocks suitable for dating by the potassium-argon technique, uranium-series (U-series) dating may be the method of first choice for clarifying when a site was occupied by early humans.

Basis of Method. Two radioactive isotopes of the element uranium (^{238}U and ^{235}U) decay in a series of stages into daughter elements. Two of these daughter elements, thorium (^{230}Th, also called "ionium," a daughter of ^{238}U) and protactinium (^{231}Pa, a daughter of ^{235}U), themselves also decay with half-lives useful for dating. The essential point is that the parent uranium isotopes are soluble in water, whereas the daughter products are not. This means, for instance, that only the uranium isotopes are present in waters that seep into limestone caves. However, once the calcium carbonate, with uranium impurities, dissolved in those waters is precipitated as travertine onto cave walls and floors then the radioactive clock is set going. At the time of its formation the travertine contains only water soluble ^{238}U and ^{235}U: it is free of the insoluble ^{230}Th and ^{231}Pa isotopes. Thus the quantities of the daughter isotopes increase through time as the uranium decays, and by measuring the daughter/parent ratio, usually $^{230}Th/^{238}U$, the age of the travertine can be determined.

The isotopes are measured by counting their alpha emissions; each isotope emits alpha radiation of a characteristic frequency. In favorable circumstances, the method leads to dates with an associated uncertainty (standard error) of ±12,000 years for a sample with an age of 150,000 years, and of about ±25,000 years for a sample of age 400,000 years. These figures can be greatly reduced by using thermal ionization mass spec-

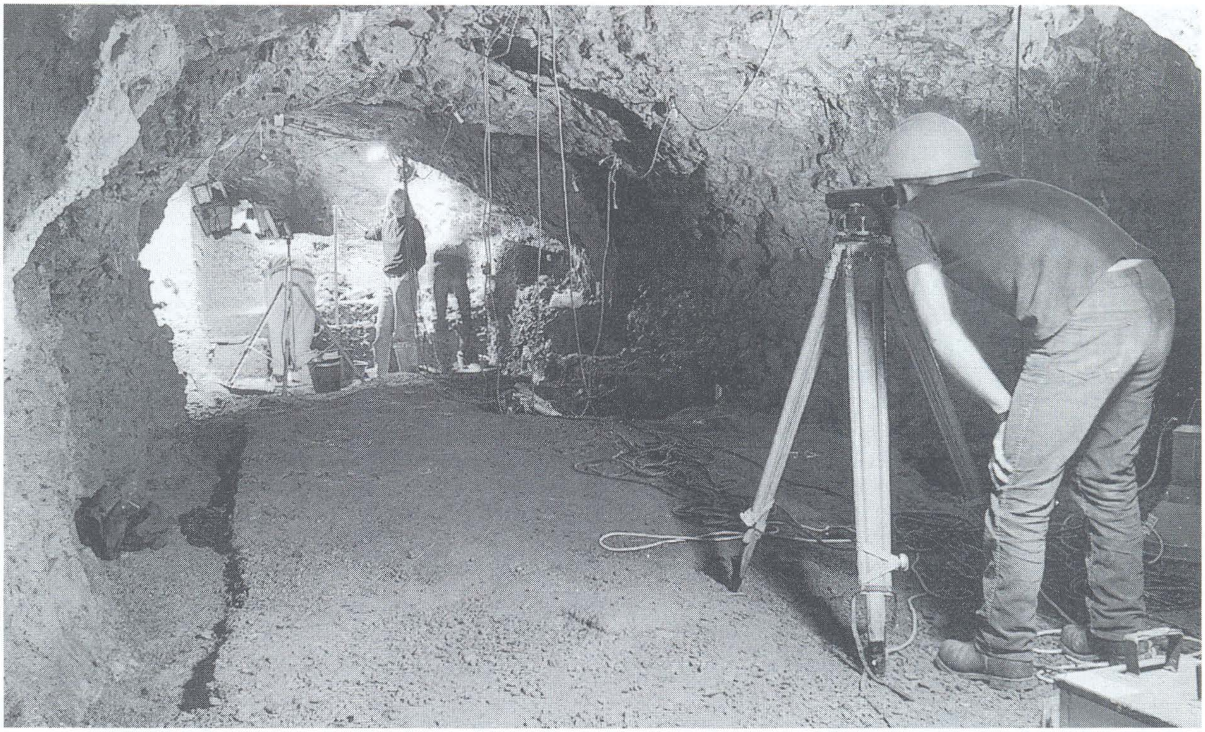


trometry (TIMS) to measure directly the quantities of each isotope present. Such high-precision dates might, for instance, have an associated uncertainty of less than 1000 years for a 100,000-year-old sample.

Applications and Limiting Factors. The method is used to date rocks rich in calcium carbonate, often those deposited by the action of surface or ground waters around lime-rich springs or by seepage into limestone caves. Stalagmites form on cave floors in this way. As early humans used caves and overhanging rocks for shelter, artifacts and bones often became embedded in a layer of calcium carbonate or in another type of sediment between two layers of the calcareous deposit.

The difficulty of determining the correct order of deposition in a cave is one reason why the U-series method is prone to give ambiguous results. For this and other reasons, several layers of deposit in a cave need to be sampled and the geology meticulously examined. The method has nevertheless proved very useful. At the Pontnewydd Cave in North Wales, the lower breccia which contained the bulk of the archaeological finds there was shown by U-series dating to be at least 220,000 years old. The important site of Bilzingsleben in eastern Germany was also dated by this method, the travertine layer which enclosed the artifacts and human skeletal remains giving an age of around 414,000 years, though some uncertainty remains, as with many U-series determinations.

Teeth can also be dated by this method, because water soluble uranium diffuses into dentine after a tooth has become buried, although there are problems estimating the rate of uranium uptake through time (see section on electron spin resonance dating, pp. 154–55). Nevertheless, TIMS U-series dating has been employed successfully to date mammalian teeth found in association with hominid skeletons in three Israeli caves. Three dates with ages of between 98,000 years and 105,000 years were obtained for strata containing Neanderthal remains at Tabun. The skeletal remains of



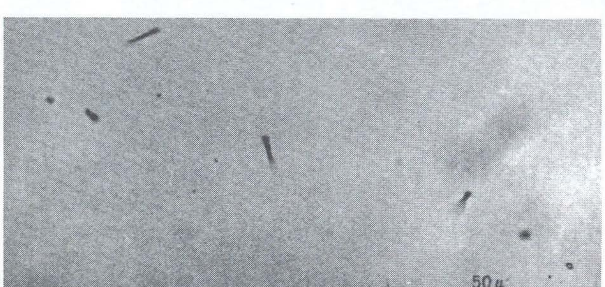
Uranium-series dating and Pontnewydd Cave, North Wales (left, deep section; above, measurements being taken in the cave). The lower breccia contained the bulk of the finds at this important Paleolithic site, including the hominid remains such as a tooth of Neanderthal type. A stalagmite on the lower breccia was found by the U-series method to be more than 220,000 years old. The result was confirmed by a TL determination on the same stalagmite, and by another TL reading on a burnt flint core – from a layer immediately underlying the lower breccia – which gave a statistically consistent age of 200,000 ±25,000 years.

early modern humans found at Qafzeh were shown to be between 85,000 and 110,000 years old, while a series of anatomically related skeletons at Skhūl were shown to be between 66,000 and 102,000 years old. Increasingly U-series dates are being used in conjunction with electron spin resonance dates using the same materials. Neanderthal individuals from Krapina in Croatia were dated by both methods using tooth enamel, both methods giving ages of around 130,000 years. However, the proposed dating of *Homo erectus* remains from Ngandong in Java, using both the U-series and ESR methods on samples from animal bones, to the surprisingly recent age of 27,000 years has been questioned – not on the basis of the analyses themselves but the uncertainty of the stratigraphy and the associations of the materials.

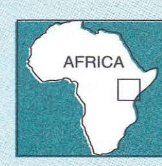
Fission-Track Dating

Fission-track dating is another method based on the operation of a radioactive clock. This time, it is the spontaneous fission of an isotope of uranium (^{238}U) present in a wide range of rocks and minerals, in obsidian and other volcanic glasses, in glassy meteorites (tektites), in manufactured glasses, and in mineral inclusions in pottery. As in the case of potassium-argon dating – with whose time range it overlaps – the method produces useful dates from suitable rocks that contain or are adjacent to those containing archaeological evidence.

Basis of Method. As well as decaying naturally to a stable lead isotope, ^{238}U occasionally also divides in half. During this process of spontaneous fission the halves move apart at high speed, coming to a halt only after causing much damage to structures in their path. In materials containing ^{238}U, such as natural glasses, this damage is recorded in the form of pathways called *fission tracks*. The tracks are counted under an optical microscope after the polished surface of the glass has



Examples of fission tracks, after etching.



DATING OUR AFRICAN ANCESTORS

In the 19th century, Charles Darwin firmly believed that human origins lay in Africa, and the 20th century has proved him right. Our earliest ancestors have been discovered at several sites in East Africa and southern Africa (see p. 145). One of the greatest triumphs of scientific chronology in the postwar years has been the successful dating and correlating of these sites – particularly those in East Africa – derived from three main methods: potassium-argon (K-Ar), fission-track, and geomagnetic dating. In addition, the relative method of faunal dating has been used to check these results.

Olduvai Gorge

Thanks to the discoveries of early hominid fossils in the gorge by Louis and Mary Leakey, Olduvai is one of the most crucial sites for the study of human evolution. It has proved possible to establish a chronology for the site, particularly on the basis of K-Ar dating of deposits of hardened volcanic ash (tuff), between which the fossil remains lie. For example, the age

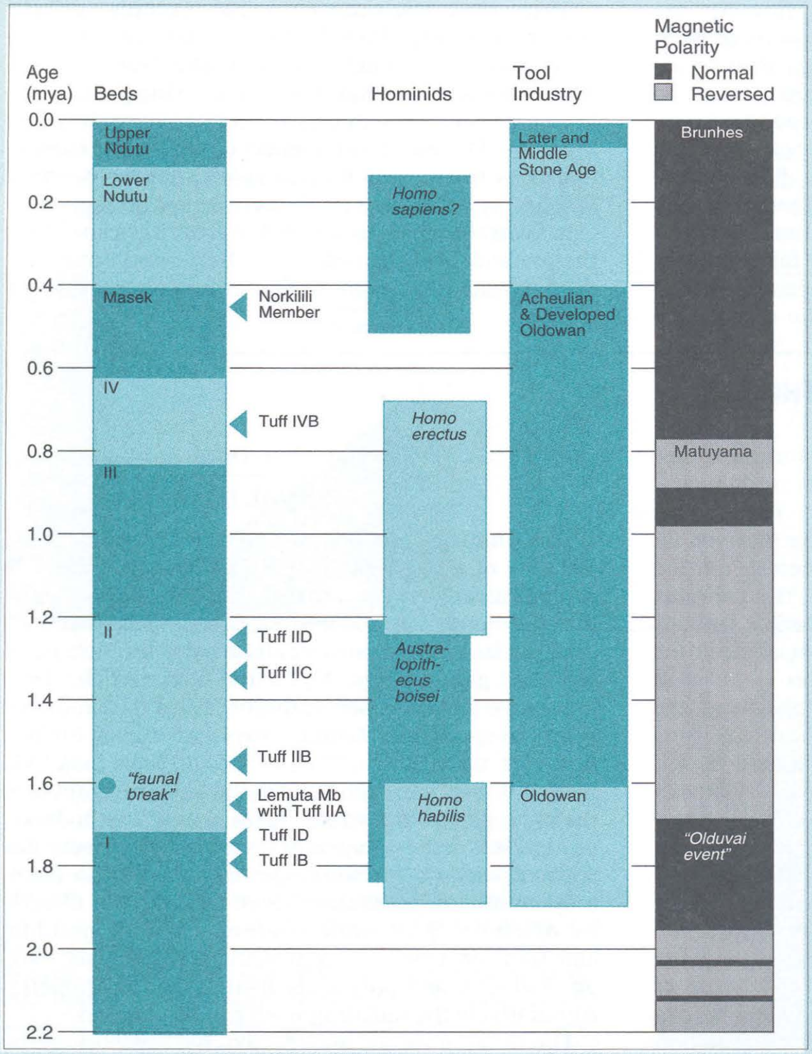
Principal early hominid sites in East Africa.

of the important Tuff IB in Bed I was estimated as 1.79 ±0.03 my (million years).

