CHAPTER 4

Dating the past

Scientific dating techniques have caused dramatic changes in our understanding of prehistory, for example by destroying the traditional framework that related Neolithic and Bronze Age Europe to the Near East, and by adding several million years to the estimated age of tool-making hominins in East Africa. In contrast, historical archaeologists incorporate material evidence into a framework of dates and cultures established from documentary sources; this is not without problems, however, and scientific dating is important in historical periods too. Dating techniques of all kinds are most valuable when applied to objects or samples from properly recorded contexts such as stratified deposits found on excavations. The study of artefacts still requires traditional methods of classification and the use of typology for ordering them in a sequence which, ideally, can then be dated by historical or scientific means.

This chapter will look at the following aspects of archaeological dating:

- A brief review of the **historical development** of dating methods.
- The use of **texts** and **inscriptions** in historical periods.
- The arrangement of artefacts into relative sequences by means of **typology**.
- **Climatostratigraphy**, which uses environmental studies to interpret and date deep-ocean cores, ice cores, varves and pollen.
- **Dendrochronology** (tree-ring dating).
- **Absolute** methods based on radioactivity, notably radiocarbon, potassium-argon, fission track and uranium series, luminescence and Electron spin resonance (ESR).
- **Derivative** (relative) techniques, including bone diagenesis, obsidian hydration and archaeomagnetism.

4.1 BACKGROUND

- key references: Trigger, *A history of archaeological thought* 2006; Renfrew, *Before civilization* 1973; Pollard, 'Measuring the passage of time' 2008; Lucas, *The archaeology of time* 2005.

Dating the past has been a central issue in archaeology throughout its development and remains fundamentally important. Chapter 1 described how, between AD 1500 and 1800, the biblical account of the Creation, the Flood and the peopling of the world had been undermined by European voyages of discovery and the development of geology. By the 1860s Bishop Ussher's date of 4004 BC for the Creation had been largely forgotten, while Darwin's theory of evolution by natural selection had extended the geological perception of the Earth's long, slow development to plants and animals (Van Riper 1993). Enlightenment ideas about social progress were supplemented by Romantic interest in origins and change and, once **prehistory** had been conceptualised, it was rapidly subdivided into ages defined by artefact technology and social evolution. However, one major obstacle remained: even if bones and artefacts *were* carefully excavated from geological or archaeological contexts and recorded in relation to stratification, this only placed them into a **relative** sequence which had no meaning in terms of absolute time (Chapter 3, p. 100).

Absolute dating in **calendar years** remained firmly in the hands of archaeologists working on historical periods, initially the Classical civilisations of Greece and Rome, and then Egypt and the Near East as their scripts were deciphered in the early nineteenth century. In contrast, archaeological finds from Scandinavia that had been arranged neatly into three successive ages of stone, bronze and iron were completely undatable until Roman imports began to appear alongside them in the Iron Age. By the early twentieth century some progress had been made in **cross-dating** prehistoric finds from northern and western Europe to Egypt, often very indirectly. Similar procedures could be carried out in South America, India, China and other parts of the Far East where literate civilisations existed, but elsewhere dating only began with the first contacts between native peoples and European explorers and colonisers. Some hope of establishing absolute dates without historical documents emerged from environmental sciences in the early twentieth century when scientists began counting annual layers of lake sediments or growth of tree rings from the present into the past. Meanwhile, the new science of nuclear physics began to provide **radiometric dates** for the age of the Earth and the succession of geological ages. Following the development of radiocarbon dating in the 1940s the first absolute dates for prehistory began to be measured from samples of charcoal, wood, bone and other organic materials.

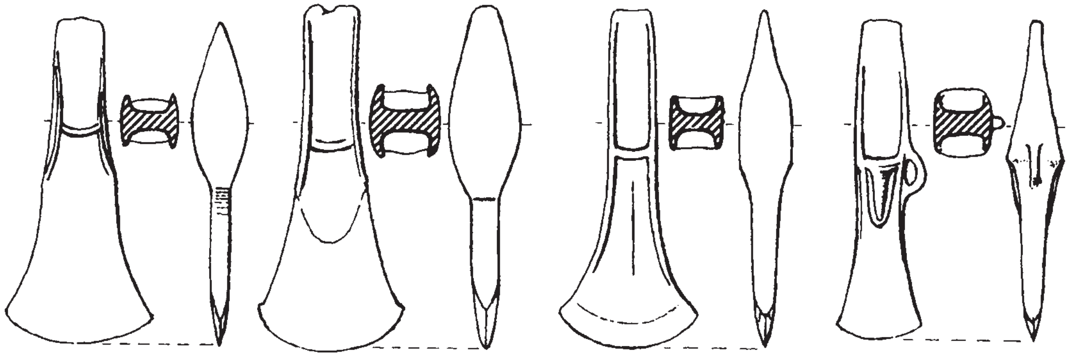
The **radiocarbon revolution** has continued for more than fifty years, gradually extending both the precision and the range of the technique. A growing number of other scientific methods have been developed for dating inorganic materials, and for extending chronology beyond the reach of radiocarbon, which is increasingly imprecise for samples more than 50,000 years old and virtually unusable by 100,000 years. It is increasingly difficult for prehistorians working in the twenty-first century to conceptualise the problems experienced by their predecessors, and approaches to interpretation before the 1960s are consistently criticised. **Culture history** and **diffusionism** may, with hindsight, seem excessively preoccupied with classification and social evolution and to have applied unsophisticated historical interpretations instead of asking fundamental questions about human behaviour (Chapter 6, p. 258). However, their exponents did not have the luxury of a global framework of independent, absolute dates; the difficulties they faced may be appreciated by looking more closely at typology and cross-dating.

4.2 TYPOLOGY AND CROSS-DATING

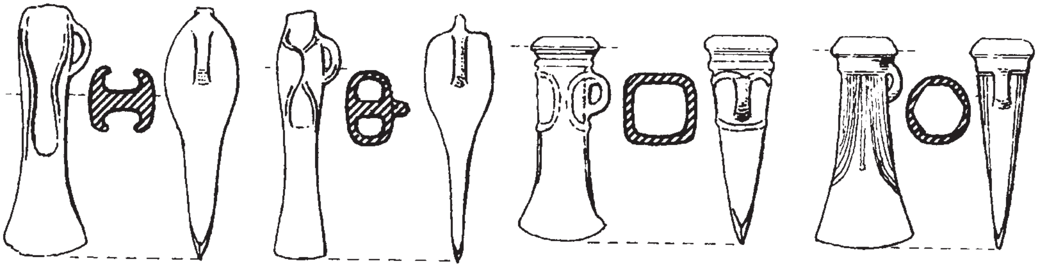
- key references: Graslund, *The birth of prehistoric chronology* 1987; Biers, *Art, artefacts and chronology in classical archaeology* 1992: 25–60; O'Brien and Lyman, *Seriation, stratigraphy and index fossils* 1999.

> It is difficult for today's students of archaeology to imagine an era when chronometric dating methods – radiocarbon or thermoluminescence, for example – were unavailable. How, they might ask, were archaeologists working in the pre-radiocarbon era able to keep track of time; that is, how were they able to place objects and sites in proper sequence and to assess the ages of sites and objects?
>
> (O'Brien and Lyman 1999: v)

It must be made clear at the outset that typology is, strictly speaking, not a dating method but a means of placing artefacts into some kind of order. **Classification** divides things up for the purposes of description, whereas **typology** seeks to identify and analyse changes that will allow artefacts to be placed into sequences (**Fig. 4.1–2**). This procedure had been carried out for living plants and animals by the eighteenth century, and geologists



Growth of the stop-ridge



Growth of the wings

Figure 4.1 Typology. Further changes in the design of axes illustrated in Fig. 1.10 took place during the middle and later Bronze Age. Pitt Rivers outlined some technical factors in 1875 (Lane Fox 1875: 507, using the nineteenth-century term celt for these axes), but also stressed the importance of non-functional decoration: '. . . the bronze *celt* was furnished with a stop to prevent its being pressed too far into the handle by the blow. Others were furnished with projecting flanges to prevent them from swerving by the blow when hafted on a bent stick. Others had both stops and flanges. By degrees the flanges were bent over the stops and over the handle, and then the central portion above the stops, being no longer required, became thinner, and ultimately disappeared, the flanges closed on each other, and by this means the weapon grew into the socket celt. On this socket celt you will see that there is sometimes a semicircular ornamentation on each side. This . . . is a vestige of the overlapping flange of the earlier forms out of which it grew, which, like the rings on our brass cannon, are survivals of parts formerly serving for special uses.' (AVC, Newcastle University, after Smith 1920)

extended the technique to fossils. As with finds from archaeological excavations, studies of fossils were greatly assisted by observing **stratification**, which provided independent evidence for the direction of a developmental sequence from the lowest (earliest) levels to the latest (Chapter 3, p. 90–2). The adoption of an evolutionary approach to fossils influenced studies of artefacts, which were sometimes treated as if they were organisms that could interbreed. Thus, although in the nineteenth century Pitt Rivers wrote extensively about typology, his evolutionary ideas about its universal validity were too abstract to have any chronological promise (Chapter 1, p. 25–6). An enduring problem with typology (familiar to evolutionary biologists before DNA clarified matters) is where to draw dividing lines between **types**, especially where one merges imperceptibly into another. Solutions may reveal fundamental differences in outlook – do types of artefact really exist for us to discover, or are our descriptive systems simply arbitrary impositions? 'The trap is the essentialist–materialist paradox' (O'Brien and Lyman 1999: 225).

From the 1880s, in Sweden, Montelius advanced typology towards actual dating by

Figure 4.2 A socketed bronze axe (similar to those at the end of Pitt Rivers' sequence) mounted on a modern wooden handle; leather strips hold it in place with the help of an integral loop on one side of the axe. Development of such copper alloy axes ended at this point, for the introduction of iron from c. 1000 BC provided a superior metal with radically different manufacturing techniques for making tools with sharp edges or blades. (GNM Hancock, Newcastle upon Tyne)

publishing comprehensive classifications and typologies of European artefacts; each form was arranged in a **type-series**, which normally developed from simplicity towards greater elaboration or efficiency (**Fig. 4.1**). He also sought **associations** between artefacts of different forms that had been buried together, such as an assortment of items deposited as grave goods in an individual burial, or a collection of objects buried in a ritual deposit or hoard. This allowed him to link different type-series together and to define phases of the past characterised by a range of artefacts at a particular stage of development (Åström 1995).

The most difficult part of Montelius' work was to **date** these prehistoric phases. The technique that he used is known as **cross-dating** (or **synchronism**) which, while entirely logical in theory, turned out to be misleading. In its strongest form, cross-dating looks for artefacts from historically-dated areas, such as Egypt or Mesopotamia, that have been imported into undated areas and found in association with local artefacts. An obvious limitation was that no historical dates extended beyond 3000 BC, so that the age of earlier artefacts could only be guessed. In 1891 Flinders Petrie identified pottery imported from Crete in Egyptian contexts dating to around 1900 BC; this date could then be applied to similar pottery found in Crete (**Fig. 4.3**). He subsequently recognised Egyptian artefacts dated to c. 1500 BC which had been imported into Mycenae on mainland Greece (Drower 1985: 182–5). Thus, dates derived from Egyptian historical records were extended to sites and cultures in Crete and Greece that lacked internal dating evidence. Whereas Petrie's links were based on direct associations with Egyptian material, Montelius extended cross-dating indirectly across Europe into Britain and Scandinavia by noting local artefacts associated with imports from other areas where cross-dating had been applied (**Fig. 4.4**).

Although these fixed points allowed phases of types in different areas to be dated, every step away from Egypt increased the possibility of a weak link in the chain. Furthermore, an independently-dated artefact imported into another area only provides a *terminus post quem* – a fixed point *after* which the context in which it was discovered was deposited (Chapter 3, p. 101). Objects imported from distant sources might have been treasured for long periods before being lost or buried with local items. Even worse, superficially similar artefacts found in different areas might have been entirely unconnected, and not contemporary at all. Confidence in Montelius' cross-dating was enhanced by a diffusionist belief that all cultural advances in Europe were inspired by earlier developments within civilisations of the Aegean and the Near East (Chapter 6, p. 260). This view survived until the 1960s, when radiocarbon dates broke the links between south-eastern Europe and the Near East and forced a

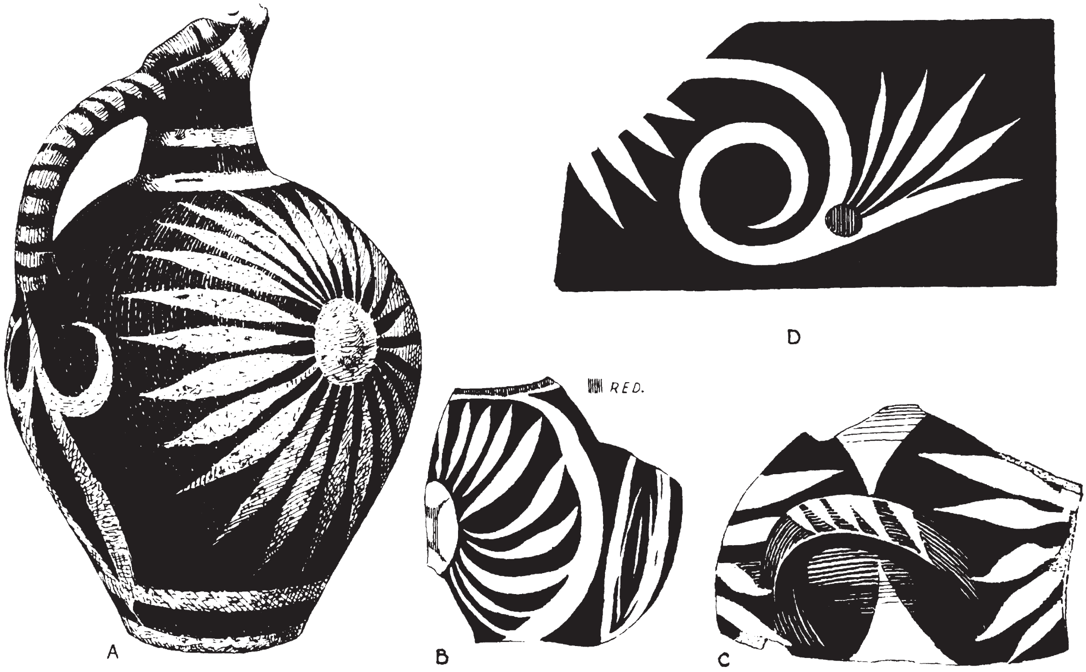


Figure 4.3 **Cross-dating** by pottery: Arthur Evans used imported Egyptian artefacts to date his excavation of the Palace of Knossos in Crete (Fig. 3.2). Local Cretan pottery found on his site could also be dated because similar sherds had been found in Egypt. A, B and D are from Crete and bear decoration of Evans' Latest Middle Minoan II Phase, while C was found at Kahun in Egypt. (Evans 1921: Fig. 198)

re-evaluation of ways in which major sites, such as Stonehenge or megalithic tombs, might have been the outcome of developments *within* prehistoric societies rather than a result of external influences (**Fig. 4.4**; Renfrew 1973a).

The traditional approach to classifying artefacts according to shape and placing them into some kind of order through typological observations of changes in their form remains sound. It is made much easier by modern excavation procedures in which findspots of artefacts are carefully recorded, and can be related to a stratigraphic sequence (Chapter 3, p. 100). Typologies can be used for understanding the technological and stylistic development of artefacts, as well as for dating. Some objects made from organic materials can even be dated directly using the **Accelerator Mass Spectrometry** (AMS) radiocarbon technique (below: p. 168) because it only requires small samples (**Fig. 4.5–6**). Association and cross-dating remain important in historical archaeology. Roman metalwork, pottery, glass and coins were traded to Scandinavia, Central Europe and even India, where they still provide valuable dates when found associated with local artefacts (Tomber 2008). Apart from coins, Roman artefacts are only datable themselves because of several centuries of classification and typological study of finds from sites, such as Pompeii, that can be related to historical records.

The principle of cross-dating is also employed in scientific contexts; radiocarbon dating was tested initially on samples of known historical age from Egypt before it could be used with confidence in prehistory. Historically-dated material is even more important for creating fixed points by which relative dating methods, such as archaeomagnetism, may be converted into calendar years (below: p. 184). Occasionally natural phenomena may be used for cross-dating; in volcanic areas **tephrochronology** is possible if ash deposits from a number of sites in a region can be related to a specific eruption. If that eruption can be dated by its effect on tree rings or ice cores,

Figure 4.4 **Diffusionism**. Archaeologists like Oscar Montelius or Gordon Childe envisaged a spread of cultural influences and innovations from the civilisations of the Near East into prehistoric Europe. This view was based on apparent connections between the typologies of artefacts found in these regions, but by the 1970s radiocarbon dates had broken the chronological sequence of links between stages 3 and 4. A complete reconsideration of phenomena such as the use of metals and the building of megalithic tombs was required when their origins and spread could no longer be attributed simply to diffusion (**Box. 6.1**). (Chris Unwin, after Renfrew 1973a)

sites may be dated and shown to be contemporary. Furthermore, the layer of ash will provide a valuable marker in stratigraphic sequences on excavations (Branch *et al.* 2005: 166–9; see **Box 4.5**).

4.2.1 Sequence dating and seriation

- key reference: O'Brien and Lyman, *Seriation, stratigraphy and index fossils* 1999.

