Archaeologists concerned with how people in the past were positioned and engaged in place need to somehow locate social actions in their spatial and temporal contexts. In their ontological and epistemological positionings, such characterizations comprise the nuts and bolts of archaeological research, the here and the now of past activity and their behavioral milieux. Our ability to understand spatial history rests on our ability to accurately characterize what happened in the past, which in turn requires us to understand the when and where of behavior. But by themselves, “when” and “where” will not enable us to fully understand the hows and whys of those sociospatial engagements. To do this, we also need to know about the broader contexts of social action—environmentally, communally, nearby, and further afield. We need to also understand what else was going on at and around the time of those human engagements we are ultimately interested in. The reliability of such investigations relies on the chronometric hygiene and spatial integrity of the data we use.

The chapters in this section explore methodologies and techniques by which researchers describe and explain both the archaeological record and the environmental contexts of social action. They outline methods that can be used to archaeologically investigate past relationships between people and their environments—how sites, stone artifacts, plant and faunal remains, charcoal, sediments, human biological traits, and genetic markers found within archaeological sites can be mapped spatially, temporally, and conceptually so as to give us an archaeology of spatial engagement. The technical dimensions of such archaeological analyses are important, but they cannot on their own produce a “landscape archaeology.” We need to keep in mind that the use of analytical techniques is from the onset positioned in ontological (how we understand the world to operate) and epistemological (how we understand the world’s operation to be capable of investigation) frameworks.

There is an active intellectual and experiential dynamism involved here, as these ontological and epistemological understandings of the world themselves continue to change through ongoing interactions with unfolding research results. For this reason, it is not enough just to know how to measure things in the field or the laboratory—say, sites, stone artifacts, or faunal remains—but, rather, we need to recognize that individual techniques are part of a broader process of understanding and investigation about the past that involves present-day world views and ethical standards (the hermeneutic process). Each of the techniques employed must thus be understood to function ontologically and epistemologically, and, reflexively, the techniques emerge from and affect how we see the world—concepts explored throughout this handbook.
This page intentionally left blank
A common need in archaeology is for objects and events of interest to be dated, so that they can be arranged in the correct temporal sequence. Here we briefly review several methods available to the archaeologist to assist in age determination of the "target" object or event—comprehensive treatments of the subject are given by Aitken (1990, 1999), Wagner (1998), and Walker (2005).

We have divided the dating methods into two broad categories: "relative" and "numerical." The latter category includes methods that produce quantitative age estimates that can be placed on a standard timescale, commonly expressed as years before present. Such methods are entirely (or mostly) self-contained, so that an archaeologist can date an artifact, for example, without needing to know where it fits into a typological sequence. By contrast, relative dating methods produce ages that can be positioned on the standard timescale only by reference to a numerical age estimate. So, for example, artifacts in a typological sequence can be chronologically ordered relative to one another, but their age in years before present requires that the sequence is anchored somewhere using a numerical dating method.

We recommend that the dating terminology of Colman, Pierce, and Birkeland (1987) be followed to avoid confusion. Hence, no dating method should be referred to as "absolute," because each age estimate has an associated uncertainty, and "dates" should be reserved for specific points in time (for example, A.D. 1950). Archaeologists mostly obtain "age estimates" or "ages," which are intervals of time measured back from the present. It is also recommended practice to date a variety of materials using multiple methods to avoid pitfalls in any single method or material and to facilitate a comparison between independent chronologies. The approximate age ranges of the various methods discussed here are summarized in Figure 35.1.

Some of the methods that we describe here are applicable to entire landscapes, as well as to individual archaeological sites. For example, optically stimulated luminescence dating is commonly employed to establish the time of formation of landforms composed of wind-blown and water-lain sediments, whereas argon-argon and fission track methods are used routinely to date regionally extensive ash layers deposited by volcanic eruptions. Many erosional and depositional features of the landscape are also amenable to dating using terrestrial cosmogenic nuclides. Such methods are capable of meeting the needs of landscape archaeologists at all spatial scales. Most dating methods, however, are more restricted in their spatial scope, being applicable to items of archaeological interest recovered from particular sites. For example, electron spin resonance can be used to date individual teeth, radiocarbon methods can be employed to date certain organic materials, and obsidian hydration may be suitable for artifacts made...
of this type of volcanic glass. Only by comparing the sequence of ages from each archaeological site, along with those obtained from deposits in the surrounding area, can the pattern of human activity be discerned across the landscape. In practical terms, therefore, all dating methods should be viewed as germane to studies of human-landscape interactions.

**Relative Dating Methods**

Relative dating methods are employed routinely by archaeologists to reconstruct the order in which events occurred. For example, time is commonly implied by placement of artifacts in a typological sequence, and consideration of relative age is also implicit in the study of superposed sedimentary layers (stratigraphy) exposed during archaeological excavation (see also Stern, this volume). In this section, we discuss a range of relative dating methods under four headings: geomorphic, biological, chemical, and physical.

**Geomorphic**

Stratigraphic sequences containing recognizable to the episodic accumulation of sediments. In general, younger deposits overlie older deposits, but there are exceptions to this “Law of Superposition” that may have archaeological consequences. For example, sediment mixing after primary deposition may be accompanied by the displacement of artifacts, so additional evidence of stratigraphic integrity must be sought from preserved sedimentary structures. Relative age may also be established from geographically widespread “marker horizons,” such as layers of volcanic ash (tephra) produced from the fallout of volcanic eruptions; consolidated tephra is known as tuff. Tephra horizons have distinctive geochemical “fingerprints,” so sites in the path of the fallout can be correlated. Numerical dating of tephra (tephrochronology) has been applied in numerous archaeological contexts, including the timing of initial human settlement of New Zealand (Lowe et al. 2000) and the earliest evidence for anatomically modern humans in Africa (McDougall, Brown, and Fleagle 2005). Varved (annually layered) sediments can also be used as relative-age indicators. Varves can form in lake and marine basins with such regularity that the incorporated biological materials can be dated...
Chapter 35: Dating in Landscape Archaeology

(Hughen et al. 2006; Kitagawa and van der Plicht 1998). Detailed records of human activities and vegetation changes in the surrounding landscape can also be gleaned from changes in the physical, chemical, and biological characteristics of varved lake sediments, as illustrated by Zolitschka, Behre, and Schneider (2003) for a late Holocene site in Germany.

**Biological**

Tree rings are the biological equivalent of varves, providing a record of annual growth of tree trunks that currently extends back to about 12,400 years before present (Reimer et al. 2004). Dendrochronology is the most precise dating method available to archaeologists. It can be applied to wood from live and dead trees to determine the pattern of ring-width, which varies in response to the prevailing climatic conditions. By comparing the ring-width patterns for trees that overlap in age, a “floating” or relative chronology can be developed and then anchored to a numerical timescale by means of radiocarbon dating.