As with all archaeological dating, for a reliable result one should cross-check age estimates derived from one method with those from another. In the case of Bed I laser-fusion argon-argon dating has produced a result of 1.8–1.75 my. A fission-track reading gave a date of 2.03 ±0.28 my, which is within the statistically acceptable confidence limits for the K-Ar estimate.

Another means of checking the K-Ar sequence proved to be geomagnetic dating. As explained on pp. 158–59, there have been periodic reversals in the direction of the earth's magnetic field (the North Pole becoming the South Pole and vice versa). Magnetically charged particles in rocks preserve a record of the sequence of these reversals (from "normal" to "reversed" and back again). It transpired that Beds I–III and part of IV at Olduvai lay within the so-called Matuyama epoch of reversed polarity, with a significant period of normal polarity 1.87–1.67 million years ago first demonstrated at the site and now known, appropriately, as the "Olduvai event." The discovery of the same sequence of reversals at other East African sites (e.g. East Turkana and Omo) has helped correlate their deposits with those at Olduvai.

A further check on the validity of these sequences is the relative method of faunal dating (biostratigraphy), explained on pp. 127–28. The evolutionary tree for the pig family has proved among the most useful, helping to confirm the correlations among East African sites, including Olduvai, derived from other dating methods.



The KBS Tuff Controversy

Nowhere has the need for extreme care in dating fossil human remains been more evident than in the case of the *Homo habilis* skull, "1470," unearthed by Richard Leakey at East Turkana, Kenya, in 1972. Preliminary K-Ar results from a British laboratory on the so-called KBS tuff above the skull deposit gave a date of *c.* 2.6 my, at least 0.8 my earlier than *H. habilis* finds elsewhere. Could the K-Ar date be right? At first, cross-checking by geomagnetic reversals and fission-track seemed to support it. But there was the worrying fact that pig fossil correlations with other sites implied a date no earlier than 2 my. And in 1974 an American laboratory produced K-Ar readings of *c.* 1.8 my for the tuff.

The controversy dragged on for several years. Eventually one of the scientists who had originally published fission-track dates supporting the older K-Ar readings re-ran fission-track tests and confirmed the younger estimate of *c.* 1.8 my. Finally, to resolve the issue, Leakey commissioned an Australian laboratory to obtain new K-Ar dates. The result was a now generally accepted age for the KBS tuff of 1.88 ±0.02 my.

***Olduvai Gorge** schematic stratigraphy, together with hominids and tool industries from the site, and magnetic reversals.*

been etched with acid to improve visibility. The quantity of uranium present in the sample is then determined by counting a second set of tracks created by artificially inducing fission in atoms of ^{235}U. (The ratio of ^{235}U to ^{238}U is known, so that the second count indirectly measures the amount of ^{238}U present.) Knowing the rate of fission of ^{238}U, one arrives at a date – the age since the setting of the clock to zero – by comparing the number of spontaneously induced tracks with the quantity of ^{238}U in the sample.

The radioactive clock is set at zero by the formation of the mineral or glass, either in nature (as with obsidian and tektites) or at the time of manufacture (as with manufactured glass).

Applications and Limiting Factors. The fission-track technique is most useful for early Paleolithic sites, especially where the potassium-argon method cannot be applied. Fission-track also provides independent confirmation of dating results. For example, the date of 2.03 ± 0.28 million years obtained by fission-track analysis for Tuff IB at Olduvai Gorge, Tanzania, falls within the age determination by potassium-argon and other methods of 2.1–1.7 million years for this early hominid site (see box, pp. 148–49). Fission-track also helped to settle the controversy over the date of the KBS Tuff and associated hominid remains and artifacts at the East Turkana sites, Kenya.

The fission-track technique is most easily applied to naturally occurring materials such as pumice and obsidian, but minerals within rock formations (e.g. zircon and apatite which contain high amounts of uranium) can also be dated in this way. The potential time range is considerable: micas from Zimbabwe in Africa have been dated back to more than 2500 million (or 2.5 billion) years ago. Generally, the method is used for geological samples no younger than about 300,000 years old. For more recent material, the method is too time-consuming to operate; here thermoluminescence dating or some other method is generally better.

There are a few exceptions. For example, artificial glass and pottery glazes less than 2000 years old have been dated successfully by the fission-track method. A different application is to obsidian artifacts that have been exposed to fire during manufacture, or during or after use. The heat has the effect of setting the radioactive clock to zero and the tracks left after the fission of ^{238}U can be counted as if this were an artificial glass.

In favorable circumstances, the error associated with the method is of the order of ± 10 percent (one standard deviation), assuming that at least 100 tracks are counted.

TRAPPED ELECTRON DATING METHODS

The following three methods – thermoluminescence dating, optical dating, and electron spin resonance – are also dependent upon radioactive decay, but indirectly, as it is the amount of radiation received by the specimen to be dated which is of interest, not the radiation emitted by the specimen itself. The methods can only be used to date crystalline materials (minerals) and are dependent upon the behavior of electrons within a crystal when exposed to radiation.

When atoms located within a crystal lattice are exposed to nuclear radiation, individual electrons absorb energy and become detached from their parent nuclei and are "trapped" in lattice defects – crystal imperfections caused by missing atoms or the presence of impurities. Provided the amount of radiation (annual dose) remains constant over time then trapped electrons will accumulate at a uniform rate and the size of the trapped electron population will relate directly to the total amount of radiation received by the specimen (total dose), and thus to the total time of exposure. The age of an archaeological specimen can therefore be determined by dividing the total radiation dose by the annual radiation dose.

$$\text{AGE} = \frac{\text{TOTAL DOSE}}{\text{ANNUAL DOSE}}$$

The annual dose is received mainly from radioisotopes of three elements which occur naturally in geological deposits: uranium, thorium, and a radioactive isotope of potassium, ^{40}K. The radiation emitted by these isotopes consists of alpha particles, beta particles, and gamma rays. Alpha and beta particles have low range and poor penetrability, about 0.02 mm and 2 mm respectively. Gamma rays can travel further, however, up to 20 cm. The isotopes all have long half-lives and their emission is assumed to be constant over the time period for which these dating methods are used. This means that measurement of present-day concentrations of radioisotopes can be used to determine annual dose. Measurement can proceed directly by determining absolute concentrations of uranium and thorium using neutron activation analysis (box, pp. 360–61), and potassium using flame photometry. Alternatively the radiation itself can be counted.

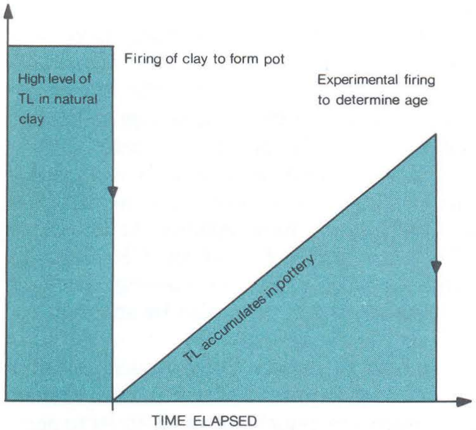
The total dose is determined by measuring the number of trapped electrons, and the different dating methods are distinguished by their different measurement techniques. Accurate determination of the size of the trapped electron population requires that all electron traps were emptied, or set to zero, during the lifetime of the material to be dated. There are various ways in which this can occur, but it is a requirement that limits the range of minerals which are suitable for dating by these methods.

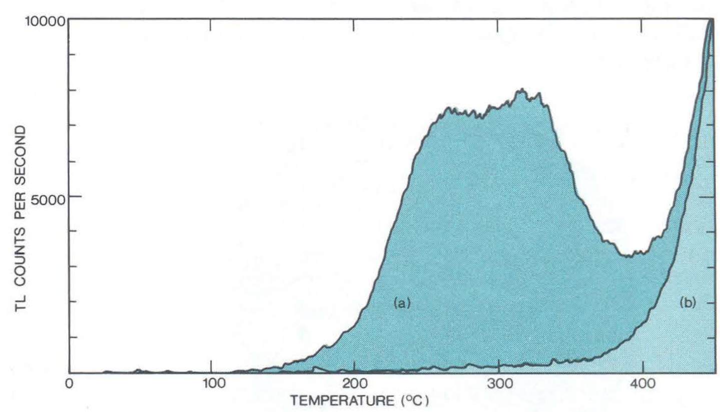
Thermoluminescence Dating

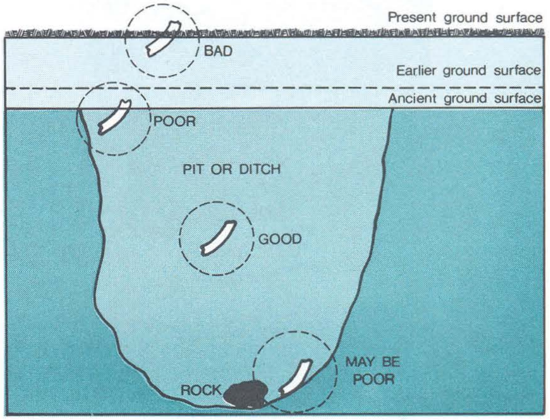
Thermoluminescence (TL) has two advantages over radiocarbon: it can date pottery, the most abundant inorganic material on archaeological sites of the last 10,000 years; and it can in principle date inorganic materials (such as burnt flint) beyond 50,000 years of age, the limit of radiocarbon. But the precision of TL is, in general, poorer than that of radiocarbon.

Basis of Method. It is possible to empty electron traps by the application of heat. Thus TL dating may be performed on minerals which have had their electron traps set to zero by exposure to high temperature prior to burial. Typically these include ceramics, which are fired during their manufacture, as well as other materials such as flint which may have been deliberately or accidentally burned before discard.

As ceramics are manufactured from a geological material, clay, they contain small amounts of radioactive elements. Thus the annual radiation dose of buried pottery is derived from two sources: externally, from the environment of the pot; and internally from the ceramic material itself. As alpha and beta particles are of such poor penetrative ability their effect on the pot can be eliminated by removing the outer few millimeters. Thus the annual dose may be calculated from the amounts of radioisotopes present within the ceramic fabric and the amount of gamma radiation a pot receives from its surroundings. Ideally the radioactivity of the soil is measured on site by the burial of a small capsule containing a radiation-sensitive material, which is left for about a year. Where this is not possible, a more rapid determination using a radiation counter can be used, or samples of the soil





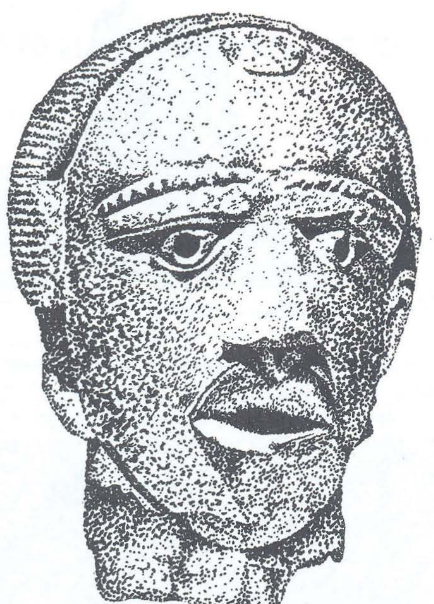


Thermoluminescence dating. (Above left) The TL clock in pottery is set to zero when a vessel is fired. TL accumulates until the pot is heated again in the present day to determine its age. (Above right) Glow-curves observed in the laboratory. Curve (a) displays the light emitted when the sample is first heated. Curve (b) is the non-TL light recorded in a second heating (the red-hot glow observable when any sample is heated). The extra light emitted in the first heating is the TL measured for dating. (Right) Good and bad locations for TL samples. Results will be inaccurate if the subsoil or rock near the sample at the bottom have a measurably different level of radioactivity from that of the filling of the pit or ditch.

collected in plastic bags and dispatched to the laboratory with the object to be dated. Where the radioactivity of the burial context cannot be determined, e.g. for an object not *in situ*, the TL date is much less accurate.