Sequence dating and **seriation** techniques both place assemblages of artefacts into relative order. Petrie used sequence dating to work back from the earliest historical phases of Egypt into pre-dynastic Neolithic times, using groups of contemporary artefacts deposited together in graves at a single time (Petrie 1899; Drower 1985: 251–4). 'Early' and 'late' artefacts, such as changing forms of pottery, were defined by typological judgements such as those used by Montelius or Pitt Rivers. Grave groups were then arranged in a sequence according to their combinations of artefacts of early or late character, in a kind of 'simultaneous typology' that considered the development of every item found in each grave. Petrie's graphs of pottery types from a sequence of fifty pre-dynastic phases showed that types did not appear and disappear abruptly, but became popular gradually before declining equally gradually (Petrie 1920: pl. L). A modern

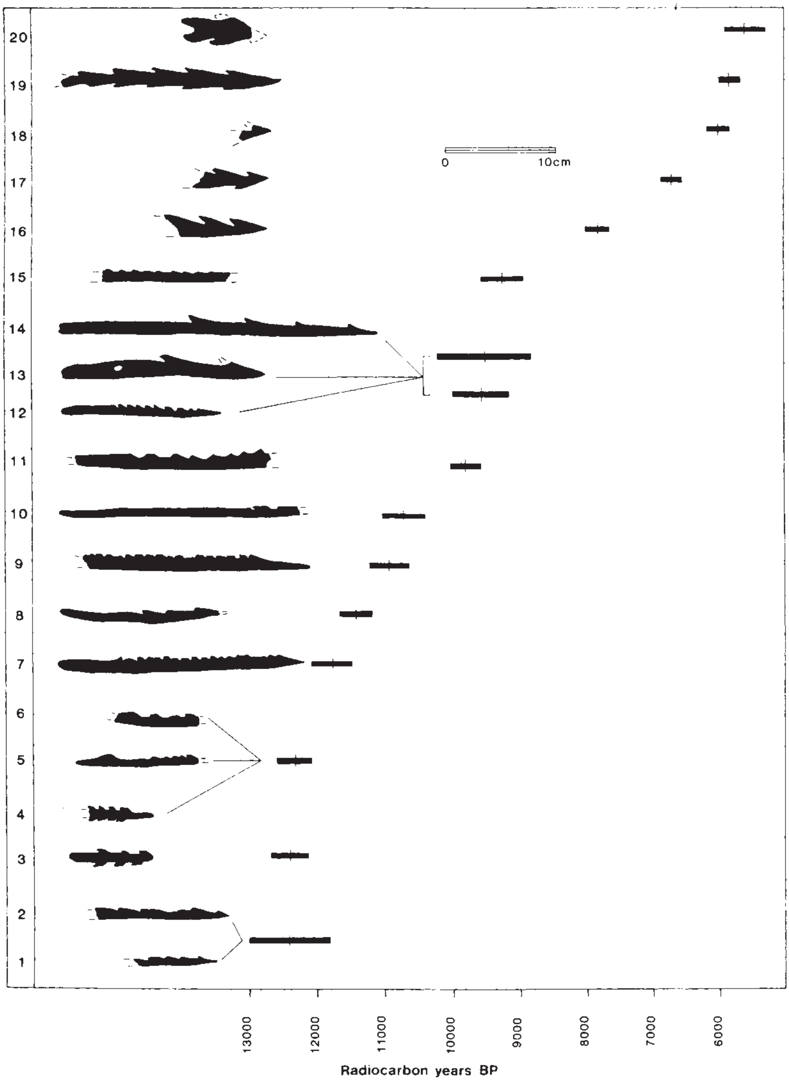


Figure 4.5 Unlike Bronze Age axes, the shapes of harpoon points (Fig. 4.6) used by Mesolithic hunters in Britain after the end of the last Ice Age show no clear typological development. However, small samples of the bone from which they were made can now be dated by the AMS radiocarbon technique, and these dates may be used to place them into chronological order. (Smith 1997: Fig. 1.2)

Figure 4.6 A Mesolithic bone harpoon point from Whitburn, Tyne and Wear; its length is 87.5 mm and, although it has not been radiocarbon dated, it was probably made more than six thousand years ago. (GNM Hancock, Newcastle upon Tyne)

analogy can be found in any car park in 2010, where there will be a few examples of the latest cars, many from the 2000s, and a much smaller number from the 1990s; even the best-selling models from the 1980s will be seen very rarely.

Seriation was developed in the USA to place in order finds from strata or other kinds of assemblages such as potsherds collected from site surfaces; O'Brien and Lyman (1999) have devoted a large part of a book to drawing distinctions between varieties of approaches. Seriation works best when assemblages contain several distinctive artefact types, such as pottery or flints, which are subject to typological change (**Box 4.1**). The artefacts are counted and converted into percentages to make them comparable. If a collection of sherds from the surface of Site 1 contains 10 per cent of pot type A and 90 per cent of type B, while Site 2 has 90 per cent of A and 10 per cent of B, it may be assumed that they are of different dates, and that, over time, type A gradually became more popular than type B or *vice versa*. If another site nearby was found to have 50 per cent of each type it would be reasonable to assume that it was dated somewhere between Sites 1 and 2. Thus, the series of sites was either 1–3–2 or 2–3–1; ideally some independent dating evidence would indicate in which direction the series ran. Seriation can, of course, be applied to much larger numbers of assemblages and they do not need to have come from the same site. Larger numbers could be arranged into the best possible sequence on the assumption that percentages of artefact types increased and declined in the orderly manner observed by Petrie in Egypt. Seriation was carried out by eye, with percentages marked on individual strips of graph paper to represent each assemblage; the strips could be shuffled to find the best sequence (O'Brien and Lyman 1999: 125; **Box. 4.1**). Returning to the modern analogy, a mixed-up set of photographs of car parks taken over several decades in one country could be arranged into order by counting the frequency of different models and changing fashions for colour and bodywork styles. Random statistical variations and differences in the character of assemblages made it rare for the results to form perfect 'battleship curves' showing the appearance, popularity and decline of each type. Seriation is a relative dating method, like artefact typology, and its use was refined and overtaken by sequences established independently by stratigraphic excavation or, more recently, by a framework of historical and scientifically determined dates.

4.3 HISTORICAL DATING

- key references: Biers, *Art, artefacts and chronology in classical archaeology* 1992; Beaudry, *Documentary archaeology in the new world* 1987; Forsberg, *Near Eastern destruction datings* 1995; Lucas, 'Historical archaeology and time' 2006.

Prehistorians sometimes overestimate the accuracy and detail of frameworks based on historical evidence; in practice, early written sources may provide little more information than a scatter of radiocarbon dates. The extent of documentation varied considerably in 'historical' cultures, and the information that survives is determined by a variety of factors. People write about a restricted range of subjects that seem significant at the time, and their successors only preserve what is still of interest. Old documents were rarely copied accurately and were frequently edited or rewritten to introduce a new point of view. Historical writing normally has a clear purpose, either to represent an event, an individual or a regime in a good or bad light (depending on the writer's attitude), or to use history to make a particular philosophical or religious point. Thus, before any written information about the past may be exploited for archaeology it is necessary to consider several factors: the date and quality of surviving manuscripts; the distance (in time and place) of the author from the events described; the author's record of accuracy if items can be checked independently; the quality of the sources available to the writer; and any personal biases or motives that might have led the writer to present a particular version of events.

In the case of Britain the invasion of AD 43 is described by several historians, including Tacitus,

BOX 4.1

Using seriation: Native American sites in New York State

Native American sites in New York State, USA, can be arranged into a hypothetical sequence according to finds of stone tools and pottery. The technique assumes that artefacts appear, grow in popularity, decline and disappear in an orderly manner, and that individual types do not replace each other straight away but overlap. This results in what are sometimes called 'battleship' curves of the appearance and disappearance of artefacts.

The transition from Fox Creek to Levanna projectile points is particularly clear and the direction of the sequence is supported by radiocarbon dates that place Fredenburg in the fourth century AD and Black Rock in the ninth. The technique does make a fundamental assumption about the comparability of the sites, however; might some differences in proportion of artefacts reflect differences in function, rather than their date? (Chris Unwin, after Funk 1976: 282–3)

who wrote a comprehensive history of the first century AD. Tacitus also wrote a biography of Agricola (governor of Britain AD 77–84), who apparently completed the conquest of Wales and subdued northern England and Scotland for the first time. While documents such as Tacitus' *Annals* and *Agricola* were written by one person with a direct historical purpose, medieval chronicles often accumulated over many centuries in monasteries. Other forms of documents such as laws, land-charters, wills, accounts and trivial correspondence were written for short-term functions rather than posterity. This kind of material is often preserved in archive offices and is plentiful in recent periods. In addition to having a general historical outline, postmedieval archaeologists may find precise dates for sites and structures in company accounts, building designs and estate maps (Hicks and Beaudry 2006). They may well be able to read personal accounts written by or about people who lived at a site that they are studying. Rembrandt's house in Amsterdam has been painstakingly restored partly with the help of his paintings of the interior, but primarily thanks to the survival of a complete inventory of its contents drawn up when he became bankrupt and was forced to move out in 1658.

Documents may be discovered in archaeological excavations. Thousands of clay tablets with cuneiform inscriptions had been found in Mesopotamia before Rawlinson deciphered their script. Everything from the lost works of Greek poets to letters full of gossip have been recovered, written on fragments of papyrus, from the desiccated rubbish tips of Graeco–Roman cities in Egypt (Bagnall 1995). The Vindolanda tablets, a collection of letters and administrative documents written on thin sheets of wood, had been thrown away at a Roman fort in Northumberland and miraculously preserved in a waterlogged context (Bowman 2003). Inscriptions carved on stone were particularly important in Egypt, the Greek and Roman world and Mesoamerica; their content ranges from terse building dedications giving the date and builder's name to lengthy historical, religious or legal material (**Fig. 4.7**). Literate societies such as the Roman Empire produced many other forms of writing that survive on archaeological sites, such as makers' names stamped on tiles and pottery (Harris 1993). These all have the advantage of being **primary documents** that have not been copied many times over the centuries by scribes who might introduce fresh errors at every stage.

4.3.1 Applying historical dates to sites

- key reference: Biers, *Art, artefacts and chronology in classical archaeology* 1992: 61–74.

One of the most precise examples of historical dating is the burial of Pompeii and Herculaneum by the eruption of Vesuvius in August AD 79. Pliny the Younger, son of Pliny the Elder (a noted natural scientist), wrote an eye-witness account of the event in which his father was killed. The volcanic deposits that sealed these cities provide a *terminus ante quem*: everything found beneath them must be *earlier* than AD 79. Objects in use at the time of the eruption (such as pottery vessels left on a table) are particularly well dated, but because these towns had been in existence for several centuries, finds from uncertain contexts could be much older. Destruction rarely has such an obvious cause as a volcano. If a context containing burnt debris and broken artefacts is excavated on a site from a historical period, it is tempting to search the local historical framework for references to warfare or a disaster in the region, and to date the excavated context accordingly. Unfortunately, historical information is patchy, and even if an apparently relevant reference is found, there might have been other unrecorded episodes that could account for the remains. In any case, buildings, and even whole towns, do burn down accidentally (for example, parts of London in 1666). If an excavated context and the artefacts that it contains are matched with the wrong historical episode, then subsequent cross-dating will apply inaccurate dates to other sites.

Thera, a Bronze Age town on the island of Santorini in the Aegean, has been compared to Pompeii because it was buried by an enormous

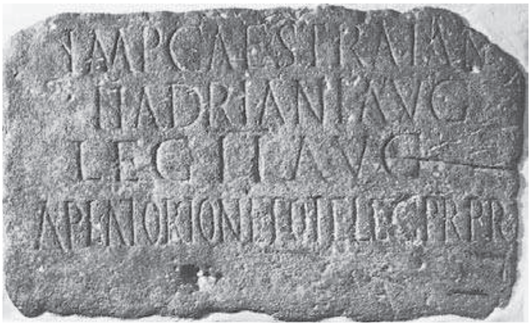


Figure 4.7 This stone slab, which is just over one metre long, is a primary source for dating the construction of Hadrian's Wall. It was found in the 1750s at the site of a milecastle that formed part of the original plan for the Wall and probably once adorned its gateway. It was common for this kind of dedication slab to be carved to mark the completion of a Roman building. The inscription states: 'This work of the Emperor Caesar Trajan Hadrian Augustus (was built by) the Second Legion Augusta under Aulus Platorius Nepos, propraetorian legate'. It associates the Wall not just with Hadrian but with Nepos, governor of Britain from AD 122 to 126 and shows that the first phase of the frontier structure had been completed early in Hadrian's reign (AD 117–38). This historical dating evidence may then be used in the study of artefacts found in the milecastle. (RIB 1638 (Collingwood and Wright 1965: 520); GNM Hancock, Newcastle upon Tyne)

volcanic eruption, but there is no documentary evidence for its date (Doumas 1983). Since the 1930s, destruction had been dated to around 1500 BC by cross-dating local 'LMIA' (Late Minoan IA) pottery to Egypt. The same eruption was thought to have destroyed several Minoan palaces on Crete, providing a valuable dating horizon for the Aegean Bronze Age through destruction levels and tephrochronology (identification of volcanic ash, see **Box 4.4**). The analogy between Thera and Pompeii proved to be misleading, however; most scientific techniques now favour a date for the Santorini eruption before 1600 BC and do not support a correlation with events in Crete, which do not even seem to have been contemporary with each other (Forsyth 1997; Manning *et al.* 2006). Some have equated the eruption with a volcanic episode detected in Greenland ice cores at around 1645 BC, which others would claim is also observable (and precisely dated) in tree rings at 1628 BC. However, the chemistry of the volcanic ash in Greenland does not unambiguously match that of Thera and it could be the result of an entirely different volcano (Baillie 1998c; Pearce *et al.* 2007) (**Fig. 4.9**). Examination of a range of radiocarbon dates using Bayesian statistics (below: p. 175) has indicated that some of these earlier suggestions, such as the 1645 BC date, do not match the radiocarbon dates and that it should be dated later, to around 1625–1600 BC (Manning *et al.* 2006). Dincauze's broader summary of the problems is still pertinent when she asks:

> Why is this so important? Why have so many excellent investigations been directed to this enigma? The entire east-Mediterranean Bronze Age chronology rides on the results, since the validity of the traditional chronology based on links with Egypt is now strongly challenged. If LMIA is earlier than 1500 BC, the entire archaeological scenario for the Bronze Age must be extensively revised and lengthened, with implications for connections in all directions.
>
> (Dincauze 2000: 134)

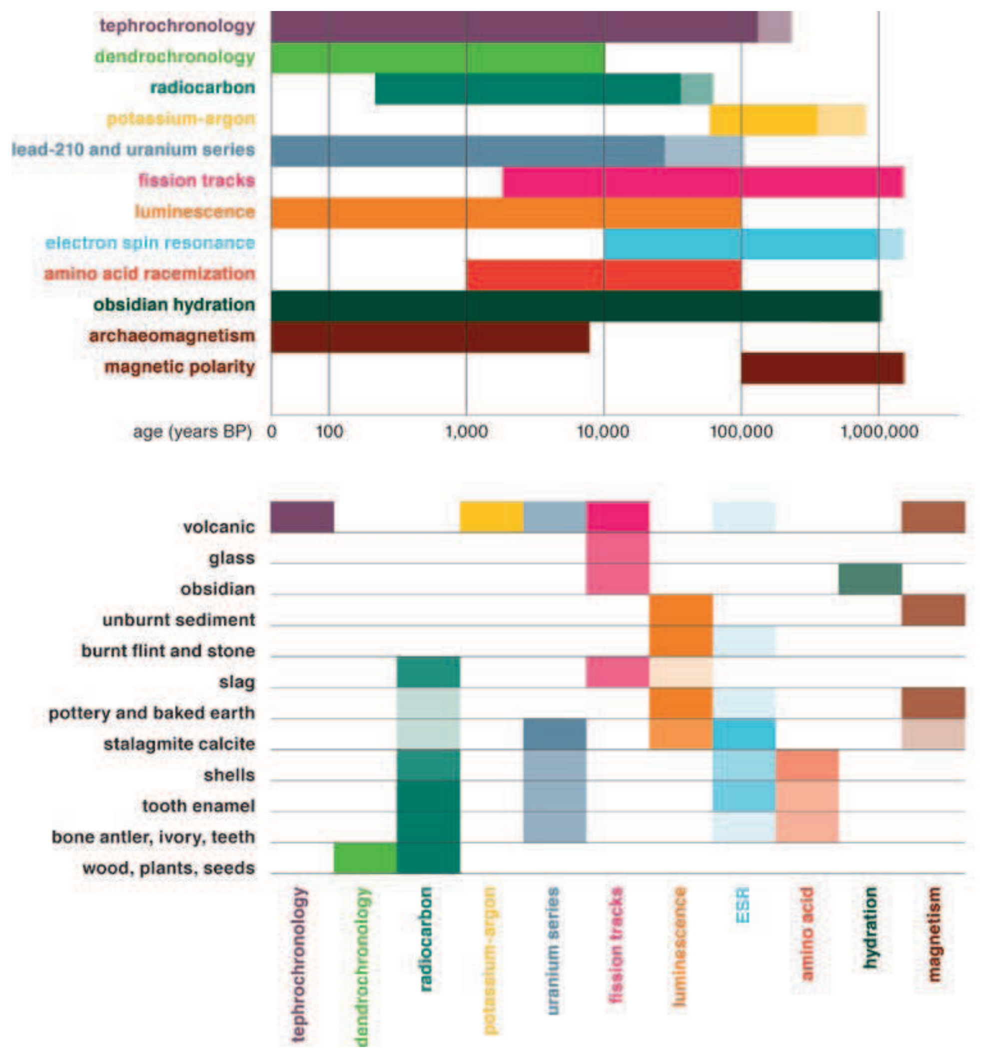
Whatever the true date may be, all forms of historical and scientific dating are vulnerable to the same risk: 'Any sloppily dated archaeological event, within a century or so, tends to be "sucked in" to the precisely dated tree-ring events. We all have to be on our guard against circular arguments' (Baillie 1989: 313).