Dendrochronology has been deployed at Holocene archaeological sites around the world, the first applications being made to ancient timbers from pueblo dwellings in the American Southwest (Towner 2002). The growth rate of other plants, notably lichens, has also been exploited as a relative dating method. Lichens rapidly colonize many hard, bare surfaces, and some species exhibit a regular pattern of growth over several hundreds or thousands of years. Lichenometry has been used mostly to estimate exposure ages for geomorphic features related to late Holocene deglaciation, such as moraine ridges and raised shorelines (e.g., Loso and Doak 2006; O’Neal 2006). Lichenometry has been used occasionally to date archaeological sites found in association with such features, and the method could also be applied to recent rock art—and not only in arctic and alpine regions (Bednarik 2002).

**Chemical**

Chemical changes can also be used to track time. Perhaps the best known of these in an archaeological context is amino acid racemization (AAR), which is based on the gradual conversion of amino acids from the exclusively left-handed (L) form in living proteins to an equilibrium ratio of left- and right-handed (D) forms in organisms after death. The D/L ratio is, thus, an indication of relative age, but the correlation is not simple, because other factors, including temperature, affect the rate of racemization, which must be calibrated against a numerical dating method (usually radiocarbon) (Clarke and Murray-Wallace 2006). The most reliable materials are those that remain chemically “closed” postmortem, such as mollusk shell and eggshell, whereas “open” systems (for example, bone) are much less reliable (Grün 2006). The amino acids trapped within the crystal structure of mollusk shell (Penkman et al. 2008) were used to constrain the age of the oldest artifacts yet discovered in northern Europe (Parfitt et al. 2005). AAR dating has also been applied to ostrich eggshell found at early modern human sites in southern Africa (Miller et al. 1999a) and to cassowary and brush-turkey eggshells from occupation sites in Australia and New Guinea (Clarke et al. 2007). Other examples include the measurement of D/L ratios in eggshells of the extinct giant birds Genyornis and Aepyornis to provide a timescale for megafaunal extinction events—which are commonly attributed to human impact—in Australia and Madagascar, respectively (Clarke et al. 2006; Miller et al. 1999b).

The oxygen-isotope composition of mollusk shells has also been used as a relative dating method for archaeological sites (Shackleton 1982). In this instance, changes in the ratios of $^{18}$O to $^{16}$O (denoted as $\delta^{18}O$) can be matched to $\delta^{18}O$ variations in deep-sea sediments and polar ice caps for which numerical timescales have been established, sometimes at annual resolution (e.g., North Greenland Ice Core Project members 2004).

Other chemical changes, that form the basis of relative dating methods, can be broadly categorized as products of weathering processes. For example, the degree of soil development (pedsogenesis) can be used as a proxy for time, provided account is taken of the many other factors that also affect their formation (Birkeland 1999). Likewise, many rock surfaces become gradually altered over time, acquiring weathering rinds (which extend inwards from the surface) or mineral coatings (which accrete on to the rock surface). Relative ages for archaeological rock-structures in Canada were obtained from the relative hardness of their surfaces, which reflects the extent of weathering (Betts and Latta 2000).

In desert regions, rock surfaces are commonly encrusted in iron and manganese oxides, which form a “varnish.” These sometimes occur on top of rock engravings, for which minimum ages could be obtained by dating the time of varnish formation. In the 1980s, cation-ratio (CR) dating was proposed as a means of estimating the age of rock varnish by comparing the relative amounts of potassium
and Cahill 1988). The first two cations are leached more readily than titanium by weathering processes, so the (K+Ca)/Ti ratio will generally decrease over time. But varnish chemistry is highly variable at a range of spatial scales (Bierman et al. 1991), making it necessary to calibrate the CR timescale (using a numerical dating method) for the varnish directly overlying the engraving of interest. This is not always practicable, and the method has since fallen out of favor, not least because of difficulties in obtaining reliable radiocarbon ages for CR calibration (Beck et al. 1998; Bednarik 2002). Another approach, called varnish microlamination (VML) dating, exploits the optical and chemical properties of microscopic varnish layers, which form in response to climate variations. This technique has been applied to stone tools exposed on dryland surfaces in the western USA, but it requires some form of calibration to obtain numerical ages (Liu and Broecker 2007).

An alternative method of estimating the relative age of rock engravings is “microerosion dating” (Bednarik 1992, 2002). This refers to the progressive increase in roundness of individual mineral crystals, as a function of exposure time to chemical weathering processes, following crystal breakage during the act of engraving. Measurements of crystal roundness, preferably for two or more minerals, are made in the field using an optical microscope. The time elapsed since an engraving was made is then estimated by reference to calibrations performed on known-age engravings on similar rock type exposed to similar environmental conditions. Because of these calibration constraints, and the restricted application of the method to comparatively resistant rock types, microerosion dating has received scant attention, although it does target the archaeological event of interest.

Another form of chemical alteration is the slow absorption of moisture by freshly flaked surfaces of obsidian, a type of volcanic glass used for tool manufacture in many regions of the world (e.g., North America, Papua New Guinea, and New Zealand). Obsidian hydration dating is based on the increases in thickness of the hydration layer over time, but other variables, particularly temperature, also control the rate of hydration (Hull 2001; Rogers 2007). This temperature dependence provides a means of reconstructing past climates (Anovitz et al. 2006), as done previously using D/L ratios in emu eggshells (Miller et al. 1997).

**Physical**

Many rocks and sediments contain iron-bearing minerals, which have magnetic properties. Archaeologists ultimately want to know the number of years that have elapsed since artifacts were made or other events of interest occurred. To achieve this degree of temporal resolution requires the application of numerical dating methods. None of these methods, however, can match the potential for annual precision offered by dendrochronology, varved sediments, and ice cores, owing to the uncertainty associated with the various measurements made to determine the numerical age. Uncertainties on numerical ages are most commonly expressed as standard errors at 1σ or 2σ, reflecting the uncertainty associated with the various measurements made to determine the numerical age. The latter application is known generally as palaeomagnetic dating, and as archaeomagnetism when applied to archaeological sites and artifacts no more than a few thousand years old. The Earth’s magnetic field has varied in both intensity and direction over time, and these changes can be reconstructed from the orientation of magnetic minerals, which align themselves with the geomagnetic field prevailing at the time of rock formation or sediment deposition. The Quaternary has been punctuated by several major magnetic reversals, including the most recent inversion to “normal” polarity about 780,000 years ago. Short-lived magnetic “excursions” (for example, Laschamp and Mono Lake) have occurred since then, and these can be used as marker horizons to correlate between sedimentary sequences that are geographically distant. Smaller, secular geomagnetic variations occur over timescales of a few hundred years and are of limited spatial extent, so an archaeomagnetic “master curve” must be established for each region, as Lengyel and Eighmy (2002) have done for the American Southwest. At the opposite end of the Quaternary, the magnetostratigraphy of sediments containing stone tools has been used to infer a human presence in northeast Asia by 1.66 million years ago (Zhu et al. 2004), and the age of the earliest-known hominin remains in western Asia (Calvo-Rathert et al. 2008) and Europe (Carbonell et al. 2008). In contrast to palaeomagnetism, magnetic susceptibility is based on the abundance, size, and shape of magnetic minerals in sediments, rather than their orientation. Variations in magnetic susceptibility reflect environmental changes and are widely used for regional palaeoclimatic reconstructions. Environmental magnetism can, therefore, be used to correlate between archaeological sites affected by synchronous environmental changes (Dalan and Banerjee 1998).