The total radiation dose is determined in the laboratory by heating the material rapidly to 500°C (932°F) or above. Energy lost by electrons as they are evicted from their traps is emitted as light radiation and is termed thermoluminescence. This luminescence is measured and is directly proportional to the number of trapped electrons, and thus to the total radiation dose. It is therefore possible to speak of a mineral accumulating a TL signal as it grows older; or, by analogy with radioactive clocks, of a TL clock.

Applications. A good example of the archaeological application of TL is the dating of the terracotta known as the Jemaa head, from the alluvium of a tin mine near the Jos Plateau of Nigeria. The head and similar examples belong to the Nok culture, but such sculptures could not be dated reliably at the site of Nok itself because of the lack of any plausible radiocarbon dates. A TL reading on the head gave an age of 1520 ±260 BC, allowing this and similar terracotta heads from the Nok region to be given a firm chronological position for the first time.



Terracotta head from Jemaa, Nigeria, belonging to the Nok culture. A TL reading for the age of the sculpture has provided the first reliable date for this and other terracottas from the Nok region. Height 23 cm.

Of even greater potential is the development of the TL method for dating artifacts made before 50,000 years ago (beyond the basic limit of radiocarbon). Pottery itself is not found at this early time, nor are baked clay artifacts. But the method can be applied to stone (lithic) materials with a crystalline structure, always provided that they were heated at the time of their production as artifacts, or at the time of their use, to a temperature of around 500°C. In this way, geological TL in the stone would be emitted and the TL clock effectively set at zero. Therefore, the measurement of their TL age genuinely dates their archaeological use. In practice, burnt flint has proved a very informative material.

For example, the method has been successfully used in France to date flint tools of so-called Mousterian type found at sites occupied by Neanderthal people (*Homo sapiens neanderthalensis*) in the Middle Paleolithic period. Most of the dates fall between 70,000 and 40,000 years ago. Despite their limited precision, the dates establish a very useful pattern for the tools that has advanced the understanding of the French Middle Paleolithic.

Hélène Valladas and her colleagues have also employed the TL method to date flint tools used at different times by both Neanderthals and the first people of modern appearance (*Homo sapiens sapiens*). Their research at caves in Israel suggests controversially and somewhat surprisingly that Neanderthals were still in the area tens of thousands of years after the arrival of the first anatomically modern humans. At Kebara an age of 60,000 years was indicated for a Neanderthal skeleton, while at Qafzeh results suggested that modern humans were already in the region by about 90,000 years ago.

TL dates can also be obtained from calcium carbonate deposits in caves (e.g. stalagmites and travertines) with which artifacts are associated as TL starts to accumulate from the time the carbonate crystallizes from the solution to form the deposit. TL dating has shown, for instance, that the stalagmitic floor of the Lower Paleolithic cave site of Caune de l'Arago in southern France formed around 350,000 years ago.

There is also a special application of TL dating, its use in the identification of fake pottery and terracotta objects. The TL method can easily distinguish between a genuine antiquity and a forgery made within the last 100 years.

Limiting Factors. Various complications remain with thermoluminescence, and TL dates rarely have a precision of better than ±10 percent of the age of the sample.

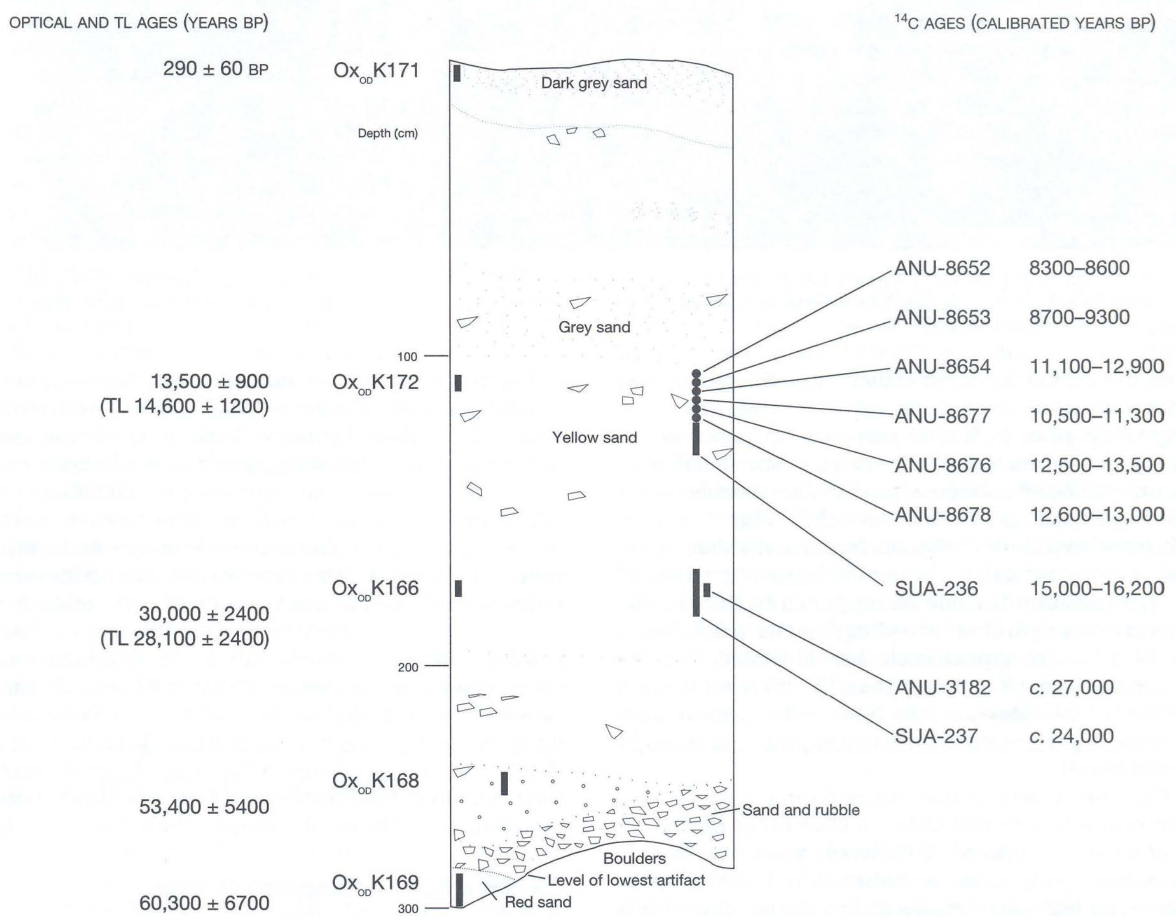
Optical Dating

This method is similar in principle to thermoluminescence, but is used to date minerals which have been exposed to light, rather than heat.

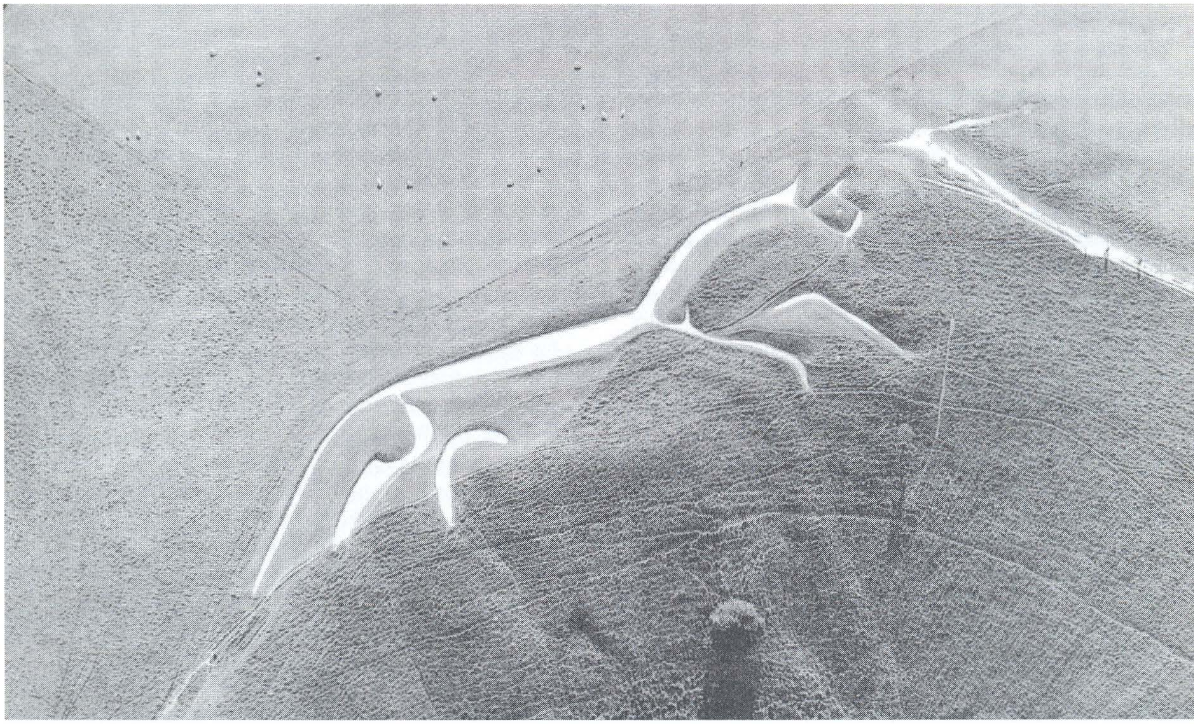
Basis of Method. Most minerals contain a sub-set of electron traps which are emptied, or bleached, by several minutes' exposure to sunlight. This phenomenon has been utilized for dating sedimentary deposits of quartz grains. Their electron traps are bleached during transport but after sedimentation and burial they begin to accumulate electrons once more. After careful sampling the total radiation dose of a sediment may be estimated in the laboratory by directing light of a visible wavelength onto a sample and measuring the resultant luminescence, which is known as optically stimulated luminescence (OSL).

Applications. Artifact-bearing sand sediments in the Nauwalabila I rockshelter in north Australia have been optically dated and shown to be between 53,000 and 60,000 years old – important evidence for an early occupation of this area by humans (see Chapter 13). The general validity of these optically stimulated luminescence results is supported by the good match between radiocarbon dates and optical dates from the Ngarrabullgan Cave in Queensland.

However, the same can certainly not be said for the controversy surrounding the Jinmium rock shelter in the Northern Territory of Australia which hit the headlines in 1996 with claims for human occupation



A section from the Nauwalabila I excavation, north Australia, with luminescence dates (TL and Optical Dating) on the left and calibrated radiocarbon dates on the right. Artifact-bearing sands could be optically dated and produced results of between 53,000 and 60,000 BP, having important implications for the date of the first human occupation of the Australian landmass.