Cross-dating is used extensively in the study of sites and artefacts in historical periods. Roman Germany provides a good sequence of forts established between the late first century BC and the later second century AD, resulting from advances and retreats along the Rhine and Danube. Sites of the first century AD are particularly useful, as new forts and frontier lines may be dated fairly closely with the help of Tacitus, who wrote about military events towards the end of the century. By the early twentieth century, German archaeologists had worked out detailed typologies for

BOX 4.2

Which dating technique?

The leading scientific dating methods are applicable to widely differing periods of the past. In the upper image, each horizontal bar indicates the range of an individual method; interrupted bars show periods where the potential is less good. Techniques with the greatest timespan are not necessarily the most useful, as examination of the lower chart reveals. The lower chart provides a summary of materials that can be examined by different scientific dating techniques; the best results will be obtained from the techniques and samples with the darkest shading. Thus, wood and other plants usually respond well to dendrochronology and radiocarbon, but no other techniques are applicable. Conversely, volcanic materials are unsuitable for either of these methods but offer many other possibilities. Archaeologists must have an understanding of these charts if they are to take the right kinds of sample for dating methods, appropriate to the period with which they are concerned; there is likely to be little point, for example, in taking radiocarbon samples if you are working on a site suspected to be hundreds of thousands of years old (Chris Unwin, after Aitken 1990, derived from various sources).



pottery and other artefacts by comparing finds from successive dated forts which could then be applied to undated sites where similar artefacts were discovered. Wheeler's use of Roman and local material for cross-dating near Pondicherry in India in 1945 was only possible because 'Arretine' tableware found there (imported from Italy) had already been classified, arranged in typological series and dated on early military sites in Germany (Wheeler 1954a: 119–25; Tomber 2008). **Coins** provide useful corroboration of typological and historical dates when found in excavated contexts in the Roman period and at other times and places where they were in sufficiently general use to be lost on sites in significant numbers (Burnett 1991).

4.4 SCIENTIFIC DATING TECHNIQUES

- key references: Brothwell and Pollard, *Handbook of archaeological sciences* 2001: 1–100; Pollard, 'Measuring the passage of time' 2008; Taylor and Aitken, *Chronometric dating* 1997; Buck and Millard, *Tools for constructing chronologies* 2004.

The transformation of archaeological dating that began around 1950 continues, but archaeologists may overlook the revolution in scientific dating that had already taken place in geology during the first half of the twentieth century. From this wider perspective, the emergence of radiocarbon dating may seem slightly less dramatic. Frederick Zeuner's book *Dating the past: an introduction to geochronology* (first published in 1946) integrated geological dating with archaeology in an exemplary manner and gives a vivid impression of the difficulties and triumphs of archaeological dating as it emerged from the nineteenth century. The text was updated and expanded several times up to 1958, by which time Zeuner was able to document the introduction of new techniques such as radiocarbon and potassium–argon dating. Zeuner began with techniques applicable to the recent past and worked back towards measurement of the age of the Earth; in contrast, Martin Aitken's survey, *Science-based dating in archaeology* (1990), is organised according to the scientific basis of each technique. We will follow Aitken's sequence, since it was retained in a major overview edited by Taylor and Aitken in 1997.

4.4.1 Geological timescales

- key references: Dalrymple, *The age of the earth* 1991; Herz and Garrison, *Geological methods* 1998.

Nineteenth-century geologists were preoccupied with the age of the Earth and accepting the Darwinian theory of evolution made it necessary to believe that it took place over very long periods of time. Glimpses of 'deep time' could be gained by estimating the rate of erosion of geological formations; Darwin suggested it took 300 million years just to produce the modern form of the South Downs. However, an estimate of at most 100 million years for the entire age of the Earth, based on the rate of cooling of the planet, was made by the influential physicist Lord Kelvin (1824–1907), and was widely accepted (Burchfield 1975). The problem was solved by a growing understanding of radioactivity and by measurement of the rate at which uranium decayed to produce lead. From 1910 Arthur Holmes and other scientists used radiometric dating to revise the age of pre-Cambrian rocks to nearly 2,000 million years. Thus, estimates of geological time went from informed guesswork to scientific precision in little more than fifty years following the publication of Darwin's *Origin of species* in 1859. Accurate knowledge of the age of the Earth was of little direct help to archaeologists, but it emphasised the potential of scientific dating techniques. The first half of the twentieth century witnessed similar progress that began with the dating of recent geological periods in which early hominins lived, and ended with the introduction of radiocarbon dating. By 1960 absolute dates were available for important stages of recent prehistory, such as the inception of farming and the first use of metals.

4.4.2 Climatostratigraphy

- key references: Lowe, 'Quaternary geochronological frameworks' 2001; Aitken and Stokes, 'Climatostratigraphy' 1997; Imbrie, *Ice ages* 1979.

While some geologists concentrated on the age of the Earth, others studied distinctive surface traces left behind by changes in the extent of polar ice during the most recent (Quaternary) geological period. They identified a succession of Ice Ages alternating with temperate conditions (**glacials** and **interglacials**) which, if they could be dated, would reveal much about the evolution of early humans in the context of changing environmental conditions. A solution suggested during the mid-1800s, and reinforced by Milankovitch in the early twentieth century, was that glacials coincided with changes in solar radiation caused by regular (and therefore measurable) variations in the Earth's orbit (Dincauze 2000: 43, fig. 3.1). This independent dating method remained hypothetical until environmental records from ocean-bed deposits and elsewhere could be checked by absolute methods, notably potassium–argon dating, between the 1950s and 1970s (Aitken 1990: 17–23). Any environmental sequences affected by global climatic change – for example pollen, layers of ice at the polar caps or wind-blown loess soil deposits – that show the characteristic alternating peaks and troughs of glacials and interglacials can now be fine-tuned in relation to orbital changes and dated to within 10,000 years, using the SPECMAP timescale (Lowe 2001: 15–17) (**Fig. 4.8**). This degree of precision is perfectly adequate for general geological and climatological purposes or the earlier parts of human prehistory; fortunately greater accuracy can be achieved with the help of other dating methods in more recent periods.

Seabed deposits

- key references: Aitken and Stokes, 'Climatostratigraphy' 1997: 8–13; Dincauze, *Environmental archaeology* 2000: 169–73.

Cores extracted from ocean floor deposits reveal variations in oxygen isotopes (in the shells and skeletal material of dead marine creatures) which reflect fluctuations in global temperature and the volume of the ocean. Ice ages lock up enormous amounts of water in glaciers; because of the chemistry of water and ice-formation, frozen water contains a greater number of 'lighter' oxygen isotopes (^{16}O) than sea-water, which has more ^{18}O. Thus, changes in the relative numbers of these isotopes (the **oxygen isotope ratio**) can be plotted, together with temperature-sensitive species of marine fauna, to reveal a pattern of climatic variations, which may be dated according to deviations in the Earth's orbit as described above. A record of 116 **marine isotope stages** has been defined covering the last three million years. In addition, seabed sediments contain iron particles that show changes in the Earth's magnetic field and occasional north–south reversals, which are also known from geological studies on land. These have been dated by the potassium–argon method where associated with suitable volcanic material (see below: p. 176), and dated reversals have been important in the validation of the astronomical dating of the isotopic stages (Lowe 2001: 13–15). Thanks to these integrated studies, geologists and archaeologists interested in the earliest stages of human development now possess a continuous record of global temperature and magnetism. Thus, bones or tools associated with early hominins recovered from geological deposits in East Africa are not only datable but also can be related to environmental conditions that might have triggered major changes ('climatic cycles and behavioural revolutions': Sherratt 1997b). These deep-sea cores reveal that rapid changes in climate took place in the last 100,000 years, changes which are important for archaeologists studying changes in past societies and cultures (Pettitt 2005: 344).

Ice cores

- key references: Aitken and Stokes, 'Climatostratigraphy' 1997: 13–19; Dincauze, *Environmental archaeology* 2000: 174–6.

A datable record of climatic change in relatively recent periods has been recovered from cores up to 3 km long, extracted from the ice sheets

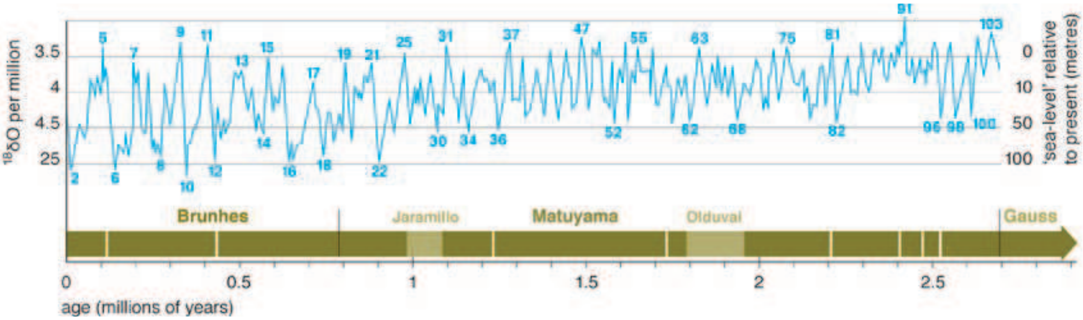


Figure 4.8 **Climatostratigraphy** is a multidisciplinary approach to determining the timescale of long-term environmental changes. These include reversals of the Earth's magnetic poles detectable in the magnetic properties of geological strata, sediments on land, and cores extracted from the seabed. When these reversals are associated with layers of freshly formed volcanic ash they can be dated using the potassium–argon technique. Magnetic reversals can also be correlated with fluctuations between warm and cold climatic conditions detectable in the chemistry of marine shells recovered from seabed cores (marine isotope stages). The SPECMAP temperature peaks may then be dated according to a regular cycle of deviations of the Earth's orbit and axis that affected its climate by varying the amount of solar radiation it received (see also **Box. 5.1**). (Chris Unwin, based primarily on Lowe 2001: Fig. 1.1)

of Greenland and elsewhere. Winter snowfall creates distinct annual layers that are visible for around 6,000 years in the upper parts of cores and may be counted reliably to within around fifty years. Deeper layers are too compressed to be distinguishable by eye, but analysis of fluctuations in dust, acidity and the oxygen isotope ratio still reveals an annual record going back 80,000 years. Thus, long-term patterns of climatic variation can be correlated with marine cores, while short-term fluctuations allow more precise interpretation of rapid environmental changes. Volcanoes known from historical records, such as Krakatoa (1883) or Vesuvius (AD 79), can be correlated with ice cores and provide support for their chronology by cross-dating (**Fig. 4.9**). Undocumented prehistoric eruptions may also be detected which, ideally, would provide dates for archaeological sites where **tephra** (volcanic ash) has been found – especially if the eruption can be correlated with tree rings showing abnormal growth patterns (see **Box 4.5**).

4.4.3 Varves

- key references: Hicks *et al.*, *Laminated sediments* 1994; Aitken, *Science-based dating* 1990: 35–6.

> During four decades de Geer's varve chronology remained an invaluable tool the significance of which for prehistory and geochronology is all too easily overlooked today.
>
> (Butzer 1971: 188)

Every summer the melting of glaciers causes erosion by streams and rivers and the resulting sediments are eventually deposited on lake beds. The sediments become sparser and finer as the year progresses, as the flow of water is reduced when temperatures begin to fall; winter freezing then stops erosion until the next summer. Sections cut through lake beds in glacial regions reveal a regular annual pattern of coarse and fine layers, known as **varves**. Variations in climate produced observable differences in the thickness of sediments and, like the patterns of variation in tree rings, this allows matches to be made between deposits in separate lake beds. Varves had been recognised and understood as early as the 1870s in Sweden. From 1905 onwards Baron Gerhard de Geer carried out extensive fieldwork with the aim of establishing a continuous sequence from overlapping deposits preserved in the beds of the hundreds of lakes that formed during the retreat of glaciers after the last Ice Age. Whereas tree rings can be counted back from a tree felled

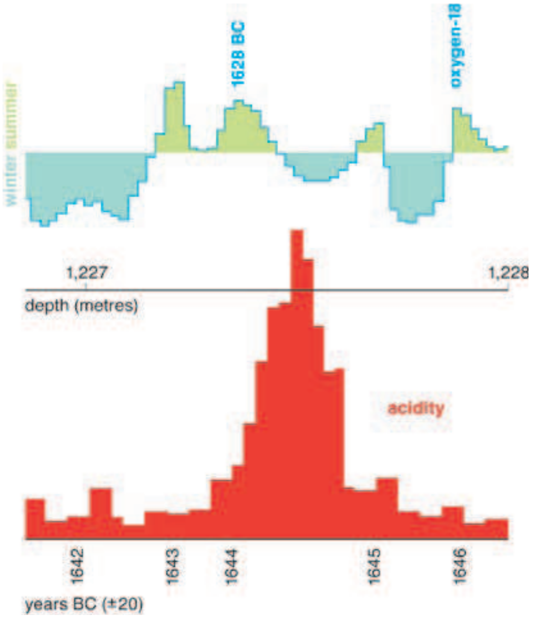


Figure 4.9 Major volcanic eruptions affect the atmosphere by emitting large quantities of acidic ash which may be detected through abnormal acidity in layers within cores taken from deep ice-sheets in Greenland. Even when the annual layers are not clearly visible, the pattern of yearly temperature variation is indicated by changes in oxygen isotope levels. Here, an eruption that left its mark around 1644±20 BC is likely to be the same event that caused damage to trees in rings dated to 1628 BC. It has been assumed that this was the explosion of Thera in the Aegean, but the evidence from the ice-core is far from incontrovertible and has been hotly debated (Hammer 2003; Keenan 2003). (Chris Unwin, after Aitken 1990: Fig. 2.10)

today, de Geer lacked a secure fixed point at the end of his sequence. A set of 3,000 varves from a lake known to have been drained in AD 1796 gave an approximate pointer and he published a sequence, covering around 12,000 years, in 1912. This sequence was finally linked to the present with the help of modern deposits from river valleys in central Sweden (Zeuner 1952: 20–45).

Varves allowed the end of the last Ice Age to be dated with confidence to around 8750 BC and introduced the first calendar dates into European prehistory. They also made it possible to date individual sites if their positions could be related to former lakes or seashores. Even more important, varves provided a means of dating the sequence of changes in vegetation known from pollen analysis that was vitally important before radiocarbon dating was introduced in the 1950s. Finally, ice cores and varves provided an additional way of checking the reliability of radiocarbon dating in periods beyond the range of samples from precisely dated tree rings. The date of signs of abrupt climatic change in ice cores and varves around 8750 BC is underestimated by approximately 700 years by radiocarbon dating, underlining the need for radiocarbon years to be converted to calendar years with the help of a calibration curve (below: p. 172). Varves also contribute information to archaeomagnetic dating because their iron-rich clay particles contain a record of the Earth's magnetic field (below: p. 184).

4.4.4 Palynostratigraphy

- key references: Branch *et al.*, *Environmental archaeology* 2005: 159–60; Dincauze, Environmental archaeology 2000: 343–62; Dimbleby, *The palynology of archaeological sites* 1985.

Microscopic wind-blown pollen grains survive well in many soil conditions, and pollen that has accumulated in deep deposits, such as peat bogs, can provide a long-term record of changes in vegetation; suitable samples may be collected from soils exposed by excavation, or from cores extracted from bogs. Work in Scandinavia in the 1920s confirmed a pattern of climatic changes since the last Ice Age that had already been proposed from visible plant remains. These changes were also found in samples taken from varves, which meant that climatic fluctuations since the end of the Ice Age could be dated. The value of this technique for archaeology lay in the fact that broad climatic phases were likely to have been fairly uniform; thus, pollen found in samples of soil from an archaeological site anywhere in north-western Europe could be related to the established sequence. Correlations could also be made between sites in different countries that belonged to the same pollen phase without relying on dubious cross-dating of artefacts. Even individual artefacts could be dated if found in peat bogs, or if sufficient soil adhered to them for samples of pollen to be extracted. For example, a Mesolithic bone harpoon dredged from the bottom of the North Sea was placed into the period when pine was declining in favour of trees that preferred warmer conditions; this was dated by varves to around 7000 BC (Zeuner 1946: 91–2). There are problems with this method, including the problems of pollen dispersal (see p. 200), and the existence of microclimates may mean correlations are not always accurate (Branch *et al.* 2005: 160). Pollen analysis has not been used for dating sites and artefacts since radiocarbon methods became available in the 1950s. It remains, however, a very important part of environmental archaeology (see Chapter 5).

4.4.5 Dendrochronology

- key references: Kuniholm, 'Dendrochronology' 2001; Dean, 'Dendrochronology' 1997; Baillie, *A slice through time* 1995; Schweingrüber, *Trees and wood in dendrochronology* 1993; Čufar, 'Dendrochronology and past human activity' 2007.