**Numerical Dating Methods**

Archaeologists ultimately want to know the number of years that have elapsed since artifacts were made or other events of interest occurred. To achieve this degree of temporal resolution requires the application of numerical dating methods. None of these methods, however, can match the potential for annual precision offered by dendrochronology, varved sediments, and ice cores, owing to the uncertainty associated with the various measurements made to determine the numerical age. Uncertainties on numerical ages are most commonly expressed as standard errors at 1σ or 2σ. Archaeologists ultimately want to know the number of years that have elapsed since artifacts were made or other events of interest occurred. To achieve this degree of temporal resolution requires the application of numerical dating methods. None of these methods, however, can match the potential for annual precision offered by dendrochronology, varved sediments, and ice cores, owing to the uncertainty associated with the various measurements made to determine the numerical age. Uncertainties on numerical ages are most commonly expressed as standard errors at 1σ or 2σ.
Chapter 35: Dating in Landscape Archaeology

Three of the most widely used numerical dating methods in archaeology are based on the radioactive decay of naturally-occurring elements: ¹⁴C (radiocarbon dating), ²³⁸U (uranium-series dating), and ⁴⁰K (potassium-argon and argon-argon dating).

Radioactive Decay. Radioactive dating was the first to be developed, in the 1940s, by a team led by Nobel laureate Willard Libby, once it had been realized that interaction between ¹⁴N and cosmic rays in the upper atmosphere results in the production of ¹⁴C. This then oxidizes to a particular form of carbon dioxide, which becomes incorporated and into carbonates formed in the oceans and on land. When the plant or animal dies, ¹⁴C uptake ceases, and the amount of radiocarbon decreases by 50% every 5,730 ± 40 years (the so-called “Cambridge” half-life of ¹⁴C), owing to radioactive decay. Each decay is accompanied by the emission of a beta particle, which can be counted to determine the concentration of ¹⁴C (in what is variously referred to as conventional, radiometric, or classical ¹⁴C dating). Alternatively, the number of ¹⁴C atoms can be counted directly using an accelerator mass spectrometer (AMS); hence, the term “AMS ¹⁴C dating.” In either case, ¹⁴C dating is restricted to the last 60,000 years or so, beyond which too little ¹⁴C remains to be measured and ages are reported as “infinite.”

Radioactive dating can be applied to a great variety of organic materials encountered at archaeological sites, including the remains of plants (for example, wood, charcoal, and seeds) and animals (for instance, bone and shell). But other sources of carbon amenable to ¹⁴C dating may also occur in archaeological contexts, such as speleothems in caves, residues on pottery, artifacts made of iron, and mineral accretions on rock art. Walker (2005) describes a number of routine and unusual applications of ¹⁴C dating, illustrated by archaeological examples from around the world, and Bronk Ramsey (2008) offers much useful advice about ¹³C dating in archaeology. For each type of sample, the ¹⁴C related to the target event must be separated from any older or younger ¹⁴C. Contamination by older, water-borne carbon needs to be considered when dating speleothems and shell, for example, and there is also the potential problem of artifacts being made from preexisting old shells (Rick, Vellanoweth, and Erlandson 2005). The “old wood” effect (Wagner 1998) may be of concern in archaeological contexts where preexisting old wood or charcoal is dated instead of the remains of plants that died during the period of human occupation (e.g., Armitage et al. 2001; Kennett et al. 2002). In such cases, the ¹⁴C age may be substantially older than the target archaeological event. The use of heartwood from long-lived tree species will increase the age discrepancy—especially for Holocene samples—so preference should be given to wood from directly below the bark or to short-lived plant remains (for example, twigs and seeds).

The most common concern, however, is the possible postdepositional contamination by younger carbon of charcoal and bone, which form the basis for many archaeological ¹⁴C chronologies. Techniques of charcoal and bone pretreatment...
the development of acid-base wet oxidation and stepped-combustion (ABOX-SC) procedures for charcoal (Bird et al. 1999) and molecular ultrafiltration procedures for bone collagen (Higham, Jacobi, and Bronk Ramsey 2006). The \(^{14}\)C ages of older samples are particularly affected by younger contaminants. So, by removing more of the latter, these techniques have increased the accuracy of the resulting \(^{14}\)C ages—compared to less rigorous sample pretreatments, which can yield \(^{14}\)C ages that are too young by several millennia—and extended the limit of the method from about 40,000 to 60,000 years (e.g., Bird et al. 2003; Jacobi et al. 2006; Turney et al. 2001). It is also feasible, but not straightforward, to isolate and to date specific biomolecules containing carbon, such as amino acids and lipids (Stafford et al. 1991; Stott et al. 2003), to further increase confidence that a \(^{14}\)C age relates directly to the target event.

Efforts have also been made to improve the reliability of \(^{14}\)C dating of rock art, using a variety of sample types. In some cases, carbon can be extracted from the material used to make the picture, as with beeswax figures (Watchman and Jones 2002), charcoal drawings (Armitage et al. 2001; Valladas et al. 2001), and plant-fiber binders in paints (Mazel and Watchman 1997). A range of carbon-bearing mineral coatings—variously referred to as “crusts,” “skins,” and “varnishes”—have also been investigated. Where these cover paintings and engravings, minimum ages for the underlying art can, in principle, be obtained by dating the organic component of the accretions. Silica skins and, in particular, calcium oxalate crusts have yielded seemingly reliable \(^{14}\)C ages (Watchman et al. 2000, 2005), whereas those obtained from desert varnish and calcite have proven more equivocal (Beck et al. 1998; Plagnes et al. 2003). But no sample type is without potential complications (Bednarik 2002; Pettitt and Pike 2007), so alternative approaches to numerical dating of rock art have also been explored (Plagnes et al. 2003; Roberts et al. 1997; Watanabe et al. 2003).