The White Horse of Uffington, a figure cut from a chalk hillside in southern England. Its date had always been disputed until soil samples taken from excavations of part of the figure were optically dated to 1400–600 BC, around 1000 years older than had previously been thought.

prior to 116,000 years ago and artistic activity, inferred from red ocher, before 75,000 years ago and rock-engravings prior to 58,000 years ago, all based on TL dating (where the laboratory analysis, conducted upon quartz grains, effectively sets out to date the time when these were last exposed to sunlight). This was soon criticized on technical grounds (specifically that decaying bedrock retaining the much earlier "geological" TL age signature became incorporated in the sample, thus giving a distorted "early" age). Later work, based on single-grain optical ages, has indicated that the Jinmium deposit is younger than 10,000 years old and confirms that some grains have older optical ages because they received insufficient exposure to sunlight before burial.

The lesson here is that novel dating methods can give misleading results unless a wide range of sources of error are considered: it is always wiser to seek corroboration from other, well-established dating methods before making sweeping claims. To do otherwise is simply scientifically incautious.

In Britain, OSL has been used to date the enigmatic White Horse at Uffington. The only prehistoric equine hill-figure in Britain, the outline of this horse was cut directly into the hillside and then packed with white chalk. On stylistic grounds both Anglo-Saxon and Celtic (late Iron Age) dates had previously been proposed for its delineation; but now three OSL dates obtained from silt laid down in the lowest levels of the horse's belly suggest instead a Bronze Age date, in the range 1400–600 BC. This date accords well with other indications of late Bronze Age activity in the area.

Limiting Factors. Although still in its developmental stage results so far suggest that the method may be used successfully to date aeolian (wind-borne) deposits. The position with alluvial deposits is less clear, however, as it is not certain that the exposure of their constituent grains to sunlight during water transport is sufficient to ensure complete bleaching.

Electron Spin Resonance Dating

Electron spin resonance (ESR) dating is less sensitive than TL, but is suitable for materials which decompose when heated. Its most successful application so far has been for the dating of tooth enamel, which is composed almost entirely of the mineral hydroxyapatite. Newly formed hydroxyapatite contains no trapped electrons, but they begin to accumulate once the tooth is buried and exposed to natural radiation. The precision of the method when used to date tooth enamel is in the order of 10–20 percent.

Basis of Method. For the determination of total dose a sample of the specimen to be dated is powdered and exposed to high frequency electromagnetic radiation (microwaves) in the presence of a strong magnetic field. The field strength may be varied and as it is, the trapped electrons in the sample absorb microwaves of different frequencies and resonate. Maximum resonance occurs at a specific conjunction of microwave frequency and magnetic field strength. The magnitude of resultant microwave absorption can be measured and is directly proportional to the size of the trapped electron population, and thus to the total radiation dose.

Hydroxyapatite does not naturally contain any radioactive isotopes, but it acquires them after burial by uptake of water-soluble uranium, as does its associated dentine. Its annual dose rate therefore increases over time and it is necessary to correct for this by modeling the rate of uranium uptake. Two models are used: the early uptake (EU) model which assumes that the uranium content of the tooth rapidly equilibrates with that of its environment so that uptake diminishes with time; and the linear uptake (LU) model which assumes that uranium uptake proceeds at a uniform rate. As with ceramics, the effect of external alpha and beta emitters can be eliminated by removal of the outer few millimeters of the sample to be dated. For determination of annual dose, therefore, it is necessary to measure the internal concentrations of uranium (and its daughter thorium isotopes) and the external levels of gamma radiation. It is conventional to present results as both EU and LU versions.

Applications. ESR dates from mammalian teeth associated with hominid remains have confirmed dates obtained by U-Series dating and by TL of burnt flints. Thus at Qafzeh dates of 100,000 ±10,000 BP (EU) or 120,000 ±8000 BP (LU) and at Skhūl 81,000 ±15,000 BP (EU) and 101,000 ±12,000 BP (LU) are associated with the remains of anatomically modern humans, while at Tabun dates in the range of 100,000–120,000 years and at Kebara dates of 60,000 ±6000 BP (EU) or 64,000 ±4000 BP (LU) are associated with the remains of Neanderthals. The dates obtained from this series of Israeli caves are important as they demonstrate that all three methods produce data that are compatible. They are also exciting as they suggest that Neanderthal populations must have coexisted in the area with early modern humans for tens of thousands of years, and that therefore the two groups must constitute separate evolutionary lineages. This finding provides support for claims that modern *Homo sapiens* evolved first in Africa and then colonized adjacent continents, replacing earlier *Homo* populations in the process.

Recently it has proved possible to date small dental fragments directly, without first powdering them. This direct ESR dating has been applied to the hominid remains found at the Florisbad spring, South Africa, giving an age of the order of 250,000 years, which was supported by optically stimulated luminescence dating.

Limiting Factors. The age range of ESR dating is limited because ultimately the stability of trapped electrons begins to deteriorate. This deterioration is temperature-dependent so that the electrons are less stable in hot environments than in cold. In theory the age range is in the order of a million years but in practice it may be less. The accuracy of the method is compromised by the need to model uranium uptake. Models have to account for the different rates of uranium uptake by dentine and enamel and also allow for the decay of absorbed uranium and the consequent formation of radioactive daughter isotopes: thorium and uranium. ESR cannot easily be used to date bone as the new minerals which form during fossilization produce consistent under-estimation of age. The behavior of uranium in the more open matrix of bone is also difficult to model.

CALIBRATED RELATIVE METHODS

Radioactive decay is the only completely regular time-dependent process known; it is uninfluenced by temperature or other environmental conditions. There are, however, other natural processes which, while not completely regular, are sufficiently steady over the course of time to be of use to the archaeologist. We have already seen how natural annual cycles produce varves and tree-rings, which of course are immensely useful because they give dates calibrated in years. Other processes that form the basis of the first three techniques described below are not naturally calibrated in years, but in principle they can be made to

Obsidian hydration dating: a hydration layer visible in an obsidian artifact. The layer increases in thickness as time passes, but there is no universally valid rate of growth.

yield absolute dates if the rate of change inherent in the process can be independently calibrated by one of the absolute methods already discussed. In practice, as we shall see, the calibration for each technique often has to be done afresh for each site or area because of environmental factors that influence the rate of change. This makes these techniques difficult to use as reliable absolute dating methods. They can, however, still prove enormously helpful simply as a means of ordering samples in a relative sequence, in which older is distinguished from younger.

Obsidian Hydration

Basis of Method and Limiting Factors. This technique was first developed by the American geologists Irving Friedman and Robert L. Smith. It is based on the principle that when obsidian (the volcanic glass often used rather like flint to make tools) is fractured, it starts absorbing water from its surroundings, forming a hydration layer that can be measured. In a section through an obsidian tool viewed under the optical microscope, the layer appears as a distinct zone at the surface. It increases in thickness through time.

If the layer increases in thickness in a linear way, then assuming we know the rate of growth and the present thickness, we ought to be able to calculate the length of time elapsed since growth began. The zero moment, when the hydration zone started forming, is the moment when the flake tool was freshly made by removing it from the original obsidian block, or by trimming it. Unfortunately, there is no universally valid rate of growth or hydration rate. For one thing, the rate is dependent on temperature, and exposure to direct sunlight over long periods increases hydration. Moreover, obsidians from different quarries have different chemical compositions, and this can affect the picture. It is necessary, therefore, to establish separately the hydration rate for the different kinds of obsidian found in a given area, and to keep in mind the temperature factor, which can be allowed for.

To use the method for absolute dating, it has to be calibrated against an established chronological sequence (taking into account the chemical and temperature factors) for the region in question. Samples for dating need to come from one or more well-defined contexts that can be dated securely by other means. A single obsidian artifact cannot be expected to give a reliable date. It is thus safer to use an assemblage of about 10 pieces, so that the date of each one can be separately calculated. In addition to providing direct chronological information, the method can be useful in assessing the relative ages of different strata within a site or region where obsidian is abundant.

Though principally relevant to sites and artifacts of the last 10,000 years (the postglacial period), obsidian hydration has given acceptable dates of around 120,000 years for Middle Paleolithic material from East Africa.

Applications. One of the boldest applications of the method so far has been by one of the pioneers of obsidian dating, Joseph Michels, in his study of the rural hinterland around the important ancient center of Kaminaljuyu in Guatemala. The sites were difficult to date from the pottery found on the surface, which was much abraded, so an attempt was made to date them by measuring the hydration layer on at least four obsidian artifacts from each site. If at least two of the obsidian dates fell within one of the already established chronological phases (ranging from Early Formative *c.* 2500 BC to Late Postclassic *c.* AD 1500), the site was assigned to that phase. In the principal survey area some 70 rural settlements were dated in this way, on the evidence of a total of 288 obsidian samples. The results indicated an increase in the density of rural settlement up to the Early Late Classic period (AD 600–800), then a gradual fall as Kaminaljuyu declined.

Amino-Acid Racemization

This method, first applied in the early 1970s and still at an experimental stage, is used to date bone, whether human or animal (only 10 g are required). Its special significance is that it can be applied to material up to about 100,000 years old, i.e. beyond the time range of radiocarbon dating.

Basis of Method. The technique is based on the fact that amino acids, which make up proteins present in all living things, can exist in two mirror-image forms, termed enantiomers. These differ in their chemical structure, which shows in their effect on polarized light. Those that rotate polarized light to the left are *laevo*-enantiomers or L-amino acids; those that rotate the light to the right are *dextro*-enantiomers or D-amino acids.

The amino acids present in the proteins of living organisms contain only L-enantiomers. After death, these change at a steady rate (they racemize) to D-enantiomers. The rate of racemization is temperature-dependent, and therefore likely to vary from site to site. But by radiocarbon-dating suitable bone samples at a particular site, and measuring the relative proportions (ratio) of the L and D forms in them, one should be able to work out what the local racemization rate is. This calibration is then used to date bone samples from earlier levels at the site beyond the time range of radiocarbon.

L-enantiomers of the stable amino acid isoleucine form D-enantiomers by a rather different process known as epimerization. The rate of isoleucine epimerization has been measured successfully in the proteinaceous residues of ostrich shells and by comparison with ^{14}C dating has been shown to be constant for the past 80,000 years.

Applications and Limiting Factors. Aspartic acid has the fastest racemization rate of the stable amino acids and is the acid usually chosen for dating bone samples. For instance, at the Nelson Bay Cave in Cape Province, South Africa, samples with a D/L aspartic acid ratio of 0.167 gave radiocarbon ages of roughly 18,000 years. This allowed a conversion rate to be calculated, calibrating the racemization rate for that site. Measurements of the ratio were then made on fossil bone samples from the important site of Klasies River Mouth in the same area, giving for the lower levels (18 and 19) D/L aspartic acid ratios of 0.474 and 0.548. From these values, ages of about 90,000 and 110,000 years respectively were estimated. In this case, the "calibration" sample was derived from a different site than the one from which the samples to be dated came. This is less than ideal, because the racemization rates for the different sites, even though geographically the sites are not far apart, could differ to some extent. It now seems that one of the major problems with amino-acid dating has been that amino acids bound up in complex proteins, such as collagen, have very different racemization rates from the same amino acids in their free state. Bone preservation therefore has a huge effect on apparent ages.