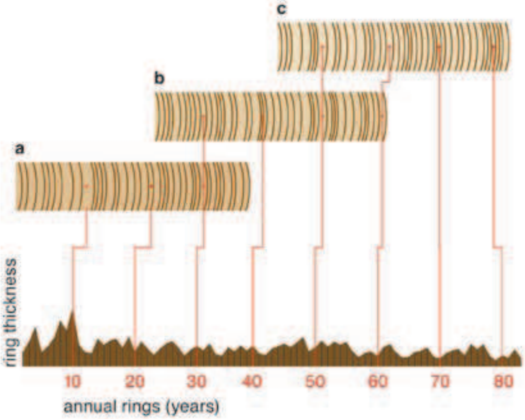


Figure 4.10 Dating by dendrochronology. A, B and C are sections from three different trees showing annual growth rings that cover a period of 83 years from the innermost ring at the left of timber A to the outermost of C. The overlapping (contemporary) portions of the timbers can be matched by observing similarities in the pattern of their rings, especially when unusually wide or narrow rings reflect particularly good or bad growing seasons for the trees. The graph records the average annual ring thickness for each year, allowing for the fact that the outer rings are always narrower than the inner because their volume of wood is spread thinly around a large trunk. Long overlapping sequences from dated timbers provide a reference graph against which individual undated samples can be compared. Thus, if this graph began in AD 1000, timber B was felled in AD 1060 and this is a *terminus post quem* for any structure into which it was incorporated. (Drawn by Chris Unwin)

Tree-ring dating is presented here, rather than with the absolute techniques described below, because it resembles the methods described above in that it is based on a regular biological process and is influenced by environmental conditions. It has been recognised since at least the fifteenth century that trees produce annual growth rings; their physiology was understood by the eighteenth century (Schweingrüber 1987: 256–7). It was also realised that rings could be counted to calculate the age of a tree when it was felled. Because the thickness of these rings is affected by annual climatic factors, distinctive sequences of rings may be recognised in different samples of timber and used to establish their contemporaneity (**Fig. 4.10**; **Box 4.3**). In addition to the thickness of tree rings, measurements may also include the density of the wood. This allows dendrochronology to be extended to so-called 'complacent' tree species with annual rings that vary little in width. Well-documented examples of tree-ring dating begin in North America in the late eighteenth century; for example, the Reverend Cutler counted 463 rings in a tree that had grown on a Native American burial mound at Marietta in Ohio and deduced (correctly) that the mound must predate Columbus (Daniel 1981: 40–2). In 1904 A.E. Douglass began to study fluctuations in solar radiation and their effect on climate by looking at variations in tree-ring thickness in Arizona.

Douglass's work included archaeological dating in the 1920s because many samples came from structural timbers preserved in *pueblos* (prehistoric Native American sites in arid areas of Arizona and New Mexico) (Nash 2003). These samples could then be dated by cross-referencing them to the sequence of rings built up by

BOX 4.3

Alchester: dendrochronology in action

A Roman fort was built at Alchester, north of Oxford, in the first century AD (Sauer 2000). Stumps of the large timbers that supported the gate structure survived in wet soil conditions, and two of them were large enough for tree-ring dating to be carried out by Ian Tyers at Sheffield University's dendrochronology laboratory. The reconstruction by Deborah Miles-Williams emphasises the enormous quantities of timber that would be required every time the Roman army constructed a base. Both trees had terminal rings dating between October AD 44 and March AD 45, showing that they came from trees cut down soon after the Roman conquest of Britain (AD 43). The excavator thinks it likely that local woodland was cut down in the autumn of AD 44 in order to complete the defences before the winter. No other form of archaeological dating could provide such a precise *terminus post quem* for the construction of the fort gateway (Eberhard Sauer).

Douglass, which eventually extended back to the fourth century BC. In 1954, bristlecone pines still growing in California were found to be up to 4,000 years old, and a combination of specimens from living trees and old trunks preserved in the White Mountains now provides a continuous record going back to 6700 BC that is of vital importance for checking radiocarbon dates (below: p. 170). The discovery that some spruce tree root systems in Sweden may be more than 9,000 years old is also important in understanding past climate changes. An even more impressive achievement is the establishment of a tree-ring sequence that extends beyond 8400 BC, based on a large number of oak trees from north-western Europe (Haneca *et al*. 2009). Many of the oldest samples have been taken from ancient tree-trunks preserved in peat bogs. The sequence in Germany is approaching 10,000 BC, using pines (Kuniholm 2001: 38–9). Some rings may have distinctive markers, such as the effects of forest fires, severe frosts or volcanic eruptions, that help with cross-dating between trees in any region, as well as providing important environmental information.

The application of tree-ring dating

Work in Arizona demonstrated the value of tree rings not simply for dating buildings, but also for studying their modification and repair; this approach has been used in many different contexts since then. Studies have been conducted in medieval buildings, such as the cathedrals at Trier in Germany and Chartres in France, to identify or date periods of construction that were not fully documented in surviving historical records. Roman forts and bridges in Germany and the Netherlands have been investigated in the same way; the precision of tree-ring dating is impossible to achieve by any other means. Once dated, such sites can be integrated into historical accounts; waterlogged timbers from the gate of a Roman fort excavated at Alchester near Oxford in 2000 came from trees felled in the autumn of AD 44, the year following the invasion of Britain (**Box 4.3**).

Unfortunately, there are many problems in the direct application of dendrochronological dating. Not all tree species are sufficiently sensitive to display distinctive variations in their ring characteristics, particularly when growing in temperate climates.

Wood only survives under exceptionally wet or dry conditions. Even when it does, large timbers must be recovered to provide sufficient rings for valid comparisons between sequences that accumulated over several decades. A precise date for a felled tree can only be established when all of the sap wood containing the outermost rings has been preserved; unfortunately this might have decayed, or have been trimmed off if the wood was used for building, in which case it is necessary to estimate how many years of growth have been lost. Timbers used in buildings were normally trimmed into regular shapes, and might also have been stored for many years before use. Worse still, roof timbers were frequently reused several times in repairs or reconstructions of wooden buildings whose foundations in contact with damp soils decayed long before the roof. Reuse is a particular problem on arid sites, where timbers do not decay easily. Despite these difficulties, tree rings are the only source of truly absolute dates, in terms of a single year. Unfortunately, they will never be universally applicable, partly because of regional and environmental variations in the growth of trees but principally because of the rarity of suitably wet or arid conditions that ensure their preservation.

The provision of samples of known age for testing the accuracy of radiocarbon dates is not the only indirect use of tree rings. Variations in ring thickness reflect climatic conditions, and there are several instances of extreme disturbances to normal growth. For example, a series of exceptionally narrow rings indicating an episode of cold, wet weather from 1159 BC, that was almost certainly the result of a volcanic eruption marked in ice cores at 1100 ± 50 BC (Baillie 1989), provides cross-dating between the two natural records. The analysis of chemicals emitted during volcanic eruptions found in individual rings may allow them to be related to specific growth declines in trees, and their chemical signatures may possibly be related to these specific volcanic eruptions (Pearson 2006).

At a more intimate level, the precision of tree-ring dates adds an exciting dimension to other finds associated with dated timbers. Star Carr, a classic settlement of Mesolithic hunter-gatherers in Britain, has benefited from the extension of tree-ring records back to the ninth millennium BC; samples that were once dated by radiocarbon with a margin of error of hundreds of years have become events that took place in a specific year (Mellars 1990; Dark 2000). This precision can be extended to other finds, such as tools and animal bones, found in the same contexts. Seahenge, a circle of timbers revealed by erosion of the coast of Norfolk in 1998, was created from timbers felled in 2050 BC, while an upturned tree-stump at its centre was felled in the following year (Pryor 2001). Such precision is impossible in the dating of contemporary stone circles. The impact is similar in historical periods. Dendrochronology is frequently used on art objects such as panel paintings and wooden sculptures made from oak, such as sixteenth and seventeenth century AD examples from the Netherlands. Again, the reuse of wooden panels may cause problems (Haneca *et al.* 2009: 6). Four hundred samples taken from a collection of Anglo-Scandinavian houses and workshops excavated at Coppergate in York showed that the majority were built from timber from trees felled in AD 975. This indicates planning and management of resources, rather than the piecemeal accumulation of buildings over a long period. If the final ring that was growing when a tree was cut down is preserved, it is possible to estimate the time of year at which wood was harvested; this allows detailed interpretations of human behaviour to be added to chronological information (Dean 1997).

> From a discipline of limited topical and geographic scope, dendrochronology has been transformed into a global phenomenon relevant to a broad range of subjects. Firmly grounded in the principal of cross-dating – using aspects of ring morphology to identify contemporaneous rings in different trees – dendrochronology provides absolute dates

> accurate to the calendar year and qualitative and quantitative reconstructions of environmental variations on seasonal to century scales. … Although problems exist, they are being seriously addressed by the world dendrochronological community and progress can be expected on all fronts. The carefully controlled expansion of tree-ring science into all areas of the globe, its application to an ever broader range of past and present phenomena, and its unparalleled utility as a source of baseline data for measuring current environmental excursions and predicting future variations endow dendrochronology with a bright future.
>
> (Dean 1997: 31, 55)

4.5 ABSOLUTE TECHNIQUES

- key references: Taylor and Aitken, *Chronometric dating* 1997; Aitken, *Science-based dating* 1990; Göksu, *Scientific dating methods* 1991; Pollard, 'Measuring the passage of time' 2008.

> The proper meaning of absolute dating is that it is independent of any other chronology or dating technique, that it is based only on currently measurable quantities.
>
> (Aitken 1990: 2)

4.5.1 Radioactive decay

- key references: Aitken, 'Principles of radioactive dating' 1991; Dincauze, *Environmental archaeology* 2000: 107–25.

Unfortunately for the study of prehistory, all of the dating techniques that emerged before 1950 required special circumstances: the survival of timber for tree rings, glacial lakes for varves, or soil conditions that favoured the preservation of pollen. However, the successful development in the early twentieth century of radiometric methods relying upon **radioactive decay** for dating geological periods offered hope that a similar technique might be found to give absolute dates for prehistoric archaeology. Many elements have different isotopes with extra neutrons besides their standard number of protons, indicated by a number showing their atomic weight (e.g. carbon-14, normally represented as ^{14}C). Isotopes of an element behave in very similar ways in chemical reactions, but may be unstable (**radioactive**) and emit radiation at a known rate. Some isotopes become stable after emitting particles, while others go through a protracted series of **progeny** (or **daughter**) **elements** before reaching a stable form (e.g. uranium to lead). The rate of radioactive decay is characterised by the **half-life** – the time taken for half of the radioactive atoms to decay; this may vary from seconds to millions of years.

4.5.2 Radiocarbon dating

- key references: Taylor, 'Radiocarbon dating' 1997; 2001; Aitken, *Science-based dating* 1990: 56–119; Pettitt, 'Radiocarbon dating' 2005; Hackens *et al.*, *^{14}C methods and applications* 1995; Taylor, 'Radioisotope dating by accelerator mass spectrometry' 1991.

Radiocarbon dating was one peaceful by-product of accelerated wartime research into atomic physics and radioactivity in the 1940s. The rate of decay of ^{14}C, which has a half-life of 5,730 (±40) years, is slow, allowing samples of carbon as old as 70,000 years to contain detectable levels of radioactive emissions, but fast enough for samples from periods since the late Stone Age to be measured with reasonable precision. What makes ^{14}C exceptionally important is that it is absorbed (in the same manner as other carbon isotopes) by all living organisms until their death (**Fig. 4.11**). In theory, all that needs to be done is to measure the radioactivity of a sample from a dead animal or plant, and to calculate the time that has elapsed since its death from the amount of ^{14}C that remains. The practicalities of age estimation are rather more complicated, and the discussion that follows will attempt to highlight the principal advantages and disadvantages of ^{14}C rather than to provide a full scientific explanation.

This simplified description does not do justice to the inspired formation and testing of hypotheses

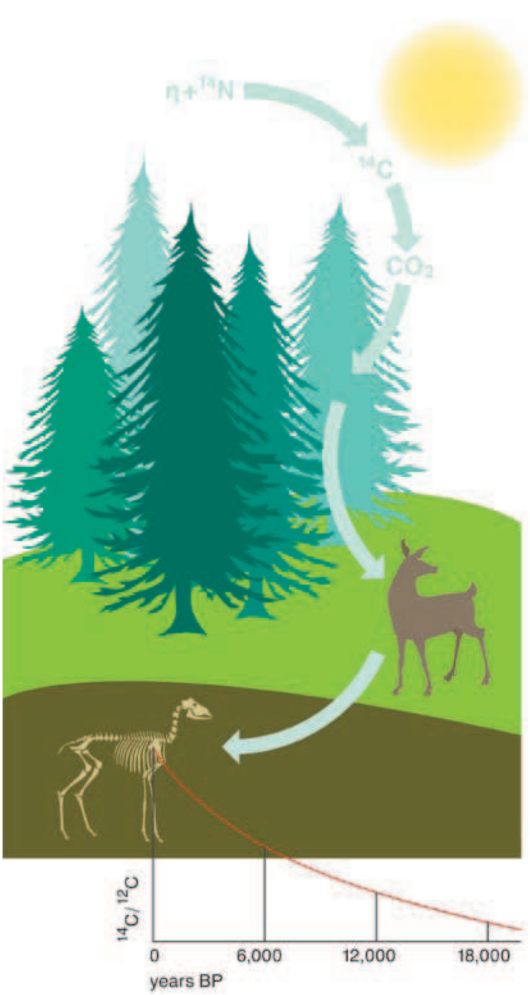


Figure 4.11 This drawing illustrates the basis of radiocarbon dating. The arrows follow the formation of the radioactive carbon isotope (^{14}C) in the atmosphere by cosmic radiation and its incorporation into a tree through photosynthesis of carbon dioxide. It then passes to a deer that has eaten the foliage, but this animal ceases to take in fresh ^{14}C when it dies. Thus, its bones are placed at the top of a graph that shows the steady decay of the radioactive isotope as time elapses after the death of the deer. (Redrawn by Chris Unwin, after an illustration by Robert Hedges, Research Laboratory for Archaeology, Oxford University)

carried out by Willard F. Libby in Chicago in the 1940s, for which he received a Nobel Prize in 1960 (**Box 4.4**). However, the publication of his preliminary results in 1949 was only a beginning. Taylor has divided the progress of the technique into three generations (1997: 70–3).

- The first generation (1950–70) established radiocarbon's accuracy for a period of particular significance to prehistoric archaeologists, encompassing the transition from hunting and gathering to farming, the emergence of the first civilisations and periods of later European prehistory that had previously relied upon indirect cross-dating to Egypt. Differences between conventional archaeological dates and the new radiocarbon dates stimulated discussion of both.
- The second generation (1970–80) looked more closely at variations in levels of ^{14}C in the past, and conducted comprehensive analyses of samples from tree rings of known date to provide a **calibration curve**. The results were surprising, and radiocarbon dates before 1000 BC were shown to underestimate calendar years by a progressively greater margin, so that a radiocarbon age of around 4000 BC had to be adjusted upwards by around 800 years. This was the final nail in the coffin of **diffusionism** (the idea that all European developments were inspired by innovations that began in the Near East and Egypt), as prehistoric stone structures in northern Europe turned out to be older than the Egyptian or Mycenaean models that had supposedly inspired them (Chapter 6, p. 251).
- The third generation refined the calibration curve and extended it beyond the range of tree rings by analysing samples of marine coral. It also included a major advance in accuracy and precision through the establishment of **Accelerator Mass Spectrometry (AMS)** laboratories in the 1980s (Tuniz 1998). AMS is fundamentally different because it measures the **concentration** of ^{14}C in relation to the 'normal' isotope ^{12}C, rather than its radioactivity. AMS reduces both sample size and counting times (the former from grams to milligrams, the latter from weeks to hours) and extends the range of radiocarbon dating back beyond 40,000 years (Taylor 1997: 82). This allows

> individual organic artefacts and bones to be dated *directly*, rather than by association with samples of other material from the contexts in which they were found. Improved precision and a greater range of calibration offer particularly exciting prospects in early prehistory, for example in dating bones associated with the disappearance of Neanderthals and the appearance of modern humans in Europe and Asia between 50,000 and 30,000 years ago (Aitken *et al.* 1993).

To Taylor's list we might now add a fourth generation: the application of Bayesian statistics to both existing and new radiocarbon dates is providing more detailed chronologies and has been called by some a new radiocarbon revolution (below: p. 175).

