

Edited by Jane Balme
and Alistair Paterson

Archaeology in Practice

A Student Guide to Archaeological Analyses

Blackwell Publishing

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4 Stratigraphy

Introduction

The interpretation of site stratigraphy is of crucial importance for understanding what happened at an archaeological site. It is the starting point for developing time sequences at the site and determining the relative ages of artifacts within the site. In conjunction with other analyses, such as sediment analyses (Chapter 12) and an absolute dating program (Chapter 5), stratigraphy can provide information about the environment at the time of deposition and the relative lengths of time over which different cultural events occurred.

It is not our intention here to teach you how to excavate, as there are many excellent textbooks on this subject (see "Further reading" below). However, it is important that as much stratigraphic information as possible is extracted during excavation and that laboratory analyses are designed to take advantage of that information. In this chapter we will instead concentrate on why archaeologists study stratigraphy, how different stratigraphic layers occur in archaeological sites, how information about stratification is extracted from archaeological sites, how stratification is interpreted to create a framework for a relative chronology of cultural remains within sites, and how that interpretation is used by archaeologists to create analytical units. The main case studies that we have referred to here (Devil's Lair and Sos Höyük) are the two sites at which we first learned the principles of stratigraphy and their application in the interpretation of archaeological sites.

What is Stratigraphy?

Stratigraphy is the study of stratification; that is, the interpretation of horizontal layers that form the deposits of a site over time. In archaeological sites, stratigraphic layers may consist of a variety of materials. They may be composed entirely of natural deposits such as sediments accumulated by, for example, wind deposition. They may consist entirely of cultural material, such as shell in a shell midden or building material, or they may consist of a combination of natural and cultural materials.

Why do Archaeologists Study Stratification?

The main reason why archaeologists study stratification is to understand the history of a site or sites. Of primary importance is the interpretation of the order in which events occurred at a site and the relative ages of artifacts and features found. Knowledge of these is crucial for decisions about analytical units for comparison of archaeological remains across time and space. The study of stratification within sites allows archaeological materials from the same relative time period to be grouped together for further analysis.

Interpretation of layers in archaeological sites can also be used to reconstruct the natural shape of landscapes at both fine and broad scales. The shape of the natural landscape can influence people's choice of the location for particular activities, such as using sheltered areas for campsites. At a fine level, the shape of the landscape affects the distribution of sites, as artifacts gather in depressions and are trampled in areas that are more likely to be traversed (Nielsen 1991). Stratigraphy also helps in the identification of modifications of the broader landscape by humans, such as those associated with agricultural practices (for agriculture in New Guinea, for example, see Denham 2003).

Like most archaeological interpretation, the interpretation of stratification is stronger when multiple lines of evidence are used. For example, the argument for the timing of plant domestication in New Guinea mentioned above is stronger when combined with other lines of evidence (Denham et al. 2003). In combination with other kinds of evidence such as sediment analysis and analyses of botanical remains, stratigraphy is used to identify environmental change over time (Chapter 12) and to understand and explain other kinds of variation in the archaeological record. For example, the fact that shell middens are only present in some horizons represented by the 35,000 or so years of human occupation of sand dunes surrounding inland lakes in western New South Wales has more to do with changes in the rate of deposition of sediments (that protect and preserve the middens) than with changes in shellfish consumption over time (Balme & Hope 1990).

How do Different Layers Occur in Archaeological Sites?

Deposition of sediments occurs through such processes as wind and water action and glacier transportation, as well as through volcanic action. These processes do not usually occur continuously and, when they do occur, the rates of deposition may vary. So, for example, in an area in which sand dunes accumulate, a period of strong winds will deposit a thick layer of sand on the dunes, whereas a period of gentler wind will deposit only a thin layer of sand on the dune. In addition, the source of the sediments can vary between different episodes of deposition. Different-colored sediments may also be caused by changes in chemical composition over time. Oxidation of iron-rich particles, for example, may cause some sediments to become red. Or, if sediments are exposed without additional deposition for enough time to allow vegetation to grow, soils may form and the vegetation mixed with the sediment may give it a rich, dark appearance. Over time, a series of layers build up that in section appear as separate horizons of different colors or different-sized particles. It is important to be aware that because the layers are deposited in different ways, the thickness of the layers is not necessarily a guide to the time that they took to accumulate.

Some of these points are illustrated in the south section of Devil's Lair, a small limestone cave (Figure 4.1) that is important for providing the oldest evidence for human occupation in southwest Australia. In this section, most of the thin layers are orange or brown sands (Figure 4.2). These sands have been deposited by water flow and probably derive from the same source. Periods in which there has been no deposition from this source are represented by bands of consolidated flowstone that forms when water flowing through the limestone of the cave walls dissolves calcium carbonate that, once deposited on the cave surface, becomes hard and crystalline. The thick layer "30 lower part" is much darker than the other layers because it contains much organic material. It appears to have been deposited relatively quickly, and was probably associated with the formation of a new cave entrance. The large pieces of rubble in the layers below this indicate deposition by water flowing at a much greater velocity than those above.

At times when humans occupy the area, they leave behind artifacts or other cultural debris that become incorporated with the surface sediments deposited at that time. At times when few sediments are deposited, or when humans create a lot of rubbish, some layers in the "layer cake" may be distinguished because they are composed entirely of cultural material. There are some kinds of sites that are composed almost entirely of layer upon layer of cultural material. Tells are an obvious example of such sites (e.g., Miller Rosen 1986). In some situations (particularly shell accumulations) it can be difficult to identify whether or not the material was deposited through natural or cultural agency (see, e.g., Henderson et al. 2002).

Principles (or laws) of stratigraphy

Interpretation of the stratification to infer the chronology of the site is based on a set of principles that summarize the implications of the way in which layers form. The principles of stratigraphy used by archaeologists draw on those developed within the discipline of geology. There are some archaeologists who believe that the discipline of archaeology requires its own stratigraphic theory. Harris is principal amongst these. His main argument is that the contribution of humans to site formation is quite unlike any natural site formation processes, and therefore geological laws cannot cover all of the circumstances that we require. The fact that many cultural layers, such as walls, are horizontal rather than vertical is one example of this. Harris' Laws of archaeological stratigraphy, detailed in Harris (1979, 1989), are nevertheless based on the geological laws, with modifications for the goals of archaeology. The need for separate stratigraphic theory is continuously debated (see, e.g., Farrand 1984; Stein 1987).

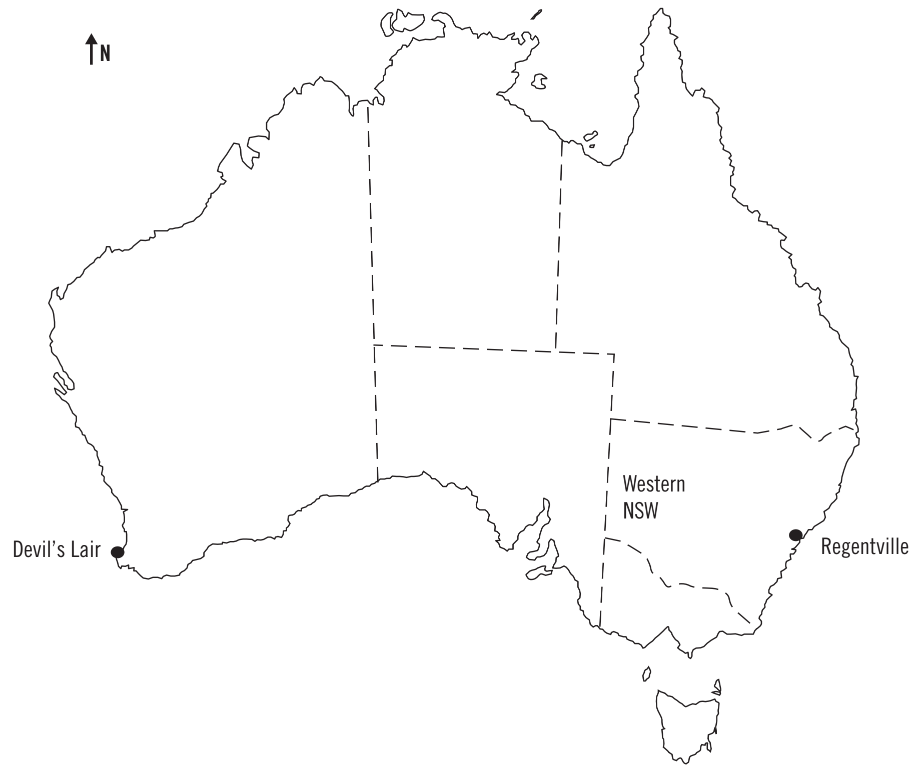

Figure 4.1 The locations of Devil's Lair, Regentville, and western New South Wales, Australia, showing places referred to in the text.

For now, we just want to draw your attention to the four main principles of stratigraphy used by archaeologists. Once you know how deposits form, perhaps these laws seem like common sense, but when you are faced with confusing stratification in an archaeological section it is useful to remind yourself of these principles when you are trying to interpret the sequence. Whether the stratigraphic layers are thick and represent long time periods, such as at some of the early hominid sites in East Africa, or very thin layers in rockshelters, the principles of deposition and interpretation of the stratigraphy are the same:

1 The *Law of Superposition*. This refers to the layer cake effect described above. Simply, it states, provided that there has been no subsequent disturbance, deeper stratigraphic layers are older than those overlying them.
2 The *Law of Association* states that, provided that there has been no disturbance, materials in the same stratigraphic layer are associated with each other. However, because some stratigraphic layers represent vastly greater time periods than others, the usefulness of this law varies.
3 The *Law of Horizontal Deposition* states that any layer deposited in an unconsolidated form will tend toward the horizontal. This means that strata found tilted lie over the contours of previous basins. Of course, the

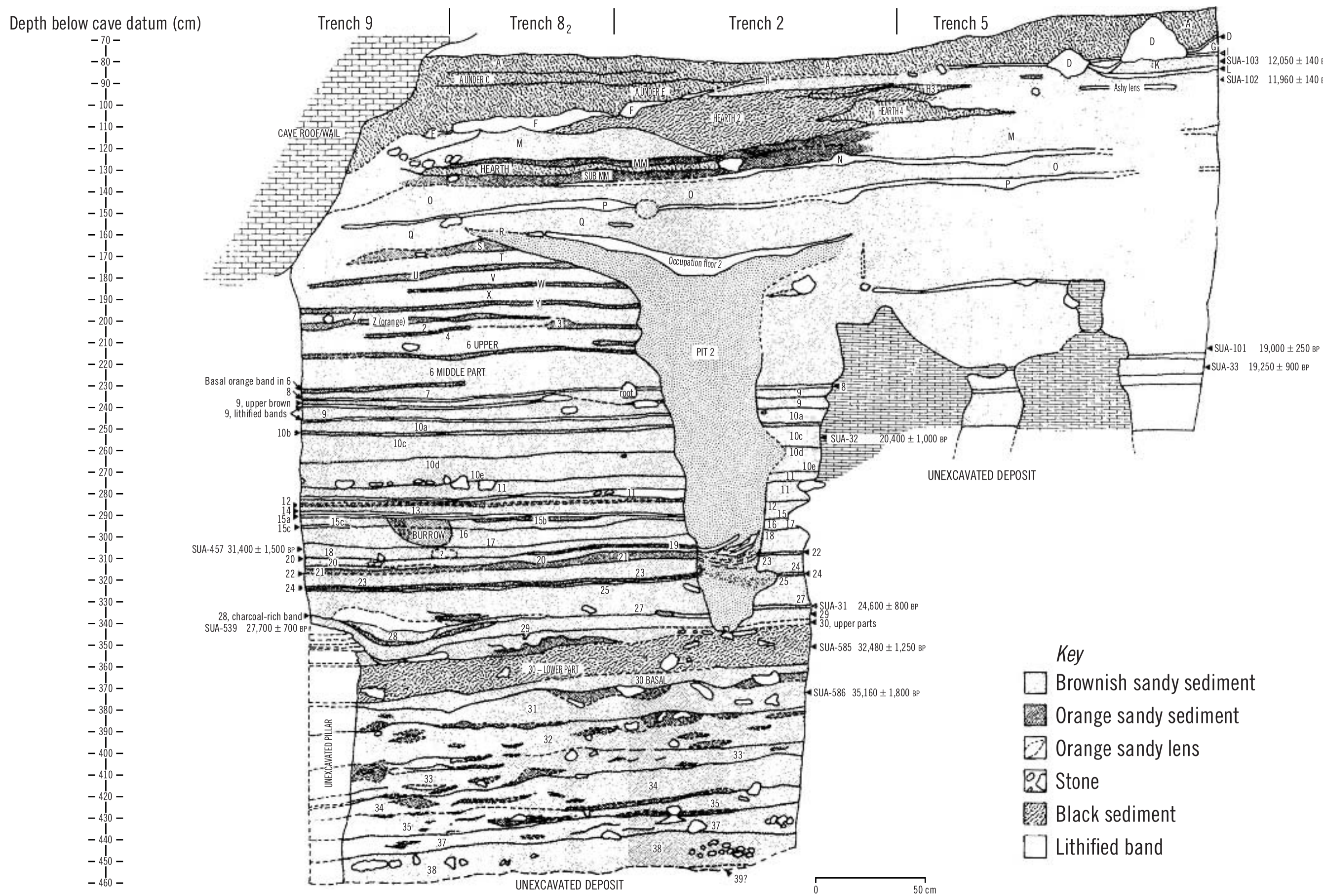

Figure 4.2 Devil's Lair: a section through the south face of the main excavation (adapted from Balme et al. 1978).

shape of stratigraphic layers composed of cultural material will not necessarily be horizontal but, rather, will be determined by the people who made them.

4 The *Law of Original Continuity* states that a natural deposit will end in a feather edge. Thus if the edge of a stratigraphic layer is not feather edged, its original extent has been destroyed.

Sources of disturbance

Following these laws, the interpretation of the stratification should be very straightforward. However, nothing is ever quite so simple and the reason for this lies in the importance of the phrase in the first two of these laws, "provided that there has been no disturbance." The stratigraphic succession in almost all archaeological sites has been disturbed. The sources of disturbance can be either natural or cultural.

Between periods of deposition, sediments often erode. The same processes that cause deposition cause erosion (often exacerbated though other agents such as animal scuffage) and sediments are scoured, mixed, and redeposited elsewhere. This can mean that it is possible to have materials side by side that are of different ages. Sometimes, such disturbance is recognizable as cuts through layers. Figure 4.3 shows a section through a sand dune bordering an inland lake in western New South Wales, Australia (Figure 4.1). In this sequence, the Buntigoola, Kinchega, and Packer are the oldest sediments and do not contain archaeological remains. The Tandou unit is an ancient soil in which extinct fauna remains have been found and, although archaeological remains dating to about 30,000 BP have been found on its surface, none have been found unequivocally within the soil sediments. The sediments lying above, and therefore younger than the Tandou unit, form the Bootingee unit, in which archaeological remains have also been recovered (Balme & Hope 1990; Balme 1995). However, either before or during the time in which the Bootingee sands were deposited, the lake side of the dune eroded away and was replaced by Bootingee sands. This means that the sediments of a much more recent layer (Bootingee) and any archaeological material contained in those sediments

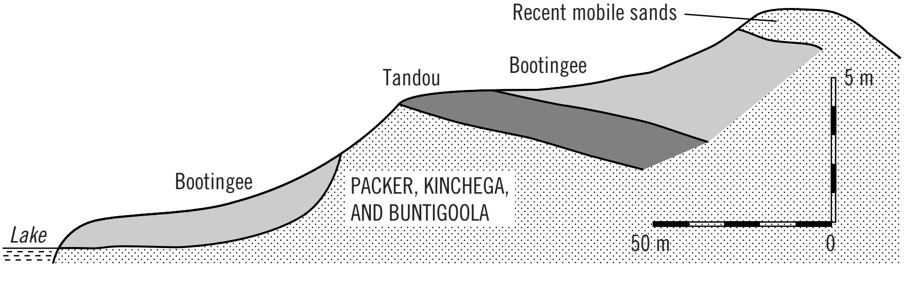

Figure 4.3 A section through a sand dune bordering an inland lake in western New South Wales, Australia (adapted from Balme 1995).

are younger than those lying alongside them. The same effect of layers alongside each other is also produced through tectonic movement, where slippage along a fault line can result in horizontal layers of vastly different ages lying alongside each other. It is this kind of slippage that created the rift valley in East Africa, so that old layers containing fossils, including early hominid fossils, are exposed in the valley.

When deposition occurs on sediments from which erosion has removed the surface, or on which there has been no deposition for some time, the boundary between the old and new sediments is referred to as an unconformity. These are often represented as wavy lines in section drawings.

Disturbance may also occur through chemical processes such as leaching (although these are not so likely to change the horizontal layering within the deposit). Shrinking and expansion of sediments caused by water retention or freezing of sediments may allow artifacts to fall down cracks, so that they are no longer in their original position. Bioturbation refers to biological processes that disturb the site. These may be caused by animals or by plants. Small animals such as worms that burrow cause sediments to become compacted, and burrowing animals that live at various times throughout the history of the site dig into layers that were laid down before they occupied the area. While digging, they will excavate materials from lower layers and kick them onto the surface from which they are digging. Once the animal no longer uses the burrow, sediments from the surface from which the burrow was dug will fill it. This means that artifacts excavated from the surface from which the burrow was dug may not be associated (Law 2 above) because they may derive from layers deeper in the site. The burrow should be visible in section, because the fill sediments will be the same as those on the surface from which it was dug rather than the surrounding sediments. Plant roots growing at a site also mix sedimentary layers. Again, the presence of tree roots in the past may be indicated by remnant dark organic matter.

When humans occupy places they also affect the horizontal layering by adding cultural materials, by clearing behaviors that remove cultural materials and sediments, and through deliberate modification of the surface, such as building foundations and digging wells, privies, trash pits, and graves. One such action is the pit dug into the Devil's Lair site from layer Q (Figure 4.2), which is between two dates of about 12,000 and 19,000 BP. The fill of the pit clearly cuts through older deposits down to layer 30, which was originally dated to about 30,500 BP (Balme et al. 1978), but has recently been re-dated using the ABOX-SC method to about 45,500 BP (Turney et al. 2001). The consequence for establishing a relative chronology is that artifacts found in layer Q deposits are very likely to not be associated. Mixing of objects between layers in the deposits can happen simply through human trampling of the site (see, e.g., Nielsen 1991).

Therefore, placing the various stratigraphic layers and disturbance features into their chronological order involves the use of the laws of stratigraphy and recognition of when and how disturbances to the site took place in relation to the deposition of sediments. This is not always an easy task. At a landscape level where erosion has exposed the section, it begins with examination and recording of the exposed sections. For excavated sites, boundaries between many stratigraphic layers and features are discovered during excavation.

Excavation and Stratigraphy

Recognizing boundaries between layers and features is clearly the best way to ensure that all materials that were deposited together (from the same stratigraphic layer) are kept separately. This is the reason why archaeologists try to excavate by stratigraphic units. That is, whenever an excavator notices a change in color or texture of the sediments, he or she begins a new excavation unit (i.e., all bags containing the material in which the evcavator has been digging are closed off and material in the new sediments are bagged separately). The bags are all labeled clearly to show which excavation unit they derive from. Where possible, features such as hearths and pits are excavated separately, since their fill will be composed of sediments that are different from, and probably of a different age to, the surrounding sediments.

However, digging by stratigraphic unit is not always possible because of the difficulties of identifying separate layers that are very similar in color and/or texture. Excavation is then usually carried out in arbitrary levels of equal depth. Because the depth of these arbitrary units is recorded during excavation, it is often possible to assign artifacts within them to stratigraphic units whose divisions are identified either after excavation has exposed the profile or – if the divisions are based on micromorphology of the sediments (see Chapter 12) – in the laboratory.

Arbitrary excavation units are also usually used when stratigraphic layers are very thick. If the absence of distinct layering can be established to be the result of long-term deposition from a single source, it can be assumed that the deepest artifacts even within a single stratigraphic unit are the oldest. This is hard to control for, so shallow artificial layers allow comparative analysis and ordering of artifacts after excavation.

It is common for archaeologists to excavate in artificial units, sometimes even when there are clearly demarked stratigraphic layers. The justification for this might be that it is quicker to use artificial units, or that unskilled excavators may not identify differences between stratigraphic units. The technique is often justified in terms of their ability to correlate the measured depths of the artificial units with natural stratigraphy once the section drawings are made. However, the technique assumes horizontal deposition, which – as has been shown – is not always true for archaeological sites. Perhaps more importantly, much resolution is lost if an arbitrary unit cuts through more than one stratigraphic unit. This can mean that occupation surfaces (and directly associated material) are missed.

Whether or not all of the stratigraphic layers can be identified during excavation and all of the artifacts for each layer are kept separate, the sequence has to be recorded to ensure that layers and features that are of similar time periods can be grouped for later analysis. It is often not possible to identify the relationships between layers and features during excavation. In particular, when you are working across large areas, and not all layers are represented in each part of the landscape, it is only possible to establish a chronology for the area by recording and cross-referencing the various stratigraphic successions in each location.