As a means of absolute dating the method is of course entirely dependent on the accuracy of its calibration (as are other relative methods). This has led to controversy, particularly as regards the date of fossil human remains from California. Early radiocarbon determinations from skulls found near Los Angeles were used to calibrate aspartic acid racemization rates, which then yielded ages as high as 48,000 years for other remains near San Diego – suggesting human colonization of the Americas much earlier than had been supposed (Chapter 11). More recent radiocarbon dates on the Los Angeles bones by the AMS method have altered the calibration, lowering the oldest age-estimates for the California remains to no earlier than 8000 years.

Cation-Ratios and the Dating of Rock Art

In the 1980s a new technique was developed which, for the first time, seemed to provide direct dates for rock-carvings and engravings, and was also potentially applicable to Paleolithic artifacts with a strong patina caused by exposure to desert dust.

Basis of Method. In desert conditions, a varnish forms on rock surfaces exposed to desert dust. The varnish is composed of clay minerals, oxides, and hydroxides of manganese and iron, minor trace elements, and a small amount of organic matter such as microscopic plant particles. The original dating method depended on the principle that the cations of certain elements (i.e. charged atoms of those elements which combine with oxide and hydroxide ions of opposite charge to form stable compounds) are more soluble than those of certain other elements. They leach out of rock varnish more rapidly than the less-soluble elements and their concentration thus decreases with time. The method simply required the measurement of the ratio of these mobile cations, usually of potassium (K) and calcium (Ca), to the more stable cations of titanium (Ti). The ratio was assumed to decrease exponentially with time (giving a decay curve similar in shape to those of radioactive isotopes discussed above). However, the pioneers of the technique, Ronald Dorn and his associates, do not claim that there is an absolute decay rate (as there is for radioactive decay processes).

Applications and Limiting Factors. Cation-ratio dating was tried out on varnish covering rock-carvings (petroglyphs) in California and in Australia where it produced minimum ages for the images of 6400 years and more than 30,000 years respectively. A detailed debate ensued about the technique's degree of reliability and accuracy. Dorn responded by stressing that CR dating is an experimental method that will always remain a "weaker sister" of other approaches owing to the many environmental influences that have to be allowed for: it is not clear in what climatic conditions the varnish may be damaged or destroyed, nor indeed whether variations in climate might affect the process of cation-ratio reduction. The calibration curves are being revised, but the method is now used primarily as a back-up for other techniques, particularly AMS which can be applied to minute amounts of organic material contained in the rock varnish: for example, dates of 14,000 and 18,000 BP have been obtained by this method for varnish covering petroglyphs in California and Arizona.

These were therefore assumed to be minimal ages for the engravings beneath the varnish; but this whole approach to dating open-air petroglyphs has been called into question by the furore over the rock art of the Côa Valley in northeast Portugal. These images, first reported in 1994 and ascribed by every specialist to the Upper Paleolithic (i.e. more than 10,000 BP), were threatened with inundation by a huge dam. In 1995, an attempt was made by the electricity company building the dam to have a few of the figures dated directly by different methods, all of them highly experimental, including the AMS dating of organic deposits on the images.

Unfortunately, some of the panels chosen had already been much affected by latex molding, chalking, and other damage. The results were mixed, to say the least, but did archaeology a major service by revealing the uncertainty that still surrounds the direct dating of open-air engravings. Unlike organic material extracted from pigments in caves and rockshelters (see below), which is thus in a closed system, organic material trapped in accretions on exposed rocks is part of an open system. Hence, even if the dating of this material is accurate, its source and therefore its chronological relationship with the petroglyphs beneath remain utterly uncertain. For example, a sample taken from the calcareous accretions covering the inscription on a Carthaginian stela, known to be about 2200 years old, recently provided an AMS result of 21,430 years – dead carbonate clearly contaminated the sample, but nobody knows how much of it comes from the underlying stone, from nearby stone, or from the atmosphere. The Côa episode has therefore sent the whole idea of direct dating of petroglyphs back to the drawing board.

As mentioned above, AMS has produced far more reliable results when applied to organic material in prehistoric paintings: for example, apparently sound results have been obtained from 12 French and Spanish Paleolithic caves where charcoal was used as a pigment, from plant fibers in paint in rockshelters in Queensland, and from human blood protein in paint in Wargata Mina cave in Tasmania. Other methods for dating rock art are being explored. For example, layers of calcite that build up on top of images in caves may be datable by radiocarbon and by uranium-thorium; oxalates (salts of oxalic acid, containing organic carbon) also form deposits that are susceptible to radiocarbon dating.

Chlorine-36 Dating

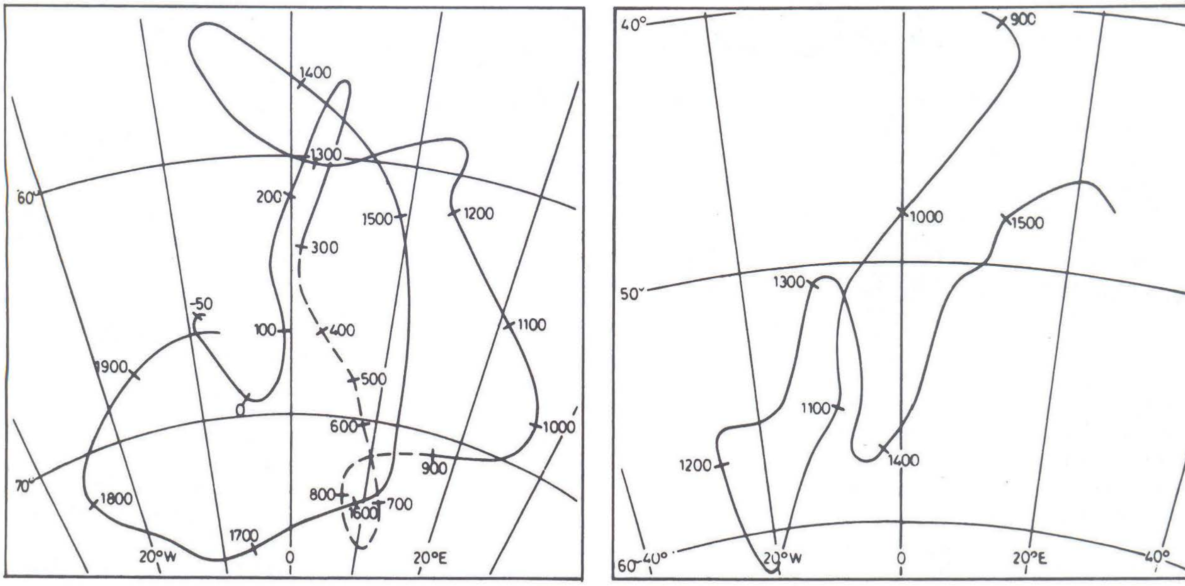
The question of the dating of rock art when no associated artifacts survive has been advanced a little by the ^{36}Cl dating method.

Basis of Method. This method depends upon the accumulation of nuclides at and near the surface of the rock when it is exposed to cosmic radiation. One or two meters of rock will block cosmic radiation. However, where thick slabs of rock spall off to expose fresh faces the accumulation of cosmogenic nuclides will be initiated at the fresh face at the time of the spall event. The concentration of ^{36}Cl in samples taken at and near the surface of the rock is determined using the accelerated mass spectrometer, and is compared with the background concentration present in samples from freshly exposed rock. When the rock exposure is an old one, the concentration is very much higher. It should be clearly understood, however, that the comparison does not given information about the date of a rock engraving as such, but simply about the length of time that the rock surface in question has been exposed since the geological event which led to its exposure.

Applications and Limiting Factors. The method has also been applied to the Côa petroglyphs of Portugal (see above), in the light of the controversy as to whether they were of Pleistocene age (greater than 10,000 BP) or modern. The results suggested exposure ages between 16,000 and 136,000 years. It should be noted that this is an imprecise technique, and the date is for the rock surface, not for the engravings. But at least the result appears to exclude the possibility that the rock surface itself was exposed in relatively recent times, as had earlier been suggested.

Archaeomagnetic Dating

Archaeomagnetic (or Paleomagnetic) dating has so far been of limited use to archaeology, in part because not enough work has been done in different regions.



Magnetic direction dating. The changing positions of magnetic north, as plotted here for Britain (left) and the American Southwest (right), can be used to date baked clay structures such as kilns which preserve a record of the direction of magnetic north at the time they were fired.

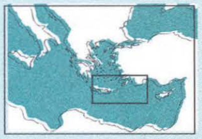
Basis of Method. The earth's magnetic field is constantly changing in both direction and intensity. Historical records from London, Paris, and Rome have allowed scientists to plot changes in the direction of magnetic north observed there from compass readings over the last 400 years. Scientists have also been able to trace these changes farther back in time in Europe and elsewhere by studying the magnetization at earlier periods of baked clay structures (ovens, kilns, hearths) that have been independently dated, for instance by radiocarbon. (Provided clay is baked to 650–700°C (1202–1292°F) and not reheated, the iron particles in it permanently take up the earth's magnetic direction and intensity at the time of firing. This principle is called thermoremanent magnetism (TRM).) Plots can thus be built up of the variation through time in magnetic *direction* which can be used to date other baked clay structures of unknown age, whose TRM is measured and then matched to a particular point (date) on the master sequence. Different master sequences have to be built up for variations in magnetic *intensity*, which varies independently of magnetic direction.

Applications and Limiting Factors. Regional variations within the global magnetic field mean that a separate master sequence is needed for each region. For magnetic direction these have been created in a few parts of the world such as Britain and the American Southwest back over the last 2000 years. A baked clay kiln or oven from this time period, measured *in situ* at a site in one of these regions, can be dated quite accurately by the magnetic direction method. Once the structure is moved, however, its ancient magnetic direction can no longer be compared with that of the present day.

Magnetic intensity can be measured when the baked clay is out of context, and so can be applied to pottery unlike the directional method. A recent application to pottery from different provinces of China has yielded a master sequence for the last 4000 years, promising to make it possible to date Chinese pottery of unknown age. But so far the intensity method has proved inherently much less accurate than the directional method.

Geomagnetic Reversals. Another aspect of archaeomagnetism, relevant for the dating of the Lower Paleolithic, is the phenomenon of complete reversals in the earth's magnetic field (magnetic north becomes magnetic south, and vice versa). The most recent major reversal occurred about 780,000 years ago, and a sequence of such reversals stretching back several million years has been built up with the aid of potassium-argon and other dating techniques. The finding of part of this sequence of reversals in the rock strata of African early hominid sites has proved a helpful check on the other dating methods that have been used at those sites (see box, pp. 148–49).

DATING THE THERA ERUPTION



More than 3500 years ago the volcanic island of Thera (also known as Santorini) in the Aegean Sea erupted, burying the prehistoric settlement of Akrotiri on its southern shore. Akrotiri – excavated since the 1960s by the Greek archaeologist Spyridon Marinatos and more recently Christos Doumas – has proved to be a prehistoric Pompeii, with well-preserved streets and houses, some with remarkable wall paintings, all buried beneath many meters of volcanic ash. The eruption itself offers interesting problems and opportunities in dating.

As long ago as 1939, Marinatos suggested that the Thera eruption was responsible for the destruction of the Minoan palaces of Crete (110 km or 69 miles to the south), many of which were abandoned during the Late Bronze Age. This idea sparked off a debate that still continues.