Radiocarbon ages are conventionally reported in “radiocarbon years B.P.,” where B.P. means “before present.” For historical reasons, “present” refers to the year A.D. 1950 and the incorrect “Libby” half-life for \(^{14}\)C (5,568 ± 30 years, which is 3% too short) is knowingly used to calculate the ages! Archaeologists should check if the \(^{14}\)C ages received from the dating laboratory are expected to convert, or “calibrate,” conventional ages into calendar-year ages, owing to long-term variations in the production rate of \(^{14}\)C. IntCal04 is the latest international effort to calibrate the radiocarbon timescale (Reimer et al. 2004). Calibration can be achieved to annual resolution over the last 12,400 years, where dendrochronology can be applied, and with much lower resolution to 26,000 years ago using varved sediments and fossil corals, the latter dated by both \(^{14}\)C and uranium-series. Before 26,000 years, there is disagreement about the extent of correction needed (van der Plicht et al. 2004), although a consensus data set is beginning to emerge (Hughen et al. 2006). To distinguish conventional \(^{14}\)C ages (in radiocarbon years) from calibrated \(^{14}\)C ages (in calendar years), the latter are expressed as “cal years B.P.” For the period 0–1,000 cal years B.P., contemporaneous samples in the Northern and Southern Hemispheres differ by between 8 and 80 radiocarbon years. Older ages are obtained from the Southern Hemisphere, for which a separate calibration (SHCal04) is available back to 11,000 cal years B.P. (McCormac et al. 2004).

Some archaeological samples, usually shells of terrestrial and marine mollusks, may require age calibration for the “reservoir effect,” which is the uptake of noncontemporaneous (usually older) carbon by the sample while alive. Terrestrial and freshwater snails, for example, may incorporate older carbon in their shells from sources such as dissolved limestone, while modern marine mollusks can give apparent ages of several hundred years (or more) because the carbon reservoir in seawater is a mixture of modern and ancient \(^{14}\)C. Because the mixing ratio varies with location, it is necessary to estimate the difference (defined as \(\Delta R\)) in \(^{14}\)C years between a known-age marine sample from the region of interest and the average global ocean reservoir age to calibrate ages for marine samples using programs such as Marine04 (Hughen et al. 2004). Site-specific \(\Delta R\) values are commonly estimated from modern samples, but these may not compensate for fluctuations in marine reservoir ages in the past (Fontugne et al. 2004).

A different effect on the carbon reservoir, but one with potential uses for historical and forensic archaeologists, is the “bomb” pulse in \(^{14}\)C concentration produced by above-ground testing of nuclear weapons between 1955 and 1963. These tests injected large amounts of \(^{14}\)C into the atmosphere, with a peak in the mid-1960s followed by an exponential decline after implementation of the international test ban treaty (Hua and Barbetti 2004). The bomb pulse can be used to estimate time since death with a precision of 1–2 years for tooth enamel, hair, and bone lipids (Geyh 2001; Spalding et al. 2005; Wild et al. 2000); other
art in Vanuatu (Wilson et al. 2001). Except at the bomb peak, the measured $^{14}$C concentration will yield two ages for a sample—corresponding to the points of equal activity on the rising and falling limbs of the pulse—resulting in an “either/or” choice of age.

**Uranium-Series Dating.** Uranium-series dating refers to a number of related techniques, all of which are based on the radioactive decay of natural uranium. This consists of two forms of uranium, that differ in their atomic mass: $^{238}$U (which accounts for almost 96% of the radioactivity) and $^{235}$U, each of which is the “parent” nuclide at the head of a decay chain of “daughter” products resulting from successive radioactive decays. The final product in each chain is a stable form of lead.

The parent nuclides have half-lives of about 4.5 and 0.7 billion years for $^{238}$U and $^{235}$U, respectively, which are too long for most archaeological purposes. But several of their decay products have much shorter half-lives, and that of $^{230}$Th (75,700 years), a daughter nuclide in the $^{238}$U chain, has proven especially useful for archaeological dating. Uranium is soluble in water but thorium is not, so the activity ratio of $^{230}$Th to $^{234}$U, its immediate parent, can be used to estimate when certain materials were formed. The most reliable $^{230}$Th/$^{234}$U ages are obtained from “closed systems” in which uranium, but not thorium, was present at the time of formation and all of the $^{230}$Th has resulted from radioactive decay of $^{234}$U. This is generally the case for speleothems and travertines formed from clean crystals of calcite, and for unaltered corals. Some mollusk shells and eggshells may also be suitable, but these archaeological materials, as well as bones, teeth, and any “dirty” samples (that is, carbonates contaminated by thorium-enriched detritus), require special measures to obtain accurate ages.

As with $^{14}$C dating, techniques of U-series dating have evolved over time; see Ivanovich and Harmon (1992) and Bourdon et al. (2003) for comprehensive reviews of the method and its applications. The original measurement technique involved counting the alpha particles emitted by radioactive decay, but this has been largely superseded by the atom-counting methods of thermal ionization mass spectrometry (TIMS) and inductively coupled plasma mass spectrometry (ICP-MS), which can generate high-precision ages for the last 500,000 years or so. Dating applications in archaeology span the full age range of the technique, from coral offerings at temples in protohistoric Hawaii (Kirch and Sharp 2005) to speleothems interbedded with 2004). Efforts at dating calcite accretions on cave paintings in Southeast Asia have met with mixed success (Aubert et al. 2007; Plagnes et al. 2003).

Bone has generally been avoided in U-series dating because of its “open system” behavior, but recent developments have renewed the possibility of obtaining reliable $^{230}$Th/$^{234}$U ages from bone and, to a lesser extent, teeth (Eggins et al. 2005; Grün 2006; Pike, Hedges, and van Calsteren 2002). The approach involves measuring the uranium concentrations across sectioned pieces of bone and comparing the U-profiles with models of uranium diffusion and adsorption. Reliable ages can be obtained from bones with certain U-profiles, but these may occur in only a minority of cases. Laser-ablation multicollector ICP-MS permits the rapid analysis of a large number of samples and is almost nondestructive, so precious samples (for example, hominin fossils) can be considered for dating. Nondestructive uranium-series dating by high-resolution gamma-ray spectrometry has also been tested on certain hominin fossils, but measurement of $^{235}$U (in particular) is neither simple nor fast (Grün 2006). Also, doubts have been raised about the accuracy of some gamma spectroscopic ages, as illustrated by the dispute over the age of the human burials at Lake Mungo in Australia (Bowler et al. 2003; Thorne et al. 1999).

Support for “closed system” behavior can be gained from protactinium ($^{231}$Pa), the only long-lived daughter product of $^{235}$U decay. The half-life of $^{231}$Pa is 34,300 years, so comparisons between $^{230}$Th/$^{234}$U and $^{230}$Pa/$^{235}$U ages can, in principle, be made for samples up to 200,000 years old (Cheng et al. 1998). In practice, however, the low natural abundance of $^{235}$U limits the precision of protactinium dating and restricts its application to samples with high uranium concentrations.