Recording Stratification

When working at a landscape scale, such as at the East African sites, where long-term erosion has exposed the stratigraphic layers in the valley walls, the first steps in interpretation begin with recording the stratigraphic layers across the landscape, trying to match up sequences. In the case of Hadar, in Ethiopia, where many early hominid fossils have been found, the study area is so large and the stratigraphy is very complicated, mainly because many stratigraphic units do not extend over the whole area. The task of establishing a regional sequence required the use of other techniques, including different kinds of absolute dating methods and the use of biostratigraphy to sort out the relative ages of layers. Establishing a sequence has occupied geologists, paleontologists, and various kinds of absolute dating experts for great amounts of time (for a history of the development of the stratigraphic sequence for the Lucy site, see Johanson & Edey 1981). As each new season of work begins in the area and new stratigraphic horizons are found, these have to be fitted into the sequence developed previously.

At a smaller scale, the stratigraphic succession is first exposed during excavation. Observations about stratigraphic differences occur during excavation as changes in sediments and structures are noticed. It is at this stage that interpretation begins. Records of stratigraphic differences are recorded in stratigraphic section drawings and by taking photographs. The drawings are scale drawings of the layers seen in trench walls. They are usually drawn after several layers have been exposed, at the end of a field season or during a break in the digging of the trench or feature.

For these drawings, the boundaries of each layer, or layer interface, are measured and drawn onto graph paper. The sections are annotated so that the color and texture of each layer is described in everyday language (as, for example, in Figure 4.2) and is usually also determined with the aid of a Munsell color chart and the texture determined by feel; for example, "clayey" or "sandy" (see Chapter 12). Intrusions and larger inclusions, such as stones or pottery exposed in the section, are described and included in the drawing. The distinction between natural and cultural inclusions may not be clear at the time of excavation (for example, fish bones in a fluvial deposit related to a site could be naturally deposited through river action or food remains). The objective is to record the stratigraphy in as much detail as possible, so that the drawing can be used as a tool for establishing the chronology of the site and for analysis of cultural materials.

Although the features and layers are measured and recorded, it is important to realize that these drawings are nevertheless interpretations of the stratigraphic layering. The recorders document their interpretation of what they see in the profile. In addition, distinctions between layers are inevitably simplified and the lines only approximately represent features and strata.

The records of the stratification in the section drawings, along with other information from the sediments, are then interpreted by using the laws of stratigraphy, and by being aware of the possible disturbance processes, to build up a chronology of the order in which the layers and features were created. In the Devil's Lair example (Figure 4.2), where most of the natural layers extended across the whole site, the Law of Superposition is applicable because there is clearly little disturbance (with the exception of the large pit). The discontinuous waves of orange sand near the base of the deposit represent sediment sorting caused by the greater velocity of the water that deposited it than in the layers further up the deposit. The ordering of events at this site is pretty straightforward, as the Law of Superposition says that the oldest material will be the deepest. Thus the pit belongs to the same period as layer Q.

It is not always possible to identify all kinds of disturbance from field observations and sediment analyses. Downward movement of small artifacts caused by trampling or compaction may not be obvious. One solution is to try refitting artifacts or bones from different layers. Both of these approaches are time-consuming, but they have yielded good results on the vertical distances that artifacts travel through the stratigraphic layers (for examples, see Cziesla et al. 1990; Morrow 1996).

The Harris Matrix: interpreting the spatial record

When there are many pits and features at a site, it becomes a bit more complicated to describe the order of events and determine which features and stratigraphic layers represent the same time period. It is for this reason that Harris developed a system for visually representing stratigraphic relationships. The system, known as the Harris Matrix, was first published in Harris (1975), and in an expanded version in Harris (1979). It was initially developed by Harris for complex sites in urban Britain, and it gained currency in the United States especially after being used at Colonial Williamsburg (Brown & Muraca 1993).

The system uses the concept of the interface (Harris 1989: 54–68) to describe boundaries (or surfaces) between layers and features. Interfaces may be the surfaces of strata equivalent to the geological "bedding plane," which Harris refers to as "layer interfaces," or surfaces formed by the destruction of existing strata (equivalent to the geological term "unconformity"), which he refers to as "feature interfaces." Layer interfaces may be horizontal – that is, deposited in a horizontal state – or vertical structures such as walls. Feature interfaces may also be horizontal, in which case they mark the level to which upstanding structures, such as walls, have been destroyed. Vertical feature interfaces involve the removal of strata such as pits and ditches. Harris also uses the term "period interface" to describe all of the layer and feature interfaces that were ground surfaces at the same time.

The matrix represents each feature, layer, or interface as a box and the relationship between each as a line. Boxes in the same vertical line are placed in sequential order with the oldest layer, feature, or interface placed at the bottom. When the stratigraphic relationship between features is not known – for example, because they are separated by a wall – they are shown as a separate branch. The strength of this approach is that clear categories can be shown for interfaces between surfaces, and all features that are the result of human activity can be placed within the sequence. Because of this, the Harris Matrix is very widely used by archaeologists around the world. Harris maintains a website (www.harrismatrix.com/) that includes references about the development of the matrix and links to computer programs that can be used to construct Harris Matrices (see also Harris 1989; Greene 1996: 68).

Figure 4.4 is a very simple example of a Harris Matrix constructed to describe the stratigraphic sequence recovered during the excavation of a drain. The drain once led from Regentville, a grand mansion built in New South Wales, Australia, by Sir John Jamison in about 1824 (Figure 4.1). Over the past 20 years or so, archaeological investigations of the remains of the mansion and associated features have been carried out under the direction of Judy Birmingham and Andrew Wilson (University of Sydney; see http://acl.arts.usyd.edu.au/projects/ourprojects/regentville/).

A cross-section of the drain is shown in Figure 4.4a. The different features, layers, and interfaces have been given numbers, which were allocated during excavation. The numbering system is used for the whole of the Regentville project. In other words, the number 191 allocated to the surface layer of this drain indicates that it was the 191st unit to be recorded in the Regentville project.

The hatched area in the section drawing is bedrock. The first activity in the construction of the drain was the excavation into the bedrock in c.1824–6 (according to colonial records, the area was not occupied prior to this date). According to Harris' definition, this is a vertical feature interface and in Figure 4.4a it is labeled 270. The next part of the construction was the placement of a large sandstone boulder cap over the drain cavity (271) and the remaining part of the excavation was filled with rubble and chips (269). The drain was the void beneath this wall. From the time of the original excavation of the bedrock until some time before the 1960s, when the site was cleared, the drain filled with sediments. Some of this fill may have occurred while the sandstone drain cover was built and some certainly occurred after. The fill is shown in Figure 4.4a and has two parts: the deeper sediments are labeled 273 and those above it (and therefore younger) are labeled 272. The hatched line between

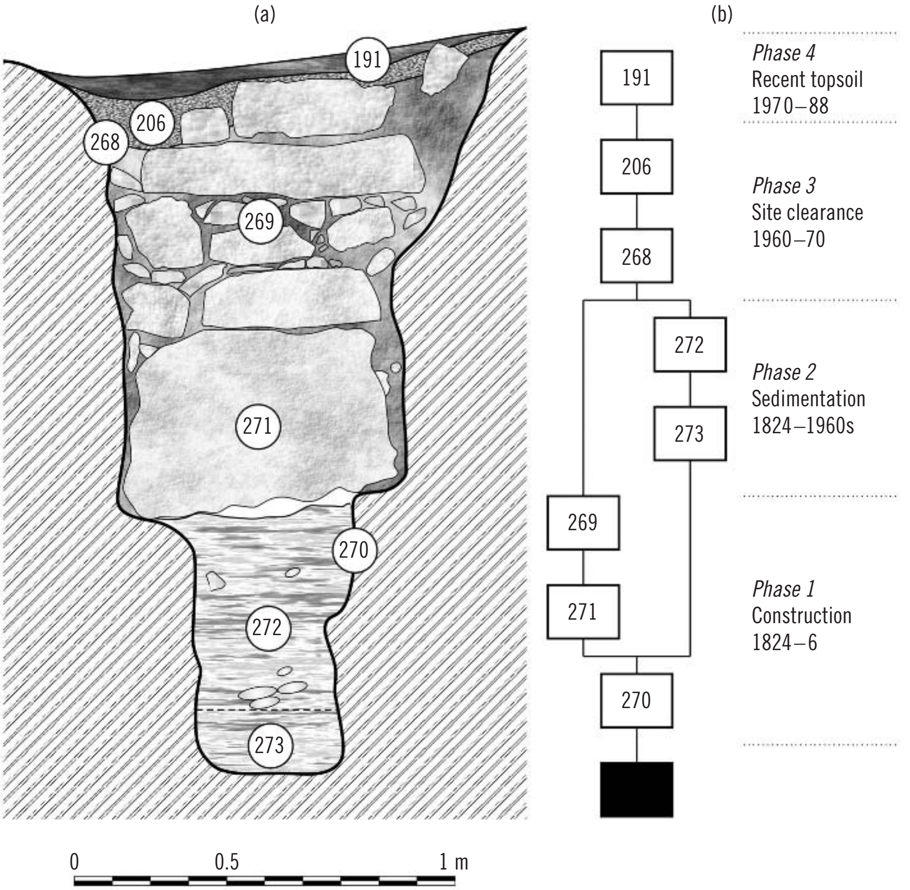

Figure 4.4 A section of the Main Drain (a) at the historic site of Regentville and the Harris Matrix (b) (adapted with permission from Andrew Wilson and Judy Birmingham).

the two units separates them: however, this barrier is slightly arbitrary, as the main difference between the fills has been established from differences between the artifacts. Early nineteenth-century artifacts were found in the deeper sediments and later nineteenth-century artifacts were found in the upper deposits. When the site was cleared in the 1960s, the drain structure was truncated and 268 marks the horizontal feature interface caused by the cut. The sediments that were subsequently deposited are labeled 206 and recent topsoil placed on the site is labeled 191.

The Harris Matrix given in Figure 4.4b shows these relationships, with the number for each layer or feature written in a box and lines drawn between the boxes to show the sequence. The black box at the base represents the base rock or "geological past." The cut is the basal archaeological feature. There are then two branches. We know that the sandstone construction was built in c.1824–6. We are not sure when the sedimentation began, but it may have begun at the same time as the wall construction and it appears to have been filled by the time the site was cleared. In the Harris Matrix these layers are shown further up the diagram because the sedimentation process was much longer than the drain construction process.

Another related technique that Harris has used to show the relationships between units is his "single-context plans" (Harris 1989; Pearson & Williams 1993). These are horizontal plans of stratigraphic units with all of their composite features and interfaces. The point of producing the plans as well as the sections is that not all layers, features, and interfaces are cut by the excavation sections, and so stratigraphic information is missing from section drawings (Brown & Harris 1993: 3–4). If, for example, we had selected our trench at Devil's Lair 30 cm further to the west, we would not have exposed its section in the trench wall (Figure 4.2). The pit profile would therefore not have appeared in the section drawings.

Creating Analytical Units

Figure 4.4b shows the four phases into which the excavators placed the stratigraphic information for the Regentville drain. In this example, the phases are used simply to describe the sequence of events. When the research aims include questions about changes in human behavior through time at the site, or between sites across space, decisions will almost certainly need to be made about how to group the archaeological evidence to form analytical units (or phases) for analysis.

Stratigraphy is the starting point for the creation of analytical units. Decisions about how to group the site material into time periods depend on your research question (which dictates the desired chronological resolution) and the quality of the stratification (which dictates the possible resolution). Other sources of chronological evidence may also be helpful in refining the resolution. If there are few artifacts at the site, a large number of stratigraphic units may need to be combined to create an analytical unit simply so that the sample sizes can be made large enough for comparisons. Obviously, much time resolution is lost if this becomes necessary.

Some research questions are about short-term events. For example, you might be interested in types of grave goods of a particular person buried in the Middle Bronze Age at Sos Höyük (see below). Because this short-term event is stratigraphically readily recognizable, all you have to do is describe the goods associated with the skeleton. Interpretation of the activities associated with the pit at Devil's Lair (Figure 4.2) is more difficult, because we know that the surface at the top of the pit has been contaminated with material from beneath (we never have worked out the purpose of this pit).

Investigation of these single activities might tell us about something specific that happened thousands of years ago, but it doesn't allow discussion about change over time and space. To answer these questions, you will need to group material from different stratigraphic units. If the stratigraphic units are fine and represent short-term time scales, it may be possible to characterize change at a very fine resolution. On the other hand, thick stratigraphic units (or thin ones that have accumulated very slowly) will only allow coarse resolution. It may, of course, be possible to subdivide undifferentiated thicker units with the help of absolute dating techniques.

For example, in the Devil's Lair sequence shown in Figure 4.2 you could look at change in artifact form by comparing artifacts from each of the very fine stratigraphic units represented in the part of the deposit on the left of the section. Because the sequence is well dated and sedimentation was reasonably uniform, analysis of change over time at a fine resolution is possible. The only difficulty here is to ensure that the sample sizes in each unit are sufficiently high to make the comparisons meaningful. To the right of the deposit, where the stratigraphic resolution is low, the artifacts would need to be treated as one assemblage representing the time period of 12,000–19,000 BP.

The main point to be aware of here is that the character of the change recorded will vary depending on how you group the material. This is explained very well, with examples, in Frankel (1988). Comparisons at a fine resolution will make changes over time at a site appear very gradual, whereas changes based on a coarser resolution will make changes appear more dramatic. However, while fine-resolution comparison will show trends in change, it will not necessarily be better because short-term events may create "noise" that obscures major changes.

A related issue is the need to choose a scale that is appropriate for the scale of the processes that you are investigating. This is discussed in some detail in Chapter 5 under "Time perspectivism," with the example of Bone Cave.

Case Study

Sos Höyük

Archaeological excavations at the multi-period mound site of Sos Höyük, in eastern Turkey, reveal a site with a complicated stratigraphy. It provides a good example of how the stratigraphic succession is used in combination with other kinds of archaeological evidence to understand the behaviors of people at sites and the chronological sequences. The results of the work at Sos Höyük so far are reported in Sagona et al. (1995, 1996, 1997, 1998), Sagona (2000), and Sagona and Sagona (2000).

The site of Sos Höyük is in the northeastern highlands of Turkey, on the natural routes between Anatolia, the Transcaucasus/Iranian region, and the Upper Euphrates Basin (Figure 4.5). For over a century, archaeologists have studied the evidence for human settlement and activities in these regions. Sos Höyük, a place where a community has existed on a small hill overlooking the Çökender Stream for thousands of years, is one of many sites studied by archaeologists. The earliest occupation of the site was around

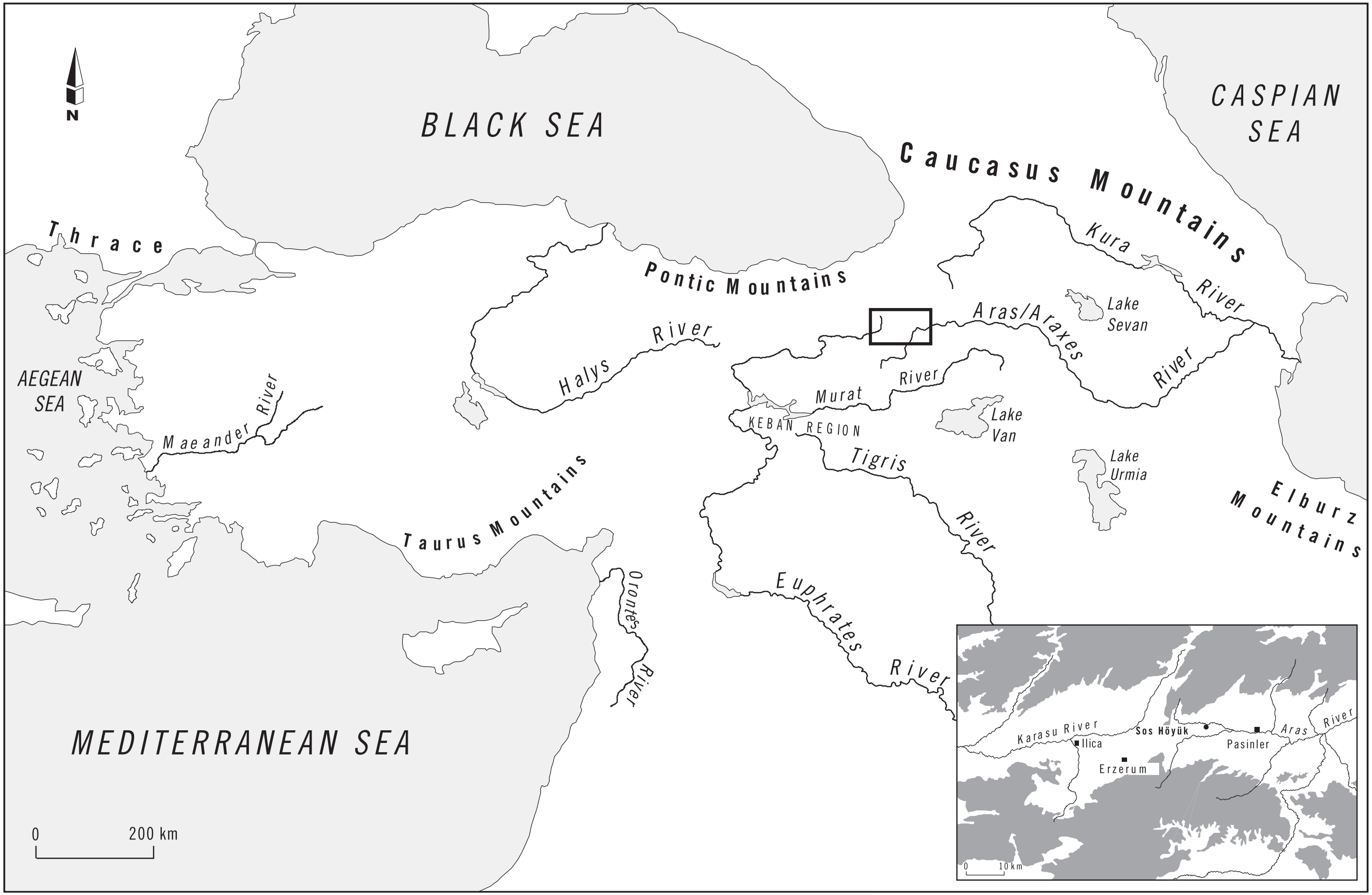

Figure 4.5 The location of the archaeological site of Sos Höyük, northeastern Anatolia (adapted with permission from Sagona 2000: 347, fig. 1).

3500 BCE and the most recent period of archaeological investigations is the Medieval Period to about AD 1200, but the mound is located within a modern village and so it represents occupation of about 5,500 years. Over time, the people living here and the natural forces acting on the site have left behind a complicated stratigraphy of human occupation.

Excavations began at Sos Höyük in 1994 and, as at many other substantial archaeological sites (the mound covers an area of about 640 m^2), the archaeologists working at Sos Höyük have returned annually to continue their excavations. Finds include houses and other built structures, ceramics, lithic artifacts, human burials, and animal bone, as well as small amounts of metal and other objects. Excavations at this site form part of a wider archaeological project of which the aims are, in part, to explore social structure and settlement patterns. At Sos Höyük one of the excavation aims is to identify chronological change and explore contacts with other cultures. As more and more evidence has been revealed, the sequence of the human use of the site has become clearer, but it is by no means complete and continues to be added to and refined each year.

As in many areas in the world, the Anatolian archaeological sequence has been divided into cultural periods associated with calendar years. Those represented at Sos Höyük are listed in Figure 4.6a. Those at the bottom of the sequence – that is, the Late Chalcolithic, and the Bronze and Iron Age ages – are based on regional trends in technology, while later phases at the site are defined by dominant regional polities. It is worth mentioning that while terms such as "Early Bronze Age" indicate regional trends in metallurgy, the amount of metal is actually very small. The Early Bronze Age at Sos Höyük is almost entirely a lithic and bone industry. The technological phases are retained for the Near East because of convenience (everyone knows the general time period). Because of the general use of these periods for the interpretation of the archaeology of the region, the evidence recovered from Sos Höyük needed to be placed into this sequence to enable comparisons with other sites.

The starting point for producing the chronology of occupation is the stratigraphy. However, 5,500 years of more or less continuous occupation in a small area has made the stratigraphy very complicated. As successive groups occupied the site, they severely disturbed the remains left by earlier occupants. Pits and burial shafts were excavated, new structures were built on old, and material was reused. This has resulted in an extremely complicated stratigraphy with many discontinuous horizons that have made it very difficult to understand the sequence for the whole site. Establishing a sequence for the whole site relies on establishing chronologies for many small areas and fitting them together to build a bigger picture.