In essence, if a sample of ancient wood, charcoal or other organic matter is processed in a laboratory so that carbon is isolated, the amount of radioactivity that remains can be measured; the older it is, the fewer radioactive emissions of beta-particles will occur during a fixed period of observation. Ten grams of modern ^{14}C produce 150 disintegrations per minute. The age of an ancient sample of the same weight that produced only 75 counts per minute should therefore be

BOX 4.4 The first radiocarbon revolution: Willard Libby

The discovery of radiocarbon dating represented perhaps the greatest advance in archaeological dating in the twentieth century, creating an independent chronological framework for prehistory. Willard Libby (1908–1980), was awarded a Nobel Prize in 1960 for the development of radiocarbon dating. His book *Radiocarbon dating*, published in 1952, ensured his place as one of the most influential individuals in modern archaeology. Libby, a professor of chemistry from California, worked on carbon-14 before the Second World War and took part in the development of the Manhattan Project, which developed the atomic bomb. He realised that the half-life of the radioactive isotope carbon-14 (^{14}C) lasted thousands rather than millions of years, and that new ^{14}C was continuously formed in the atmosphere by cosmic radiation. Freshly formed isotopes were added to the carbon contained in all living plants and animals until their death. At this point a 'radioactive clock' started ticking, and the age of the sample could be estimated by measuring how much of its original radioactivity remained, and by using the known half-life of ^{14}C to work out how many years it would have taken to fall to the observed level. After the war, Libby refined radiocarbon dating by testing samples of known age. Suitable organic material up to 5,000 years old was available from Egypt, preserved in dry conditions and dated by inscriptions. Once a correlation between radiocarbon estimations and tree rings could be established, the technique could then be applied to undated prehistoric samples. This 'first radiocarbon revolution' often had dramatic results, pushing back the suspected dates of some archaeological phenomena and leading to wholesale reassessments of parts of prehistory (Chapter 6, p. 251) (Getty Images) equal to the half-life of the isotope, around 5,730 years. The use of ^{14}C dating remains complex, and the following section looks at factors that limit its precision and application. Radiocarbon age estimations require careful examination before they can be turned into calendar dates. Some of Libby's original assumptions have been found to be incorrect, and methods of measuring ^{14}C and calculating dates have changed several times during the half-century in which the technique has been employed.

Key factors

- **Radiocarbon dating is universal**, because the radioactive isotope ^{14}C is formed continuously throughout the Earth's atmosphere by the effects of **cosmic radiation**.
- ^{14}C has a known **half-life** and **decays** at a known rate, but the original **half-life** was too low by around 3 per cent; it is now judged to be around 5,730 years, rather than 5,568.
- The rates of **formation and decay are in balance**; cosmic radiation in the past should have maintained ^{14}C in the atmosphere at a constant level. However, the level of cosmic radiation has fluctuated over time, perhaps in relation to sunspot activity and the Earth's magnetic intensity. This means that the formation of ^{14}C in the atmosphere has varied; thus, samples from organisms that absorbed abnormally larger or smaller amounts of ^{14}C will give misleadingly earlier or later dates. In addition, calibration reveals that dates from the **southern hemisphere** are around 30 years too old compared with those from the northern hemisphere; this is probably because the greater area of oceans in the southern hemisphere has affected the distribution of ^{14}C in the atmosphere.
- **All life-forms contain carbon**, and living organisms absorb carbon from the atmosphere, mainly in the form of carbon dioxide; photosynthesis by plants is one common mechanism. Animals and plants therefore maintain the same proportion of newly formed ^{14}C as the atmosphere until their death, when it begins to decay. However, different isotopes of carbon are taken into organisms at different rates (**fractionation**); proportions of ^{13}C and ^{14}C must be checked and an adjustment made to the estimated date. Furthermore, marine organisms absorb **'old' ^{14}C** from sea water; samples taken from shells or bones of marine mammals give dates which are misleadingly early by several hundred years. Some of this old carbon has been absorbed by humans – in Scotland, for example, by people living in the Mesolithic period on Oronsay (Richards and Sheridan 2000), and in the Viking period on Orkney (Barrett *et al.* 2000), as well as by other animal species which eat large quantities of seafood.
- A **calibration curve** must be used to convert radiocarbon years into calendar years (**Fig. 4.12**). Tree rings have revealed not only short-term fluctuations in ^{14}C levels but also a long-term divergence between ^{14}C estimations and calendar years that grows increasingly wider before c. 1000 BC. Samples with a radiocarbon age of 5,000–7,000 years require upward adjustment of as much as 500–1,000 years, while uranium–thorium dating shows that coral dated to around 26,000 BC by radiocarbon is actually 30,000 years old. **Dendrochronology** provides independently dated samples of wood from annual tree rings stretching back more than 11,000 years, while earlier samples come from dead trunks preserved in semi-arid habitats and from oak trees found in bogs or river sediments in Europe. Samples from **marine corals** may extend the calibration curve back as far as 50,000 years (Fairbanks *et al.* 2005) by comparing ^{14}C with dates derived from uranium–thorium isotopes.
- A statistical estimation of error, expressed as a **standard deviation**, is attached to laboratory counts of radioactivity. Since isotope decays occur at random, a reasonably long counting period is needed to reduce this inherent error. Several counting sessions are carried out, along with measurements of laboratory standards to monitor the performance of the equipment. The standard deviation derived from the counting statistics is preceded by '±'; **Fig. 4.13** shows how the reliability of a date may be envisaged.

Table 4.1 Summary of factors involved in radiocarbon dating

Positive factors	Complications
Radiocarbon dating is universal because ^{14}C is distributed throughout the atmosphere	There is a 30-year difference between dates from the northern and southern hemispheres
^{14}C has a fixed half-life and decay rate	The half-life is now known to be 5,730 years, rather than 5,568
The formation and decay of atmospheric ^{14}C are in balance	Variations in cosmic radiation have caused ^{14}C levels to fluctuate
All life-forms contain carbon	Isotopes of carbon are taken into organisms at different rates (fractionation)
Plants and animals take in newly formed ^{14}C until their death	Marine creatures absorb old carbon from deep sea water
Dendrochronology provides an independent measure of accuracy	Radiocarbon underestimates the age of tree rings to an increasingly serious extent beyond 2000 BP (*B*efore *P*resent; for consistency the 'present' is standardised as AD 1950)
A calibration curve converts radiocarbon estimations into calendar dates	The curve contains many sections where calibration is imprecise or ambiguous
Conventional and AMS dating now provide very precise dates	The results are still subject to a statistical margin of error, indicated by the standard deviation
Excellent results may now be obtained from small samples	Good results depend on the careful selection of appropriate samples, and the quality of the archaeological context remains crucial

Table 4.2 Radiocarbon estimation from Galgenberg

Lab no.	Arch. no.	Uncalibrated determination BP	Archaeological context
GrN-12702	T14 1P	4385±35	collapsed palisade fence in W ditch

Table 4.3 Calibrated dates from Galgenberg

Uncalibrated determination BP	Corresponding historical dates BC	Estimated standard errors
4385±35	2947, 2973, 3025	59, 80, 30

4.5.3 Presenting and interpreting a radiocarbon date

- key references: Reimer, 'IntCal09' 2009; Stuiver and Van der Plicht, *INTCAL 98: calibration issue* 1998; Banning, *The archaeologist's laboratory* 2000: Pettitt, 'Radiocarbon dating' 2005: 332–4.

> **Health warning!** Proper calibration is not easy for the non-mathematician, but doing it incorrectly, wrongly interpreting the result, or even not understanding the potential of calibration may seriously damage your archaeology. Take advice from the experts, know what calendrical band-width is necessary for correct interpretation and discuss this with the dating laboratory, preferably before taking and certainly before submitting samples. Think first, not after you get the radiocarbon date.
>
> (Pearson 1987: 103)

Because interpretation is so complex, all radiocarbon dates included in an archaeological

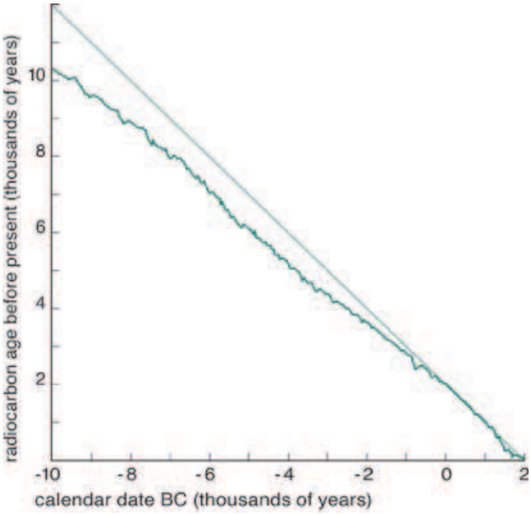


Figure 4.12 ***(above left)*** Tree-ring calibration curve for radiocarbon dates based on calculations published in 1998. The straight line shows what the relationship would have been if the amount of ^{14}C in the atmosphere had remained constant so that 4,000 radiocarbon years would be equivalent to c. 2000 BC. However, beyond 500 BC there is an increasing divergence, so that a radiocarbon age of 8,000 years before present has to be increased from c. 6000 to c. 7000 BC. The process of calibration looks deceptively simple at this scale, but 'wiggles', combined with other statistical uncertainties, make calculations very complicated. Fortunately, computer programs such as OxCal are freely available for this purpose. (Chris Unwin, based on data from Stuiver and Van Der Plicht 1998)

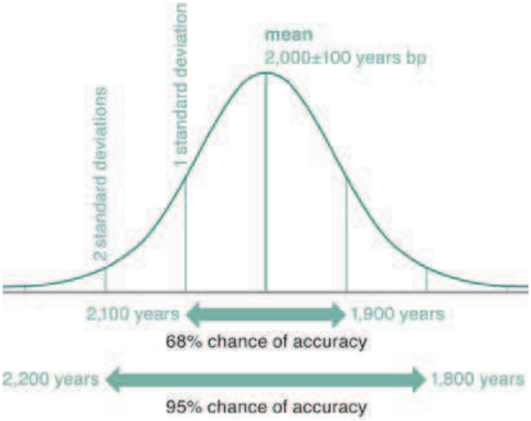


Figure 4.13 Every radiocarbon measurement has a statistical margin of error, which is quoted in terms of the mean and one standard deviation (e.g. 2000±100 BP). A normal distribution curve shows how it should be interpreted: one standard deviation either side of the mean will give a 68% probability that the age lay within a 200-year bracket (and consequently a 32% chance of it not doing so), whilst two standard deviations increase the probability of accuracy to around 95%. (Chris Unwin)

publication must be presented in a standard format. For example, a series of charcoal samples obtained from a late Neolithic site at Galgenberg, Bavaria, were quoted as shown here in Table 4.2 (Aitchison *et al.* 1991: 113; Ottaway 1999: 240).

The first column contains the code for the Groningen radiocarbon laboratory (GrN) together with a unique serial number for this particular sample, so that it could be checked with laboratory records if any problem arose. The archaeological number refers to an excavated context at the Galgenberg site, and its nature is explained in the final column. The determined age of this sample is expressed in uncalibrated form in **years BP** (the periodical *Antiquity*, where these dates were published, uses **b.p.**), complete with a small but unavoidable counting error estimated by the laboratory (±35). The 'raw date' has been adjusted to compensate for fractionation, but it is calculated according to Libby's half-life of 5,568 years rather than the more recently determined estimate of 5,730 years; this practice is maintained to avoid confusion in comparisons with older results, but modern calibration programmes such as OxCal take account of it automatically. The standard counting error of ±35 years means that the (uncalibrated) date has a 68 per cent chance of lying between 4350 and 4420 BP, and there is a 95 per cent chance that it lies between 4315 and 4455 BP. This emphasises the importance of regarding radiocarbon age estimations as ranges of possibilities, rather than as 'dates'.

The age of this sample was calibrated with reference to a calibration curve, derived from dated tree-ring samples. Updated versions of this curve are published in the periodical *Radiocarbon*, the most recent being IntCal09 (Reimer 2009). A rapid inspection of the curve suggested that the radiocarbon estimation would be transformed into a calendar date with a range falling roughly between 2900 and 3100 BC.

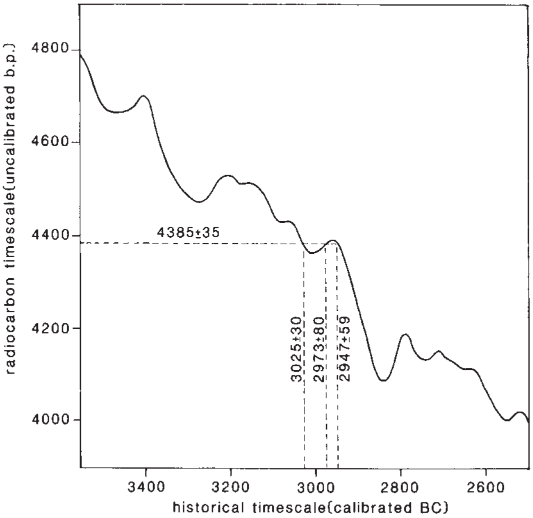


Figure 4.14 This diagram shows how a single radiocarbon age estimation (from Galgenberg, Germany) may produce three different calendar dates of varying reliability if it happens to coincide with a difficult 'wiggle' in the calibration curve. For the purposes of dating a Neolithic sample, it would normally be sufficient to know that the calibrated date lay somewhere between 2800 and 3100 BC, but a margin of error of this size would be too great for historical periods. (Chris Unwin, after Aitchison *et al.* 1991: Fig. 4)

However, closer inspection of this particular age determination revealed a common problem: a 'wiggle' in the calibration curve at around 4400 BP meant that it could represent three different 'historical' (or calendar) dates (Aitchison 1991: 113) (**Fig. 4.14**).

The tree-ring calibration curve is itself subject to statistical variations; for this reason the standard deviation should be considered as only a *minimum* estimate of uncertainty. Furthermore, precision varies according to which part of the curve is being consulted; if the line is steep, the prospects are good, but if it is flatter, the date range will be very wide. Thus, the 'date' of 3025 has the lowest of the three estimated levels of error. When all thirteen samples from Galgenberg were examined together, the main period of the whole site's occupation was estimated to lie between 2810 and 3100 BC (Ottaway 1999: 243–4). Computer programmes used for calibration (primarily OxCal or CALIB: **Fig. 4.15**) present the probability in the form of a graph which emphasises that results are estimations of ranges, not dates in the sense understood by historians.

Thus, Galgenberg illustrates some of the problems that lie between the receipt of an age estimation from a laboratory and its interpretation in meaningful chronological terms for a site or an artefact. This is why Pearson (1987) advised archaeologists to consider the 'calendrical band-width necessary for correct interpretation' before submitting samples. In the context of later prehistoric Britain, a sample from the British Late Bronze Age and Early Iron Age that was expected to give calibrated results between 1100 and 800 BC would be very worthwhile as it would coincide with a steep slope on the calibration curve. In contrast, samples from the period between 800 and 400 BC are almost useless because this part of the curve is much flatter and does not permit refinement within a range of around four centuries; traditional forms of dating would be more precise (Bowman 1990: 55–7).

An International Radiocarbon Convention in 1985 recommended that uncalibrated age determinations should always be quoted in the form 1000 BP with the 'present' standardised as AD 1950. If dates are calibrated according to 'an agreed curve', they should be cited in the form 1000 Cal BP. In areas of the world where the AD/BC division is useful, calibrated dates can be converted to 1000 Cal BC or 1000 Cal AD (Gillespie and Gowlett 1986: 160). 'Perhaps with the benefit of hindsight it might have been preferable if radiocarbon measurements had never been expressed as "ages" or "dates"; then there could be no misunderstanding' (Bowman 1990: 49).

Radiocarbon samples

- key references: Ashmore, 'Radiocarbon dating: avoiding errors by avoiding mixed samples' 1999; Waterbolk, 'Working with radiocarbon dates' 1971; Protsch, 'Dating of bones' 1991.

Most organic materials are suitable for dating but the lower the carbon content, the larger the sample needs to be. Charcoal derived from the burning of wood is a common find on archaeological sites and samples of around 10–20 g dry weight are

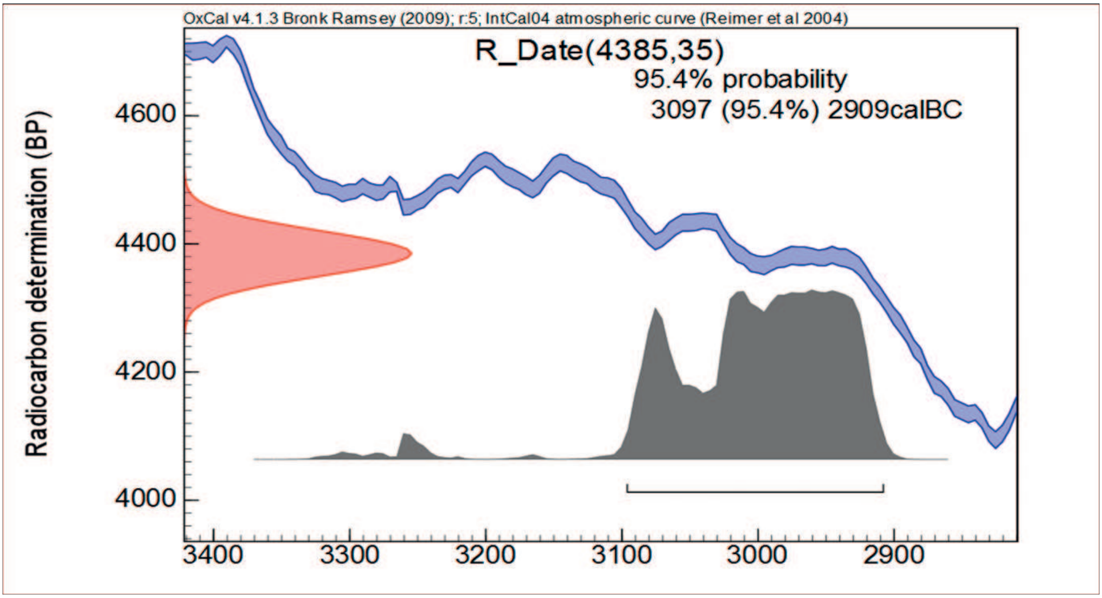


Figure 4.15 This image shows the calibration plot produced by the computer program OxCAL v4.1 (released by Bronk Ramsey in 2009), for one of the dates from Galgenberg. The uncalibrated date is 4385±35 BP, with calibration indicating that there is a 95% probability that the sample dates from between 3097 and 2909 BC, demonstrating how use of the latest calibration program may refine old dates. As calibration and Bayesian statistics are introduced, such dates may be refined even further. Normally, archaeologists will rely on the 95.4% (2 sigma) date when using the radiocarbon date, whether they feel a tighter date range is more likely or not.

adequate for conventional counting, compared with around 50–100 g of peat or 100–500 g of bone; AMS requires only around one hundredth (e.g. 0.01–0.1 g) (Aitken 1990: 91). Many other materials may be tested, including cloth, flesh, pollen, shell, soil and even iron, which usually contains some carbon impurities. The collection of samples needs to be scrupulous, and their storage and handling must avoid contamination, even though they are subjected to a chemical 'laundry' process before being tested.