Much older archaeological events may be amenable to uranium-lead dating (Richards and Dorale 2003). The basis of the technique is the same as above, with the age being obtained from the activity ratios of $^{206}$Pb to $^{238}$U and of $^{207}$Pb to $^{235}$U—the parent nuclide and final (stable) daughter product in each decay chain—measured by TIMS, multicollector ICP-MS (Woodhead et al. 2006) or with a sensitive high-resolution ion microprobe (SHRIMP). In theory, the age range of U-Pb dating extends significantly beyond that of $^{230}$Th/$^{234}$U dating, but the limits are governed in practice by the extent of sample contamination by lead-enriched detritus. Walker, Cliff, and Latham (2006) used the U-Pb method to obtain ages of about 2.2 million years for speleothems above and below hominin fossils at Sterkfontein...
It is also possible to use $^{210}\text{Pb}$, one of the decay products late in the $^{238}\text{U}$ chain, to date recent lake, estuarine, and marine sediments. The method is based on the continuous, natural fallout of “excess” $^{210}\text{Pb}$ from the atmosphere on to exposed surfaces, and its subsequent incorporation into sedimentary deposits (Ivanovich and Harmon 1992). The term “excess” refers to the fact that the $^{210}\text{Pb}$ of interest is not supported by radioactive decay of in situ parent nuclides, and so will decay away over time. With a half-life of 22 years, $^{210}\text{Pb}$ can be used to date sediments deposited in the last 120 years by making some assumptions about how much unsupported $^{210}\text{Pb}$ was deposited at the site over time and if there has been any postdepositional mixing. Ages are inferred from vertical profiles of excess $^{210}\text{Pb}$ activity versus depth, by assuming either a constant rate of supply (CRS) or a constant initial concentration (CIC) of excess $^{210}\text{Pb}$. But the accuracy of the chosen model can be validated only by comparing the $^{210}\text{Pb}$ chronology with some independent measure of age (Smith 2001). The latter is commonly obtained from the A.D. 1963 peak in concentration of the short-lived radionuclide $^{137}\text{Cs}$ (half-life of 30 years), which was deposited worldwide as atmospheric fallout from nuclear weapons testing. Recent archaeological applications of $^{210}\text{Pb}$ dating include studies of human impacts on vegetation and landscape development using lake sediments in northeast England (Oldfield et al. 2003) and shallow marine deposits off western Java (van der Kaars and van den Bergh 2004).

**Potassium-Argon and Argon-Argon Dating.**

Potassium-argon and argon-argon dating are closely related techniques, both based on the decay of the radioactive form of potassium ($^{40}\text{K}$) to argon ($^{40}\text{Ar}$), a stable, gaseous daughter product. Potassium is present in many natural minerals at the time of formation, being especially abundant in volcanic minerals, and $^{40}\text{K}$ accounts for a very small proportion (0.012%) of this. The principle of the method is simple. When molten, volcanic minerals contain $^{40}\text{K}$ but not $^{40}\text{Ar}$, because all of the argon gas escapes into the atmosphere. After cooling below a certain “closure temperature” (which depends on the particular mineral), $^{40}\text{Ar}$ will slowly accumulate inside the crystal owing to the decay of $^{40}\text{K}$, and the $^{40}\text{Ar}/^{40}\text{K}$ ratio can be used to estimate the time elapsed since crystallization.

The potassium-argon method is applicable to most of Earth history, because of the long half-life of $^{40}\text{K}$ (1250 million years), but dating of archaeological events during the last 100,000 years is limited by the low precision on the ages.

Archaeological applications at the younger end technique, whereby the age is obtained from the ratio of $^{40}\text{Ar}$ to another form of argon ($^{39}\text{Ar}$) in the crystal (McDouggall and Harrison 1999). The basic premise of the method is the same as for potassium-argon dating, with the difference being that some of the $^{40}\text{K}$ is converted into nonradioactive $^{39}\text{Ar}$ by bombarding the sample with fast neutrons in a nuclear reactor. The $^{40}\text{Ar}/^{39}\text{Ar}$ ratio can then be measured using the same instrument (a mass spectrometer), with a resulting improvement in the precision of the ages. Their accuracy can also be improved by measuring $^{40}\text{Ar}/^{39}\text{Ar}$ ratios for individual crystals to identify samples composed of crystals of differing age.

There are three possible complications with potassium-argon and argon-argon dating: sample or instrument contamination with atmospheric $^{40}\text{Ar}$ (as opposed to the tiny amount of radiogenic $^{40}\text{Ar}$ produced in the crystal by decay of $^{40}\text{K}$), the presence of “excess” $^{40}\text{Ar}$ that never escaped from the crystal at the time of its formation, and the loss of radiogenic $^{40}\text{Ar}$ after crystallization due to weathering, for example. The first of these concerns is addressed by also measuring the amount of atmospheric $^{36}\text{Ar}$ and making the necessary corrections, while the other two concerns are dealt with by heating the sample to successively higher temperatures to release the $^{40}\text{Ar}$ and $^{39}\text{Ar}$ in a series of steps. The age is determined for each increment, with the “plateau” region taken as the most reliable indicator of crystallization age. This approach can be applied to individual crystals, using a laser to release the argon, so that any contaminant grains in a sample can be identified and discarded.

Argon-argon dating has been used in many archaeological contexts, especially in east Africa where fossils of early hominins (e.g., Leakey et al. 2001) and the genus *Homo*, including the oldest-known remains of our species (McDougall, Brown, and Fleagle 2005), have been found in stratigraphic association with tuffs. Early *Homo* fossil sites on the island of Java in Indonesia (Swisher et al. 1994) and at Dmanisi in the Republic of Georgia (Gabunia et al. 2000) also have $^{40}\text{Ar}/^{39}\text{Ar}$ age constraints, while recent volcanic events, such as the eruption that destroyed Pompeii around 2,000 years ago (Renne et al. 1997), can be dated if the deposit contains large crystals of potassium-rich sanidine. However, when artifacts and human remains are not situated between *in situ* volcanic deposits, and cannot be provenanced with certainty, archaeologists should bear in mind that the age obtained from $^{40}\text{Ar}/^{39}\text{Ar}$ dating is that of mineral crystallization and not that of any subsequent event.
Radiation Exposure

Five techniques make up this group of numerical dating methods: thermoluminescence (TL), optically stimulated luminescence (OSL), electron spin resonance (ESR), fission track (FT), and terrestrial cosmogenic nuclide (TCN) dating. Ages are obtained by measuring the cumulative effect of ionizing radiation on the crystal structure of certain minerals, some of which (for example, hydroxyapatite) occur in teeth and bones. The greater the amount of energy absorbed (TL, OSL, ESR, and TCN) or crystal damage (FT), the longer the duration since first exposure to radiation and, consequently, the greater the age of the material being dated.