Figure 4.6b shows a stratigraphic section through trench M16. In this cross-section only the period from the Middle Bronze Age to the early Iron Age is represented. The age of the lowest deposits was determined by recognizing that this part of the deposit was a grave. The grave lies beneath some plaster layers and was clearly intrusive and deliberately filled and capped with stone rubble that can also be seen in the section. The

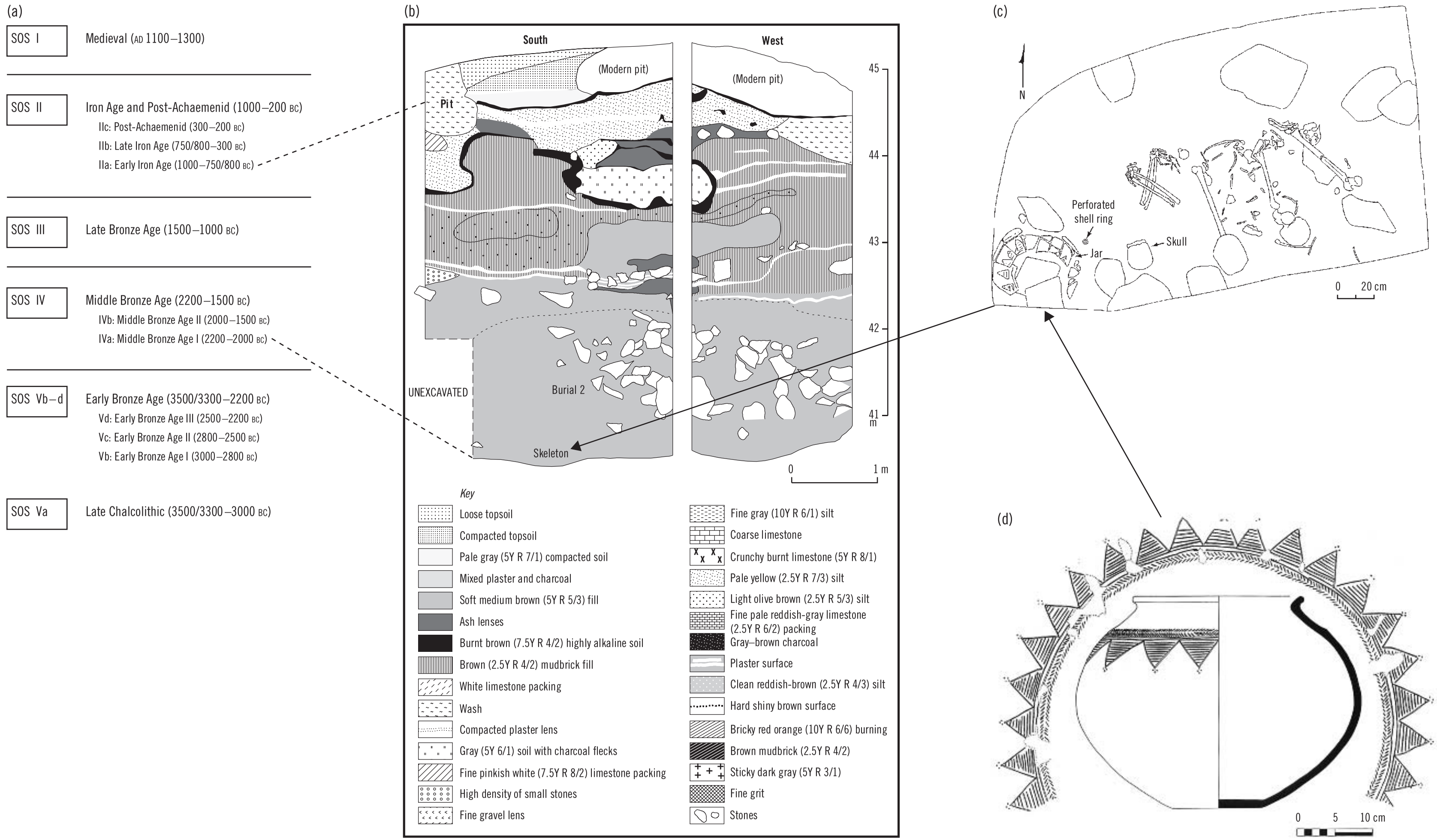

Figure 4.6 Sos Höyük. (a) The sequence of ages at the site. (b) A section showing the Middle Bronze Age to the Early Iron Age IIa in Trench M16 c/d, south and west sections. (c) A burial shown in section. (d) A ceramic vessel to date the associated burial. (Adapted with permission from Antonio Sagona.)

grave is about 1.75 m deep and at its base was a partly disarticulated skeleton (Figure 4.6c). The age of the burial could be determined from the grave goods associated with it, in particular an incised black burnished jar (Figure 4.6d) that had been placed directly above the body. This jar is of a type found in the Trialeti region in Georgia, dated to the Middle Bronze Age (Sagona et al. 1997: pl. 8; Sagona 2000: 337). In this case, the stratigraphic evidence could be used to identify the association between objects that provided a date for both the burial and cultural affiliations in the region. Another burial from the same period was found with a pot that was similar to, but not exactly the same as, grave goods in the Trialeti burials (Sagona 2000: 336–7). In this case, the age of the burial could be confirmed with the help of a radiocarbon date.

Ceramics have been very useful at Sos Höyük for providing dates for the stratigraphic sequence, because the style change over time in the region is well established. For the Post-Achaemenid and Medieval Periods, other kinds of artifacts can be used to pin down the age.

Conclusion

Stratigraphy is the starting point for interpreting the chronological order of events and artifacts at a stratified site, and it is the basis of the analytical units used to discuss the human activities at the site. However, a firm understanding of the geological principles and of the effects of site formation processes are required to disentangle all of the events that have produced the stratification at the site. When there has been much disturbance, or when layers are not continuous over the site, other kinds of evidence, such as an absolute dating program, biological evidence, and artifact seriation, may be needed to help put the layers and features into chronological order. Like most archaeological analyses, multiple kinds of evidence lead to the strongest conclusions.

Acknowledgments

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Resources

The Harris Matrix is described at www.harrismatrix.com/, which includes a comprehensive related publications list. There are also links to computer programs to construct Harris Matrices (see also Harris 1989; Greene 1996: 68).

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Simon Holdaway

5 Absolute Dating

Introduction

Most discussions of dating in archaeology spend a great deal of time dealing with the physics of dating, the principles and practice of measuring time-dependent radioactive decay, radiogenic processes, or some other mechanism by which an age estimate may be determined. A variety of authors refer to this as *chronometry* and differentiate it from the tasks involved in constructing a relationship between the age estimate and its archaeological significance (e.g., Dean 1978; Ramenofsky 1998; O'Brien & Lyman 2000). In this chapter you will find a great deal of discussion of the problems involved in establishing the archaeological significance of age estimates and rather less on chronometry, although some of the more common techniques used by archaeologists who work in a number of different places in the world are described in the next section. For those interested in details of the different methods that are available, a large amount of material exists in print (e.g., Taylor & Aitken 1997; Brothwell & Pollard 2001), and on the Internet (e.g., Higham 1999).

Rather than concentrate on chronometry alone, this chapter reviews some of the problems faced by archaeologists who attempt to "date" their sites (both the term and the concept of "dating" are critiqued below). This is done in four stages, using – where applicable – examples drawn from my own research in Australia. First, some chronometric methods are reviewed, with the aim of demonstrating just what it is that archaeologists have to consider when they begin to construct a chronology using one or more of the variety of methods currently on offer. As suggested, the emphasis is less on the mechanics of the various techniques and more on the nature of the assumptions that must be made and inferences that can be drawn. Secondly, the discussion moves to problems of interpretation. What issues are involved when archaeologists have to associate an age estimate with a set of artifacts that are not directly datable? Problems of interpretation are also encountered when archaeologists are forced to deal with deposits that span different periods of time. Age estimates may sometimes indicate the year or decade during which a site was occupied, while at other times the temporal resolution will be measured in millennia. Differences in time resolution such as this impact on the nature of the interpretations that can be drawn from the archaeological record. Those familiar with the paleontological literature first drew problems such as these to the attention of archaeologists, and some of the concepts and terms drawn from paleontology are useful for archaeologists to consider. This leads into the third topic, a more general discussion of the archaeological theory of time, particularly the need to consider processes operating at multiple temporal scales when evaluating the archaeological record. This is termed *time perspectivism*, a complicated sounding name, but one that is now well established in the literature. Finally, I illustrate how you might go about dealing with some of the problems of interpretation encountered when constructing a chronology through examples drawn from my own fieldwork in Australia, dealing first with the definition of multiple scales of temporal enquiry at Bone Cave, a Pleistocene site in the southwest of Tasmania, and then with the late Holocene archaeology of western New South Wales where, with Patricia Fanning, I have directed a research project during the past few years.

Chronometry

Why make a distinction between *chronology* and *chronometry*? The answer largely reflects different areas of expertise and differences in research interests. Using radiocarbon dating as an example (Taylor 1997, 2001), researchers have either become involved in assessing the impact of deviations from the primary assumptions upon which the method is based or, alternatively, they have concentrated on the results of the dating process and the nature of the behavioral inferences that can be drawn from these results about the past. One of the clearest examples of such a divergence concerns efforts to estimate the age of some ancient archaeological sites with radiocarbon, where one group of researchers has emphasized the need to overcome problems of sample contamination (e.g., Chappell et al. 1996) while another group has emphasized the difficulties involved in correlating age estimates from charcoal samples with the location of artifacts (e.g., O'Connell & Allen 1998). We begin with the issues raised by the first group of researchers and return to the second group below.

The reasons why archaeologists are able to "date" a site, deposit, or artifact with radiocarbon begin in the upper atmosphere, when atomic nuclei are hit by cosmic rays, split apart, and then collide with other nuclei. If one of these particles (a neutron) happens to hit a passing nitrogen nucleus, the nitrogen nucleus changes to carbon, but to a special form of carbon with 14 atomic particles rather than the normal 12. This form of carbon, called carbon 14 – and hence the term carbon 14 (or ^{14}C) dating – is unstable and begins to decay immediately. The decay process continues to occur over several thousand years. Carbon 14 occurs throughout the biosphere and so is metabolized in the same way as carbon 12, being constantly replaced in living organisms.

However, when an organism dies, no new carbon is added, so the amount of carbon 14 will start to decrease according to the rate of decay. Archaeologists excavate things abandoned by people in the past and if these things are organic (i.e., contain carbon) they can often be "dated" by the radiocarbon method using this process of carbon 14 decay. Higham (1999) lists 27 materials (including such things as shell, leather, peat, and coprolites, as well as the more common charcoal) containing carbon in some form of which the age is regularly determined with radiocarbon. As he comments, the great advantage of radiocarbon is the range of materials that can be used to obtain uniform age estimates throughout the world.

Every 5,730 years, the amount of carbon 14 in the abandoned material will halve (hence the term *half-life*). Because the half-life is known, it is possible to calculate the time elapsed since an organism died on the basis of the amount of carbon 14 remaining in the sample. The half-life value is some 1.03 percent greater than the value originally proposed by the Libby, who calculated the half-life as 5,568 ± 30 years. This rate is known as the *Libby half-life* and is still used by radiocarbon dating laboratories, the difference between the new and old rates being incorporated into the conversion process in which radiocarbon ages are changed into calendar ages (see discussion below) (Higham 1999).

Of the three most common naturally occurring isotopes of carbon, carbon 14 accounts for only 0.0000000001 percent (Higham 1999), so there is very little carbon 14 in a modern sample, let alone one that is several thousand years old. This means that samples of organic material for dating must meet certain minimum weights (Table 5.1).

It is also important for archaeologists to remove possible carbon contaminants, since age estimates will be obtained for any organic material. Higham (1999) notes a range of common contaminants ranging from cigarette ash (so don't smoke!) to paper from packing materials (foil is a useful material with which to package samples). Samples from the heat-retainer hearths excavated in western New South Wales, Australia, discussed in the second case study

Table 5.1 Sample size requirements as dry weights (from Waikato Radiocarbon Dating Laboratory 2002, with permission).

Material	Radiometric samples		AMS samples
	Ideal weight[a]	Minimum weight	
Wood	8–12 g	1.0 g	10 mg
Charcoal	8–12 g	1.0 g	10 mg
Carbonates	35 g	5.0 g	30 mg
Peat[b]	–	5–10 g	0.5 g
Bone[b]	100–200 g	20–80 g	0.5 g
Lake sediment[b]	30–100 g	10–20 g	1 g

[a] This is the minimum weight to avoid dilution

[b] Ranges reflect varying carbon content (weights approximate)

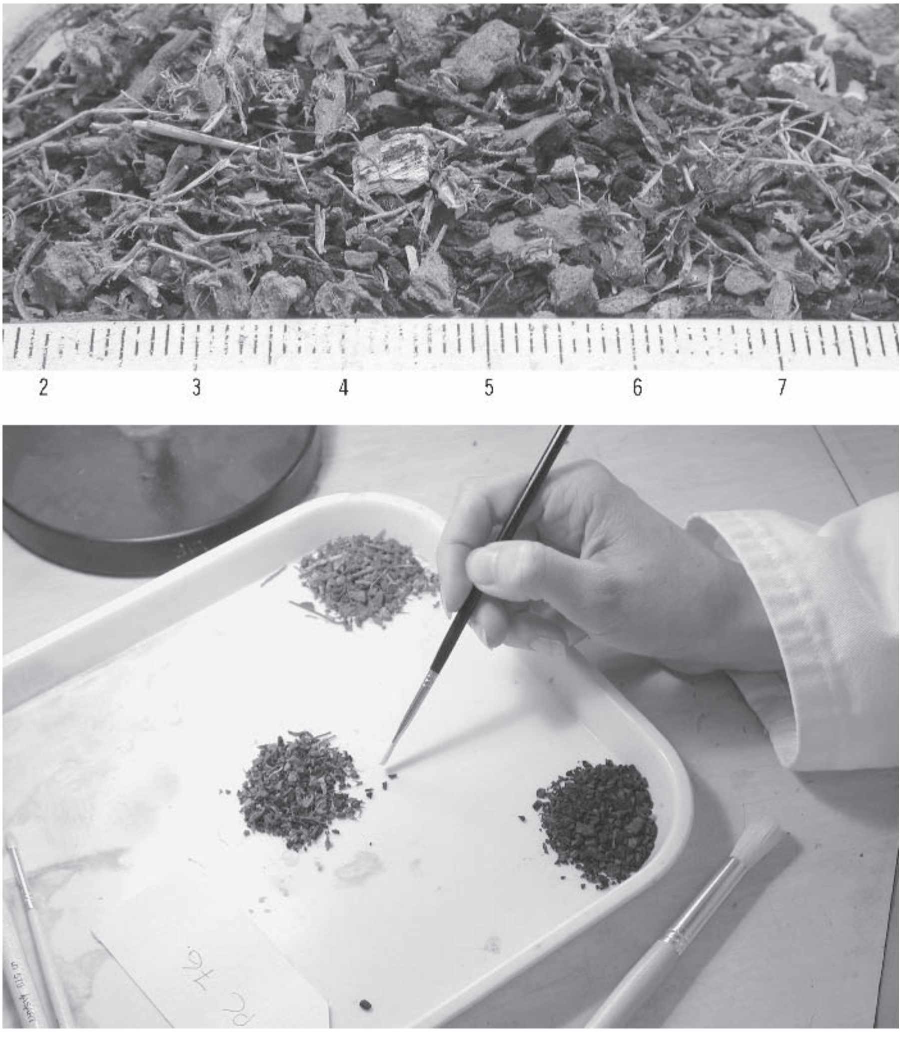

Figure 5.1 A sample from the excavation of a heat-retainer hearth before pretreatment. Rootlets, pieces of wood, and other organic contaminants are removed from the charcoal by hand.

below are typically filled with root hairs, pieces of wood, lumps of soil (Figure 5.1), and even the occasional dead ant! This material is carefully separated from the charcoal to be submitted to the laboratory. Another source of contamination comes from humic acids (from decayed plant matter). These may be adsorbed onto the surface of the sample material, particularly charcoal, so the exteriors of lumps of charcoal are often carved down with a scalpel blade. Cleaning the sample in this way is termed the *physical pretreatment*, and is differentiated from the *chemical pretreatment* usually undertaken by the dating laboratory. The latter involves the use of acid and base washes to remove inorganic carbonates and humic acids.

Once treated, a sample provided to a radiocarbon laboratory will be analyzed in one of two ways. Following the first method – the *beta-counting method* – the sample will be converted into a gas, or sometimes into another form, weighed, and then placed in a machine that is shielded from outside sources of radiation. Over a set period of time, some carbon 14 will radioactively decay by ejecting an atomic particle and changing back to nitrogen. The machine counts the number of times that this occurs and the number of disintegrations that take place over a set period of time is used to calculate the amount of carbon 14 remaining in the sample. When combined with the known rate of decay given by the half-life, this measurement can be used to calculate an estimate of the time elapsed since the organism that provided the sample died. Following the second method, termed *Accelerator Mass Spectrometry* (AMS), the proportion of carbon 14 in the sample is measured directly rather than through radioactive decay. Carbon atoms are converted into ions (charged atoms) and their mass measured by the application of magnetic and electric fields (Higham 1999). AMS permits the dating of very small samples (30 μg – 3 mg of carbon; see Table 5.1, and note that 1 μg = 10^{-6} g), well below those possible with the beta-counting method, so careful sample preparation is critical to minimize the chance of contamination. AMS dating is more expensive than the *beta-counting method* and so it is usually reserved for small samples that cannot be dated using the former methods.

Radiocarbon is only one of a number of techniques employed by archaeologists and other researchers interested in the Quaternary. Table 5.2 lists dating methods grouped together on the basis of shared assumptions, mechanisms, and applications (following Coleman et al. 1987). Descriptions of a number of these techniques as used in archaeology can be found in a volume of papers

Table 5.2 Dating methods grouped by shared assumptions, mechanisms and applications (from Colman et al. 1987).

Dating method groups	Description and examples
Sidereal methods (calendar or annual)	Calendar dates or count annual events; e.g., dendrochronology, varve chronologies, historical records
Isotopic methods	Change in isotopic composition due to radioactive decay; e.g., radiocarbon, potassium argon
Radiogenic methods	Cumulative nonisotopic effects of radioactive decay; e.g., crystal damage and electron energy trap methods (fission-track, OSL, thermoluminescence)
Chemical and biological methods	Measure some time-dependent chemical or biological processes; e.g., AAR, obsidian hydration
Geomorphic methods	Measure the results of complex interrelated time-dependent geomorphic processes; e.g., chemical and biological processes, soil profile development and progressive landscape modification
Correlation methods	Establish age equivalence using time-independent properties; e.g., tephrachronology, paleomagnetism

edited by Taylor and Aitken (1997) as well as more recent books on archaeological science (e.g., Brothwell & Pollard 2001; Goldberg et al. 2001).

Sidereal methods

Historical records and dendrochronology provide the best temporal resolution of any of the techniques, often allowing age estimates with a resolution of a single year. Dendrochronology is based on the annual rings of wood laid down by climatically sensitive trees beneath the bark (Dean 1997; Kuniholm 2001). Patterns of growth rings are matched between trees, and the rings used to count back in years from a known date. In some cases, very precise age estimates are possible. In the European Alps, for instance, it is sometimes possible to assign Neolithic lake settlement structures to the year (Billamboz 1996) and a similar level of precision is possible for some pueblo sites in the southwest of the United States (Dean et al. 1978).

Isotopic methods

At the other extreme from sidereal methods are a number of isotopic methods, useful for periods in excess of one million years (expressed as 1 m.y.a.), which have a resolution of 10,000–100,000 years (often expressed as 10–100 ka) (Blackwell & Schwarcz 1993). These methods are based on changes in the isotopic composition of a range of elements found in different materials, along the lines of radiocarbon dating described above. For truly ancient sites, with ages of 1–5 m.y.a., and which contain volcanic deposits, $^{40}Ar/^{39}Ar$ dating methods have proved useful (Rink 2001). The technique works by using a mass spectrometer to measure the amount of the two argon isotopes directly. The amount of ^{40}Ar originally in the sample is estimated by determining the amounts of various potassium (K) isotopes in the sample, one of which, ^{40}K, is the parent of ^{40}Ar. With a long half-life, the technique has formed the basis for age determinations for early hominin sites in Africa (e.g., Walter et al. 1991) and elsewhere.

For more recent periods, the radioactive decay of uranium 234 (^{234}U) into thorium (^{230}Th) provides a means of dating calcite. The technique, termed *U-series dating*, works because uranium is soluble and thorium is not; therefore uranium is present when calcite is precipitated but thorium is not. Thorium will gradually accumulate through time as ^{234}U decays, and this provides a technique with a range from 1,000 to 500,000 BP. U-series dating may also be used to date teeth (enamel, dentine, and cementum) and even eggshell, but because the uranium isotope may absorb onto the teeth at any time after burial, the technique gives only a minimum age (applications are described in Schwarcz & Blackwell 1991).

Radiogenic methods

Coleman et al. (1987) differentiate isotopic methods from radiogenic methods, where change occurs not through isotopic decay but through the accumulation of changes due to the presence of natural radiation. Four radiogenic techniques are commonly used: *thermoluminescence* (TL), *Optically Stimulated Luminescence* (OSL), *Electron Spin Resonance* (ESR), and *fission-track*. The availability of radiogenic methods has increased dramatically over the past 20 years and these changes have proved particularly useful for providing age estimates beyond the limits of radiocarbon. Good examples come from Australia, where thermoluminescence and OSL are both commonly used radiogenic techniques to provide age estimates for some of the earliest sites on the continent (e.g., Roberts 1997 and discussion below), and from the Levant and Europe, where thermoluminescence provides age estimates for sites connected with the arrival of modern humans (e.g., Valladas et al. 1988; Mercier et al. 1991).