Archaeologists must know exactly what is being dated and, in the case of samples from excavations, their precise stratigraphic relationship to the site. The nature of charcoal and wood samples is important: twigs or nuts are ideal because they only contain ^{14}C taken in during a short growing season, whereas the central portion of a large tree will obviously give a date decades (or even centuries) earlier than its use for fuel or construction. Thought must also be given to exactly *how* samples are related to the objects or contexts that they are intended to date; the significance of charcoal fragments from a general occupation level is a lot less clear than a sample taken directly from a wooden artefact or a human body. One of the most widely publicised examples of direct dating was the examination of the Turin Shroud; since only very small samples of linen could be provided from this unique artefact, AMS was an ideal method (Gove 1996; Taylor 1997: 84–5). They were tested in three laboratories along with a sample of ancient linen from Egypt that had been dated by AMS to 110 Cal BC–75 Cal AD. The combined result for the shroud samples was 689±16 BP and for the Egyptian linen 1,964±20 BP; when checked against the calibration curve the shroud samples gave a date of 1260–1390 Cal AD at the 95 per cent confidence level. Whatever the nature and date of the strange image painted(?) on the shroud, the linen from which it was woven grew no earlier than the thirteenth century AD, making it impossible that it was associated with Jesus, unless, of course, some undetected factors distorted the small sample selected for testing.

Even in prehistory, radiocarbon raises questions of a 'historical' nature. For example, evidence of very early human settlement linked with a hunter-gatherer economy was found on the island of Cyprus, which had previously been thought to have been settled by farming communities in the Neolithic period. However, since the relevant radiocarbon dates were too early for the conventional calibration curve, it was difficult to provide a calendar date for the earliest occupation. Evidence from varves, floating tree rings, uranium–thorium dates from coral and various other forms of dating suggest a date around 11,500–10,000 BC in calendar years (Manning 1991). Later research found that the farming communities had also arrived on the island earlier than previously thought, in the tenth millennium BC (Peltenburg 2000). Technical limitations upon radiocarbon dates are just as significant in the case of relatively recent (and in European terms, historical) periods. The question of the date of colonisation of New Zealand is a good example; estimates ranged up to 2,000 years ago, with a majority favouring a date of around 1,000 years ago. A large number of radiocarbon estimations now demonstrate that it took place as recently as the fourteenth century AD; misleading earlier dates had been given by samples from shell, bone and old wood (Anderson 1991, Higham *et al.* 1999).

4.5.4 The Bayesian radiocarbon revolution

- key references: Bayliss and Bronk Ramsey, 'Pragmatic Bayesians' 2004; Pollard, 'Measuring the passage of time' 2008: 157–9.

Radiocarbon dating has been revolutionised by the growing use of a statistical method developed more than 250 years ago by Thomas Bayes (1702–61) to refine estimations of probability. Single radiocarbon dates are relatively uninformative for constructing a chronology, whereas multiple dates help to achieve a closer approximation of the true date of the context from which samples were taken (Pollard 2008: 157). Bayesian statistics allow dates to be refined by taking account of additional information, such as other dates from the same site, or the sequence of dates from stratified contexts: sample A must be later in date than sample B, if B was found in a context lower down the stratigraphic sequence than A (Bayliss and Bronk Ramsey 2004). Thus, the margin of statistical error attached to a radiocarbon estimation can be reduced in size in the light of other dates and evidence. It is important to stress that excavation, observation and recording must be carried out to a very high standard to ensure that the stratigraphic sequence and contexts really do show that sample A is later than B (see Chapter 3). If the interpretation of the archaeological record is incorrect, it will lead to erroneous statistical modelling of the radiocarbon dates.

Bayesian statistics have already produced interesting results by adding precision to the dating of archaeological monuments. A project that re-analysed existing radiocarbon dates from early Neolithic sites in southern Britain showed that, in many long barrows, burials only took place for a few decades, rather than over many centuries as had previously been thought (Bayliss *et al.* 2007). Bayesian analyses of radiocarbon dates have only recently begun to be undertaken on a large scale, but they are likely to lead to many similar revisions of current chronological frameworks for prehistory.

The impact of radiocarbon dating

- key references: Taylor, *Radiocarbon dating: an archaeological perspective* 1987; Taylor *et al.*, *Radiocarbon after four decades* 1992.

Radiocarbon dating has grown exponentially, and many problems and inaccuracies have been isolated and examined, some leading to major adjustments of the results. Despite many problems, radiocarbon dates now provide a framework for the prehistory of the world; for the first time its study has become more like that of historical periods and emphasis has shifted away from pure chronology towards more fundamental human behavioural factors. Without doubt, it has made the greatest single contribution to the development of archaeology since geologists and prehistorians escaped from the constraints of historical chronology in the nineteenth century.

The major stages of human development from hunting through to urbanisation are now well dated over most of the world. However, so few ^{14}C atoms remain in samples more than 40,000 years old that they are difficult to measure, even using the AMS technique; this adds still further to the existing difficulties of calibrating radiocarbon age beyond 30,000 years ago (Richards and Beck 2001). Fortunately, a related method based on an isotope of potassium allows the examination of early hominin developments beyond the range of radiocarbon.

4.5.5 Potassium–argon (^{40}K/^{40}Ar) and argon–argon dating (^{40}Ar/^{39}Ar)

- key references: Walter, 'Potassium–argon/argon–argon dating methods' 1997; Aitken, *Science-based dating* 1990: 120–4.

> Potassium–argon (K–Ar) dating has played a key role in unravelling the temporal patterns of hominin evolution as far back as the first significant discovery of East African australopithecines at Olduvai Gorge in 1959. It was in large part due to the desire to understand the age of the Olduvai hominin remains that pioneering attempts were made to date geologically early materials using the K–Ar method.
>
> (Walter 1997: 97)

Potassium is abundant throughout the Earth's crust. Like carbon, it contains a small percentage of radioactive isotopes, notably potassium-40 (^{40}K), which decays into calcium-40 (^{40}Ca) and the gas argon. This gas escapes while volcanic rocks are being formed, but once new minerals have cooled and crystallised they trap the argon. The gas can be released in the laboratory by heating, and can then be measured; the quantity may then be related to the amount of ^{40}K and its age estimated from its half-life (1,250 million years). Since this half-life is staggeringly long in comparison with that of ^{14}C, its potential was initially limited to geological dating; archaeological applications only began in the 1950s when the controversy over the date of fossil hominins from East Africa stimulated the demand for absolute dates beyond the range of radiocarbon. Another contrast with radiocarbon dating is that ^{14}C is based upon a **decay clock**, while ^{40}K (like other geological methods such as uranium series dating) is an **accumulation clock**. Thus, while recent samples of carbon contain high levels of its radioactive isotope because they have not yet decayed, recently formed geological deposits have very low levels of ^{40}Ar because there has been so little time for it to accumulate. As a result it is difficult to measure ^{40}Ar in samples less than 100,000 years old, although work on samples of known date, such as volcanic material from Pompeii (AD 79), is helping to provide a solution to this problem (Renne *et al.* 2001).

Improvement in the precision of K–Ar dating came with the introduction of the **argon–argon** technique, which allows smaller samples to be dated than the K–Ar method. ^{40}K is converted into ^{39}Ar in the laboratory, and instead of comparing the potassium and argon content of two separate samples, the ratio between ^{39}Ar and ^{40}Ar in a single sample is measured. A revolution began in the 1970s with **laser-fusion**, which allows extraordinarily small samples – even individual mineral grains – to be measured rapidly. The ability to measure single grains circumvents the problem of samples from eroded deposits where older grains of volcanic material have been mixed with younger ones. Further improvements in precision have extended K–Ar dating to relatively recent samples that overlap with the earliest part of the range of radiocarbon dating between 100,000 and 50,000 years ago (Walter 1997: 107, 121).

Potassium–argon is ideal for dating early hominin fossils in East Africa, as they occur in an area that was volcanically active when the fossils were deposited between one and five million years ago; pioneering results in the 1950s doubled previous estimates of their age (Walter 1997: 109–20). At Olduvai Gorge the hominin remains were shown to be 1.8 million years old, rather than the 0.6 million years suggested by radiocarbon. Layers containing bones and artefacts may be found 'sandwiched' between volcanic deposits of ash or lava that provide excellent samples of newly formed minerals for measurement. Very occasionally the association between human remains and volcanic deposits may be much more intimate, as in the case of hominin footprints around 3.6 million years old found on a layer of freshly deposited ash at Laetoli, Kenya (Leakey and Lewin 1992: 103). The laser-fusion method has been able to check and refine dates of geological stratification in Olduvai Gorge, while 'Lucy', one of the most famous hominin discoveries, from Hadar in Ethiopia, is now precisely dated to just under 3,180,000 years. Furthermore, better dates for stratification in East Africa have improved our understanding and precision of changes in the Earth's magnetic field, notably the reversals of polarity which can also be detected in cores from the seabed. Thus, climatic fluctuations revealed by oxygen isotope ratios in deep sea cores may be checked and correlated with geological deposits on land. Early stages in the evolution of human ancestors can now be placed in a secure chronological *and* environmental context. 'The future of K–Ar dating lies in its versatility. It will be intriguing to see where, how and in what form the next generation of this method will be applied' (Walter 1997: 121).

4.5.6 Uranium series dating

- key references: Latham, 'Uranium-series dating' 2001; Schwarcz, 'Uranium series dating' 1997; Aitken, *Science-based dating* 1990: 124–32.

The dating of rocks back to the Pre-Cambrian geological period by measuring the proportions of uranium to lead or uranium to helium was possible because isotopes of uranium remain radioactive for such a long period. Fortunately the decay of uranium produces a series of progeny isotopes with much shorter decay times relevant to recent geological and archaeological periods; uranium-234 is particularly useful because it decays to produce thorium-230 in the same way that potassium-40 decays to argon-40. An ideal sample material is coral, which takes in ^{234}U dissolved in sea water when it forms, but lacks (insoluble) thorium; *speleothems* (stalagmites, stalactites or flowstone formed in caves) may also be sampled. ^{230}Th begins to accumulate in these newly-formed materials at a known rate relative to the original amount of ^{234}U, and measurements can be used for dating early human activity in caves anywhere between a few hundred and 500,000 years ago. Large samples of up to 200 g are required unless **mass spectrometry** is available; mass spectrometry has revolutionised uranium series dating in the same ways that AMS enhanced radiocarbon. The precise relationship between any sample and an archaeological event or activity must always be established; human occupation levels sandwiched between layers of flowstone in a cave are ideal – for example the successive levels associated with Neanderthals and modern humans at La Chaise de Vouthon in Charente, France (Schwarcz 1997: 175–6). Uranium series dating is less satisfactory when carried out on porous material such as bones or shells, although studies of tooth enamel are more satisfactory because they can be checked against ESR dates (below: p. 182). Unlike coral or speleothems, which only take up uranium when they are formed, porous material such as bone absorbs uranium while buried in the ground. Finally, a crucially important role of uranium–thorium dating of coral has been the calibration of radiocarbon dates back towards 50,000 BC; this is possible because coral, a living organism, also contains carbon.

4.5.7 Fission-track dating

- key references: Westgate *et al.*, 'Fission-track dating' 1997; Yegingil, 'Fission-track dating' 1991; Aitken, *Science-based dating* 1990: 132–6.

> The spontaneous fission of ^{238}U follows the law of radioactive decay. … Simply put, given that the spontaneous fission of ^{238}U occurs at a known rate, the age of a mineral or glass can be calculated from the amount of uranium and the number of spontaneous fission-tracks it contains.
>
> (Westgate *et al.* 1997: 129)

This method involves counting microscopic tracks (damage trails) caused by fragments derived from the fission of uranium-238 in glassy minerals, whether of geological origin or of human manufacture. In practice the most useful samples come from zircon or obsidian, which was used extensively for making tools. However, an obsidian artefact must have been subjected to heating if it is to provide a date for an archaeological context or event; heating removes earlier fission-tracks that had accumulated since the obsidian first solidified after its volcanic formation. Obsidian tools, or obsidian waste flakes, dropped into a hearth would make ideal samples. New tracks can be counted and related to the amount of radioactive ^{238}U they contain to estimate how much time has elapsed since their last heating. Like potassium–argon dating, the fission-track method has been invaluable for checking the age of volcanic deposits associated with early hominin remains in East Africa. The two techniques test different minerals found together in the same volcanic beds, giving more confidence in each method's reliability when results agree; both methods can now analyse individual grains to avoid including older minerals that had eroded into later deposits (Westgate *et al*. 1997: 146–50).

Fission-track dating is also important in **tephrochronology** for checking the age of volcanic material found on sites or in seabed cores that can be shown by its chemical characteristics to have come from a particular volcano. This has proved very useful in establishing the contemporaneity of sites on the Indian subcontinent, where early stone artefacts have been found, thanks to ash derived from a volcano more than 3,000 km away in Malaysia (Westgate *et al*. 1997: 143–6). Likewise, layers of tephra separating deposits of loess in Alaska have been dated and these estimated ages may be checked against occasional reversals of the Earth's magnetic field, which have themselves been dated by astronomical and potassium–argon techniques (*ibid*.: 150–3).

4.5.8 Tephrochronology

- key reference: Pollard, *Measuring the passage of time* 2008: 162–3.

Pollard has suggested that tephrochronology is one of the most promising forms of archaeological dating that is being developed. Tephrochronology uses fine-grained deposits from volcanic eruptions which are scattered over wide areas. Tephra from individual volcanoes and even specific eruptions has been shown to be quite distinct; thus layers of tephra can be linked to individual events. In areas where layers of tephra are common, such as Iceland, detailed chronological sequences can be constructed with the aid of radiocarbon dating (**Box 4.5**). In addition to constructing detailed chronologies of land-use in Iceland, stratified tephra can play a significant role in relating longer geochronological sequences to sequences in ice-cores (Pollard 2008: 163). The use of tephra for archaeological dating is of course limited to areas of the world, such as Iceland, North America and New Zealand, where active volcanoes had an direct impact upon human lives.

4.5.9 Luminescence dating

- key references: Grün, 'Trapped charge dating' 2001; Aitken, 'Luminescence dating' 1997; Aitken, *Science-based dating* 1990: 141–86; Aitken, *Introduction to optical dating* 1998; English Heritage, *Luminescence dating* 2008; Wintle, 'Fifty years of luminescence dating' 2008.

The physical phenomenon of luminescence can be used to date artefacts that were made from (or include) crystalline minerals which have been subjected to strong heating. The first successful application was to pottery made from fired clay, but it is commonly used now for dating flint tools that have been burnt, for example by being dropped accidentally into a fire. Most recently it has been extended to unburned material, notably natural sediments that were exposed to sunlight for a short period and then buried, using **optical dating** (optically stimulated luminescence, abbreviated to OSL) in addition to **thermoluminescence** (TL).

Crystalline minerals have defects in their structure that 'trap' electrons displaced by radiation and by the decay of radioactive isotopes in minerals contained either in the artefacts themselves or in the soil in which they have been buried. 'Deep traps' do not release these electrons until heated above 300°C; as soon as heating

BOX 4.5

Vikings, fire and ice: the application of tephrochronology

Tephrochronology uses layers of volcanic ash, known as tephra, to date specific volcanic eruptions. Tephra is retrieved from a wide variety of locations including archaeological sites, peat bogs and lake sediment sequences. The most famous example is that which buried Pompeii under a thick layer of volcanic ash from Vesuvius in AD 79. However, most tephra layers are very thin, with the tephra only detectable with the aid of a microscope. Different volcanoes, such as those in Iceland, the Mediterranean and on the Pacific Rim, produce ash of a specific size, shape, colour and geochemistry. These characteristics are used to source the ash in the archaeological and palaeoenvironmental sites to a specific volcano or eruption that can sometimes have occurred hundreds of miles away. For example, tephra from Icelandic volcanoes has been found all over north-west Europe, with tephra from some of the largest eruptions found as far away as Russia.