Luminescence Dating. Luminescence dating is a term that embraces a range of related methods that can be applied over different time periods to different minerals and in different archaeological settings. When one method is not appropriate for a particular situation, then another may be. The technique is based on the fact that natural minerals (such as quartz and feldspar) are not perfectly formed but contain defects in their crystal lattices that are able to trap negatively charged electrons and positively charged vacancies ("holes"). Some of these charges can remain trapped for millions of years and provide a measure of the energy absorbed by the crystal owing to exposure to ionizing radiation. The latter consists mainly of gamma rays, beta particles, and alpha particles, which are emitted during the decay of uranium, thorium (and their daughter products), and potassium contained inside the mineral grains and dispersed throughout the surrounding deposit; there is also a lesser contribution from cosmic rays. The energy absorbed increases with the amount of radiation exposure, and estimation of the corresponding radiation dose is the "clock" that forms the basis of all luminescence dating methods. These have been shown to work for samples as young as a few years, to sediments deposited several hundreds of millennia ago. Luminescence ages are obtained in calendar years and typically have precisions of 5–10%.

Luminescence dating relies on the fact that the charge-traps of interest were emptied ("zeroed") at, or close to, the time of the target event, such as that of pottery or flint tool manufacture or the time of burial of artifacts and human remains. For archaeological applications, there are two main zeroing processes: heating of the crystal to at least 300°C by, for example, the intentional firing of pottery or the accidental burning of stones in a hearth; or exposure of the crystal to sufficient sunlight to empty the charge-traps of interest were emptied ("zeroed") at, or close to, the time of the target event, such as that of pottery or flint tool manufacture or the time of burial of artifacts and human remains. For archaeological applications, there are two main zeroing processes: heating of the crystal to at least 300°C by, for example, the intentional firing of pottery or the accidental burning of stones in a hearth; or exposure of the crystal to sufficient sunlight wind-blown sediments, for example. Once the crystal has been emptied of its preexisting trapped charge and then buried, the traps become refilled at a predictable and measurable rate. They can be emptied in the laboratory, with an accompanying emission of light, using an appropriate means of stimulation. This can involve heating the sample to a red-hot temperature to generate the TL signal (Aitken 1985), or exposing the sample to a light source of specified wavelength to generate an OSL signal (Huntley, Godfrey-Smith, and Thewalt 1985). Blue or green light is typically used for quartz, and infrared excitation for feldspars; the latter induces infrared stimulated luminescence (IRSL). Age estimation using OSL and IRSL signals is commonly referred to as optical, or OSL, dating.

To determine the energy absorbed by quartz or feldspar grains since they were last exposed to heat or sunlight, the TL or OSL signal from a "natural" sample is compared to the signals induced in the laboratory after administering known doses, using a calibrated radiation source, to portions (" aliquots") of the same sample. The latter signals are used to construct a TL or OSL dose-response curve, from which an estimate can be made of the equivalent dose (Dₑ), or "palaeodose," defined as the amount of radiation needed to generate a TL or OSL signal equal to that produced by the natural sample (Lian and Roberts 2006).

To calculate a luminescence age, one further parameter has to be determined: the environmental dose rate, which is the rate of supply of ionizing radiation to the sample in the natural environment, integrated over the entire period of sample burial. This involves assessing the radioactivity of the sample and the surrounding material, to a distance of about 30 cm, using chemical or physical methods, such as gamma and alpha spectrometry, alpha and beta counting, neutron activation and ICP-MS. Some forms of disequilibrium between parent and daughter nuclides are commonplace in the U-series—such as the loss of radon gas to the atmosphere—and should be taken into consideration (e.g., Olley, Roberts, and Murray 1997). An age estimate is obtained by dividing the equivalent dose (Dₑ) by the environmental dose rate.

TL dating was developed in the late 1960s for dating of fired pottery (Aitken 1985), but its main application in archaeological contexts today is dating of burnt stones, especially flint (e.g., Mercier et al. 1995, 2007). The method can cover the time span of the controlled use of fire by humans. Flint is an ideal material because it is homogeneous in composition and preserves evidence of past heating in the form of characteristic cracks and potlids,
in the field or museum. When flints are not present at a site, other materials, such as burnt quartz, quartzite, silcrete, and hornfels, may be used (e.g., Henshilwood et al. 2002; Valladas et al. 2005). However, these materials do not necessarily exhibit burning characteristics, so only a small fraction of such samples may be suitable for TL dating. Also, radionuclides are not always homogeneously distributed in stones made of these materials, with radioactive “hot spots” that increase scatter in the ages (e.g., Tribolo et al. 2006). TL dating of unheated sediments has been largely superseded by OSL dating because the OSL charge-traps are emptied by sunlight far more rapidly and completely than those that give rise to the TL signal. But there are some circumstances in which OSL dating cannot be applied and the use of light-sensitive red TL emissions is a possible option (e.g., Morwood et al. 2004).

OSL dating can be applied to naturally-deposited sediments in which artifacts and faunal remains are buried, giving an age estimate for the last time the sediments were exposed to sunlight (Aitken 1998; Lian and Roberts 2006). By association, the age of the buried archaeological materials can be inferred. Quartz is generally preferred to feldspar, which suffers from a physical phenomenon known as “anomalous fading” that can result in age shortfalls unless corrections are made. Methodological and technological developments in OSL dosimetry (Botter-Jensen, McKeever, and Wintle 2003) now enable the routine measurement of small, individual aliquots and sand-sized grains of quartz, so a statistically significant number of independent estimates of $D_E$ can be obtained. This has allowed issues such as insufficient sunlight exposure and postdepositional mixing to be addressed (Jacobs and Roberts 2007). For example, Jacobs and colleagues (2006) investigated the possibility of sediment mixing at Blombos Cave in South Africa, and single-grain methods were used at Jimmium rock shelter in northern Australia to determine the extent of contamination of the archaeological deposit with unbleached grains liberated by in situ disintegration of roof spall (Roberts et al. 1998). Although deposits in rock shelters and cave entrances may be exposed to scattered, rather than direct, sunlight, this is usually sufficient to zero the OSL “clock.” By contrast, deposits in deep cave systems are poorly suited to OSL dating, because the sediment may have been reworked in the darkness of the cave, long after initial deposition.

OSL dating is now applied routinely in archaeology (Feathers 2003; Roberts 1997; Wintle 2008) and has proven especially useful for deposits that lie beyond the reliable age range of the $^{14}$C method. Some examples of the latter include OSL dating of the earliest-known evidence for modern human behavior (Bouzouggar et al. 2007; Henshilwood et al. 2002; Marean et al. 2007), the oldest artifacts and human remains discovered in Australia (Bowler et al. 2003; Roberts et al. 1994), and the timing of megafaunal extinction in Australia (Roberts et al. 2001).