Both thermoluminescence and OSL work by measuring the light emitted when a sample is heated to over 250°C (480°F); hence the name *thermoluminescence* (Aitken 1997; Grün 2001). The light comes from the release of trapped electrons that are held in the crystal structure of quartz, feldspar, and calcite when these minerals are heated. Over time, electrons in a sample become trapped as the result of exposure to natural radiation. For thermoluminescence, the radiogenic clock is "set" by a heating event at some point in the past that was sufficient to remove all the electrons from the trapping sites. This allows the calculation of an age estimate for the period since this heating event occurred. The calculation is made by dividing the thermoluminescence signal by the product of a measure of the rate of exposure to natural radiation and the sensitivity of the sample to the uptake of this radiation (Aitken 1997).

Thermoluminescence is best known as a technique applied to gain age estimates from pottery, where the firing process sets the clock, but the technique is now also routinely applied to obtain age estimates from burnt chert or flint artifacts (Valladas et al. 1988; Mercier et al. 1991), particularly from Paleolithic sites.

Optically Stimulated Luminescence works in a similar manner to thermoluminescence, except that it is light, rather than heat, that causes the trapped electrons to be released. As discussed below, OSL is often used to obtain age estimates for the sediments that surround archaeological deposits.

Electron Spin Resonance uses the same electrons, trapped in what are termed *paramagnetic centers*, that form the basis for OSL and TL, but measures them directly by applying microwave energy. The amount of microwave energy absorbed by the sample is proportional to the number of centers, and therefore to the age of the sample (Grün 2001). The main application to archaeology is seen in age estimates for tooth enamel and the technique has proved useful for obtaining ages ranging from a few thousand years to more than a million years (Rink 1997). One of the problems experienced when obtaining age estimates from teeth is uptake of uranium, which complicates the natural radiation dose and therefore the number of paramagnetic centers (Grün 2001). For this reason, U-series determinations and ESR are often conducted together (e.g., Grün et al. 1998).

One final radiogenic technique needs to be mentioned. Fission-track dating also makes use of structural changes in minerals as a result of exposure to natural radiation through time, but the results of the radiation exposure are measured optically. Minerals that naturally contain high amounts of uranium and thorium impurities accumulate zones of damage called *tracks* due to natural radioactive decay. This damage can be measured optically with a microscope, since the fission tracks are of the order of 0.02 mm in length (Rink 2001). Archaeological applications generally involve age estimates for volcanic materials, as discussed by Wagner and Van den Haute (1992).

Chemical and biological methods

Chemical and biological techniques are not based on radioactive systems at all, but instead use a variety of other time-dependent processes. *Amino Acid Racemization* (AAR), for instance, is based on a change in the orientation of amino acids detectable in polarized light. Through time, the predominantly *left* (L) version (isomer) transforms to the *right* (D) isomer in a process that is temperature dependent. If paleotemperature can be controlled for, the ratio of the D to L forms can be used to provide an age estimate for a sample, as long as the results are calibrated against a second age estimation technique (Hare et al. 1997; Dincauze 2000: 102). Johnson and Miller (1997) review archaeological examples noting that after an initial period of controversy, the technique is now used successfully with avian eggshell, mollusk shell, teeth, and bone over age ranges that extend beyond the limit of radiocarbon.

Chemical changes also form the basis for *obsidian hydration dating*, a technique that is based on the rate of absorption of water into freshly fractured obsidian surfaces. Results vary considerably according to temperature, and this has led to much debate about the effectiveness of the rate of hydration through time. In New Zealand, the combination of abundant obsidian outcrops, a relatively short period of time since human colonization, and difficulties in interpreting radiocarbon age estimates have led to the development of the technique (e.g., Ambrose 2001), but large numbers of age estimates are also available from archaeological sites in Mesoamerica. Here, Freter (1993) differentiates between results where obsidian hydration is used directly to obtain age estimates for artifacts and studies where the technique is used to place artifacts in chronological order rather than establish actual age estimates. This latter technique has found application in the Great Basin of the USA, where obsidian artifacts occur in surface deposits that are otherwise difficult to age (e.g., Beck & Jones 1994).

Geomorphic methods

Geomorphic methods of dating rely on a range of time-dependent processes. A well-known application of this technique is at Lake Mungo in Australia, where Bowler (Bowler & Price 1998) defined a series of stratigraphic layers representing episodes of lake filling and emptying to which age estimates were assigned. Bowler was able to relate the stratigraphic position of archaeological deposits to the sequence of layers, and through this means assign age estimates.

Correlation methods are sometimes used to provide age estimates for archaeological materials. *Tephrachronology* uses the stratigraphic position of volcanic ash deposits, where an estimate is available for the date of the eruption to provide either the starting point (the *terminus post quem*) or the ending point (the *terminus ante quem*) for artifacts that are deposited above or below the ash layer. The technique forms the basis for the early hominin chronologies from East Africa, but has also proved useful in obtaining age estimates for more recent records. In the Bismarck Archipelago in the western Pacific, for instance, a series of eruptions bracket archaeological deposits, permitting age estimates to be obtained (e.g., Machida et al. 1996).

Limits on Chronometric Techniques

Maximum limits

The selection of which method to apply depends partly on the context, particularly which materials are available, but also on the upper and lower limits of the ages that can be determined using each of the techniques. For the isotopic methods, including radiocarbon, the maximum age that can be obtained is limited largely by the half-life of the element that decays. Using radiocarbon as the example, the reason for the maximum limit can be displayed graphically (Figure 5.2). As the proportion of radiocarbon compared to its decay product decreases, the decay curve in Figure 5.2 asymptotically approaches a flat line. After this point, there is no change in the relative abundance of carbon 14. An age estimate (expressed as half-lives in Figure 5.2) is read from the decay curve at the point of intersection with the relative proportion of carbon 14. As described by Blackwell and Schwarz (1993), the maximum age occurs when the error associated with the age estimate intersects with zero. Around this point, when the abundance of the radioactive element is low, the signal-to-noise ratio decreases, leading to an exponential increase in errors. The signal refers to the relative proportion of radiocarbon, while the noise reflects contamination of the machines used to measure radiocarbon. This noise means that even a sample that contains no radiocarbon will give a positive reading. Also important is contamination of the sample itself. Even minute amounts of modern carbon in an ancient sample will drastically alter the age estimate. For instance, the addition of just 1 percent of modern carbon to a sample that is 50,000 years old will produce an apparent age of 35,000 BP.

Contamination of radiocarbon samples has proved to be of great significance in dating archaeological sites at the limits of the radiocarbon technique. The estimation of the age of the earliest sites in Australia provides one of the best examples discussed in the world literature. A number of years ago, Allen (1989) noted that radiocarbon determinations obtained by archaeologists, which had steadily increased in age since the first Pleistocene-aged determination obtained by Mulvaney (Mulvaney & Joyce 1965), had reached a plateau, with no determinations attaining ages older than 40,000 BP. The radiocarbon record

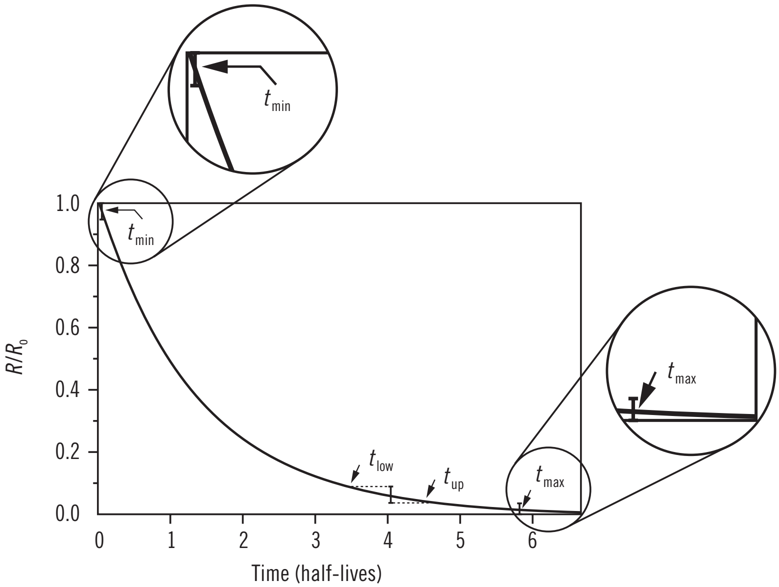

Figure 5.2 The limits of radiometric techniques for age estimation, displayed as a radiometric decay curve. The radioactive isotope ratio R/R_0 decreases through time. Precision is shown by the vertical bar and the t_{low} and t_{up} age estimates. The maximum and minimum ranges are indicated when the error bars strike the 0 and 1.0 values on the *y*-axis, respectively (modified from Blackwell and Schwarcz 1993).

appeared to be at odds with age estimates obtained from diagenic techniques (e.g., thermoluminescence) from sites in the Northern Territory (Roberts et al. 1990a). A variety of explanations were put forward to explain the discrepancy (e.g., Bowdler 1990; Hiscock 1990; Roberts et al. 1990b,c; Allen 1994; Roberts et al. 1994; Allen & Holdaway 1995); however, discussion quickly turned to the problem of sample contamination (e.g., Chappell et al. 1996; Roberts 1997). Recently, special techniques have been developed to pretreat samples in an effort to remove contaminants. Only through the application of these techniques have age estimates in excess of 40,000 BP been achieved for early Australian archaeological sites (e.g., Fifield et al. 2001; Turney et al. 2001), although in some cases even these rigorous treatments are not sufficient to remove all contaminants and the radiocarbon age estimates appear too young in comparison to ages obtained using other techniques (e.g., Bird et al. 2002).

This limit on radiocarbon imposed by the contamination of radiocarbon samples is better understood as a reflection of the resolution of radiocarbon age estimation rather than as the "problem" of sample contamination. Faced with this limitation, archaeologists have increasingly turned to radiogenic techniques. As discussed above, the techniques are now applied to burnt flint or chert artifacts in Europe and the Levant, which are thought to be older than the limit of radiocarbon dating. However, it is in Australia where these techniques have provided some of the most dramatic results. Here, thermoluminescence and OSL have been used to provide age estimates from the lowest layers in sites thought to date the earliest human entry into the continent (e.g., Roberts et al. 1990a; Roberts 1997). In some cases, the diagenic techniques have provided results significantly older than for samples aged with radiocarbon.

As with radiocarbon dating, contamination can sometimes pose problems for radiogenic techniques as illustrated by age estimates for the Australian site of Jinmium (Fullagar et al. 1996). At this site, incomplete optical bleaching of some sand grains produced age estimates well in excess of the likely age of the associated artifacts (Roberts et al. 1998, 1999). In effect, the OSL samples used from Jinmium contained quartz grains from the rockshelter itself, as well as those from sands exposed on the surface at the time artifacts were deposited at the site. Waters et al. (1997) and Gibbons (1997) discuss another example based on a controversial set of age estimates from Siberia.

Minimum limits

At the other end of the scale, the minimum limit for radiocarbon and other isotopic techniques is set when the error associated with the relative proportion of the radioactive element cannot be differentiated from one (Figure 5.2). This is simply the reverse of the signal-to-noise problem encountered at the maximum limit of any given technique. In this case, however, the errors are such that the change in the relative amount of radiocarbon cannot be differentiated from the natural levels in living organisms.

For radiocarbon, three factors contribute to the size of the error for recent samples and so contribute to the minimum limit for the technique (Taylor 1997). First, since the seventeenth century there has been considerable variability in the natural levels of radiocarbon production in the atmosphere due to changes in solar radiation. In fact, this is just part of a much wider problem connected with changes in the production of radiocarbon in the past. Changing the amount of radiocarbon available when an organism was alive will change the age estimates after its death, since the age is calculated by measuring the amount of radiocarbon left in the sample relative to the amount that existed at the moment of death.

Variation in the natural production of radiocarbon proved to be a problem when the technique was first developed, but was solved by matching radiocarbon ages with those obtained from tree rings (Taylor 1997). As discussed above, counting tree rings (dendrochronology) back from the outermost layer provides a sidereal (solar) chronology. What is more, the wood laid down each year can be used to obtain radiocarbon ages. Therefore, in principle, calibration simply involves correlating the radiocarbon age of a tree ring with its sidereal age (Higham 1999). However, for some periods, atmospheric concentrations of radiocarbon have varied so much that several possible sidereal ages correlate with one radiocarbon age estimate (an illustration of this is provided in the second case study below). This is the case after the seventeenth century, limiting the utility of radiocarbon for recent periods. The need to calibrate radiocarbon determinations into ages in sidereal years also explains why some age estimates are presented in "radiocarbon years" and some in "calibrated years." Computer programs such as OxCal v. 3.8 (Bronk Ramsey 2002) are available that automatically provide one and two standard deviation ranges for calibrated age estimates as well as graphical output. The term *radiocarbon years* therefore refers to an age estimate that is uncorrected for variation in the natural production of radiocarbon, while *calibrated* age estimates incorporate an estimate of this effect.

The second factor that affects recent samples is attributable to burning of fossil fuels since the nineteenth century, which has released a large amount of "ancient" carbon (i.e., carbon that has no radioactivity) into the atmosphere. Organisms absorbing this carbon have a reduced relative proportion of radiocarbon at the point of death, which means that their radiocarbon ages will appear too old.

The final factor that affects recent samples relates to atmospheric tests of nuclear bombs during the twentieth century. This greatly increased the available levels of radiocarbon in the atmosphere, hence making samples appear too old. The complex interplay between these three factors means that, in general, it is not possible to assign ages to materials that are less than 300 years old using radiocarbon.

It is important to mention one other set of corrections that sometimes must be applied. As in the case of fossil fuels, these corrections make adjustments for what are termed *apparent ages*, a correction needed when, in life, an organism accessed a carbon reservoir that was relatively depleted in carbon 14. The most common archaeological example concerns the oceans, where the apparent age is caused by the delay in the exchange between atmospheric CO_2 and dissolved bicarbonates. At times, the apparent age caused by this delay in exchange can be of the order of centuries. Tables of corrections are available for the world's oceans (for more details, see Higham 1999).

Limits on radiogenic techniques

Just as there are maximum and minimum limits to isotopic dating techniques, so similar limits exist for radiogenic techniques (Table 5.2). These techniques are based on measurement of the degree of physical damage in solids caused by natural radiation. The maximum limit is imposed by a saturation point, after which additional radiation exposure is not recorded. In part, this depends on the nature of the material being dated, but it also depends on the environmental radiation rate. Like radiocarbon dating, the minimum limits are determined by signal-to-noise levels (Blackwell & Schwarcz 1993).

Precision

Signal-to-noise levels place limits on the age ranges over which techniques may be used, but within these limits techniques vary in the precision with which age estimates may be obtained. Using the radiocarbon technique as an example, the precision of an age estimate reflects the nature of carbon

14 decay. Although this decay is continuous, it is also spontaneous. The rate of decay can be measured, but each decay event can only be predicted statistically, not precisely. Over time, the distribution of decay events forms a normal curve spread around the average. It is this distribution that is one source for the estimate of the standard error associated with an average radiocarbon age determination (indicated by the "±" term). Another source of error comes from the laboratory multiplier, effectively a measure of the laboratory reproducibility of radiocarbon age estimates. This multiplier is applied by many laboratories to the calculated standard error based on the distribution of decay events (Higham 1999). Typically for a radiocarbon estimate, the calculated standard error will span several decades and means that the true radiocarbon age estimate will fall within the range formed by subtracting and adding the error from the mean, 68 percent of the time (the proportion increases to 95 percent if two standard errors are subtracted and added). The precision of radiocarbon age estimates as measured by the standard error means that events that occurred in the past that were separated by a few days, months, or years, or in some cases decades or centuries, will not be distinguishable from one another. Note that this does not mean that radiocarbon age estimates are inaccurate. Accuracy refers to whether the age estimate is a true estimate of the death of the carbon-bearing organism. A radiocarbon age estimate with a standard error of ± 500 years may be accurate even though, with this size of error, it may not be very precise.

From Age Estimates to Chronology

Radiocarbon provides an estimate of the age at death of the organism, but it is up to the archaeologist to relate this process to constructing a chronology of past human behavior. This process may seem simple but, as a number of authors have pointed out (e.g., Dean 1978; Ramenofsky 1998), this simplicity is an illusion. Imagine, for instance, concentrations of charcoal derived from a hearth buried within a stratigraphic layer in a cave site such as those excavated at the front of the Bone Cave (Figure 5.3), one of a series of rockshelter sites excavated in Tasmania with age estimates ranging back to older than 30,000 BP (Allen 1996). These sites are important because they represent a Southern Hemisphere equivalent to the European Upper Paleolithic, and provide archaeologists with the opportunity to compare and contrast the archaeological records of modern humans who occupied glacial environments at opposite ends of the globe (e.g., Holdaway & Cosgrove 1997).

At Bone Cave, concentrations of charcoal were identified toward the front of the cave. Within the same layer are scattered a number of stone artifacts and bones from animals. Using a sample from the concentrations of charcoal, an archaeologist may obtain a radiocarbon determination to "date" hearth construction and, by extension, the stone artifacts and animal bones. In fact, use of the term *date* in contexts such as these has been much criticized, since the word implies a specific moment in time and, as discussed above, age

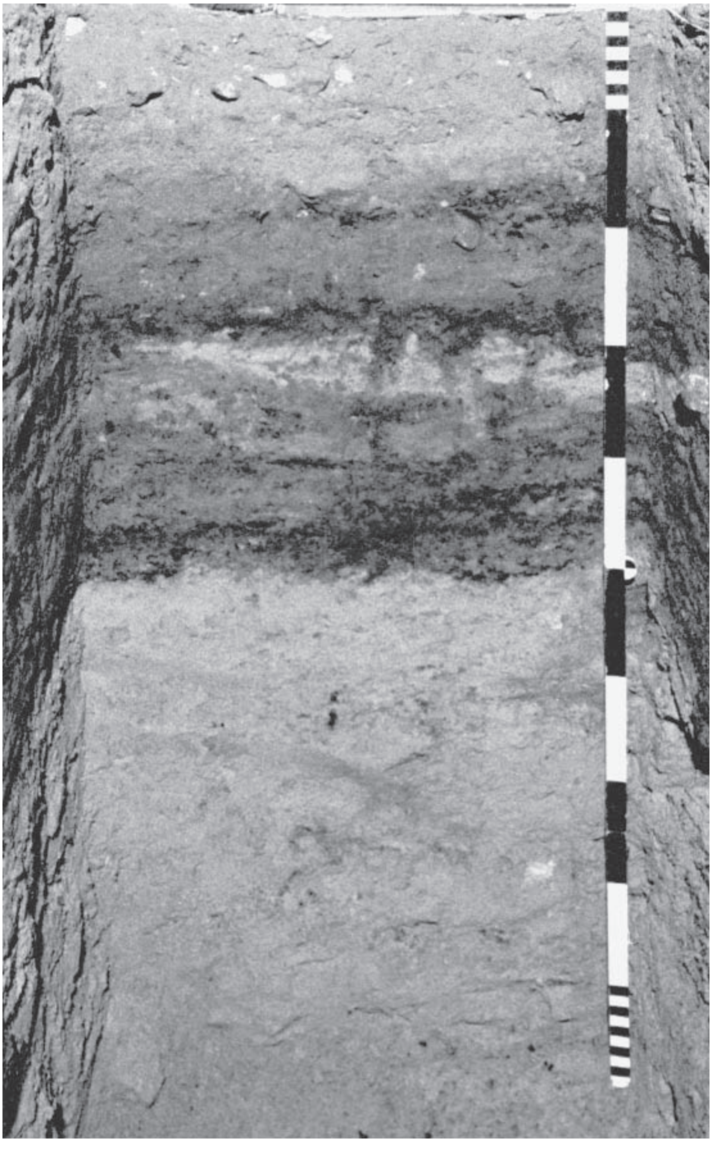

Figure 5.3 Concentrations of charcoal from hearths as seen in the section at Bone Cave (Allen 1996: pl. 6, reproduced with permission).

estimates using radiogenic techniques such as radiocarbon return means and associated standard errors, not fixed dates (Coleman et al. 1987). The preferred term is *age* or *age estimate* (as used throughout this chapter), because these terms convey the uncertainty connected with age estimation while the term *date* does not.

Archaeologists are able to obtain an estimate for the age of a hearth using the radiocarbon technique, but the age that is provided (assuming no contamination problem) does not relate to the construction of the hearth but to the death of the carbon-based organism (i.e., the plant) that provided the wood that was burned to form the charcoal that was "dated." The archaeologist must ensure that these two events are not separated by too great a period of time. Determining both the type of plant and the nature of the wood (heart wood or twigs) that was burnt in the hearth will give an indication of the length of time likely to have elapsed between the death of the organism and the construction of the hearth. Clearly dating the heartwood of a long-lived species will lead to a considerable age difference. The problem is common in some regions of the world (e.g., New Zealand and the Northwest region of the USA), where long-lived tree species are found and where driftwood was a common source of fuel in the past.