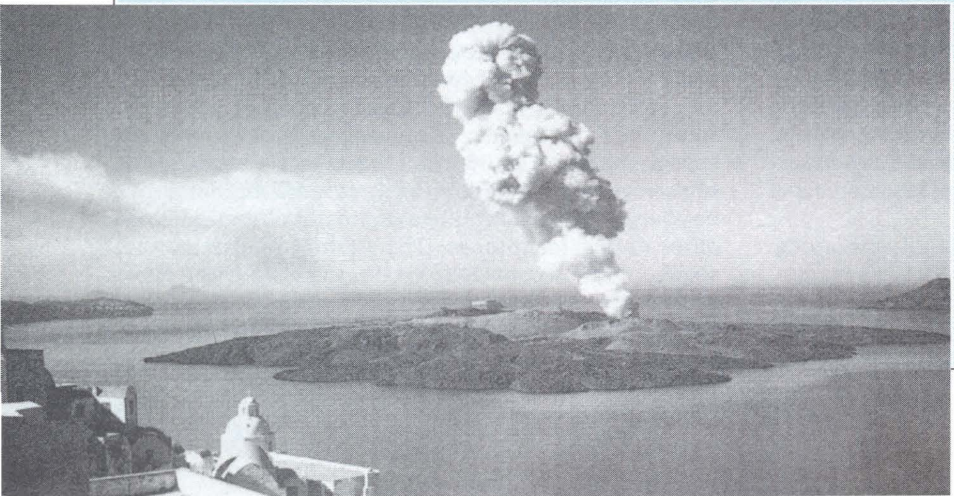
In the first place, the problem can be approached in terms of the **relative chronology** offered by the evolution of pottery styles. There is a well-established stylistic sequence for Minoan pottery, and it was found that the most recent pottery style in the relevant Minoan palaces was Late Minoan IB. This was assigned an absolute date in years by cross-dating between the Minoan sequence and the well-established Egyptian historical chronology. On this basis, the end of Late Minoan IB (and hence the destruction of the Minoan palaces) was dated around 1450 BC.

This date, however, made any link with the destruction of Akrotiri on Thera problematic, because Akrotiri has no Late Minoan IB pottery but abundant material of the Late Minoan IA style. Some scholars thus concluded that the Thera eruption had nothing to do with the destruction of the Minoan palaces, which might well have been a later event. They were therefore happy to date the Thera eruption within the Late Minoan IA period, perhaps (again using the Egyptian-based chronology for Minoan Crete) around 1500 BC.

Other scholars, however, believed that the effects of the Thera eruption would have been widely felt. Here, they were certainly aided by the application of **tephra studies**. Deep-sea coring on the bed of the Mediterranean gave evidence for the Thera ash fall (and the ash was shown by laboratory analysis to be from the appropriate eruption of this particular volcano). Subsequently, traces of ash from the Thera eruption were identified (using refractive index studies) in samples from sites on Minoan Crete, and also from the site of Phylakopi on the Aegean island of Melos. However, this ash has not yet been documented in strata at archaeological sites where there is a clear distinction between the use of Late Minoan IA and Late Minoan IB pottery, so it is premature to speak here of tephrachronology. Nevertheless a major ash layer has been recognized at the archaeological site of Trianda on Rhodes, so the method should offer an answer in due course. Well-stratified pumice found at the Egyptian site of Tell Dab'a has been shown on analysis to derive from the Thera eruption and has been used by some scholars using the accepted Egyptian historical chronology to support a date around 1500 BC.

The problem is one that **radiocarbon dating** should theoretically help resolve, but the distinction between 1500 BC and 1450 BC is a relatively narrow one. However, samples have been analyzed, including short-lived samples (carbonized grain, etc.), that could not have been old at the time of the eruption. The mean date obtained from such short-lived samples is 1615 BC (after calibration). The date range for a single standard deviation, which implies 65 percent probability, is 1630 to 1530 BC. (The range is not symmetrical about the mean date because of irregularities in the calibration curve at this time.) The radiocarbon data thus favor the earlier of the two dates in question.

The matter does not rest there. It has been shown for more recent times that major volcanic eruptions have global effects (since the dust thrown into the atmosphere reduces solar radiation reaching the earth). These can show up as anomalously narrow rings for a year or two in **tree-ring sequences**. Such effects have been sought in the tree-ring record of the California bristlecone pine during the middle of the 2nd millennium BC. One such, firmly dated 1628–1626 BC, has been proposed for

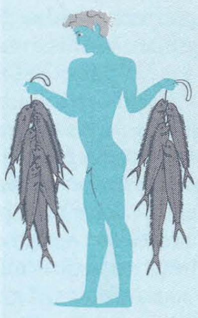


***The Thera volcano** is still sporadically active, the focus of the eruptions being on this small island in the center of the semi-submerged volcano.*

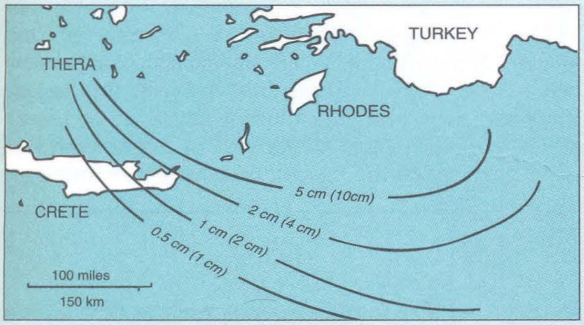
the Thera eruption. A comparable ring has been noted for the tree-ring sequence for Irish oak. A recently developed tree-ring sequence from Anatolia with a markedly anomalous ring has been used to support this early date, but the arguments for associating this ring with the eruption are not conclusive.

It has been similarly shown that **ice cores** reveal a short peak of high acidity for recently observed major eruptions, when these are on a scale large enough to have global effects. An ice core from Greenland shows such a peak for 1390 BC, and this has been claimed as a possible date for the Thera eruption. More recent work at the Dye 3 site in Greenland has, however, suggested that an acidity maximum in 1645 BC would be more appropriate which could be used to support the tree ring date of 1628 BC. The problem is that there was absolutely nothing in the tree-rings or indeed in the ice cores that allows one major volcanic eruption in one part of the world to be distinguished from another, other than its date in years.

Now, however, a tiny fragment of tephra has been found in the Dye 3 ice core corresponding to the 1645 BC acidity peak – and it proves on analysis not to derive from the Thera eruption, so the early date of 1645 BC (or 1628 BC) is called into question again and the debate continues.



Fresco from Akrotiri called the "Fisherman."



Map indicating isopachs (contours of equal thickness) for tephra fallout from the eruption of Thera, as determined from deep-sea cores. The figures in brackets give an estimate of the corresponding depth of tephra falling on land.

CHRONOLOGICAL CORRELATIONS

One of the most promising avenues for future work in chronology is the correlation of different dating methods. The use of one absolute method in support of another can often bring very powerful results. An excellent example is the way that tree-ring dating has been used to support and indeed calibrate radiocarbon, as a result of which the latter has gained greatly in accuracy and reliability. The same observation is true of the relationship between relative and absolute dating. Although actual dates in years are provided by absolute methods, much of the reliability and internal consistency of those dates (and therefore the possibility of recognizing and weeding out inaccurate absolute age determinations) comes from the framework provided by the relative dating method.

Links between chronological sequences that are geographically remote from each other – "teleconnections" – can present considerable difficulties. The most common are those that depend on the comparison of sequences – for instance of tree-ring widths. This is certainly valid for adjacent trees or for trees within a small area; over a wide region such "teleconnections" must be treated with caution. In the same way, the correlation of varve sequences in Scandinavia and in North America has proved contentious. With such methods there is always the risk of arriving at a "correlation" between sequences which, while initially plausible, is incorrect.

Global Events

One of the most powerful ways of establishing a correlation between sequences is by seeing within them the occurrence of the same significant event, one with wide repercussions geographically, even on a global scale.

Such events are naturally very rare, and are generally catastrophic in their nature. The impact on earth of large meteorites would fall in this category. Much more common are large-scale volcanic eruptions. Close to the volcano these events have striking effects, with mud and lava flows and thick falls of ash, often with devastating consequences for human occupation. At intermediate distances, up to a few hundred kilometers, they can still have a marked effect, with tsunamis ("tidal waves," although they are not in fact tidal) and falls of tephra (volcanic ash). Scientists have sought to correlate earthquake damage at intermediate distances with volcanic eruptions, but the two events are often not connected. Major volcanic eruptions also project significant quantities of tephra into the earth's upper atmosphere, with global effects. Such ash or dust increases the acidity of the snow falling in polar areas, and thus leaves its trace in ice cores. Its effect on tree-rings has also been noted: by reducing the amount of solar radiation reaching the earth (and thus also reducing the temperature) the volcanic dust reduces the growth rate of trees for a short but significant time.

The developing field of tephrachronology is proving useful. Its aim is to distinguish unequivocally, and hence date, the tephra from different volcanic eruptions that may be present in terrestrial deposits, or in deep-sea cores. The products of each eruption are often significantly different, so that measurements of refractive index may be sufficient to distinguish one ash from another. In other cases, analysis of trace elements will separate the two.

When all the sites and objects in an area are buried under a layer of volcanic ash at the same instant – a "freeze-frame" effect – one has a very precise dating method that can be used to correlate the age of all those archaeological materials. Examples include the great eruption of Mount Vesuvius in AD 79 that covered Pompeii, Herculaneum, and other Roman settlements (pp. 22–23); and the eruption of the Ilopango volcano in El Salvador in about AD 175 that buried Early Classic settlements there under 0.5–1 m (1.6–3.3 ft) of volcanic ash. The Ilopango eruption must have disrupted agriculture for several years and interrupted pyramid construction at the site of Chalchuapa, where the break in work can clearly be seen.

Another good example of tephrachronology comes from New Guinea, where various sites have been related chronologically by the presence of up to a dozen identifiable ash falls within them. Australian archaeologists Edward Harris and Philip Hughes were able to relate the horticultural system at Mugumamp Ridge in the Western Highland Province of Papua New Guinea with another at Kuk Swamp, some kilometers to the south, by the characteristics of the volcanic ash overlying both horticultural systems. The ash is thought to derive from the volcanic Mount Hagen some 40 km (25 miles) to the west. A combination of tephrachronology and radiocarbon suggests that horticulture in this area may have begun as early as 7000 BC (see box, pp. 262–63).

The most intensively studied question in the field of tephrachronology, however, is the date of the major eruption of the volcanic island of Thera in the Aegean sometime around the late 17th century or the 16th century BC (see box, pp. 160–61). The eruption buried the Late Bronze Age town of Akrotiri on the island and there were also marked effects on islands nearby.

An important general moral arises from the long dispute over the date of the Thera eruption. It is indeed all too common, when dating evidence is being discussed, to assume long-distance connections without being able to document them. For instance, several writers have tried to link the volcanic eruption of Thera with the Plagues of Egypt reported in the Book of Exodus in the Bible. This is intriguing, and worth investigating. But when it is actually used to date the eruption, as it has been by some, this is no more than a supposed equivalence, a supposition masquerading as a dating.

At the same time, however, there is an important future for the use of several methods in combination to date the eruption. For instance, it is perfectly appropriate to date the eruption approximately using radiocarbon on samples from Thera and then to seek a more precise date, indeed a date in calendar years, from indications in ice cores or tree-rings. The assumptions underlying the correlation – that these different kinds of evidence are telling us about the same event – should not, of course, be forgotten. It would be much more satisfactory if traces of tephra could be found in the ice cores, and if these could be shown by analysis to derive from the eruption in question. Were this to be done, it would be the Greenland or Antarctic ice cores that would, in effect, become responsible for the very precise dating of one important event in the Aegean Late Bronze Age, and hence for a calibration of Aegean Late Bronze Age dating in general. It might even lead to modifications in the Egyptian historical chronology.

WORLD CHRONOLOGY

As a result of the application of the various dating techniques discussed above, it is possible to summarize the world archaeological chronology.