**Electron Spin Resonance.** Electron spin resonance dating is founded on the same basic principles as luminescence dating—namely the measurement of the time-dependent accumulation of trapped charge in particular minerals, some of which are found in fossils (Grün 2006; Rink 1997). In ESR dating, however, the number of trapped electrons is estimated from their paramagnetic properties, rather than from their release by heat or light. This is accomplished using an ESR spectrometer, whereby the sample is placed in a microwave cavity and exposed to a strong, external magnetic field. A paramagnetic center (that is, the trapped electron or hole) has a magnetic moment of the same orientation as the magnetic field in which it is placed. By slowly changing the direction of the magnetic field, electrons will resonate (“spin”) at a certain frequency. This process involves the magnetic moment reversing direction due to absorption of microwave energy administered to the sample by the microwave generator. The amount of absorbed microwave energy is directly proportional to both the strength of the ESR signal and the number of paramagnetic centers and, hence, the age of the sample; for this reason, the technique is sometimes known as electron paramagnetic resonance (EPR) dating. As in luminescence dating, a dose-response curve is constructed and the signal intensities are compared to that of the “natural” sample to estimate the equivalent dose. The dose rate, internal and external to the sample, must also be determined. In archaeological contexts, ESR is mostly used for dating of hydroxypatite in the enamel of teeth formed between a few thousand years and several hundreds of millennia ago; in exceptional circumstances, the age range can be extended to a few million years (Schwarz, Grün, and Tobias 1994).

There are some potential complications with ESR dating, of which resetting of the ESR signal and uncertainties in dose rate determination are the most noteworthy. The former is not a problem when dating teeth: in this case, the zeroing event is assumed to be the time of death and burial, as very few (or no) electrons are trapped in the tooth enamel of living animals. In many situations, however,
(Grün 2006; Rink 1997). Ideally, the dated sample and surrounding deposits should form a geochemically “closed system” with regard to the relevant radionuclides. But teeth are notorious (as are bone and shell) for the uptake of uranium after burial, and the history of U-uptake (and sometimes later U-loss) commonly cannot be reconstructed in any simple manner. To address this problem, tooth enamel is used in preference to dentine, which typically accumulates between 10 and 100 times as much uranium (Grün and Taylor 1996), and attempts are routinely made to model the process of U-uptake. Two main models have been suggested for teeth (Ikeda 1982): the early-uptake (EU) model assumes that uranium accumulated soon after burial of the tooth, whereas the linear-uptake (LU) model is based on the premise that uranium accumulated steadily throughout the period of tooth burial. Typically, the EU and LU model ages are both reported in publications. It is commonly assumed that the ages of most samples lie somewhere between these estimates, although many samples do not satisfy this assumption (Grün 2006). The EU model will yield a minimum age if there has been no recent U-loss, but a combination of ESR and 230Th/234U dating—both of which are dependent on U-uptake, but to different extents—can help narrow the likely age range. Two such approaches have been developed for teeth: the “coup- ed” ESR/U-series model (Grün et al. 1988) and the closed-system U-series/ESR (CSUS-ESR) model (Grün 2000). These yield the youngest and oldest possible ages for a tooth, respectively, provided no U-loss has occurred.

ESR dating has been used in many archaeological contexts but is perhaps best known for its application to Middle Palaeolithic sites in Israel (Grün and Stringer 1991; Schwarcz et al. 1988) and Middle Stone Age sites in southern Africa (Grün et al. 1996, 2003). The ESR chronologies constructed for both regions showed that the evolutionary history of early modern humans was far more complex than had hitherto been appreciated.

**Fission Track Dating.** Fission track dating is based on the presence of micrometer-sized, linear damage tracks that occur in minerals due to the spontaneous fission of 238U. Instead of emitting an alpha particle during radioactive decay, the nucleus of a 238U atom may split into two smaller nuclei, which recoil and cause damage to the crystal lattice. Spontaneous fission occurs at a known rate, so the age of a sample can be estimated by measuring the uranium content and the density of spontaneous fission tracks. The latter is determined by chemically etching the sample with the tracks visible under an optical microscope, and then counting the number of tracks. The uranium content is measured by irradiating the sample with thermal neutrons in a nuclear reactor to induce fission of the less abundant 235U. The induced fission tracks are etched and counted in the same manner as for the spontaneous 238U tracks, to provide a measure of 235U abundance. The concentration of 238U can then be obtained, because natural uranium has a known, constant 235U/238U ratio of 0.073. The most commonly used materials in FT dating are zircon, apatite, and obsidian. The age range of the technique depends on the uranium concentration in the sample, and extends from well beyond the archaeological timescale to some lower limit, which is dictated by track density. Ages as young as 100 years have been achieved using zircons with high uranium concentrations.

The main complication with FT dating is track fading or “annealing” (Wagner 1998; Westgate et al. 2007). Fission tracks are thermally unstable and disappear partially or totally over time at ambient temperature, owing to restoration of the crystal lattice. This leads to fewer fission tracks and, therefore, an underestimation of age. Fading is especially problematic with volcanic glass (for example, obsidian). In archaeological applications, consideration must also be given to the relationship between the zeroing event and the archaeological event of interest. Because heat anneals the tracks and sets the FT “clock” to zero, the heating of obsidian artifacts in a hearth, for example, will date the time of this event. The age of the last significant heating event is also obtained for minerals extracted from *in situ* volcanic tuffs. But in such cases—where artifacts are not dated directly—the association between the dated mineral and the target archaeological event must be secure, because fission tracks are not erased when minerals are reworked from the original deposits unless they are also reheated.

Archaeological applications of FT dating have been limited. The method was used to confirm the K-Ar ages of Bed I at Olduvai Gorge in Tanzania (Fliescher 1965) and the KBS tuff in Kenya (Gleadow 1980), both deposits being associated with Early Pleistocene hominin remains. In Indonesia, FT ages of up to 840,000 years were obtained for zircons buried alongside stone tools in Flores (Morwood et al. 1998; O’Sullivan et al. 2001). This island lies east of Wallace’s Line, suggesting that some early hominin species, possibly *Homo floresiensis*, was capable of repeated water crossings long before *Homo sapiens*. At the younger end of the timescale, FT dating has been used...
tephra deposited across India following the Toba super-eruption 74,000 years ago (Westgate et al. 1998), while in South America FT dating has been applied to obsidian artifacts and to trace trade routes in the Holocene (Miller and Wagner 1981).