Assuming that there is no major discrepancy between the age of the death event estimated with radiocarbon and the age of the hearth construction, the archaeologist may argue that because the hearth is located within a layer that also contains a number of stone artifacts and animal bones, the age of these artifacts and faunal materials may be inferred through association with the age estimate of the hearth. This process is referred to as *cross-dating* (Ramenofsky 1998). As Spaulding (1960) discussed many years ago, cross-dating involves a series of archaeological inferences, since age estimates refer to events rather than things. In other words, it is the attributes of the artifacts and their spatial distribution that form the basis for inference about the association of the age estimate obtained by radiocarbon and the archaeological materials. Such an inference might be possible if the characteristics of the sediment in which the artifacts are deposited suggest deposition over a relatively short period of time (e.g., Stein 2001; see also Chapter 12 of this book). They may, for instance, derive from the flooding of a stream (e.g., Stern et al. 2002). Additionally, the state of the artifacts may suggest that exposure on the surface before burial was of a relatively short duration. For instance, archaeologists have used changes in the nature of bone to suggest relatively short periods of exposure (e.g., Potts 1986; Holliday et al. 1999; but see Lyman & Fox 1989). Finally, refitting stone artifacts may indicate that the artifacts within the layer were manufactured at one time, because flakes can be placed back onto a core, suggesting that they were knapped together during a single event (e.g., Villa 1982). If all these lines of evidence converge, it may be possible for the archaeologist to infer that the age estimate for the death of the plant burnt to form the charcoal in the hearth forms a reasonable estimate of the age of the hearth, and of the abandonment of the artifacts and animal bones deposited in the same layer as the hearth. However, the more various lines of evidence diverge, the greater is the temporal separation between the dated event and the other events that make up the artifact assemblage.

It should be clear from this example that "dating" of a "site" is not something that actually occurs in archaeology. But even if the phrase is rewritten to read "obtaining an age estimate for a group of archaeological materials thought to derive from a contemporary set of events discovered in one part of a site," it involves a series of inferences that extend well beyond those related to obtaining a radiocarbon determination. Instead, "dating" involves a complex set of inferences derived from a wide array of archaeological methodologies.

Temporal Resolution and Behavioral Variation

In the example of the Bone Cave hearth, the archaeologist was able to infer that the radiocarbon age estimate and the hearth manufacture, along with artifact and faunal deposition, were nearly contemporaneous. However, even in this example, "contemporaneous" is a relative term. For some purposes, differences in the amount of time represented by sediment deposition and estimates of the time that it took for the burial of faunal material to occur, based on the state of preservation, may become important. Even when items are found together within a single stratigraphic context, the archaeologist may be interested in developing measures that indicate, at least in a relative sense, the amount of time represented by different behaviors. As Ramenofsky (1998) emphasizes, construction of a chronology is as dependent on the nature of the research question being posed as any other archaeological investigation. The units used to build a chronology and how close the age estimates must be to be treated as deriving from different depositional events depend on the research goals (e.g., Fletcher 1992). There are no universal or superior chronologies; nor are there chronological units that existed in the past, waiting to be discovered by archaeologists. Time is a continuum that takes different forms depending on the scale at which it is observed. At the scale of the universe, time is warped, while Earth time appears to be linear (Hawking 1998). Therefore, the perception of time depends on the location of the observer and the scale at which this individual is considering time. On the basis of this observation, Ramenofsky (1998) argues that archaeologists are not in the business of discovering time. Because time is a continuum, archaeologists impose their own conceptual units, breaking the continuity that is time into a series of arbitrary packages that reflect their interests in inferring the outcomes from past actions. In this sense, units of time cannot be discovered because there is nothing to discover (see the discussion of time in Chapter 2).

Fidelity and resolution

Paleontologists have dealt with many of the same issues faced by archaeologists when considering geological fossil deposits (Stern 1994). Like archaeologists, they recognize that the way in which time is packaged has more to do with the nature of the research question than it has to the discovery of something from the past. For instance, *fidelity* and *resolution* are two terms developed by paleontologists to describe the fossil record (Behrensmeyer et al. 2000). Fidelity refers to how faithfully the fossil record captures biological information, while resolution refers to the sharpness of the record in a temporal sense, the finest temporal or spatial unit into which the fossils may be placed. These concepts may be rewritten in archaeological terms.

Imagine a site at which several lines of evidence point to short occupation duration with a limited number of activities. For many years, the classic portrayal of such a site has been the Meer site in Belgium (Cahen et al. 1979). At this site, a combination of technological, refitting, and usewear studies all suggest that the stone artifacts were deposited together during a short period. The site provides high time and space resolution but has low fidelity. We know what went on at the Meer site in great detail; the high time resolution and refitting tells us where those activities occurred – hence the high spatial resolution. But fidelity is low, because the site can tell us little about the full range of activities undertaken by the people who manufactured, used, and abandoned the artifacts. We know nothing about what occurred at other places in the landscape at different times.

Sites such as Meer are of little use if we are interested in studying behavioral variability, because we will learn nothing about the set of different behaviors that occurred outside the time-slice that we are viewing. Other sites used by the same or related groups of people might contain artifacts relating to quite different types of behaviors. If we want to learn about behavioral variability, we have to wait around (i.e., allow time to pass) so that these behaviors can occur at locations at which artifacts are preserved (i.e., archaeological sites). To study variability in an archaeological sense, we do not always want sites such as Pompeii, where life stopped in an instant in time; rather, we want sites where much behavior has accumulated through time, so that we can see the accumulated variability. Discussion of this idea formed part of a famous debate between Binford (1981) and Schiffer (1985) (discussed by Murray 1999; see also Knapp 1992; Smith 1992).

The alternative to thinking about Meer is to consider an assemblage that represents a very large number of behavioral events, with material deposited over an extended period of time. Depending on the location of the assemblage, a wide range of activities may have taken place, leading to the deposition of many types of artifacts. Such a site will have low temporal resolution, because so many events that may not be separable are mixed together. But the fidelity will be high, because a high proportion of all the activities that occurred within a landscape are represented in the assemblage. This follows from the reasoning that, over time, many people will eventually visit the point in the landscape represented by the site under study. In this sense, the spatial resolution will also be high, not in the same way as at the Meer site discussed above, but in the sense that the artifact assemblage will represent a good example of all the artifacts that have been used within the landscape that surrounds the site.

Time averaging

Sites with low temporal resolution but high fidelity are referred to as *time averaged* (Stern 1993, 1994). In paleontology, time averaging (the term was first introduced by Walker & Bambach 1971) refers to the difference in rates of population turnover of individual taxa versus the rate of sedimentation (Behrensmeyer et al. 2000). Because rates of sedimentation at many fossil locations are relatively slow, the fossil remains of many organisms that did not live together in contemporaneous populations will accumulate together within a single geological bed (the equivalent of a single archaeological site). Thus time-averaged assemblages group together organisms that may never have functioned together in a living community but provide a good idea of the range of organisms that have existed through time in an environment. The application of the concept to archaeology uses a similar definition.

As Stern (1994) comments, the sedimentary processes that lead to the formation of archaeological sites vary in magnitude and frequency, just as they do for paleontological sites. The rates at which artifacts are deposited also vary depending on a range of factors, including the functions for which the artifacts were created, the way they were disposed of, and the degree of curation (Wandsnider 1996). This means that, depending on the mode and rate of accumulation of sediment, and the mode and rate of artifact accumulation, artifact assemblages may include a variety of objects deposited at different times that were never used together for the same purposes (e.g., that never formed functionally related "toolkits").

Stern (1993, 1994) uses time averaging as the basis for a critique of conceptual models for inferring behavior from the earliest African Paleolithic sites. As she points out, models based on ethnographic or ecological theory effectively ignore the time-averaged nature of many artifact assemblages, because they ignore the time it took for assemblages to accumulate (more will be said on this subject below).

There are two things to consider when assessing the time averaging of an archaeological deposit. First, there is the time span represented by the sediment layer in which artifacts are found. Secondly, there is the time span represented by the artifacts themselves: paleontologists refer to these as the *scope* and *micro-stratigraphic acuity*, respectively (Schindel 1982). It is not hard to imagine a layer represented in a site that took several centuries or even millennia to accumulate. Bone Cave again provides good examples. Here, a series of radiocarbon age estimates indicate that accumulation occurred at various times from as early as 29,000 BP through to the end of the Pleistocene. It is possible to calculate the rate of sedimentation for one of the excavated squares in the cave by plotting the depth against age in radiocarbon years (Figure 5.4). This gives a value of 145 radiocarbon years per centimeter of deposit as an estimate for the rate of sedimentation in this square over the whole occupation of the cave. This rate can in turn be used to provide an estimate of the rate of artifact accumulation. Bone Cave was excavated in 2.5 cm deep excavation units and it is a simple matter to total the number of artifacts in each of these 55 excavation units for one of the squares ($n = 3{,}187$) and use this number to provide the estimate of the rate of artifact deposition per year. The result suggests that on average 0.16 artifacts from the largest

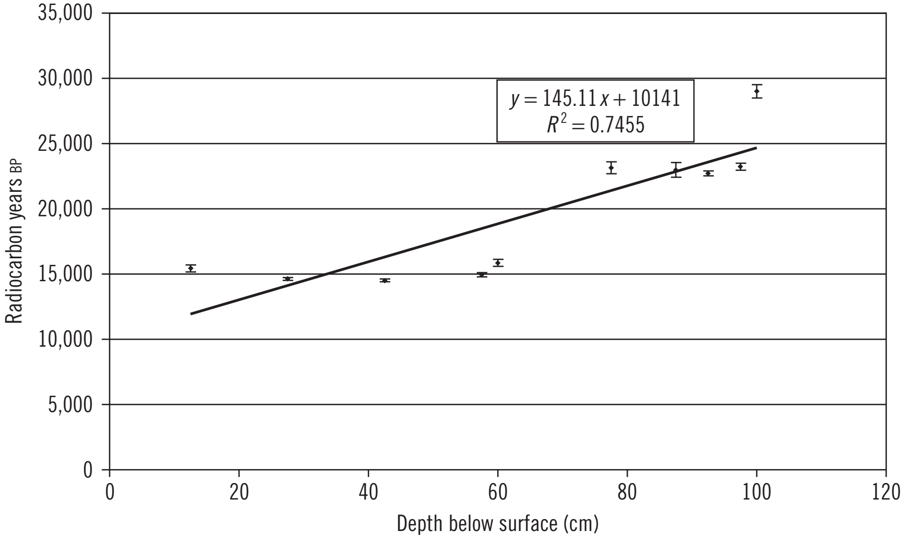

Figure 5.4 The sedimentation rate for Square C, Bone Cave, southwest Tasmania, calculated by plotting radiocarbon age against depth. The linear regression line and associated equation indicate an average deposition rate of 1 cm of deposit every 145 radiocarbon years. The R^2 statistic indicates that 74 percent of the variance is accounted for by the regression line (however, see the text for further discussion).

sieve fraction with a maximum length of 7 mm or greater were deposited each year over the length of the occupation. The Tasmanian sites contain some of the richest Pleistocene artifact assemblages in Australia, so while this rate may appear to be low, it is in fact much higher than that calculated at other Pleistocene Australian sites. O'Connor, for instance, reports rates of only 0.046–0.099 artifacts per year for Koolan Shelter 2 (O'Connor 1999: 36). Nevertheless, the rate at Bone Cave suggests that it took a little over 6 years to deposit a single artifact, a rate that is far below the number of artifacts that ethnographic studies would suggest were normally deposited by small groups of hunter–gatherers over time (e.g., Hayden 1979). The discrepancy reflects the action of time averaging. As Stern (1994) points out, there is little reason to assume continuous rates of sedimentation in archaeological sites. In fact, studies of cave sites indicate that a variety of factors (including human occupation) will lead to changes in the mode and frequency of sediment accumulation (e.g., Stein 2001).

It is also clear that rates of artifact accumulation vary. Calculating an overall rate of artifact deposition assumes that humans behaved in highly uniform ways in the past. In fact, the opposite is likely to be true, both in a short-term behavioral sense (people undertook a variety of tasks at more or less the same time) and in a longer-term processual sense. Empirically, in many instances it may be better to model rates of artifact accumulation not as a straight line but as a sigmoid curve (Shennan 1988: 154). This is because of a phenomenon termed *autocorrelation*. At many archaeological sites, there is a greater probability of sequential occupations occurring in groups (i.e., sets of occupations occurring over relatively short periods of time separated from other sets by long periods of time) rather than spaced evenly throughout the whole sequence (Holdaway & Porch 1996). People who use an archaeological site at one time will, more often than not, return to this site at some time in the future, because even as people move around to exploit seasonally available resources, they will eventually return to a place that they inhabited before. This means that occupations will tend to form clusters that are closely related in time. Eventually, however, a region may be abandoned or the utility of a particular site may decline. The site will then be abandoned, often for long periods of time. As periods of use and abandonment alternate, archaeological materials will tend to form clusters separated by sterile or near-sterile deposits. Such sequences are not well modeled by straight lines.

At Bone Cave, there is stratigraphic evidence to back up a nonlinear trend. A nearly sterile layer separates radiocarbon age estimates that indicate occupation around 15,000–17,000 BP and another group of estimates that indicate occupation around 24,000–29,000 BP (all age estimates are in radiocarbon years). Clearly there is a significant gap in deposition at Bone Cave, one that is made obvious by the large number of radiocarbon determinations that were acquired for the site. As an aside, imagine the difficulty faced by an archaeologist who, in the absence of the sterile layer, obtained only a small number of radiocarbon determinations for a site such as Bone Cave. Selecting three or four determinations and plotting these against depth makes the rate of sedimentation appear much more linear (Figure 5.5).

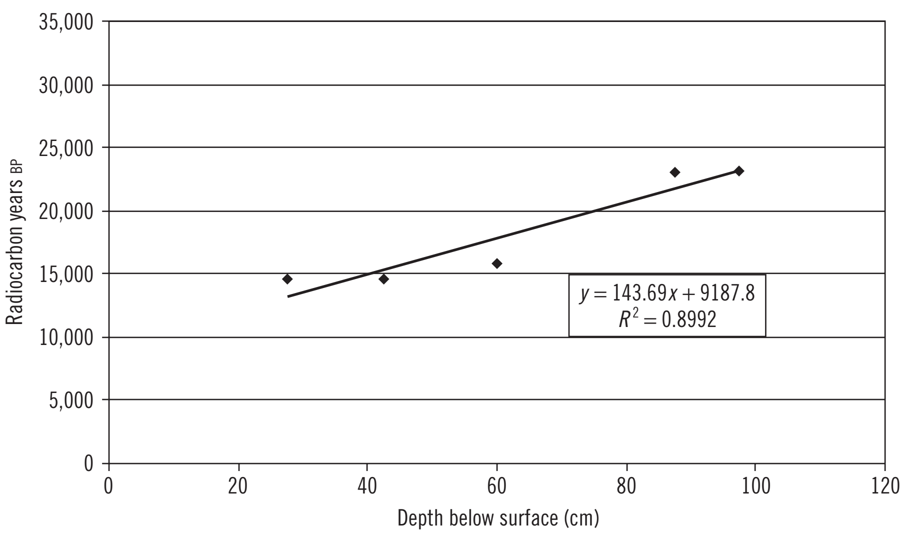

Figure 5.5 Selected radiocarbon determinations from Bone Cave Square C plotted against depth versus the full suite of determinations. The R^2 statistic is higher for the linear regression based on these five radiocarbon determinations than it is for the ten determinations that were actually obtained (Figure 5.4). The example illustrates how a small number of determinations can mask nonlinear trends.

Geologists refer to the presence of gaps in the sequence, the proportion of a time interval that is represented by actual sedimentation versus the actual duration of sedimentation in a section, as the *stratigraphic completeness* of a deposit (Stern 1994). If this concept were ignored, the difference between the maximum and minimum radiocarbon determinations at Bone Cave would indicate a period of occupation spanning 15,000 radiocarbon years. But when the concept is applied, the gaps indicated by the stratigraphic record combined with the distribution of radiocarbon determinations throughout the deposit suggest age estimates for the actual occupation of the cave that span much shorter periods of time. Actual periods of artifact deposition are liable to be shorter still. At one extreme, periods as short as a few days each could easily account for the number of artifacts represented in one of the Bone Cave squares. In effect, this would mean that during the majority of the time represented by the archaeological record, nothing happened that resulted in the deposition of artifacts.

Figure 5.6 shows two plots of the number of artifacts per radiocarbon year for one square at Bone Cave. In Figure 5.6a, the rate of accumulation and the number of artifacts per excavation unit have been used to provide a plot of the number of artifacts deposited per year as though occupation at the site were continuous. In Figure 5.6b, the rate of accumulation has been recalculated taking into account the distribution of radiocarbon determinations that suggest significant temporal gaps in the record. In Figure 5.6b, three separate deposition rates are used to display the number of artifacts deposited per year at the site. The result is two plots that give quite different impressions of the nature of deposition at Bone Cave and thereby suggest quite different behavioral interpretations for the cave. Clearly, our procedures can have a dramatic effect on the way we think about modeling behavior in the past. A number of archaeologists have considered this topic under the heading of "time perspectivism."

Multiple Scales of Time

Different types of processes operate at different time scales, so if archaeologists are going to be able to study these processes they must be willing to alter the time scale at which they investigate the archaeological record. This simple notion is termed *time perspectivism* (Bailey 1983). The operation of the concept is easiest to see in the Earth sciences, where the subjects considered range widely in temporal scale (Bailey 1983, 1987). At one extreme, it may take millions of years for some processes such as continental drift to occur, while at the other end of the temporal scale, changes in the course of drainage lines found in arid regions can happen in a matter of a few hours during rain events. Clearly, investigators interested in these two different types of phenomena have to view their data at radically different temporal scales or else their research endeavors would become ridiculous.

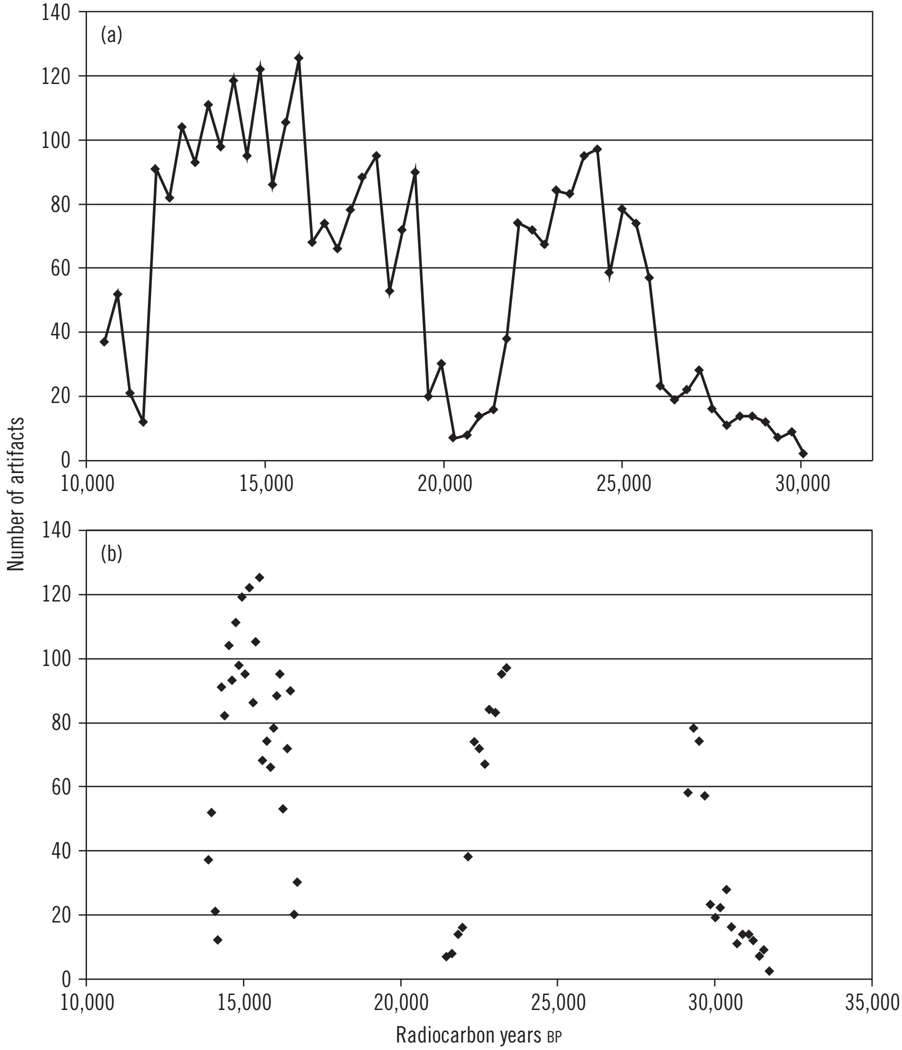

Figure 5.6 Two views of the rate of artifact deposition in one square from Bone Cave. In (a), the average rate of deposition for the whole site combined with the number of artifacts per excavation unit provides one view of the differing rate of artifact deposition. In (b), the long temporal gaps in the sequence of radiocarbon determinations are incorporated, suggesting three quite different periods of artifact deposition.

Bailey and others who have written on time perspectivism in archaeology (e.g., Fletcher 1992; Stern 1994; Murray 1999) argue that just as in the Earth sciences, explanations of past behavior must be tailored to the temporal scale of the phenomena being studied. Stern (1993) for instance, has criticized attempts by archaeologists interested in the earliest African Paleolithic sites, because the models that they use to interpret the distributions of artifacts and animal bones that they find are largely derived from ecological theory or ethnographic observations. Both bodies of theory are founded on short-term observations, yet the artifact and faunal assemblages that these theories are being used to interpret come from time-averaged deposits where the *scope* (to use Schindel's [1982] term, introduced above) is measured in tens of thousands of years or more. Stern questions whether it is useful to mix temporal scales in this way.