When sourcing an eruption, the tephrochronologist needs to refer to a regional tephrochronology around the source volcanoes to match with the characteristics of the tephra from their site. In Iceland in particular there is a very detailed tephrochronology for most of the volcanoes and volcanic systems across the island, one that has taken over 60 years to compile. This was achieved by comparing soil sections from close to the source volcano with historical accounts of eruptions in the historic period (c. AD 870 to the present day) and dating prehistoric eruptions (pre c. AD 870) with other absolute dating techniques, such as radiocarbon or Greenland ice cores. The eruption of the volcano Hekla in AD 1341 was recorded by many contemporary accounts and tephra is widespread across much of southern Iceland. In the section of a charcoal pit (below) from Langanes, southern Iceland, tephra was used to date the use of the pit to the late fourteenth century AD, as the pit cut tephra from Hekla 1341 (providing a *terminus post quem)* and was overlain by tephra from Katla 1500 (providing a *terminus ante quem*) (Church *et al*. 2007). The eruption of a volcanic system called Veiðivötn at the time of Icelandic settlement was dated by geochemically sourcing tephra shards from the eruption in the Greenland ice cores, producing an estimated date of AD 871±2 (Grönvold *et al*. 1995). This so-called Landnám tephra (Landnám is Old Norse for ‘land take’) has been found all over Iceland and immediately underlies the very earliest Viking settlements of Iceland, providing a very precise *terminus post quem* for the colonisation of Iceland. Most of the volcanic eruptions producing tephra layers before Landnám are dated by using radiocarbon dating on organic material immediately underlying the tephra layers in peat bogs. A large eruption of the volcano Hekla, known as Hekla 4, covers much of Iceland and is found as microscopic tephra in palaeoenvironmental sites across many parts of the British Isles and Scandinavia. It was dated with multiple radiocarbon dates in Irish peat bogs to 2310±20 BC (Pilcher *et al*. 1995) (photograph: Mike Church).

is over, electrons begin to accumulate again. When electrons are released, some recombine immediately with a **luminescence centre** (another type of defect) and emit light in proportion to their number. Thus, the basis of TL dating is measurement of the amount of light emitted when samples from artefacts such as potsherds or flints are reheated in the laboratory to release electrons that have accumulated since they were originally fired or burned.

The first stage in calculating a date is to measure the amount of light released and to plot its glow-curve on a graph as the sample is heated up to 500°C (the temperature at which a 'natural' glow-curve is produced). This is compared with an 'artificial' glow-curve derived from an identical sample that has been subjected to a known amount of radiation in the laboratory (**Fig. 4.16**). The relationship between the two curves gives information about the reliability of the sample, as well as revealing the amount of energy that had accumulated since it was last heated (the **palaeodose**). Pots are fired at a temperature high enough to release all the electrons trapped in the crystal lattices of minerals in their clay. Thus all of the energy released in the laboratory must have built up since the date of their firing; the older the pots, the more energy that should have accumulated. The palaeodose does not reveal the age without the **annual dose** received from radioactive minerals within the sample having first been measured; in addition, measurement of radiation from the soil that surrounded a buried artefact is crucial, especially for artefacts made of flint. The age is equivalent to the palaeodose divided by the annual dose. Thus, a palaeodose of 8.5 Gy (Grays – a standard measurement of absorbed radiation) divided by an annual dose of 5.18 Gy would give an age of 1,640 years – around AD 350 (Aitken 1990: 151).

Thermoluminescence (TL) dating is particularly valuable in situations where no suitable materials for radiocarbon dating have been found or if the age exceeds 40,000 years, beyond which radiocarbon is of rapidly diminishing usefulness. It may also assist in problem areas of the calibration curve such as the first millennium BC. TL dating is also useful in areas where volcanic materials suitable for potassium–argon dating are absent. Fortunately, early prehistoric caves or campsites normally produce many finds of stones and flint implements burnt in fires at a sufficiently high temperature to release their trapped electrons. Flints found in deposits with relatively low surrounding radioactivity may be datable up to 500,000 or even a million years.

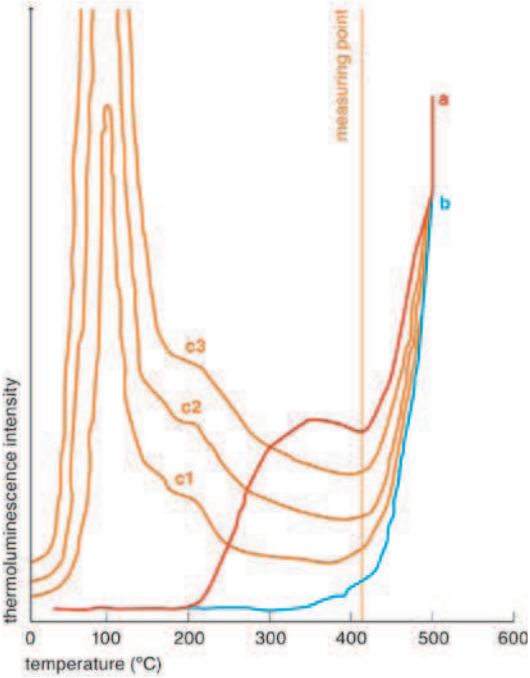


Figure 4.16 Thermoluminescence apparatus provides a graph of light released by a sample prepared from an ancient artefact as it is heated (a). A second measurement of the same sample provides a different graph for the same material *without* its ancient energy (b); the bulge in curve (a) between 300° and 400°C resulted from the electrons trapped in the sample. Curves c1–3 are further measurements taken to study the luminescence produced after the sample has been exposed to known levels of modern radiation in order study its sensitivity. When further factors about the context in which the artefact was found have been taken into account, a date may be calculated. (Drawn by Chris Unwin)

TL dating has been extended to specialised materials such as stalagmite, volcanic material and even the soil over which molten lava has flowed (Aitken 1990: 172). More exciting is the potential to date deposits of sand or sediment that were subjected to intense sunlight and subsequently buried. It has been established that this kind of exposure to heat and light is sufficient to remove trapped electrons ('bleaching'), which begin to accumulate again as soon as the deposit is covered (Aitken 1997: 202–9). TL has made a significant contribution to dating early human dispersal; for example, its ability to date sand deposits has been useful in dating windblown sand sealing a cave with early human remains in South Africa (Wintle 2008: 298). Quartz grains from sites in Australia have been dated to reveal the arrival of humans, which lies beyond the accurate range of radiocarbon dating more than 50,000 years ago (David 1997) (**Box 4.6**). **Optically stimulated luminescence** (OSL) has proved to be particularly suitable for examining unburned sediments; this technique uses light, rather than heat, to release only those electrons stored in 'traps' that are easily bleached, ensuring that only electrons stored since burial of the sediment are measured (Aitken 1997: 206–7). This method can be used on mineral grains (feldspar and quartz) which may be found in archaeological features such as ditch fills. However, the suitability of samples for dating depends on how the material was exposed to light and how it was deposited; it is not suitable in all geological areas (English Heritage 2008: 19–20).

New methods of obtaining and measuring luminescence signals are currently being developed and their accuracy refined, often by comparing radiocarbon and luminescence dates. OSL has been demonstrated to be extremely useful in dating brick buildings where tree-ring dating is unavailable (**Fig. 4.17**: Bailiff 2007). Bayesian statistics (above: p. 175) are also being applied to multiple luminescence dates, as well as to radiocarbon dates (Wintle 2008: 303). TL or OSL dating of artefacts may not have the precision of radiocarbon, but they do not require calibration since it relies on constant rates of radioactive emissions; uncertainty lies in the accuracy of measurement and control of the many variables that affect a sample.

While it is not possible to measure all of the necessary variables for accurate dating of objects in museum collections, especially if their precise findspot is unknown, TL can easily detect the lack of trapped electrons in recent forgeries. In Aitken's words:

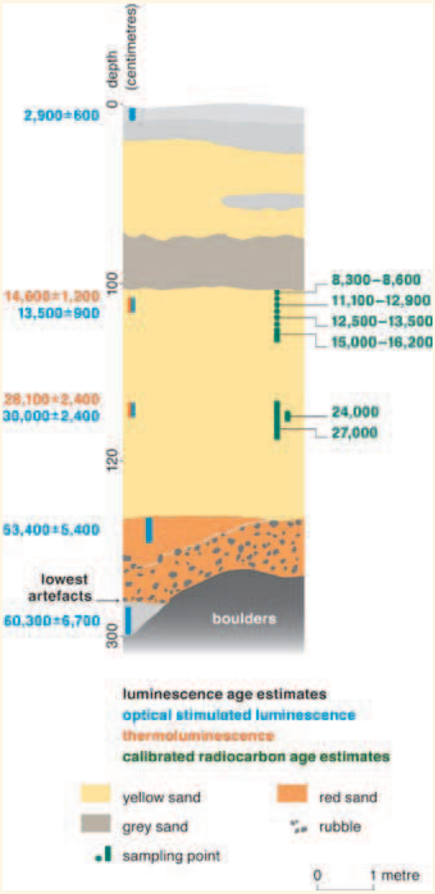
> The span of time encompassed by the various luminescence techniques is remarkable: from a few decades to approaching a million years. Extension beyond the range of calibrated radiocarbon dating is particularly to be noted and also that luminescence ages are not distorted by intensity fluctuations in cosmic radiation.
>
> (Aitken 1997: 212)

Figure 4.17 OSL is particularly useful in dating structures for which other techniques such as tree ring dating, are not possible, e.g. structures built from fired bricks. Well dated structures can also be used to confirm the accuracy of thermoluminescence dates. At Tattershall Castle, in Lincolnshire, which was known from historical sources to have been constructed between AD 1445 and 1450, was dated using OSL. The OSL dates of 1455±33 and 1453±34 matched closely the historic dates, demonstrating the relative accuracy of the method and its potential application for dating buildings of unknown date (Bailiff 2007). (Photograph: Ian Bailiff)

BOX 4.6

Optical stimulated luminescence: Deaf Adder Gorge, Australia

Excavation at Deaf Adder Gorge, Northern Territory, Australia, uncovered a deep profile of layers of sand overlying human artefacts. Samples were collected for radiocarbon and luminescence dating, and the correspondence between results from the two very different methods was encouraging. The deepest layers with earliest evidence of human occupation are rather early for reliable radiocarbon dating, but well within the range of luminescence, which suggests that people had arrived at this location at least 40,000 and possibly as many as 60,000 years ago (Roberts *et al.* 1994).



4.5.10 Electron spin resonance (ESR)

- key references: Grün, ‘Trapped charge dating’ 2001; Grün, ‘Electron spin resonance dating’ 1997; Aitken, *Science-based dating* 1990: 187–203.

Like thermoluminescence, ESR is a ‘trapped charge’ dating method, but it is applied to different kinds of samples and the method of measurement is also different. ESR does not release trapped electrons, but subjects them to electromagnetic radiation in a magnetic field, which causes electrons to resonate and absorb electromagnetic power. The strength of resonance reflects the number of electrons that have become trapped since the crystals were formed. As with TL, age is estimated by relating the amount of resonance to the radioactive content of samples, combined with any external radiation that they have received, and calculating how long it would have taken for that amount of radiation to produce the level of resonance recorded.

Tooth enamel is the best sample material, rather than the dentine of the tooth core. The dentine is porous, allowing new minerals to form after the death of the animal; this can lead to an underestimate of true age by making it possible for uranium to be transported into or out of it. Early hopes that ESR would be applicable to speleothems have not been fulfilled, but this material is very suitable for uranium-series dating. Aitken and Grün both cite convincing examples of ESR dates derived from samples of teeth from Canada, Germany and France; the dates were credible because they correlated well both with the climatic stages to which the animal species belonged and with uranium-series dates. ESR has been used in dating Border Cave in South Africa, indicating much earlier dates (around 170,000 years ago) for potential human occupation than previously suspected (Pettitt 2005: 363).

Future progress with ESR is likely to take place alongside uranium-series and other dating methods so that anomalies and errors may be detected and investigated. In contrast to potassium–argon dating, ESR is a direct method that dates teeth from animals and humans rather than the stratigraphic context in which they were found. 'This approach will overcome one of the main problems of the interpretation of dating results in palaeoanthropological contexts, namely the precise relationship between the samples that have been dated and the hominin specimen whose age is to be determined. Certainly, the best dating strategy is to analyse the human remains themselves' (Grün 1997: 243).

4.6 DERIVATIVE TECHNIQUES

Aitken (1990: 2) drew a clear distinction between **absolute** and **derivative** dating methods and this has been reinforced by Sternberg (1997: 324). Derivative methods may only be used for dating if their results can be related to a timescale or reference curve that has been established by absolute dating methods. Thus, the level of thorium-230 found in a sample of stalagmite is a product of its uranium content, and the sample's age is calculated from the known radioactive half-life of ^{230}Th; since this is not affected in any way by its environment the result can be described as **absolute**. In contrast, dating the change of one form of amino acid to another, or the absorption of water by obsidian (outlined below: p. 184), is **derivative** because the rate of alteration varies and is heavily dependent on the temperature and humidity of the context in which the sample was buried.

Fluorine, uranium and nitrogen testing (**FUN**) was one of the first scientific dating methods used in the examination of bone (Ellis 2000: 219–26; Aitken 1990: 219–20). It did not attempt to provide an estimate of age, but addressed a more fundamental problem that affects bones or artefacts of any kind: are the finds that were excavated from a single level, for example a layer containing artefacts and bones in a cave, really contemporary? Does the stratum contain older items that have eroded out of earlier contexts, or items dug up accidentally during a later phase of occupation? Bones buried in uniform conditions over the same length of time should produce identical results; if they do not, some disturbance must have taken place. FUN dating has a special place in the history of archaeological science because it revealed in the 1950s that 'Piltdown Man' – a skull that apparently linked apes to humans, excavated in Sussex in 1912 – had actually been fraudulently assembled from human and ape bones of widely differing ages. Exactly who carried out the fraud and why is a fascinating story that has been investigated several times with differing results (Russell 2003).

4.6.1 Protein and amino acid diagenesis dating

- key references: Hare *et al.*, 'Protein and amino acid diagenesis dating' 1997; Aitken, *Science-based dating* 1990: 204–14; Dincauze, *Environmental archaeology* 2000: 101–4; Berger and Protsch, 'Fluorine dating' 1991.

Bones, teeth and shells contain proteins that break down after death, and the most commonly investigated products of decomposition are amino acids. **Amino acid racemisation** dating (AAR) measures changes between the L- and D-forms of these amino acids; their ratio is an indication of age. However, the rate of change is highly dependent on temperature and burial conditions, and it is necessary to make many assumptions before any date can be suggested. Ideally, comparisons using another dating method such as ^{14}C are required before any confidence can be achieved. Shell samples have proved more reliable than bone, and ostrich eggs have been useful in dating early hominin sites in East Africa (Johnson and Miller 1997). Shell is more reliable in geological and climatic contexts than in archaeology, as samples from occupation sites might have been affected by burning or other human processes that upset the natural chemistry. Research into the essential process of calibrating and refining these techniques continues, however, despite setbacks such as the very early dating of human remains from North America that appeared to push colonisation back beyond 40,000 years, rather than the conventional 11,000 years. The specimens have been re-dated by the AMS radiocarbon technique and are now only around 5,000 years old (Hare *et al.* 1997: 272–3).

4.6.2 Obsidian hydration dating

- key references: Ambrose, 'Obsidian hydration dating' 2001; Friedman *et al.*, 'Obsidian hydration dating' 1997; Shackley, *Archaeological obsidian studies* 1998; Aitken, *Science-based dating* 1990: 214–18.

Like amino acid racemisation, this dating technique relies on a transformation that takes place over time, and, likewise, it varies according to the context in which the sample has been buried. Obsidian, a natural volcanic glass, was a popular alternative to flint for making flaked tools in many parts of the world (**Fig. 5.16**). As soon as a fresh surface of obsidian is exposed, for example during the process of making it into a tool, a microscopically thin **hydration rim** begins to form as a result of the absorption of water (**Fig. 4.18**). Unfortunately, the hydration rim forms at different rates according to the temperature and humidity of the burial context as well as the chemical composition of the obsidian. An additional problem is precise measurement of the microscopic hydration rim and the laborious (and destructive) preparation of samples cut from obsidian artefacts. In regions where radiocarbon dates are available (notably North and Central America), large numbers of measurements can be compiled to provide a calibration curve that may be used for checking the rim thicknesses of individual artefacts or assemblages found on sites with similar burial conditions. In most cases the radiocarbon method dates the **context**, rather than the **artefact**, while obsidian hydration dates the artefact directly: 'Given the importance of association between the carbonaceous material and the obsidian, it is imperative that only bona fide associations be used to avoid constructing inaccurate rates' (Friedman *et al.* 1997: 317).

4.6.3 Archaeomagnetic dating

- key references: Sternberg, 'Magnetic properties' 2001; Sternberg, 'Archaeomagnetic dating' 1997; Aitken, *Science-based dating* 1990: 225–61; Tarling, 'Archaeomagnetism and palaeomagnetism' 1991.

The Earth's magnetic field undergoes continuous change. The position of magnetic North wanders around the North Pole and even reverses completely to the South Pole for extended periods on a geological timescale. From any reference point its position is measurable in terms of two components: movement up or down (**inclination** or 'dip') and from side to side (**declination**). The **intensity** of the magnetic field also varies over time; it is a measure of strength rather than direction. Unlike regular variations in the Earth's

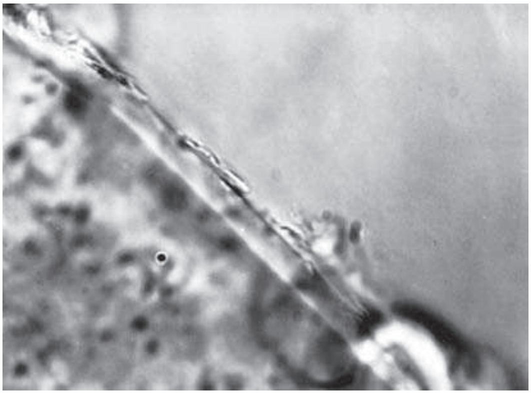


Figure 4.18 This photomicrograph shows a section through the **hydration rim** of an obsidian artefact. The interior of the specimen is on the left; the diagonal band is a layer of weathering on the surface; its depth is demarcated by a **diffusion front** that shows up as a paler line. This can be measured quite accurately, even though it is only three microns thick in this sample. (Prof. J. Michels)

orbit, changes in magnetic field do not follow a pattern that can be used as a reference scale for dating. Past variations have to be reconstructed from archaeological or geological samples dated *independently* by some other means, such as historical evidence or radiocarbon.