The human story as understood at present begins in East Africa, with the emergence there of the earliest hominids of the genus *Australopithecus*, such as *A. afarensis*, around 4 or 5 million years ago, and the possibly earlier *Ardipithecus*. By around 2 million years ago, there is clear fossil evidence for the first known representative of our own genus, *Homo habilis*, from such sites as Koobi Fora (Kenya) and Olduvai Gorge (Tanzania). The earliest stone tools (from Hadar, Ethiopia) date from about 2.5 million years ago, but it is not known which hominid made them because *Homo habilis* fossils of this age have not yet been found. It is possible that australopithecines also had a tool culture before or during *Homo habilis*'s time. The early toolkits, comprising flake and pebble tools, are called the Oldowan industry, after Olduvai Gorge where they are particularly well represented.

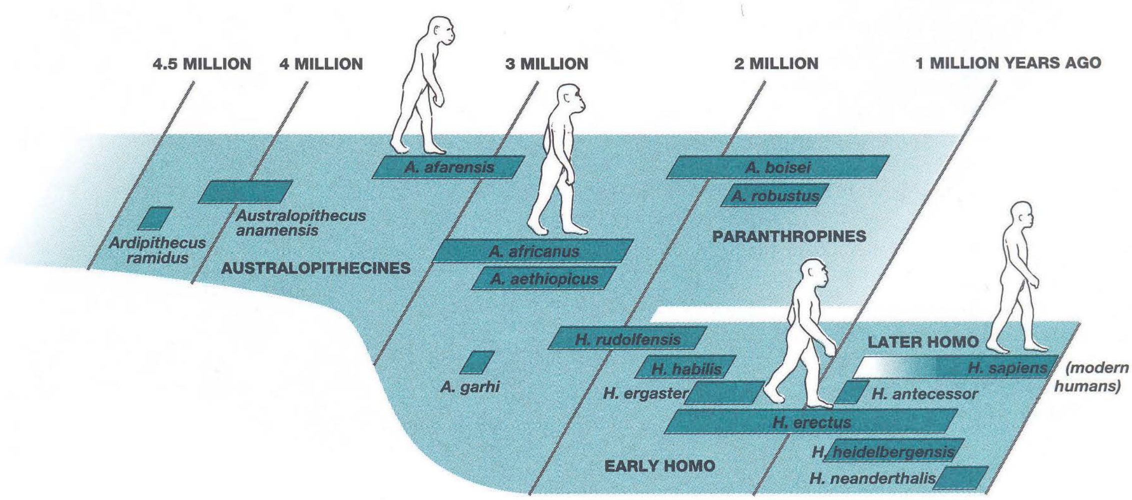
By more than 1.6 million years ago, the next stage in human evolution, *Homo erectus*, had emerged in East Africa. These hominids had larger brains than *Homo habilis*, their probable ancestor, and were makers of the characteristic teardrop-shaped stone tools flaked on both sides called Acheulian hand-axes. These artifacts are the dominant tool form of the Lower Paleolithic. By the time *Homo erectus* became extinct (400,000–200,000 years ago), the species had colonized the rest of Africa, southern, eastern, and western Asia, and central and western Europe.

The Middle Paleolithic period – from about 200,000 to 40,000 years ago – saw the emergence of *Homo sapiens*. Neanderthals, who are generally classed as a subspecies of *Homo sapiens* (*Homo sapiens neanderthalensis*), lived in Europe, and western and central Asia from about 130,000 to 30,000 years ago. Their role in later human evolution is unclear, some specialists believing Neanderthals ultimately evolved into fully modern humans, others that they were an evolutionary dead end. The latter theory is gaining ground now that we have increasing evidence for fully modern people – that is our own subspecies, *Homo sapiens sapiens* – in Africa by at least 100,000 years ago. They seem to have reached the eastern Mediterranean 100,000–90,000 years ago, and Europe and Asia by at least 40,000 years ago. Australia was colonized by humans at least 50,000 or 60,000 years ago (the date is currently being hotly debated, falling as it does at the very limit of radiocarbon dating). It is uncertain when humans first crossed from northeastern Asia into North America across the Bering Strait, and south to Central and South America. The earliest secure dates for early Americans are around 14,000 years ago, but there is controversial evidence that the continent was populated before then. The Brazilian rockshelter at Pedra Furada (see box, p. 314) has produced disputed evidence for human occupation over 30,000 years ago.

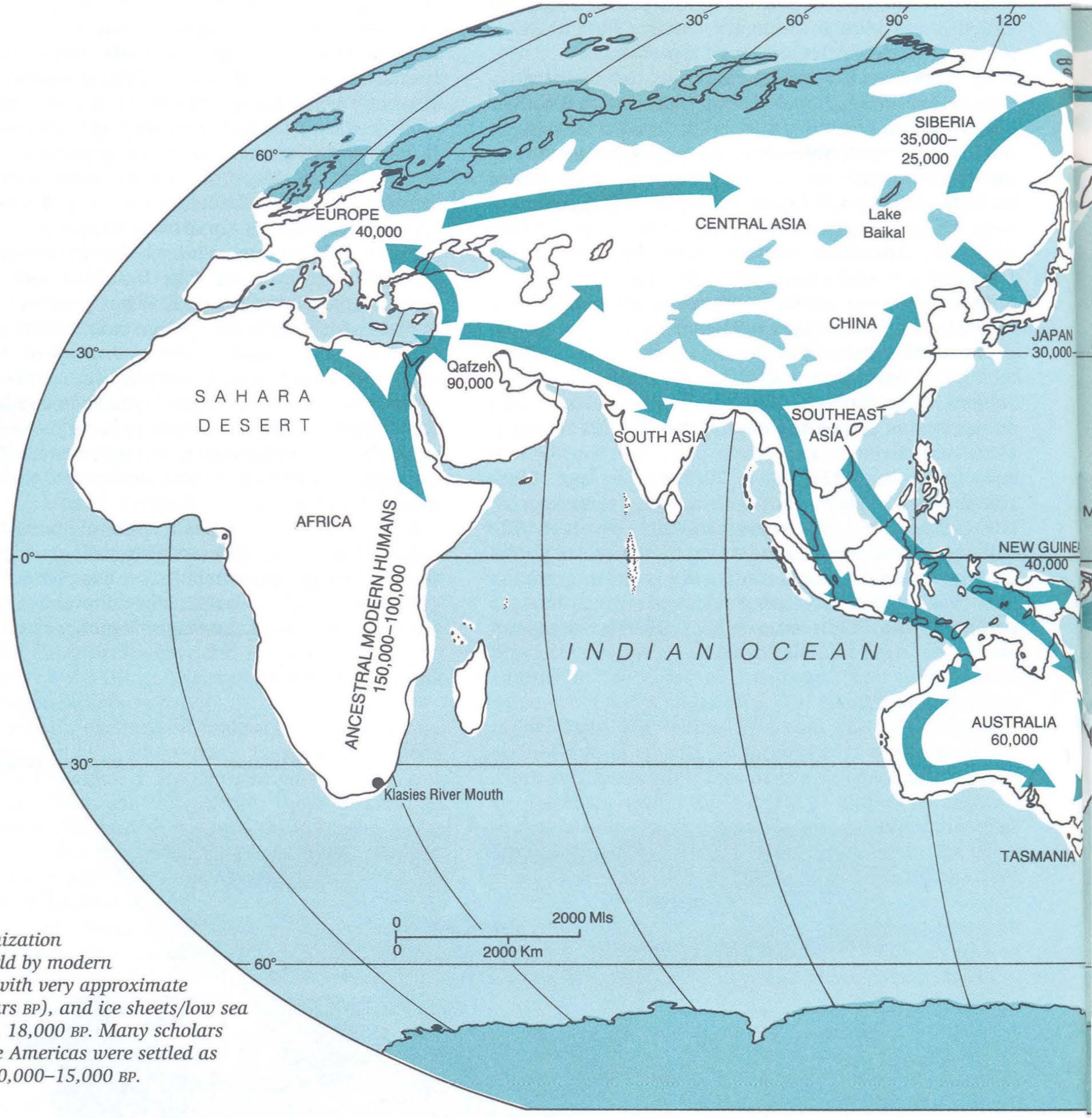
By 10,000 BC, most of the land areas of the world, except the deserts and Antarctica, were populated. The most conspicuous exception is the Pacific, where Western Polynesia does not seem to have been colonized until the first millennium BC, and Eastern Polynesia progressively from *c.* AD 300. By AD 1000 the colonization of Oceania was complete.

Nearly all the societies so far mentioned may be regarded as hunter-gatherer societies, made up of relatively small groups of people (see Chapter 5).

When surveying world history or prehistory at a global level, one of the most significant occurrences is the

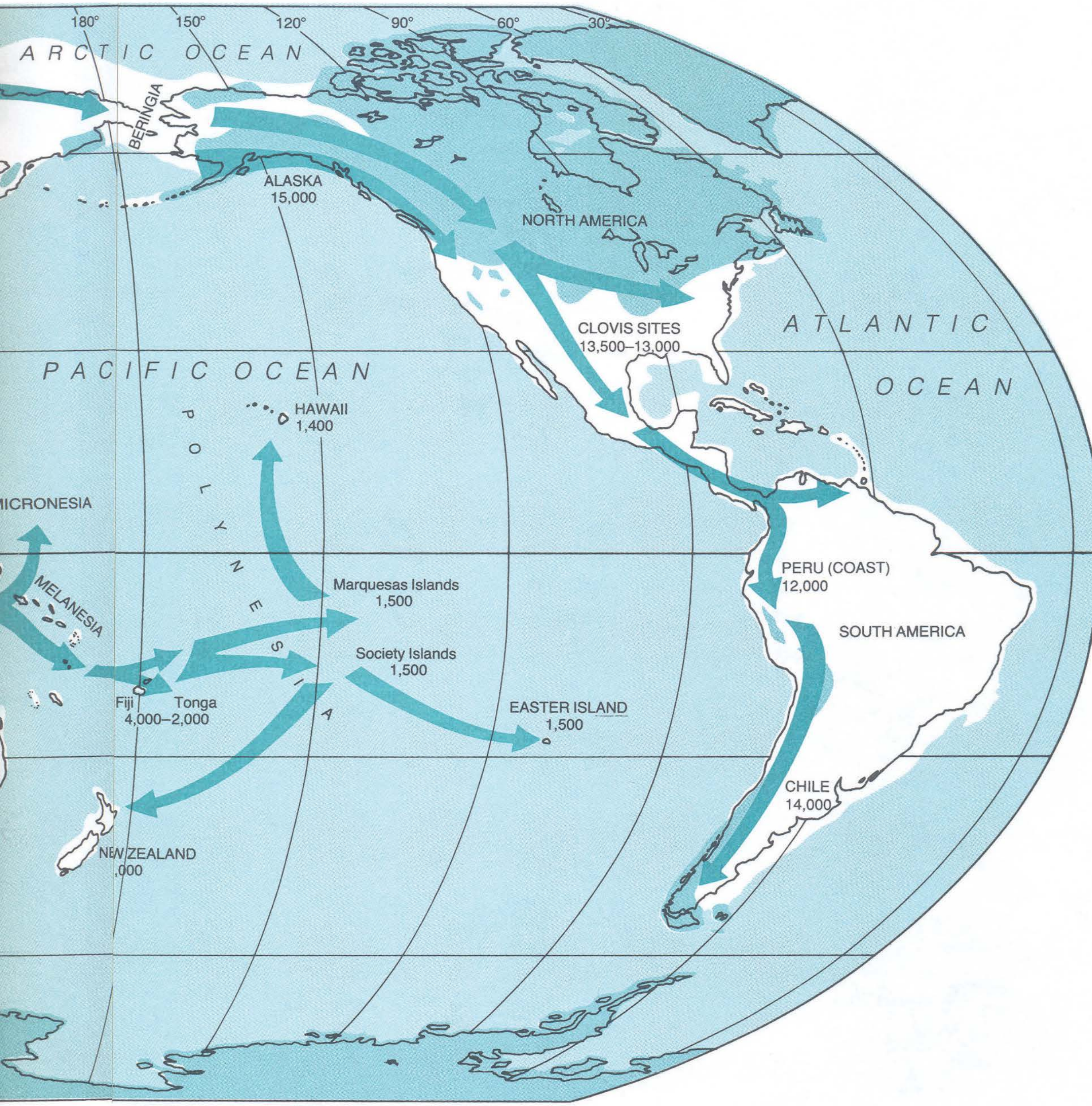


Paleoanthropologists hold strongly differing views on how the fossil remains for human evolution should be interpreted. This family tree presents the evidence as four adaptive radiations: the australopithecines, paranthropines, early Homo, and later Homo (including modern humans).