**Terrestrial Cosmogenic Nuclide Dating.** Cosmogenic nuclide dating is based on the principle that high-energy cosmic rays entering the atmosphere collide with atomic nuclei and generate a surge of fast neutrons, as well as some protons and muons, which reach the Earth’s surface. When these energetic particles then collide with the nuclei of atoms in certain minerals, such as quartz and calcite, the impacted nuclei are broken apart and the lighter, residual nuclei are known as “terrestrial in situ cosmogenic nuclides” (to distinguish them from the vastly more abundant cosmogenic nuclides created in the atmosphere, such as $^{14}$C, which is incorporated into living tissues and forms the basis for $^{14}$C dating). Terrestrial cosmogenic nuclides include two noble gases—$^3$He and $^{21}$Ne (both of which are stable)—and four radioactive elements: $^{10}$Be, $^{14}$C, $^{26}$Al, and $^{36}$Cl. The production of these nuclides is largely restricted to rocks within the upper meter or so of the ground surface, so their concentrations (and, for the radioactive nuclides, those of their daughter products) are related to the length of time that the rocks have been exposed to cosmic rays. The greater the elapsed time since initial exposure, the higher the concentration of cosmogenic nuclides within the minerals. Muons penetrate much more deeply than neutrons and are important for TCN dating of transported sediments. The age range of TCN dating extends from a few thousand years to a few million years, depending on the nuclide used.

TCN dating is a rapidly developing field; recent reviews of the technique, and its limitations, are given by Gosse and Phillips (2001), Granger and Muzikar (2001), and Blard and associates (2006). The method has two main potential uses of relevance to archaeologists: to estimate either the exposure age of a rock surface, or the burial age of sediments eroded from the ground surface and deposited deep underground (for instance, in a cave). Determining an age is not straightforward in either case, because it is generally assumed that the “exposure clock” started at zero, such that the dated minerals did not inherit any cosmogenic nuclides produced by previous exposure events. If this assumption does not hold then the age of the most recent exposure event will be overestimated. For exposure dating of a rock surface, it is also commonly assumed that no erosion or weathering has occurred since its initial exposure to cosmic period of time to accumulate measurable amounts of cosmogenic nuclides. The validity of these assumptions rests largely on careful field interpretations, although the use of two or more nuclides with different half-lives (for example, $^{26}$Al and $^{10}$Be in quartz) can provide some constraints on the first two assumptions.

The dual-nuclide approach also enables the estimation of burial ages for sediments that have entered deep caves with cosmogenic $^{26}$Al and $^{10}$Be. The two nuclides will decay at different rates, so the burial age can be obtained from the ratio of their concentrations, although the initial ratio at the time of sediment entry into the cave must be assumed (Granger et al. 2001). Accurate estimation of TCN production rates is a further complication, because they vary with altitude, latitude, depth below the ground surface, and the angle of inclination of the rock surface (as the cosmic-ray flux is greatest overhead and decreases to the horizon). For sediments deposited less than 30 m underground, continued TCN production due to muons must be taken into account. Also, in TCN dating—as with $^{14}$C dating—consideration should be given to past variations in the intensity of the Earth’s magnetic field, which affects the fraction of cosmic rays that reach the atmosphere. Given these uncertainties, TCN exposure and burial ages typically have precisions of 5–15%.

TCN dating has been used extensively to study the evolution of landscapes but has had limited application in archaeology. Partridge and associates (2003) used $^{26}$Al and $^{10}$Be to determine burial ages for cave breccia containing early hominin remains at Sterkfontein in South Africa, and the same approach was taken to date the oldest hominin remains in Europe (Carbonell et al. 2008). Phillips and associates (1997) used $^{36}$Cl to obtain maximum ages for rock engravings in the Côa valley in Portugal, and maximum ages for two chert artifacts exposed on the ground surface at Luxor, in Egypt, were estimated using $^{10}$Be (Ivy-Ochs et al. 2001). Be-10 has also been used to determine burial ages for early hominids at open-air sites in Chad—including the locality at which the world’s earliest known hominid, *Sabelanthropus tchadensis*, was discovered (Lebatard et al. 2008)—but in this instance the $^{10}$Be represents atmospheric fallout and not terrestrial in situ production.

**Conclusions**

Landscape archaeologists have a wide choice of dating methods at their disposal, including several numerical-age methods that complement one another and add rays, and that it has been exposed for a sufficient period of time to accumulate measurable amounts of cosmogenic nuclides. The validity of these assumptions rests largely on careful field interpretations, although the use of two or more nuclides with different half-lives (for example, $^{26}$Al and $^{10}$Be in quartz) can provide some constraints on the first two assumptions. The dual-nuclide approach also enables the estimation of burial ages for sediments that have entered deep caves with cosmogenic $^{26}$Al and $^{10}$Be. The two nuclides will decay at different rates, so the burial age can be obtained from the ratio of their concentrations, although the initial ratio at the time of sediment entry into the cave must be assumed (Granger et al. 2001). Accurate estimation of TCN production rates is a further complication, because they vary with altitude, latitude, depth below the ground surface, and the angle of inclination of the rock surface (as the cosmic-ray flux is greatest overhead and decreases to the horizon). For sediments deposited less than 30 m underground, continued TCN production due to muons must be taken into account. Also, in TCN dating—as with $^{14}$C dating—consideration should be given to past variations in the intensity of the Earth’s magnetic field, which affects the fraction of cosmic rays that reach the atmosphere. Given these uncertainties, TCN exposure and burial ages typically have precisions of 5–15%.

TCN dating has been used extensively to study the evolution of landscapes but has had limited application in archaeology. Partridge and associates (2003) used $^{26}$Al and $^{10}$Be to determine burial ages for cave breccia containing early hominin remains at Sterkfontein in South Africa, and the same approach was taken to date the oldest hominin remains in Europe (Carbonell et al. 2008). Phillips and associates (1997) used $^{36}$Cl to obtain maximum ages for rock engravings in the Côa valley in Portugal, and maximum ages for two chert artifacts exposed on the ground surface at Luxor, in Egypt, were estimated using $^{10}$Be (Ivy-Ochs et al. 2001). Be-10 has also been used to determine burial ages for early hominids at open-air sites in Chad—including the locality at which the world’s earliest known hominid, *Sabelanthropus tchadensis*, was discovered (Lebatard et al. 2008)—but in this instance the $^{10}$Be represents atmospheric fallout and not terrestrial in situ production.
much needed rigor to archaeological chronologies. Some of these techniques (for example, $^{40}$Ar/$^{39}$Ar, OSL, FT, and TCN) are applicable to major landforms, entire catchments and to geographically widespread marker horizons (for instance, tephras), as well as to archaeological deposits at individual sites. Such methods are, therefore, of immense value for understanding human-environment interactions at a range of temporal and spatial scales. We have also described a number of dating options for individual artifacts and for associated organic and inorganic remains at specific sites, but it is the task of the archaeologist to collate these disparate data sets to reveal patterns of human activity across the landscape. Given the potential pitfalls of each method, it is recommended practice that a multiple methods approach be taken, then landscape archaeologists can construct reliable chronological frameworks with a high degree of confidence.

References


Chapter 35: Dating in Landscape Archaeology


Part V: Characterizing Landscapes