Records of magnetic alignment have been made by scientists in Britain since before AD 1600, but not as recently as elsewhere. The reference curve of inclination and declination has been extended back to 1000 BC in Britain; unfortunately, the Earth's magnetic field varies from region to region, so that results from Britain are not even applicable to most of France (**Fig. 4.19**). Thus, magnetic dating clearly illustrates Aitken's definition of a **derivative** method, as it is necessary to establish a separate independently-dated series of measurements for every region where the technique is required (Batt *et al.* 1998). Because the polarity of the Earth's magnetic field reverses every few hundred thousand years, it is possible to use these **geomagnetic reversals** to date geological deposits. However, because such reversals are so infrequent this is only useful for dating early hominin species, for example at Olduvai in East Africa (Leakey and Roe 1994), where the number of reversals which have taken place in the rocks above their remains can be counted (English Heritage 2006b: 3).

Magnetic dating may be applied to archaeological samples because fine grains of iron oxide with random magnetic alignment are present in most clays and soils. The alignment of grains containing iron is lost if they are heated above 650°C, but they align with the Earth's magnetic field on cooling. This new **thermoremanent** magnetic alignment may be preserved for hundreds of thousands of years as long as heating has not been repeated. Magnetic alignment may also take place during the **deposition** of sediments, for instance in lake beds, where particles suspended in water may align with the prevailing magnetic field as they settle. This technique has been used to date sediments that formed in prehistoric ditches in Britain (English Heritage 2006b: 7). Dating according to the direction of the magnetic field is only reliable on sites where solid clay structures are found that have not moved since becoming magnetised; kilns, hearths and burnt clay walls

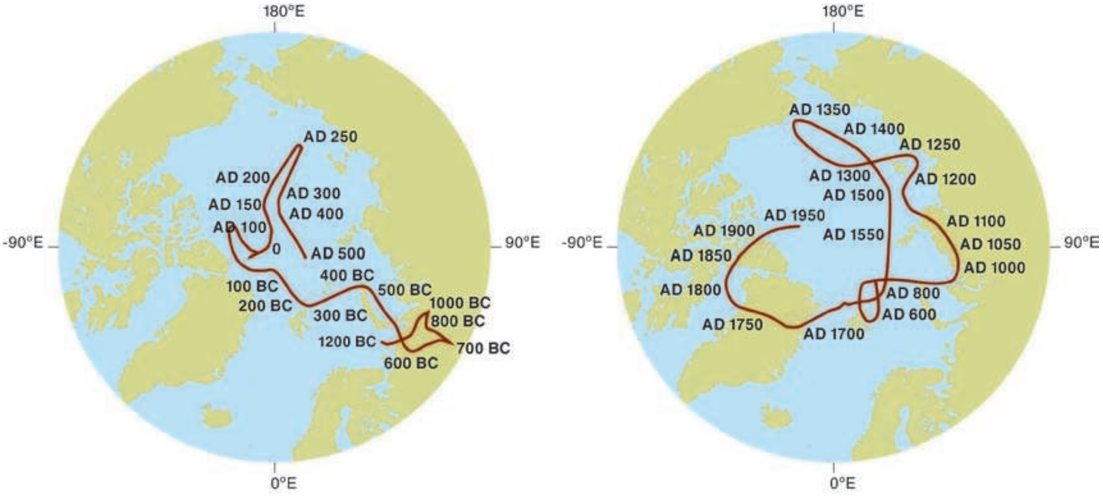


Figure 4.19 The movement of magnetic North, measured from Britain. The map shows the movement of the magnetic North pole over time since 1200 BC. These wandering lines are compiled from observations from as far back as records allow, but samples from dated deposits or structures on archaeological sites must be found to project them further back into the past. Samples from undated sites can be measured in the laboratory and dated according to where their magnetic alignments coincide with the curve established for the relevant geographical area. Difficulties do exist, for example approaching AD 1700, when the same reading also matches late Saxon measurements at the points at which the curve crosses itself. (Redrawn by Chris Unwin, based on English Heritage 2006b, Fig. 4)

or floors are ideal. Small samples are selected and their positions are carefully recorded in relation to the present magnetic field before they are removed. Their modern alignment is duplicated in a laboratory and the difference between the ancient and present alignment measured. The alignment of the ancient sample must then be related to a record of past changes in the magnetic field in the same region as the site from which it was taken. Examination of the movement of magnetic North shows that the line on the diagram crosses at many points, meaning that a sample could belong equally to more than one date. One particular date may sometimes be selected as most likely on archaeological or historical grounds. Fortifications that were possibly erected by Charles the Bald at Pont-de-l'Arche on the Seine in France produced dates around 360 BC, AD 580, AD 860 and AD 1580; of these, only AD 860 ± 20 matched a historical reference to a Viking attack in AD 865 (Dearden and Clark 1990). Even when there is no reference curve, archaeomagnetism may be used to study whether events on different sites were contemporary; measurements established that destruction by burning of Minoan sites on Crete did not happen at the same time as the eruption of Thera, which destroyed the town of Akrotiri further north in the Aegean (Sternberg 1997: 344–5).

Although archaeomagnetic dating normally requires samples that have not moved since they aligned with the Earth's magnetic field, portable fired objects such as bricks or pots that were fired in a horizontal position may be examined to determine the 'dip' angle (inclination), although the declination will have been lost. This is of limited use, but might be used to test whether objects were of the same date or indeed which way up they were fired. Magnetic intensity does not depend on a sample remaining in a particular position, but like thermoremanent magnetism it varies from area to area. An independently-dated reference series of measurements is needed before it can be used for dating; in practice, intensity varies too little for it to be useful, but it does make a valuable addition to measurements of direction, particularly at points where the reference curve crosses. Thanks to a particularly long record of magnetic measurements of intensity *and* direction, prehistoric sites in Bulgaria can be related to a reference scale back to 6000 BC (Sternberg 1997: 336–8), while samples of known age from fired structures and sediments from near Xi'an, China, could contribute to a calibration curve (Batt *et al.* 1998). Such work underlines Sternberg's warning that, 'As a derivative dating method, the success of archaeomagnetic dating ultimately depends on the complementary success of other chronometric methods' (1997: 350).

4.7 THE AUTHENTICITY OF ARTEFACTS

- key references: Stoneham, 'Authenticity testing' 1991; Jones, *Fake? The art of deception* 1990.

When major museums buy items for their collections they become involved in expensive commercial dealings in the fine art market. The profits to be made encourage not only illicit plundering of ancient sites, but also skilful forgeries. Scientific dating techniques can provide reassurance; when what is needed is confirmation that an object is not a modern fake, rather than a precise date, full control of all the variables that affect accuracy is not necessary. Thermoluminescence and archaeomagnetism provide adequate checks on pottery and elaborate ceramic sculptures from Africa and South America that fetch high prices; samples of suitably heated clay may also be found inside cast bronze artefacts and statues if their cores have not been fully removed. It is difficult (but not completely impossible) for a forger to simulate the levels of radioactivity or magnetism that should be found in genuine items. Radiocarbon dating by the AMS technique allows very small samples to be taken from wooden, bone or other organic artefacts without affecting their appearance. Dendrochronology is helpful in the study of wooden panels used in furniture and early paintings, while paints and pigments may be examined by means of various forms of radioactive isotope dating. Other analyses can establish whether the materials and techniques used for making ancient objects existed at the time of supposed manufacture, but these are not primarily dating methods (Chapter 5, p. 227). There are ethical aspects to providing evidence of authenticity (which will reinforce high prices) if the artefacts concerned have been extracted from sites and/or exported illegally; Oxford University's laboratories withdrew this service because it might encourage further looting (Inskeep 1992).

4.8 CONCLUSIONS

> Thus scientific dating is not just a boring necessity that tidies things up by providing numbers; it is vital for valid interpretation.
>
> (Aitken 1990: 1)

Archaeological dating has been strengthened immeasurably by the growth of the extraordinarily diverse range of scientific techniques outlined above, which underline the multidisciplinary nature of archaeology (**Box 4.7**). Traditional methods have *not* been replaced, however, and the definition of stratigraphic sequences by careful observation and excavation of structures and finds is essential for understanding the development of sites and for typological studies of artefacts. Scientific dating techniques add accuracy and allow interpretation to move beyond simple hypotheses about the chronological relationships between sites, regional cultures or forms of artefacts. The transition from hunting and gathering to agriculture, and the emergence of early civilisations, may be interpreted in increasingly meaningful human terms now that we know – thanks to radiocarbon dating – when they occurred and how long the processes of transformation took. Similarly climatostratigraphy and potassium–argon, uranium series and fission-track dating have provided a framework for the study of hominin evolution and dated the point at which stone tools began to be used. The emergence of anatomically modern humans and the replacement of Neanderthals is being placed on an increasingly secure footing (Aitken, Stringer and Mellars 1993) and the recolonisation of Europe after the last Ice Age is being refined (Blockley *et al.* 2000a, b).

Scientific dating techniques play more of a supporting role in historical periods and they are particularly valuable where there is doubt over historical dates, or where gaps exist in the historical framework. It must not be forgotten that even absolute methods such as radiocarbon had to be validated first by testing samples of known historical date. Libby used finds from Egyptian pyramids up to 5,000 years old, dated by historical records of the reigns of pharaohs, to test the consistency of ^{14}C measurements beyond the record of tree rings available in the 1940s (Aitken 1990: 58, Fig. 3.2). The refinement of radiocarbon dating, combined with dendrochronology, now feeds information back into this process. Although problems remain with the eruption of Thera, detailed scientific dating of the late Bronze Age around the Aegean generally confirms the sequences built up from artefact typologies and historical records over the last century (Manning and Weninger 1992). As with other scientific approaches to archaeology, the whole procedure is founded on cooperation, and the increasing complexity of methods used to refine the accuracy of scientific dating techniques demands ever-closer collaboration between scientists, historians, prehistorians and excavators to produce results that benefit all in different ways.

Schwarcz's concluding comments about uranium series dating apply to most other scientific techniques:

> As with all methods of chronometric dating, it is important to collect the best possible samples for analysis. For this reason it is desirable to have the site visited by the scientists doing the dating; even experienced archaeologists have difficulty identifying the optimal samples, or appreciating how much material of any given type may be needed for analysis. Repeated visits to a site after initial attempt at dating may be very useful …
>
> (Schwarcz 1997: 179)

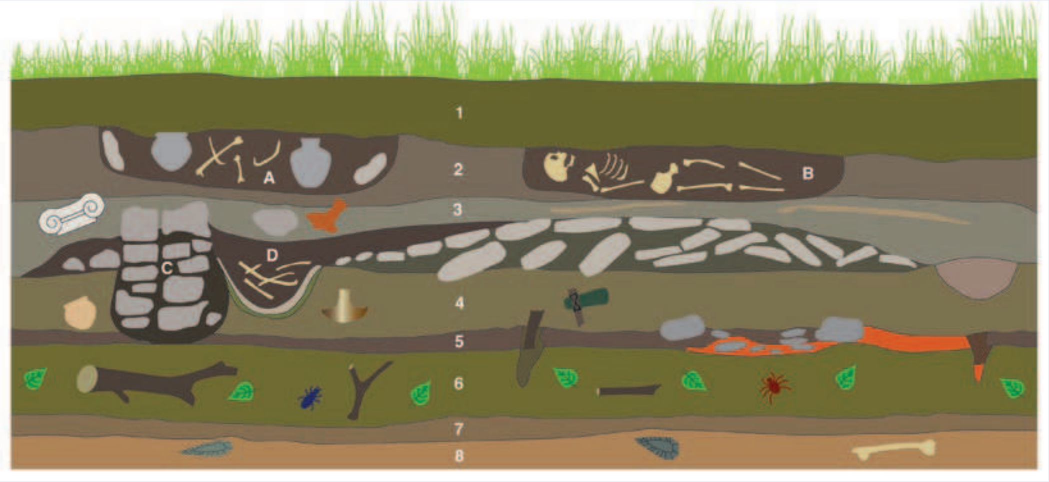
Pollard has issued a valuable warning: 'Perhaps the greatest challenge to be overcome is the widespread perception that producing an

BOX 4.7

Dating an archaeological excavation

This hypothetical excavation trench demonstrates the methods of dating which might be applied. The relative sequence of the **stratification** can clearly be established and applied to any finds and structures associated with each level. Layer 8 contains early Stone Age animal bones which might be suitable for dating by **ESR** or **amino acid racemisation**, while some animal species may have datable evolutionary features (**biostratigraphy**) or may indicate a particular **climatic phase**. The early deposit might be related to a period when the **polarity** of the earth's magnetic field was reversed. As it is sealed by volcanic material (7) it should be datable by the **potassium–argon** method, or, if comparatively recent, by reference to eruptions that can be correlated with **ice cores** or abnormal **tree rings**. Layer 6 consists of waterlogged deposits containing well-preserved wood and other botanical material; if it dates to a period younger than the last Ice Age, the large timbers may be datable by **dendrochronology**, while **pollen** and other plants will give detailed climatic information; **radiocarbon** will be the primary technique, however. The latest dates from this level will give a valuable *terminus post quem* for layer 5, which has the first clear evidence of structures. The burning associated with hearths offers possibilities not only for radiocarbon but also **thermoluminescence** (TL) and **archaeomagnetic** dating. The **typology** of tools and pottery should also be very helpful for giving a general idea of chronology; artefacts burned at the time of their use or when discarded may be checked by TL.

The wall of a building (C) and a road with drainage ditches (D) may belong to a period when **documentary evidence** could be important. The carved block of masonry to the left of the wall looks significant from a **stylistic** or **typological** point of view, and finds of **coins** may well offer more precision than any scientific techniques. However, the period of abandonment indicated by the decay of the building, the silting up of the road ditches and the accumulation of a layer of soil (layer 3) may require radiocarbon dating on suitable organic samples, or, if those are not available, **optically stimulated luminescence** (OSL) or archaeomagnetic dating of distinct layers of sediment. Cut into layer 2 are two graves (A and B) containing skeletons, along with grave-goods such as pottery that should give clues to the age and cultural connections of the deceased people; historical records may pinpoint the period of the cemetery. Again, scientific techniques would only be needed if other sources of evidence were absent. Documentary sources may also indicate how long ago the site was abandoned and given over to the agricultural use represented by topsoil layer 1 (drawn by Chris Unwin).



archaeological date is a routine procedure' (Pollard 2008: 146). He reminds us that the use of Bayesian statistics and the increasing implementation of rigorous sampling strategies are far from straightforward. Without an understanding of error margins, the source of the material being dated and the nature of the science involved, archaeologists can all too easily misinterpret or misuse the dates which they obtain. 'Dates serve archaeology, not the other way around, and a date is only as good as the quality and integrity of the samples actually dated and their archaeological relevance' (Pettitt 2005: 332).

4.9 GUIDE TO FURTHER READING

The subject of archaeological dating is sufficiently precise for the most important works to have been included in the text; consult the works cited as key references beneath section headings within this chapter first.

Dating was a crucial part of the emergence of modern archaeology in the nineteenth century (Chapter 1) and is an important element in any excavation (Chapter 3) or fieldwork project (Chapter 2); it is also intimately related to archaeological science (Chapter 5). Thus, much may be learned by looking at discussions of chronology in excavation and fieldwork reports and in studies of archaeological objects ranging from museum catalogues and typological classifications to analyses involving laboratory science. Truncer, *Picking the lock of time* 2003, provides an interesting account of the development of chronologies in American archaeology in the early twentieth century.

Dating forms part of all general works about archaeological methods, but where specific books are concerned a good starting point is Biers, *Art, artefacts and chronology in classical archaeology* 1992. The best overview of scientific techniques remains Aitken, *Science-based dating in archaeology* 1990, which may be read selectively because it is carefully divided into introductory sections and more detailed discussions of technicalities. Authoritative essays on many forms of dating are included in Ellis, *Archaeological method and theory: an encyclopaedia* 2000; this book, along with 'Section 1: dating' in Brothwell and Pollard, *Handbook of archaeological sciences* 2001, also gives guidance about further reading. As with archaeological science, many articles about dating appear in the journals *Archaeometry* and *Journal of Archaeological Science*, as well as in non-archaeological periodicals such as *Science* and *Nature*. The tables of contents of these periodicals are available on-line, and many libraries allow access to abstracts and even complete texts of papers published in them. English Heritage has produced a number of detailed guidelines on luminescence, archaeomagnetism and dendrochronology which are particularly useful for examining sampling strategies, but which also discuss principles and case studies. A specific set of discussions about the interaction of scientific and historical dating in one of the most contentious areas of archaeology can be found in Levy and Higham, *The Bible and radiocarbon dating* 2005. Some good papers discussing problems in creating chronologies for Later European prehistory can be found in Lehoërff, *Construire le temps* 2008.