Bailey (1987) likened the problem that Stern subsequently raised to a scientist using an instrument like the Hubble telescope not to study the distant universe, but instead pointing it toward Earth to demonstrate that, from the point of view of a person standing on the ground, the Earth appears to be flat. The procedure appears silly because the Hubble telescope was not designed to look at phenomena at the scale of a person standing on Earth.

Archaeologists interested in time perspectivism suggest that besides the short time scale processes that we experience as part of our daily lives, and which form the basis for the processes recorded in many ethnographies, there are other processes operating at larger scales over longer periods of time to which attention should be paid. If inferences are drawn only on the basis of analyses that focus on the operation of short-term processes, then these longer-term processes are liable to remain unanalyzed.

While discussing time, Ramenofsky (1998) makes the point that the units in which time is measured must be closely related to the nature of the question being posed by the archaeologist. The outcome of this position – and a time perspective view of the archaeological record – is that there is not one time, but many times; or, as Bailey (1983) corrects himself after making this statement, not one way of representing time, but many ways in which time may be represented. The need to talk of ways of representing time rather than time itself occurs because time cannot be measured directly, but is assessed in terms of a series of processes. This means that archaeologists may usefully group their artifacts into a number of different temporal units, depending on the scale of the processes that they are interested in studying.

Examples of how this may be done are provided in two case studies. In the first, a number of potential temporal scales are discussed that are useful for answering different research questions at the stratified Tasmanian Pleistocene cave site of Bone Cave, which was introduced at the start of this chapter. The second example discusses a quite different form of archaeological record. Stud Creek, in the arid zone of western New South Wales, Australia, contains no stratigraphy in the conventional sense at all. Rather, artifacts and the remains of hearths are distributed across an eroded surface, providing evidence of occupation by Indigenous Australians during the past 2,000 years. The research summarized here indicates how geoarchaeological techniques may be used to construct a chronology even when the archaeological record is deflated onto a single surface.

Case Study 1

Assessing Different Scales of Time at Bone Cave

As discussed above, Bone Cave is interesting because it is one of a number of cave sites in Tasmania that preserve a record of late Pleistocene human occupation, the Southern Hemisphere equivalent of the European Upper Paleolithic. During the late Pleistocene, low sea levels meant that Tasmania was joined to mainland Australia, forming the continent known as Sahul.

Depending on the scale at which the record at Bone Cave is analyzed, a range of different research questions may be addressed. Four of these have proved useful in formulating different types of questions.

To place Bone Cave into a regional context, the temporal scale needs to be adjusted so that comparisons may be made with other Tasmanian cave sites, including those on what are today islands between Tasmania and the mainland, since during the Pleistocene these islands were hills distributed across an ancient land bridge.

Figure 5.7 provides a graph on which many radiocarbon determinations from Tasmanian cave sites are displayed together (the methods used are described elsewhere – see Holdaway & Porch 1995, 1996; see also Housley et al. 1997). The plot effectively sums the number of radiocarbon age estimates and plots this sum radiocarbon year by radiocarbon year (many of the age determinations fall outside the current limits of

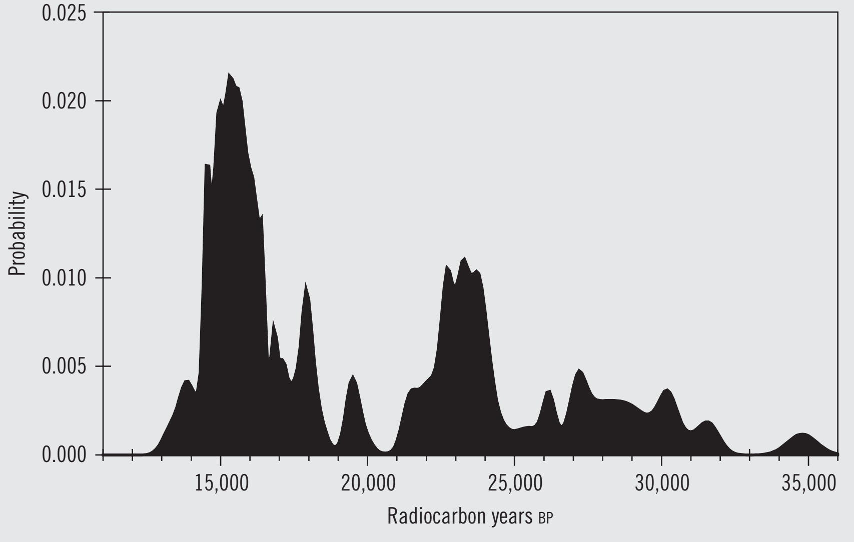

Figure 5.7 An area plot, showing the probability of a particular year having one or more radiocarbon age estimates based on a moving average of Pleistocene radiocarbon determinations from Tasmanian cave sites (modified from Holdaway & Porch 1995).

calibration programs). Moving through time along the *x*-axis, the plot fluctuates up and down, indicating that there are times when more deposits have radiocarbon age estimates than at others. Fluctuations occur every few thousand years and markedly increase in amplitude after the Late Glacial Maximum (approximately 18,000 BP).

The pattern illustrated in Figure 5.7 suggests two sets of research questions. First, the results may indicate that deposition in the sites was not continuous over the late Pleistocene. This may reflect times either when the sites were not occupied and/or when the conditions for preservation were poor over some or all of Tasmania. Secondly, there is a possible correlation between the fluctuating numbers of radiocarbon determinations and a series of long-term environmental changes documented at a Tasmanian swamp site (Pulbeena Swamp) that has a particularly good record of past environments, including periods of wetter and drier climate (Holdaway & Porch 1995). If this correlation does not reflect differential preservation of deposits, then it may reflect long-term adjustments in the way people used the ancient Tasmanian landscape. Individuals inhabiting the southern extreme of Sahul could not have perceived the climatic variations indicated at sites such as Pulbeena, so this is not a case of individuals reacting to climatic changes. Rather, looking at the pattern created by multiple radiocarbon determinations at this scale reflects the long-term outcome of a large number of distinct individual behaviors.

To discover what adjustments people made to the changing environment, it is necessary to shift from a global to a local scale. If the radiocarbon determinations are considered on a site-by-site basis, it becomes apparent that most of the artifacts found at the sites come from deposits associated with radiocarbon determinations that overlap. This is illustrated in Figure 5.8 by the deposits at Bone Cave. Despite the long sequence at this site, most of the artifactual material was deposited during four periods of occupation indicated by artifact-rich deposits, for which a number of radiocarbon determinations

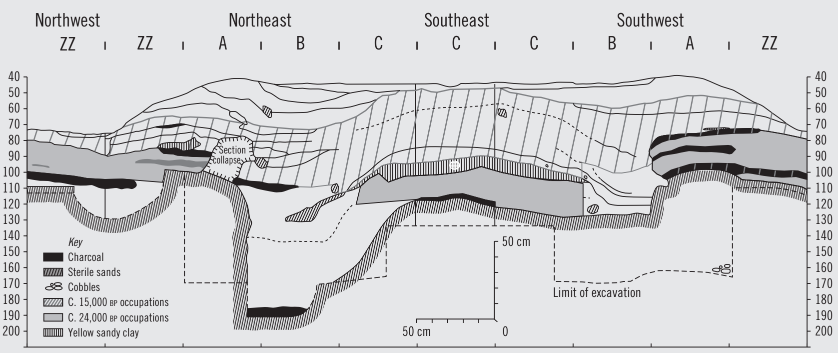

Figure 5.8 A stratigraphic diagram from Bone Cave, Tasmania, showing layers covered by groups of radiocarbon determinations. Most of the deposit belongs to periods with age estimates ~ 15,000 BP and ~ 24,000 BP. Two shorter periods of occupation indicted by the radiocarbon results are not shown (from Holdaway 2004: fig. 1.4).

have returned results that overlap. Although the duration of these periods cannot be determined precisely, they appear to be relatively short compared to the overall time for which the site was available for use. Thus, at this scale one of the research questions becomes why Bone Cave and its neighbors fell out of use between periods of occupation and whether these periods of disuse correlate between sites. Correlation of occupation and disuse between sites may indicate the operation of long-term regional processes perhaps related to changes in the regional environment.

By looking at the nature of the artifacts from each of the four periods suggested by the radiocarbon determinations, changes in the way Bone Cave itself was used through time may be investigated. One of the interesting patterns to emerge from an analysis of the stone artifacts from Bone Cave is that the relative proportions of different raw materials obtained locally versus those brought to the site change through time (Holdaway 2000, 2004). This suggests changes in the mobility of people who occupied the site at different times throughout its 15,000-year history, since more mobile people had more access to nonlocal raw material sources. There is a change represented at the site, with relatively more sedentism after the Late Glacial Maximum than before (approximately 18,000 BP). However, differences in mobility are not the same as, and in fact may be independent of, the changes that led to the formation of four discrete periods of occupation indicated by the radiocarbon determinations from Bone Cave, since each is apparent at a different chronological scale.

The fourth chronological scale is used to investigate the duration of occupation at Bone Cave after the Late Glacial Maximum. A series of radiocarbon determinations indicate that deposits belonging to this period were formed around 15,000 BP, but do not indicate how long it took for the deposits to build up. Radiocarbon determinations indicate that occupations at 15,000 BP were spread over several centuries, but give no indication of the length of these individual occupations. Were they fleeting visits by small groups, or longer occupations by groups who remained at Bone Cave to exploit resources for longer periods of time? It is not possible to answer this question directly, but it is possible to provide an estimate of the relative duration of occupations by constructing an analysis that uses another time-dependent process, in this case raw material depletion through time, to estimate the impact that occupation had on resources. A greater impact would imply longer occupation duration rather than a series of fleeting visits.

As people occupied Bone Cave, they made use of quartzite cobbles that even today lie outside the front of the cave. Through time, if large cobbles are flaked preferentially (a very common pattern in stone artifact assemblages), people will increasingly be forced to rely on relatively smaller cobbles. The more clearly this process is documented, the greater is the occupation duration. Raw material depletion can be detected by comparing the size of quartzite flakes with the proportion of the flakes that retain cortex.

At Bone Cave, the 15,000 BP assemblage flake size diminishes through time, just as the proportion of cortical flakes increases. On the basis of the relative increase in the cobble surface area to volume ratio as cobble size decreases, this result suggests that cobble size diminished through time, and therefore occupation was sufficiently prolonged to have a detectable effect on raw material availability (Holdaway 2000, 2004). As more sites are analyzed, the application of similar measures will help to build a richer view of the chronology of ancient Tasmanian occupation – not simply when sites were occupied, but also for how long, as reflected in the impact on resources.

There is no one "correct" scale at which to analyze the artifacts from Bone Cave; nor is there one "correct" interpretation of the radiocarbon chronology for the site. Depending on the nature of the research questions asked, time can be understood in different ways. For some questions, long-term correlations with regional paleoenvironmental records are of interest. For these types of questions, age estimates for general trends in the occupation of many sites are needed. For other questions, radiocarbon determinations merely indicate how artifacts may be grouped together. Changes that indicate raw material depletion, and therefore occupation duration, are seen within deposits producing radiocarbon determinations that overlap. As Ramenofsky (1998) contends, scale of analysis depends very much on what questions are asked.

Case Study 2

Time Perspectivism in Practice, Stud Creek, Western New South Wales

Conventional archaeological sites consist of artifacts buried in layers of sediment. These layers often provide the means by which artifacts are grouped for analysis and associated with age estimates obtained from datable materials. But what about artifacts left lying on surfaces? These surface sites dominate the archaeology of many regions of the world, particularly in arid areas where sedimentation processes do not lead to burial. Even if features that retain datable material (such as the hearths discussed in this example) exist on these surfaces, how can age estimates for these features be applied to the artifacts found lying next to them?

Part of the answer to these questions requires that we stop thinking of age determinations as simply a sequence of dates and start thinking about searching for patterns among groups of age estimates, much as we seek for patterns in assemblages of artifacts. We also need to broaden our understanding of stratigraphy and what it means to develop a chronology for an archaeological site.

In western New South Wales, on the edge of the Australian arid zone, stone artifacts and associated heat-retainer hearths dominate the archaeological record (Holdaway et al. 1998, 2000). The heat-retainer hearths, once constructed as shallow stone-lined pits, in which a fire was lit to heat the stones, are today exposed as concentrations of heat-fractured stones and fragments of charcoal resting on the modern surface. Surrounding these are many thousands of stone artifacts.

The artifacts and hearths are exposed today as lag deposits because of erosion of the sediments into which they were originally incorporated. Much of this erosion occurred in the 150 years following the introduction of sheep grazing by European pastoralists (Fanning 1999), with the result that artifacts and hearths representing occupations that differ in age today are found mixed together on a single surface.

This archaeological record may appear to lack stratigraphy, since it is exposed on the surface. But if we step back a bit and look at the record from a landscape perspective, it is not hard to see that the surface deposit itself rests on a sedimentary layer. Therefore, in this sense, the surface forms a stratigraphic layer. Understanding the chronology of this surface will begin to tell us something about the age of the artifacts, since in the absence of processes that have transported them from older deposits, they cannot be older than the age of the surface on which they rest (although they could be considerably younger). The age of the surface on which they rest therefore gives the *terminus ante quem* for the artifacts.

Geomorphological history

Like many archaeological projects, at Stud Creek much effort was expended on determining the geomorphological history of the deposit on which the artifacts rested. Surface deposits were mapped into a Geographic Information System (GIS) with units defined on the basis of their depositional or erosional history (Fanning & Holdaway 2002). A 3-m deep trench and smaller bank sections were excavated adjacent to the present-day stream channel to provide a sedimentary history of the valley (Fanning & Holdaway 2001). These excavations allowed the definition of a series of sedimentary units with age estimates determined by OSL and radiocarbon.

Two sedimentary units are of interest here, the first representing remains of a former floodplain that existed prior to European occupation and the second a series of deposits resulting from stable pools of water. An OSL age estimate of 2,040 ± 100 BP (OxL 1050) was obtained from the first sedimentary unit. In reporting OSL determinations such as this, age estimates are given in sidereal years before present. The OxL number that appears after the age estimate refers to the laboratory where the estimate was obtained (the Oxford Luminescence Laboratory (RLAHA 2003) and the individual determination number). At Stud Creek, many of the artifacts currently resting on the surface adjacent to the modern stream channel are scattered across this sedimentary unit.

Below this layer, a gravelly, sandy mud was laid down by a series of relatively stable pools. Six radiocarbon age estimates for this unit provide calibrated ages around 5,000 BP (Fanning 1999; Fanning & Holdaway 2001). The results of the radiocarbon

Table 5.3 (a) Radiocarbon and (b) selected OSL determinations from valley fill sediments in the catchment of Stud Creek. NZA, Rafter Radiocarbon Laboratory, New Zealand (AMS); OxL, University of Oxford Luminescence Dating Laboratory, United Kingdom (OSL); Wk, University of Waikato Radiocarbon Dating Laboratory, New Zealand (radiometric). Note that the OSL determinations are given as before AD 2000, while the radiocarbon determinations are given as before AD 1950. From Fanning and Holdaway (2001).

(a) Radiocarbon determinations

Unit	$\delta^{13}C$	% Modern	^{14}C BP	Depth (m)	Laboratory no.
GSC	–23.2 ± 0.2	58.8 ± 0.4	4,221 ± 58	0.48	NZA8957
	–25.9 ± 0.2	57.9 ± 0.5	4,340 ± 64	0.27	NZA8958
	–25.8 ± 0.2	59.1 ± 1.3	4,220 ± 180	0.50	Wk5326
	–26.6 ± 0.2	58.0 ± 0.6	4,380 ± 80	0.29	Wk5327
	–25.4 ± 0.2	57.4 ± 0.4	4,460 ± 60	0.38	Wk5325
	–27.9 ± 0.2	56.4 ± 0.7	4,600 ± 100	0.18	Wk5328
RSG	–25.4 ± 0.2	47.5 ± 0.4	5,939 ± 60	1.73	NZA8959
	–26.1 ± 0.2	21.2 ± 0.2	12,452 ± 68	1.48	NZA8960

(b) OSL determinations

Unit	OSL yB2k	Depth (m)	Sample code
PEM	192 ± 23	0.35	OxL1051
	1,220 ± 50	0.38	OxL1054
PRE	2,040 ± 100	0.47	OxL1050
GSC	7,640 ± 380	0.92	OxL1057

determinations are presented in Table 5.3 and the calibration plots of the ages are given in Figure 5.9 (generated using the OxCal software discussed above).

Table 5.3 provides a variety of different types of information needed when reporting radiocarbon determinations such as those from Stud Creek (Higham 1999). The laboratory code number is a unique identifier for the radiocarbon sample. Laboratories each have a letter code and number their samples sequentially. The conventional radiocarbon age is given using the original Libby half-life (rather than the more recent half-life, as discussed above) and referenced to one of a number of standards that give the modern level for radiocarbon activity. The age estimate is given in radiocarbon years before present, where present is taken as AD 1950 (the decade closest to when Libby discovered radiocarbon). The percent modern refers to the proportion of carbon 14 remaining in the sample relative to the standard. Finally, $\delta^{13}C$ measures fluctuation in the isotopic ratios as a result of certain natural processes (e.g., photosynthesis). These processes change the relative proportions of carbon 13 and 14 relative to carbon 12. The term $\delta^{13}C$ represents the parts per mille difference between the carbon 13 content of the sample and that of a standard used by the laboratories. Laboratories generally correct radiocarbon

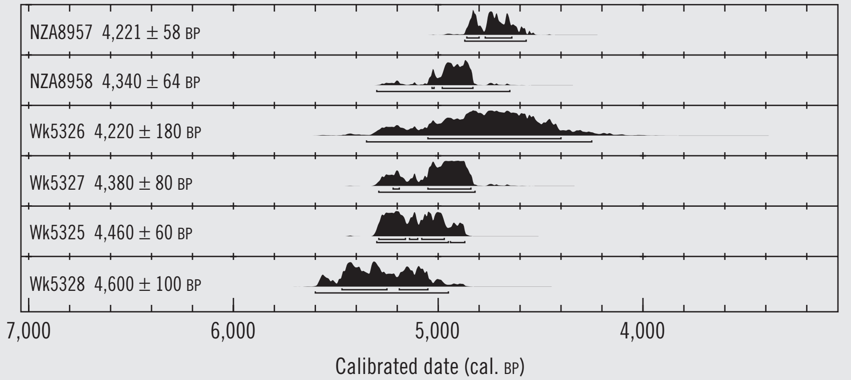

Figure 5.9 A multiplot for radiocarbon determinations from the GSC unit, Stud Creek, produced using OxCal v. 3.8 (Bronk Ramsey 2002).

age estimates for isotopic fractionation relative to this standard, reporting what are described as normalized estimates (Higham 1999).

The nature of the calibration process is well illustrated by the radiocarbon determination Wk5328 (as for the OSL determination given above, "Wk" stands for the radiocarbon laboratory that supplied the determinations, in this case the University of Waikato Radiocarbon Dating Laboratory in New Zealand) (Figure 5.10). In this figure, the wavy line that runs diagonally across the graph represents the calibration curve, while the normal curve on the left represents the probability distribution of the radiocarbon age estimate centered on 4,600 BP. The calibration is given by the area plot at the bottom of the figure, a graph that represents the probability of true age falling within any one calendar year. The higher this area graph, the greater is the probability that the true age is represented by a particular calendar year. Because the calibration curve has a number of oscillations in this time period, there are several points at which the probability plot for the radiocarbon determination strikes the calibration curve. This is the reason for the rather mountainous looking calibration area graph below the calibration line. In fact, for this age estimate, the probability that the true age falls within one standard deviation from the mean radiocarbon age produces two calibrated age ranges: one accounting for about 44 percent of the probability for the range 5,740–5,250 BP and a second accounting for 25 percent of the probability for the range 5,190–5,050 BP. Clearly, this is a more complex picture than is apparent from the radiocarbon age estimate itself.

Two of the determinations listed in Table 5.3 have NZA prefixes in front of their laboratory numbers. The "NZ" refers to the Rafter Laboratory in Wellington, New Zealand, while the "A" indicates that the age estimate was obtained by AMS.

Figure 5.9 shows the calibration plots for the four conventional radiocarbon age estimates and the two ages determined by AMS plotted on the same graph. The effect of variations in the calibration curve for this time period is clearly visible in the spread of

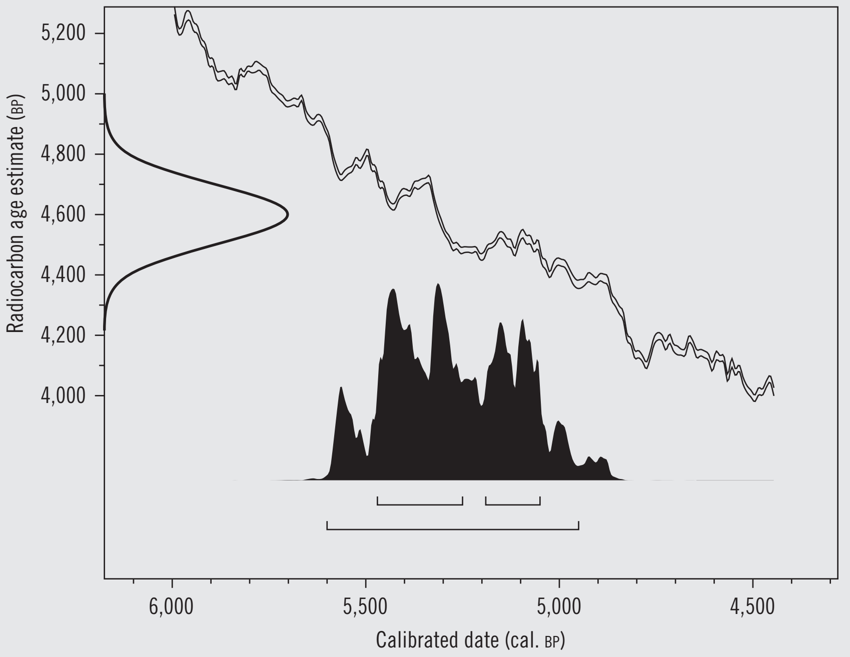

Figure 5.10 An OxCal calibation plot for radiocarbon determination Wk5328, redrawn from OxCal v. 3.8 output (Bronk Ramsey 2002).

the probability area plots for the calibrated age ranges. However, it is also clear that there is relatively good agreement among the six determinations. All fall immediately before or after 5,000 BP. The age estimates suggest that Stud Creek was characterized by a series of relatively stable pools during the mid-Holocene, after which there was a period of erosion until around 2,000 BP (Fanning & Holdaway 2001).