First colonization of the world by modern humans, with very approximate dates (years BP*), and ice sheets/low sea levels of c. 18,000* BP*. Many scholars believe the Americas were settled as early as 30,000–15,000* BP*.*

development of food production, based on domesticated plant species and also (although in some areas to a lesser extent) of domesticated animal species as well. One of the most striking facts of world prehistory is that the transition from hunting and gathering to food production seems to have occurred independently in several areas, in each case after the end of the Ice Age, i.e. after *c.* 10,000 years ago.



In the Near East, we can recognize the origins of this transition even before this time, for the process may have been gradual, the consequence (as well as the cause) of restructuring of the social organization of human societies. At any rate, well-established farming, dependent on wheat and barley as well as sheep and goats (and later cattle), was under way there by about 8000 BC. Farming had spread to Europe by 6500 BC, and


NORTH AMERICA
SOUTH AMERICA
EUROPE
ASIA
AFRICA
AUSTRALIA
Potato
Maize
Gourd
Squash
Beans
Cotton
Amaranth
Sunflower
Llama
Alpaca
Guinea pig
Dog
Cat
Pig
Sheep
Goat
Cattle
Chicken
Wheat & Rye
Barley
Sorghum
Yam
Oil palm
Millet
Rice


NORTH AMERICA
Chaco Canyon
Cahokia
Teotihuacan
MESOAMERICA
Maya
Chavin
SOUTH AMERICA
Inca
Stonehenge
EUROPE
Mycenae
ASIA
Mesopotamia
Indus Valley
Shang
Egypt
Axum
AFRICA
Great Zimbabwe
Cambodia
AUSTRALIA

YEARS AD / BC	NEAR EAST	EGYPT & AFRICA	MEDI-TERRANEAN	NORTH EUROPE	SOUTH ASIA	E. ASIA & PACIFIC	MESO-AMERICA	SOUTH AMERICA	NORTH AMERICA
1500		Great Zimbabwe			MUGHAL		AZTEC	INCA	
1000			BYZANTINE EMPIRE	Medieval states	Medieval states	New Zealand settled	TOLTEC	CHIMU	Cahokia Chaco
500	ISLAM	Towns (Africa)			GUPTA	States (Japan)	MAYA TEOTI-HUACAN	MOCHE	HOPEWELL PUEBLOS
AD / BC		AXUM	ROMAN EMPIRE	ROMAN EMPIRE	Writing	Great Wall (China)			
500	PERSIA BABYLON	LATE PERIOD	CLASSICAL GREECE		MAURYAN Cities				
1000	ASSYRIA	NEW KINGDOM	Iron	IRON AGE		Cast iron (China)		CHAVIN	Maize (Southwest)
1500	HITTITES	MIDDLE KINGDOM			Iron Megaliths	Lapita (Polynesia)	OLMEC		
2000	Iron		MYCENAE	BRONZE Stonehenge AGE		SHANG (China)	Pottery		
2500	SUMER	OLD (pyramids) KINGDOM	MINOAN		Writing INDUS Cities				Squash, Sunflower, Chenopodium
3000	Writing	EARLY DYNASTIC				Walled villages (China)		Temple-mounds	Pottery
3500	Cities	Towns (Egypt)			Towns			Llama, cotton	
4000	Wheeled vehicles								
4500				Megaliths	Copper				
5000			Copper (Balkans)	Farming, pottery					
5500	Irrigation							Manioc Maize	
6000					Pottery	Millet (China)	Maize? (Panama)		
6500	Copper	Cattle (N. Africa)	Farming, pottery				Beans, peppers?	Beans, peppers?	
7000	Pottery				Cattle Farming	Gardens (New Guinea)	Squash		
7500		Pottery (Sudan)						Pottery (Brazil)	
8000	Wheat							Squash? (Ecuador)	
8500	Pigs? (Turkey)							Maize? (Argentina)	
9000	Sheep?								
9500						Rice (China)			
10,000									
11,000	Rye? (Syria)					Pottery (Japan) (14,000 BC)			

The rise of farming and civilization. (Opposite page, above) Locations where major food species were first domesticated. (Opposite page, below) Locations of some of the earliest architecture in various regions of the world. (Above) Chronological chart summarizing worldwide cultural development, including first domestication of certain plants and animals.

is documented in South Asia at Mehrgarh in Baluchistan at about the same time.

A separate development, based at first on the cultivation of millet, seems to have taken place in China, in the valley of the Huang Ho by 5000 BC. Rice cultivation began at about the same time in the Yangzi Valley in China and spread to Southeast Asia. The position in Africa south of the Sahara is more complicated due to the diversity of environments, but millet and sorghum wheat were cultivated by the 3rd millennium BC. The Western Pacific (Melanesian) complex of root and tree crops had certainly developed by that time: indeed, there are indications of field drainage for root crops very much earlier.

In the Americas, a different crop spectrum was available. Cultivation of beans, squash, peppers, and some grasses may have begun by 7000 or even 8000 BC in Peru, and was certainly under way there and in Mesoamerica by the 7th millennium BC. Other South American species, including manioc and potato, were soon added, but the plant with the greatest impact on American agriculture was maize, believed to have been brought into cultivation in Mexico by 5600 years ago, though possibly earlier in northwest Argentina.

These agricultural innovations were rapidly adopted in some areas (e.g. in Europe), but in others, such as North America, their impact was less immediate. Certainly, by the time of Christ, hunter-gatherer economies were very much in the minority.

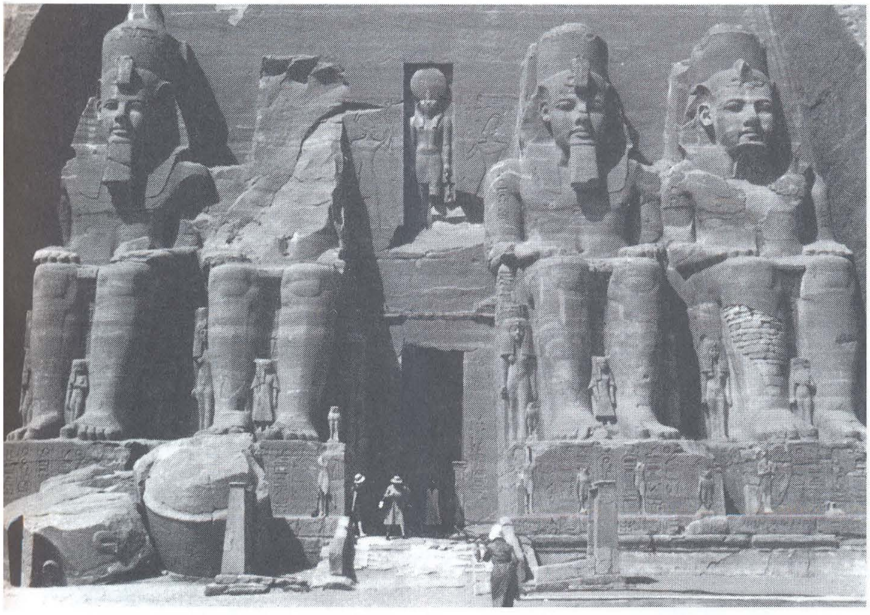
It is not easy to generalize about the very varied societies of the first farmers in different parts of the world. But in general they may, in the early days at least, be described as *segmentary societies* (see Chapter 5): small, independent sedentary communities without any strongly centralized organization. They seem in the main to have been relatively egalitarian communities. In some cases they were related to their neighbors by tribal ties, whereas in others there was no larger tribal unit.

In each area, following the development of farming, there is much diversity. In many cases, the farming economy underwent a process of intensification, where more productive farming methods were accompanied by an increase in population. In such cases, there was usually increased contact between different areas, associated with developing exchange. Often, too, the social units became less egalitarian, displaying differences in personal status and importance sometimes summarized by anthropologists by the term *ranked societies*. Occasionally, it is appropriate to use the term *chiefdom* (Chapter 5).

These terms are usually restricted, however, to non-urban societies. The urban revolution, the next major transformation that we recognize widely, is not simply a change in settlement type: it reflects profound social changes. Foremost among these is the development of *state societies* displaying more clearly differentiated institutions of government than do chiefdoms. Many state societies had writing. We see the first state societies in the Near East by about 3500 BC, in Egypt only a little later, and in the Indus Valley by 2500 BC. In the Near East, the period of the early Mesopotamian city-states was marked by the rise of famous sites such as Ur, Uruk, and later Babylon, and was followed in the 1st millennium BC by an age of great empires, notably those of Assyria and Achaemenid Persia. In Egypt, it is possible to trace the continuous development of cultural and political traditions over more than 2000 years, through the pyramid age of the Old Kingdom and the imperial power of New Kingdom Egypt.

On the western edge of the Near East, further civilizations developed: Minoans and Mycenaeans in Greece and the Aegean during the 2nd millennium BC, Etruscans and Romans in the 1st millennium BC. At the opposite end of Asia, state societies with urban centers appear in China before 1500 BC, marking the beginnings of the Shang civilization. At about the same time, Mesoamerica saw the rise of the Olmec, the first in a long sequence of Central American civilizations including Maya, Zapotec, Toltec, and Aztec. On the Pacific coast of South America, the Chavín (from 900 BC), Moche, and Chimú civilizations laid the foundations for the rise of the vast and powerful Inca empire that flourished in the 15th century AD.

The further pattern is the more familiar one of literate history, with the



Monuments constructed by state societies around the world: the Lion Gate at Mycenae, Greece, 13th century BC (opposite above); the ziggurat of Ur, in modern Iraq, c. 2000 BC (opposite below); the temple of Ramesses II at Abu Simbel, Egypt, with statues of the pharaoh, c. 1285–1265 BC (left); and a giant Olmec head, possibly a portrait of a ruler, Mexico, c. 1200–600 BC (above).

rise of the Classical world of Greece and Rome as well as of China, and then of the world of Islam, the Renaissance of Europe and the development of the colonial powers. From the 18th century to the present there followed the independence of the former colonies, first in the Americas, then in Asia and in Africa. We are talking now not simply of state societies but of nation states and, especially in colonial times, of empires.

SUMMARY

The answer to the question "When?" in archaeology has two main components. Relative dating methods allow us to determine that something is *relatively* older or younger than something else. Absolute methods make it possible to give a date in years. Archaeological dating is at its most reliable when the two methods are used together, e.g. when the relative order assigned to layers in an excavation can be confirmed by absolute dates for each layer. Wherever possible, results from one absolute method should be cross-checked by those from another, e.g. radiocarbon by tree-ring dating, or uranium-series by TL.

Ultimately the precision of dating attainable for each period helps determine the kinds of questions we ask about the past – for the Paleolithic, questions are about long-term change; for later periods, the questions are more usually concerned with the shorter-term variations in worldwide human development.

FURTHER READING

The following provide a good introduction to the principal dating techniques used by archaeologists:

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