Combining the results from both techniques suggests that the sediments into which the stone artifacts at Stud Creek were deposited, and from which they have been lagged, are certainly no older than 5,000–6,000 BP, and probably a lot younger, perhaps as young as 2,000 BP. This provides the terminal age for the Stud Creek archaeological deposits. Despite the lack of stratigraphy in a conventional sense at Stud Creek, taking a landscape perspective and applying what are termed geoarchaeological techniques provides an initial estimate of the age of the surface archaeological record.

Heat-retainer hearths

Table 5.4 gives the radiocarbon age estimates for 28 heat-retainer hearths excavated at Stud Creek. The oldest age estimate, Wk6630, has a calibrated age expressed as two ranges at two standard deviations: 1,690–1,650 BP (4.5 percent probability) and 1,630–1,400 BP (90.9 percent probability). Both of these ranges are more recent than the

Table 5.4 Radiocarbon determinations from heat-retainer hearths, Stud Creek (modified from Holdaway et al. 2002).

Hearth ID	Lab. ID	$\delta^{13}C$	% Modern	Result (BP)
Phase θ1				
H98-75	Wk6632	–23.1 ± 0.2	97.3 ± 0.6	220 ± 55
H98-16	Wk6621	–23.6 ± 0.2	95.4 ± 0.6	380 ± 50
H98-46	Wk6625	–23.2 ± 0.2	94.5 ± 1.4	450 ± 120
H98-13	Wk5332	–23.3 ± 0.2	94.3 ± 0.6	470 ± 50
H98-12	Wk5127	–22.0 ± 0.2	93.1 ± 0.6	580 ± 60
H98-59	Wk6627	–24.1 ±] 0.2	92.5 ± 1.4	630 ± 130
H98-11	Wk5125	–22.6 ± 0.2	92.2 ± 0.5	660 ± 50
H98-71	Wk6631	–23.4 ± 0.2	92.1 ± 0.6	660 ± 50
H98-21	Wk5330	–23.6 ± 0.2	91.8 ± 0.5	690 ± 50
H98-32	Wk6624	–24.0 ± 0.2	91.4 ± 0.6	720 ± 55
H98-4	Wk6038	–23.0 ± 0.2	93.1 ± 4.9	790 ± 50
H98-60	Wk6628	–23.3 ± 0.2	90.7 ± 0.8	790 ± 75
H98-15	Wk5329	–22.0 ± 0.2	90.3 ± 0.5	820 ± 50
Phase θ2				
H98-65	Wk6629	–23.3 ± 0.2	86.4 ± 1.4	1,170 ± 130
H98-28	Wk5124	–22.8 ± 0.2	86.0 ± 0.5	1,210 ± 50
H98-22	Wk5122	–22.5 ± 0.2	85.5 ± 0.4	1,260 ± 40
H98-25	Wk5126	–23.2 ± 0.2	85.5 ± 0.6	1,260 ± 60
H98-19	Wk6622	–22.7 ± 0.2	85.2 ± 0.6	1,280 ± 60
H98-10	Wk6036	–23.2 ± 0.2	85.2 ± 0.4	1,290 ± 50
H98-20	Wk5331	–23.2 ± 0.2	85.1 ± 0.5	1,300 ± 50
H98-30	Wk6037	–23.4 ± 0.2	84.9 ± 0.5	1,310 ± 60
H98-54	Wk6626	–23.0 ± 0.2	84.8 ± 1.5	1,330 ± 150
H98-23	Wk6623	–22.6 ± 0.2	84.5 ± 0.8	1,350 ± 75
H98-8	Wk6620	–23.6 ± 0.2	84.1 ± 0.7	1,390 ± 70
H98-27	Wk5123	–23.6 ± 0.2	83.9 ± 0.5	1,410 ± 50
H98-2	Wk6039	–22.9 ± 0.2	83.6 ± 0.6	1,440 ± 60
H98-9	Wk6035	–22.5 ± 0.2	83.4 ± 0.5	1,460 ± 50
H98-66	Wk6630	–23.6 ± –0.2	81.7 ± –0.5	1,630 ± 50

OSL-based estimate for the age of the valley floor on which the hearths and artifacts rest (i.e., more recent than 2,000 BP).

There are two ways to think about the results of these hearth age estimations. At one level of interpretation, they provide an indication of when Indigenous Australians occupied Stud Creek, a sequence that spans the past 1,700 years or so. Interpreted in a different way, the hearth age estimates provide an opportunity to search for pattern in long-term human behavior in ways similar to those discussed for Bone Cave. Placing the hearth age estimates in sequence shows that they fall into two groups, one before and one after 1,000 BP, indicated as Phase 1 and Phase 2 in Table 5.4. Between these phases there appears to be a gap when no hearths were constructed (or at least none have survived).

Both the existence and duration of the gap in hearth construction can be assessed statistically using a technique called *sample-based Bayesian inference* (Holdaway et al. 2002) that is increasingly being applied to the analysis of age estimates. Bayesian inference owes its origin to the work of Thomas Bayes in the eighteenth century; however, its application to archaeological problems is comparatively recent. The technique allows information coming from different sources to be combined, evaluated statistically and integrated into the interpretation process. Buck (2001) provides a good introduction to Bayesian analysis and details of the application to the Stud Creek hearths are provided in Holdaway et al. (2002).

Applying a Bayesian analysis, we can supplement the probability plots for the calibrated determinations produced by programs such as OxCal with a probability plot that provides an estimate of the duration for the gap between the two phases of hearth age estimates (Figure 5.11). Figure 5.11 was produced using the Datelab v. 1.2 software, which performs radiocarbon age calibration and allows Bayesian analysis (Nicholls & Jones 1998; Jones & Nicholls 2002). The software was also used to provide probability plots for the beginning and ending of each of the two phases of hearth construction (Figure 5.12).

Figure 5.11 suggests a duration for the gap in hearth construction in the range 320–460 calibrated years at 68 percent probability and 200–500 calibrated years at 95 percent probability (i.e., one and two standard deviations, respectively). Both before and after this gap, hearths were constructed every few decades and the combined probability plot for the hearths in each phase gives an indication of the duration of hearth construction.

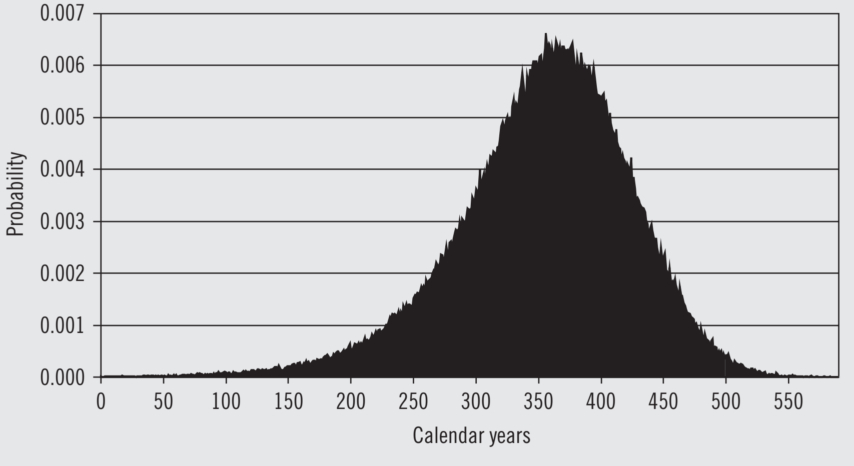

Figure 5.11 The probability distribution (read as the area beneath the plot) of the length in calendar years for the hiatus between the two phases of hearth construction at Stud Creek (from Holdaway et al. 2002).

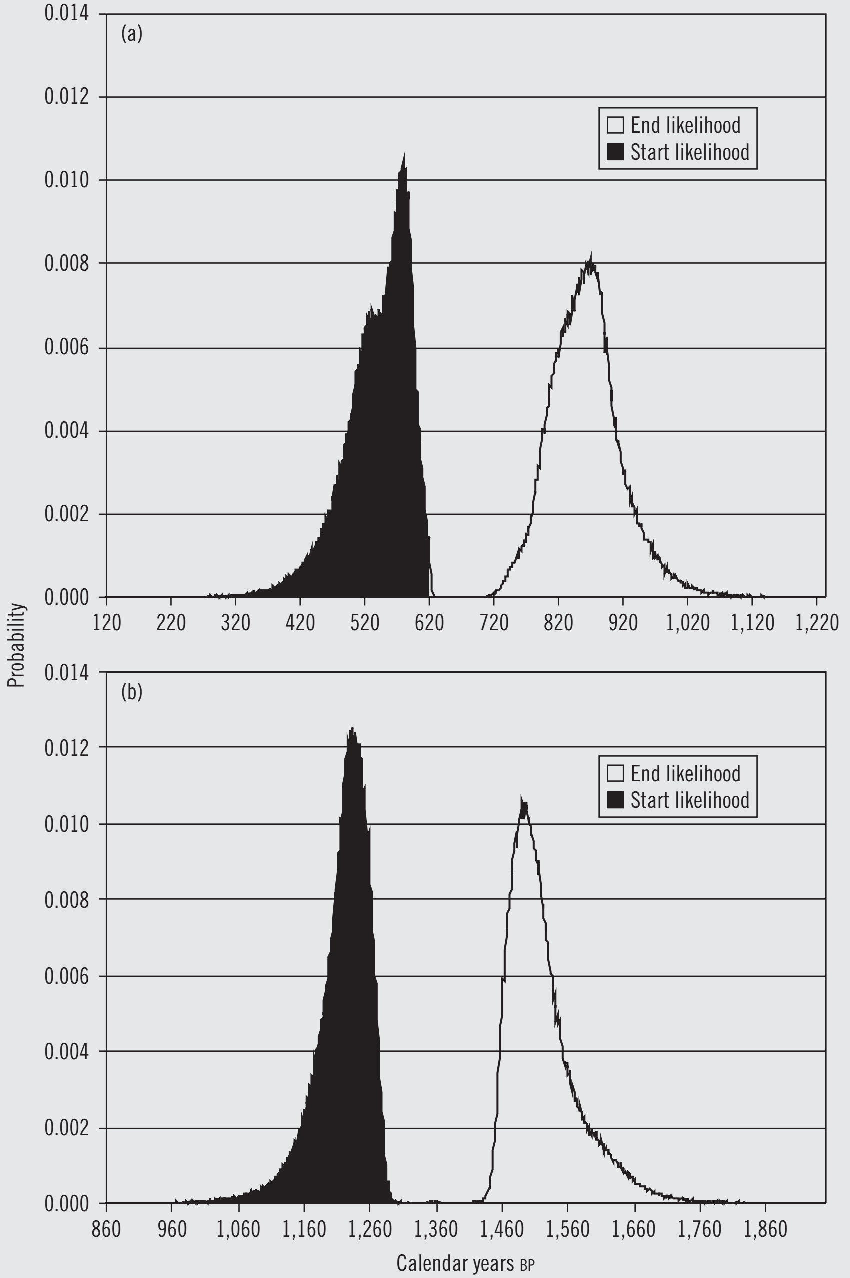

Figure 5.12 The probability distributions for the start and end of (a) Phase 1 and (b) Phase 3 hearth construction at Stud Creek, in calibrated years BP (from Holdaway et al. 2002).

Stud Creek chronology

Combining the hearth chronology with the results of the sediment history study discussed above allows a number of inferences to be drawn. First, if the results of the heat-retainer hearth chronology were viewed alone, it might be tempting to conclude that human occupation of Stud Creek began only within the past 1,500 years. This pattern might then be correlated with paleoenvironmental evidence that suggests a period of drier climate from ~4,000 BP to 1,500 BP, together with studies that suggest that people moved to better-watered areas during such times. However, such an interpretation would ignore the sediment history documented at Stud Creek. It is clear that in the Stud Creek valley at least, the lack of archaeological evidence older than 2,000 BP is likely to reflect increased erosion that would have destroyed older archaeological deposits rather than a lack of human occupation (Holdaway et al. 2002).

Secondly, placing the Stud Creek hearth chronology within a wider context indicates that the hiatus in hearth construction correlates with a worldwide period of climatic variability indicated by paleoenvironmental records from other parts of Australia, and known as the *Medieval Warm Period* (Holdaway et al. 2002). As is the situation at Bone Cave, changing the scale of analysis produces correlations that suggest new types of research questions.

Thirdly, the chronology for Stud Creek has important implications for the way in which the stone artifact assemblages associated with the hearths should be interpreted. Although the hearths do not provide age estimates of the stone artifacts directly, the spatial association of both strongly suggests that the artifacts were deposited over a number of occupations, and that these occupations occurred through time in a clear temporal pattern. Most archaeologists would expect discontinuous occupation by groups of hunter–gatherers as they moved from location to location in a seasonal round. In the Australian arid zone, such movement is often reconstructed in relation to the availability of water. However, the Stud Creek chronology suggests something more than this. The hearths in the two phases of occupation do not cluster together tightly; rather, they are more or less uniformly distributed during each of the phases. This suggests intermittent use of the valley rather than occupation as part of a regular cycle measured in years. During the gap in hearth construction, this pattern changed substantially enough for no hearths to be constructed for some centuries. Hearth reconstruction then started again, returning to the pattern of intermittent hearth construction until the historical period.

Given this chronology, it would be wrong to consider the stone artifact assemblages as the material record of a single set of functions, the equivalent of toolkits deposited by people who used Stud Creek in the same way through time. Nor would it be correct to interpret the assemblages as the result of a single settlement pattern (Holdaway et al. 2000, 2004). Instead, the hearth chronology suggests at least three separate patterns, represented by Phases 1 and 2 and the gap. The stone artifact assemblages therefore most likely form a time-averaged record, incorporating variability produced as a result of a number of differing occupations, and so must be analyzed accordingly.

Conclusion

As illustrated both by the case studies described here and virtually any other archaeological report, time is a key dimension in archaeology and the ability to obtain age estimates for events in the past has revolutionized the discipline. A wide range of chronometric techniques is now available, applicable to many materials and able to provide age estimates that span all two million years of the archaeological record. There is now a wealth of resources describing these techniques, only a small sample of which is cited in this chapter. Yet despite the wealth of material dealing with the mechanics of obtaining an age estimate, the literature dealing with the method and theory behind the formation of archaeological chronologies is rather less developed. Understanding the bases on which chronometric techniques are founded is certainly a key to their successful application. As is clear from the experience of obtaining age estimates for some of the earliest archaeological sites, there are limits to all of the techniques, and only some of the problems will be solved by better technologies. But, as should also be clear from the discussion and examples provided here, many of the problems involved in "dating" archaeological sites are problems of archaeological inference rather than dating technology. Time is an elusive quarry that cannot be observed directly. Therefore, archaeologists must be at their most resourceful when attempting to investigate temporality.

In the past, some archaeologists have sought to determine "the chronology for a site," but clearly such an approach will provide only a very limited understanding of the past. The past can be viewed at a variety of scales and in doing so, a variety of inferences may be drawn concerning behavior in the past – inferences, moreover, that will not necessarily build into a neat ordered picture of past ways of life. In dealing with dating, archaeologists must therefore rise to a challenge that is every bit as theoretical as it is methodological. As a discipline, we have access to an increasingly sophisticated array of procedures for considering time. The challenge that we face is to understand more fully how to integrate the results from these procedures with explanations of cause and effect in the past that ensure we are pointing the archaeological telescope in the correct direction.

Acknowledgments

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Further reading

There are a number of books that bring together specialists who write about different chronometric techniques: see Taylor and Aitken (1997), Brothwell and Pollard (2001), and Goldberg et al. (2001). Dincauze (2000) provides details of a number of techniques in a textbook on environmental archaeology. Articles in journals that review the application of specific techniques may supplement these sources: see, for example, Roberts (1997) on TL/OSL, Rink (1997) on ESR, Schwarcz (1989) on U-series dating, and Johnson and Miller (1997) on AAR. Blackwell and Schwarcz (1993) provide a good general treatment of chronometric methods. In addition, there is now a growing body of information on the Internet. Higham (1999) is a particularly useful site for radiocarbon, with links to a range of other useful sites including radiocarbon laboratories, most of which also have their own websites. The OxCal (Bronk Ramsey 2002) site provides a good discussion of calibration. Godfrey-Smith (2001) has useful information on OSL, TL, and ESR, as does RLAHA (2003).

Rather less is written on the theory of time and archaeology. The classic sources include Bailey (1983) and Binford (1981). Murray (1999) discusses Bailey's time perspectivism in a book that that includes a number of papers on time and archaeology. Ramenofsky (1998) and, more recently, Holdaway and Wandsnider (2005) deal with issues of scale. Stern (1994) discusses paleontological approaches to time from an archaeological perspective, while Behrensmeyer et al. (2000) reviews the paleontological literature itself.

Holdaway et al. (2004) provides a detailed discussion of the Stud Creek evidence, while Allen (1996) provides details of the Bone Cave excavation in a book with papers on a number of other Tasmanian Pleistocene sites.

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Gary Huckleberry

12
Sediments

Introduction

Archaeology and other historical sciences have the daunting task of reconstructing past phenomena from present material evidence. Artifacts and sediments are the primary material evidence that archaeologists have for reconstructing past human events and behavior. As a geoarchaeologist trained in soils and geomorphology, much of my work is focused on archaeological sediments and stratigraphy, and how they can provide a wealth of information regarding past natural and cultural processes. Although the focus in archaeology is material culture, it is the sedimentary matrix containing the material culture that provides key contextual information such as chronology, site formation, and paleoenvironments (Hassan 1978; Butzer 1982; Stein & Farrand 1985, 2001; Waters 1992) essential for fully understanding human behavior. Consequently, archaeologists need to understand the basics of sedimentology and soil formation as it pertains to the history of cultural deposits. This includes defining sediment origin, mode of transport and deposition, and any post-depositional processes (e.g., soil formation) that influence the nature of the archaeological record. To analyze cultural evidence without reference to its biophysical context can lead to incomplete if not incorrect inferences of the archaeological record.

For the past nine years, I have taught a graduate course titled "Sediments and Geoarchaeology" that aims to teach archaeologists with little to no training in Earth science some of the basic principles of sedimentology, stratigraphy, and soil formation, and their archaeological relevance. The course is a mixture of lectures, laboratory exercises, and field trips, the latter two components emphasizing hands-on learning. Whereas field trips to exposures of natural and cultural deposits are designed to develop skills in describing and sampling sediments and stratigraphy, the laboratory component gives students opportunities to learn common laboratory methods employed in geoarchaeology. In addition to learning the basics of measuring the physical and chemical attributes of sediments, students develop an ability to critically assess the potential applications of laboratory data, as well as their limits and uncertainties. At a minimum, laboratory analyses of archaeological sediments can provide objective documentation and supplement field descriptions. However, students learn that there is greater potential in using laboratory data in conjunction with rigorous field observations to construct and/or test hypotheses regarding archaeological site formation and function.

There are many laboratory methods for investigating archaeological sediments, and any one physical or chemical attribute can be usually assessed by multiple techniques (Holliday & Stein 1989). Most of these techniques are derived from the disciplines of geology and soil science, and have applications as diverse as from assessing nutrient availability to modeling water flow in porous media. A discussion of the full panoply of laboratory methods potentially relevant to archaeological research is well beyond the scope of this chapter (for a more extensive review, see Herz & Garrison 1998). Suffice it to say that most geoarchaeological laboratories emphasizing sediments tend to focus on physical and chemical properties such as mineralogy, micromorphology, granulometry, pH, organic matter, calcium carbonate, and phosphorus (Table 12.1). The types of analyses performed will depend on the nature of the samples, the research questions at hand, and – of course – cost. In this chapter, I focus on the laboratory tests performed in my "Sediments and Geoarchaeology" course with which most archaeologists should become familiar: granulometry, pH, organic matter, and phosphorus. I conclude with two personal case studies where such sediment analyses were applied to archaeological research.

Table 12.1 Common sedimentological analysis and methods employed in archaeological studies.

Type of analysis	Methods	References
Mineralogy	Petrography X-ray diffraction	Whittig and Allardice (1986) Mackenzie and Adams (1994)
Micromorphology		Brewer (1964), Bullock et al. (1985), Courty et al. (1990)
Granulometry	Sieve Settling (hydrometer and pipette) Laser diffraction	Krumbein and Pettijohn (1938) Bouyocous (1962) Gee and Bauder (1986), Janitzky (1986a)
Organic matter	Walkley–Black LOI	Walkley and Black (1934) Ball (1964), Janitzky (1986b)
Calcium carbonate	Acid-neutralization method Chittick	US Salinity Laboratory (1954) Machette (1986)
pH	Colorimetric Electrometric	McClean (1982)
Phosphorus	Spot or ring chromatography Visible light spectrometry	Olsen and Sommers (1982) Eidt (1985), Meixner (1986)

Granulometry The texture of sedimentary deposits refers to the percentages of different grain sizes, such as gravels, sand, silt, and clay. *Particle-size analysis* or *granulometry* is performed to determine texture and characterize the population of different grain sizes within a deposit. Particle-size analysis is routinely performed in disciplines such as hydrology, geomorphology, pedology, soil physics, and engineering. Likewise, in geoarchaeology, the applications of particle-size analysis are many (Table 12.2). Because texture is a fundamental physical property of deposits, granulometry serves the basic purpose of objectively characterizing archaeological sediments. This not only helps to document stratigraphy but also provides a basis for correlating deposits between spatially discrete areas. Beyond description, granulometry provides a basis for testing hypotheses regarding sediment origin and mode of deposition. Seemingly simple depositional settings may have sediments derived from several possible sources. For example, rockshelters and caves are generally protected from the elements and yet can contain deposits that are geogenic, biogenic, and anthrogenic, with each origin containing a multitude of different depositional

Table 12.2 Some applications of particle-size analysis in reconstructing sedimentary history and paleoenvironments.

Sediment origin
Identify sediment source areas (*in situ* versus exogenic)
Correlate deposits and stratigraphy between and within sites
Mode of deposition
Distinguishing alluvial, eolian, colluvial, and glacial sediment transport
Distinguish natural and cultural deposition
Distinguish discrete depositional events (e.g., graded bedding as markers of discrete events)
Depositional environment
Estimate depositional energy regimes
Distinguish geologic from pedogenic processes
Estimate surface roughness (for hydraulic reconstructions)
Estimate particle-entrainment requirements
Post-depositional processes and environments
Characterize soil properties
Determine precise soil classification
Distinguish pedogenic from geologic processes
Assess duration of surface stability and soil formation
Assess slope stability
Assess soil erosion potential
Assess bioturbation, cryoturbation, soft-sediment deformation, and other mixing processes
Other
Assess potential for paleomagnetism studies
Assess potential for microbotanical preservation
Assess potential for reworking of archaeological materials
Estimate soil productivity (fertility)

mechanisms (Farrand 1985, 2001). Granulometry can be a tool for distinguishing these different sources and mechanisms, as each is likely to produce different grain-size populations (e.g., rockfall versus eolian sedimentation).

Likewise, exposed archaeological sites can be buried by a variety of mechanisms, depending on the geomorphic context. For example, sites located in floodplains could be naturally buried by a combination of alluvial (water-borne), colluvial (movement of material down a slope), or eolian (wind-borne) mechanisms, each with their own implications regarding the preservation of cultural deposits and the ability to reconstruct archaeological systemic context (Waters 1992). Archaeological sites are commonly located on stream terraces along the margins of floodplains. In such locations, overbank deposits from the river commonly interfinger with colluvium and alluvium from hillslopes outside the floodplain, and potentially wind-reworked floodplain deposits. Ostensibly, you can expect that hillslope contributions of sediments on the margins of floodplains would have more variable grain sizes (depending on the nature of hillslope material available for transport) and be more poorly sorted than those formed by low-energy, backwater fluvial deposition or wind-reworked flood deposits. Statistical measures of grain-size distributions, such as particle-size mean, sorting, and skewness values (see Boggs 2001), used in conjunction with other stratigraphic and/or minerological information, can provide more rigorous data supporting interpretations of different sediment origins and modes of deposition.

Equally as important as using granulometry to infer depositional processes is its application for defining post-depositional processes and paleoenvironmental information (Mehringer & Wigand 1986). If a deposit remains at or near the surface for decades, centuries, or millennia, it will undergo a variety of transformations, translocations, and removals that are collectively referred to as *soil formation*, or *pedogenesis* (Holliday 1992; Birkeland 1999; Brady & Weill 1999). Identification of soils is important, as they represent surfaces of stability where past human activity is likely to be concentrated (Mandel & Bettis 2001). Soil formation involves a variety of biochemical processes and mass transfers, and changes to the original grain-size distribution of the parent material are only a small part of the process. Nonetheless, whether it is *in situ* formation of clay minerals or input of eolian dust, relatively coarse-textured deposits become finer textured with time, and the distribution of silt and clay related to pedogenesis should follow a pattern that is recognizable in particle-size data. This pattern is usually a zone of sediment that is low in silt and clay content (e.g., the "A" and "E" horizons of soil) overlying a zone of sediment that is enriched in silt and clay (e.g., "B" horizon) (for an explanation of soil horizonation letters, see Birkeland 1999: 3–8). Hence, vertical changes in texture with depth can be used as an important line of evidence in defining pedogenesis and thus can help in reconstructing depositional history.

In general, post-depositional processes disrupt the systemic context of archaeological materials. Although the best evidence for post-depositional disturbances is field observation and documentation of disturbed stratigraphy, particle-size data can help to distinguish to what degree sediments have been mixed. Geologic processes such as wind and water tend to sort materials by grain size, whereas biotic activity (roots, insects, worms, humans) tends to mix and make deposits less sorted. Sometimes, the type of disturbance process results in particular particle-size patterns. For example, bioturbation by rodents, insects, and roots, particularly in tropical and subtropical environments, often results in a mixed, poorly sorted "biomantle" overlaying a distinct stone line (Johnson 2002). In contrast, sedimentary deposits located in arctic or alpine environments prone to intense freeze–thaw conditions tend to experience the lifting of clasts toward the surface (Wood & Johnson 1978; Waters 1992: 292–9). Each process results in distinctly different vertical grain-size distributions with depth, and granulometry can be used to help elucidate which biomechanical process is likely to have modified the archaeological deposit.

Methods employed in particle-size analysis depend on the sizes of geologic material encountered. In general, large clasts (> 5 cm) can be measured manually with tape or calipers. However, it is more often the case that archaeologists are dealing with deposits that contain a multitude of different grade sizes that are less than 5 cm. In such cases, you are not measuring individual grains but, rather, populations of different grains or soil texture. The overall texture of a deposit can be estimated in the field by adding water to a small sample and assessing plasticity, stickiness, and grittiness by hand (Thien 1979), but the more precise determinations necessary for statistical analyses are usually made in a sediments laboratory. There are several possible laboratory methods used in granulometry (Table 12.1), but all require two basic steps. The first is to pretreat the sediment sample in order to remove materials that might interfere with the measurement of actual mineral grains. The two most common contaminants are organic matter, which adds extraneous mass to the sample, and calcium carbonate, which contributes the calcium ion (Ca^{2+}) that flocculates clay and fine silt. These two contaminants can be removed relatively easily by adding hydrogen peroxide and dilute hydrochloric acid, respectively, and rinsing with distilled water.

The second step in particle-size analysis is to actually break apart and measure the populations of different grain sizes. Traditional methods of measurement involve some combination of sieving and settling analysis (Krumbein & Pettijohn 1938; Janitzky 1986a). Sieving can be performed with dry sediments provided that the sediments are fully disaggregated, usually with a mortar and pestle. Alternatively, sediments can be wet sieved, which better ensures complete disaggregation of silts and clays, but requires drying and thus more processing time. Silt and clay fractions are usually determined by mixing in water and measuring their settling velocity, which can be related to grain size via Stokes' Law (Hillel 1982: 32–3). The two most common approaches for measuring settling velocity in a sediment suspension are the hydrometer and pipette methods (Table 12.1). These traditional methods have the benefit of requiring relatively inexpensive laboratory equipment and reagents, and both have withstood the test of time as reliable techniques for determining sediment texture and/or grain-size distributions. Other, more technologically advanced, methods of granulometry exist, including laser diffraction, where the grain size is related to the scattering of laser light in a sediment/water mixture. Laser diffraction has the benefit of automation (i.e., increased sample processing speed) and the ability to calculate particle-size distributions for small, fine-textured samples. However, the initial start-up costs are greater and traditional methods (e.g., pipette) provide comparable results (Konert & Vanderberghe 1997).

In performing granulometric analysis, you have to decide whether to divide the grain-size population into many precise grades or lump it into fewer, larger grades. The precision – that is, the number of size grades measured – depends on the objectives of the study. If the purpose is simply to define soil texture and objectify field descriptions, then fewer size grades are probably adequate (e.g., gravel, sand, silt, and clay). If the purpose is to deduce and contrast different environments of sediment transport and deposition, and some basic statistical parameters (e.g., particle size mean, sorting, and skewness) are desired (Boggs 2001), then more particle-size grades are necessary. Grain-size distributions can then be presented as relative frequency curves and histograms, cumulative frequency curves, or in tabular format. In most geoarchaeological applications, it is important to display granulometric and other sedimentological data in a way that best demonstrates changes with depth. In tabular format, the samples should be presented in stratigraphic sequence from top to bottom. In graphic format, it is useful to plot changes in values with depth. Because laws of stratigraphic superposition dictate that older deposits occur below younger deposits, vertical changes with depth can help you to reconstruct depositional sequences and identify potential pedogenic or mixing processes. When combined with other chemical data (e.g., pH, organic matter, and calcium carbonate), particle-size data can be a very useful tool for defining site formation processes.

pH

Soil pH is one of the most commonly measured properties of soils. This is because soil pH is a reflection of many important physical and chemical properties (e.g., solubility of metals, nutrient availability, and soil fertility), and is relatively easy to measure. The pH is a measure of hydrogen ion activity in a solution (written as $[H^+]$). Although activity and concentration are not the same, pH can be thought of as a measure of H^+ concentration or, more precisely, the negative logarithm of H^+ concentration expressed in moles per liter:

$$pH = -\log [H^+]$$

Soils in arid and semiarid environments tend to have basic pH values; that is, pH > 7. Soils that contain calcium carbonate almost always have a pH close to that of calcite or 8.0. In contrast, soils in humid environments tend to have more neutral to acidic pH values, especially near the surface where organic acids reside.

In geoarchaeology, pH may be used to help characterize a soil or assess its fertility, or to help test for cultural signatures. Theoretically, cultural sediments should have more organic material that decomposes into humic acids, thus lowering the soil pH. However, archaeological middens that contain abundant wood ash and charcoal may contain elevated pH values (Weide 1966). Agriculturally modified soils ostensibly should have different pH signatures than nearby soils that were never tilled and cultivated, although the direction of pH change will vary with local conditions. In all cases, it is important to note that soil pH is a highly ephemeral property of soil, one that can change relatively rapidly in response to changes in the soil environment. Factors that can affect soil pH include parent material, texture, climate, vegetation, and groundwater, as well as human activity.

Soil pH is usually measured either by colorimetric or electrometric methods (Table 12.1). The colorimetric method is based on the fact that certain organic materials change color at different pH values. Indicator solutions – for example, phenolpthalein and methyl orange – can be used to determine pH, as can strips of paper coated with such solutions (e.g., litmus paper). Colorimetric methods can be useful in the field, but are not as precise as electrometric methods.

The electrometric method is based on the fact that H^+ concentration is proportional to electrical potential (Bohn et al. 1985: 227–31). Hence, a pH meter is a modified voltmeter that converts electrical potential into pH. It is important to be aware that several factors influence the measured pH. These include (1) the nature of the material being measured – in other words, what is contributing the H^+ – (2) the soil/solution ratio, (3) the salt content of the soil and solution, (4) the carbon dioxide (CO_2) content, (5) the temperature of the soil solution, and (6) errors associated with equipment calibration (McClean 1982). Consequently, when reporting pH results, it is important to state the method and some of these parameters if known.

Organic Matter

Determination of organic matter content in sediments is a common and useful type of analysis in archaeology. For archaeological studies, recognition of soil organic matter is important because it may indicate former surfaces of stability that supported human activity, and cultural materials are more likely to be concentrated within such zones. There are two general pathways for organic matter to occur in sediment: (1) organic matter that is formed elsewhere and deposited with nonorganic sediment, and (2) organic matter that forms *in situ* through *pedogenesis* (Stein 1992). Attempts to distinguish depositional and soil organic matter in an archaeological deposit may turn out to be difficult. Where different lines of evidence point toward pedogenesis (e.g., color change, structure, bioturbation features, or abrupt upper surface contact but gradual lower surface contact), an *in situ* origin is likely. *Humification* – that is, the *in situ* development of soil organic matter – is probably the most rapid pedogenic process (Birkeland 1999: 215), and incipient soils are often identified by increased soil organic matter. However, both processes are not mutually exclusive, and indeed alluvial and colluvial soils normally have both components.

Furthermore, if numerical age control is desired, organics in sediments can be ^{14}C dated (see Chapter 5), and interpretation of the result will depend heavily on whether the origin of the organic matter is depositional or pedogenic. If pedogenic, the ^{14}C age can be viewed as an apparent mean age of the organic matter formed during that period of surface stability (Taylor 1987; Wang et al. 1996). If depositional, then the resulting age will be older than the depositional event, with a greater apparent discrepancy between the apparent and true ages.

The identification of organic matter in sediments also has paleoenvironmental implications, especially if derived through pedogenesis, where A horizon development may reflect environmental change (Moody & Dort 1990; Reider 1990; Nordt 2001). In most paleoenvironmental studies, the focus is on changes through time in organic matter accumulation. However, in archaeological sites, it may also be useful to define vertical and horizontal variability in organic matter content. In archaeological contexts, irregular spatial patterning might relate to intra-site features such as storage pits, hearths, and middens, or human activity areas such as animal processing sites. Obviously, the sampling strategy for assessing organic matter content will be heavily influenced by whether the intended goal of the study is to identify surfaces of stability (paleosols) or human activity areas.

Organic matter consists mostly of carbon, hydrogen, and oxygen, with smaller amounts of nitrogen, phosphorus (discussed below), and sulfur. Obviously, there are different types of organic matter with different proportions of these elements. Organic matter content is commonly determined in a laboratory by measuring only the amount of organic carbon and then multiplying by an empirically derived value to estimate total organic matter. A traditional method for measuring total soil organic carbon has been to determine the weight loss of a soil sample after cooking at 500°C (932°F) in a furnace (commonly known as "loss on ignition" or LOI; Table 12.1). This method works best with sandy, well-drained, nonalkaline soils (Ball 1964). Alternatively, the Walkley–Black method can be used, whereby organic matter is oxidized with a chemical reagent (Walkley & Black 1934). The method works relatively well, although sources of error include incomplete oxidation of organic matter and problems with interference by other oxidizable material; for example, ferrous iron (Fe^{3+}) in magnetite. In the latter case, samples can be treated with a magnet prior to analysis to minimize the problem. In the Walkley–Black method, the resulting organic carbon content is multiplied by a conversion factor to arrive at an estimate of percent soil organic matter. Traditionally, a conversion factor of 1.72 is used (the Van Bemmelen factor), because it was assumed that organic matter contained 58 percent organic carbon. However, it is now known that the percentage of organic carbon in organic matter is variable, and thus any factor selected is only an approximation. Consequently, some soil scientists feel that the results obtained from the Walkley–Black method should be considered semiquantitative (Nelson & Sommers 1982). On the other hand, the method is still commonly employed in both geoarchaeological and geomorphological studies due to its relative simplicity and reasonably accurate results (Holliday & Stein 1989).

Phosphorus Phosphorus analysis is commonly employed in archaeological studies as an indicator of previous human activity in soil. Like organic carbon, phosphorus is incorporated into soil through both soil formation and deposition of organic matter. Although it is a minor constituent of soil organic matter, unlike most of the other organic elements, phosphorus binds with other soil materials, resists leaching, and persists for a relatively long time. Hence, areas of cultural activity may have elevated phosphorus levels in soil whereas other chemical indicators are no longer present. In general, elevated phosphorus is a signature for cultural activity at archaeological sites, and it has been applied to locating past settlements, reconstruction of land use, and identification and explanation of human activity areas (Schuldenrein 1995; Vizcaino & Canabate 1999; Terry et al. 2000). In most cases, human activity is associated with elevated phosphorus levels in soil, presumably due to the disposal of organic wastes. However, prehistoric agricultural areas may actually be identified by reduced phosphorus levels (Sandor et al. 1986). Furthermore, Eidt (1977, 1985) believes that the ratios of different phosphorus fractions in soil can be used to provide relative ages for cultural deposits. Hence, phosphorus analysis has many potential applications in archaeology.

There are different ways to measure soil phosphorus. A simple, qualitative method is called the *spot* or *ring* test. This can be performed in the field by adding acid extractant and color reagents to a sediment sample and assessing color changes on filter paper. Although qualitative (or semiqualitative if diffusion of color on filter paper is measured; e.g., Dormaar & Beaudoin 1991), this method has been repeatedly used in archaeological survey to identify human-affected soils and occupation areas where overt evidence of human activity is absent. More accurate measures of phosphorus are performed in a laboratory and commonly employ elaborate extraction techniques and analysis (Olsen & Sommers 1982). In such cases, the researcher has to determine what type of phosphorus is to be measured. Phosphorus seldom occurs in its elemental form. Instead, it is usually bound with oxygen-forming phosphate ion (PO_4^{3-}), which in turn bonds with other materials such as iron oxyhydroxides, aluminosilicate clay minerals, and organic compounds (Bohn et al. 1985: 190–4). In general, phosphorus occurs in one of three forms in soil: fixed, soluble, and organic (Eidt 1985). Fixed inorganic phosphorus is tightly bound with iron and aluminum minerals in acidic soils and calcium minerals in alkaline soils. Soluble phosphorus is loosely bound or in solution (normally present in very small quantities), and organic phosphorus is that still incorporated within organic matter. All three phosphorus types can be measured as "total phosphorus," or individual fractions can be analyzed, the latter requiring greater laboratory work. Eidt (1977, 1985) is an advocate of analyzing different fractions that might yield more precise cultural and chronological information, whereas others are less certain of the results (see Bethell & Mátè 1989). Spot or ring tests analyze only the amount of soluble or "available" phosphorus, which does not always correlate with inorganic or total phosphorus.

Once the type of phosphorus to be analyzed is determined, the first step is to extract it from sediment. Phosphorus extraction is performed using either an acid or alkali solution, depending how the phosphorus is bound: low-pH soils require an acid extraction, whereas high-pH soils require an alkali extraction (Olsen & Sommers 1982). Hence the pH should be determined first to help select the appropriate extraction method. Inorganic phosphorus is more tightly bound and requires more rigorous extraction methods than soluble phosphorus. Total phosphorus requires rigorous digestion or ignition of the soil sample in order to oxidize organic matter and mineralize the organic phosphorus. After PO_4^{3-} is extracted, it is ready to be analyzed. Commonly, a colorimetric method is used whereby PO_4^{3-} is complexed with a reagent (e.g., ammonia molybdate), yielding a colored solution. Spectrophotometry, which measures the absorbance and transmission of polarized light through a colored solution, can subsequently be performed on the samples of unknown phosphorus content and then compared to a set of control samples of known phosphorus concentration. If phosphorus is to be used as a discriminator of possible areas of past cultural activity, it is essential that analyses be performed on both sediments suspected to have been affected by human activity and nearby "nonimpacted sediments" for control, and such control samples should be from comparable pedogenic and geomorphic contexts.

Case Study 1

Prehistoric Canals in the American Southwest

Despite the possible applications of the laboratory methods described above in regards to reconstructing site formation processes and paleoenvironmental context, whether or not these methods should be employed in an archaeological investigation depends in large part on the questions to be addressed. Clearly, it is best to have specific research questions in hand and an idea of how laboratory analyses will help to answer those questions prior to sampling sediments in the field. Whereas sedimentological analyses usually yield some type of information relevant to archaeological enquiry, especially where excavation is involved, the cost of a full set of laboratory tests may not be warranted. In some cases, only one type of analysis may be required, whereas in others, multiple types of sedimentological analyses would be beneficial. In the first case study presented here, granulometry was selected as the key laboratory method for a geoarchaeological study of prehistoric canals.

An exciting research domain in American Southwest archaeology is to define the development and expansion of agriculture over the past 4,000 years. Maize worked its way up from central Mexico into the arid and semiarid lands of the Southwest by 2000 BCE (Matson 1991; Huckell 1996). The impact that this new way of life had on previous Archaic peoples was tremendous in terms of population, mobility, and social–political organization (Hard & Roney 1998). It had long been thought that it took a couple of thousand years for food production to evolve from horticultural dry and floodwater farming to intensive canal irrigation. However, recent discoveries of prehistoric canals in Arizona and New Mexico, dating to c.1000 BCE (Mabry et al. 1997; Damp et al. 2002), indicate that indigenous farmers began engineering and controlling water for food production much earlier than previously realized. By CE 600, canal irrigation had become a major way of life for farmers living in the low deserts of Arizona. The Hohokam (CE 600–1450) constructed the largest pre-Columbian canal systems in North America, with over 500 km of canal alignments mapped in the Phoenix Basin alone (Masse 1981; Howard & Huckleberry 1991; Figure 12.1). For reasons that are not fully understood, the Hohokam began struggling to meet the dietary needs of their people in the 1300s (Abbott 2003), and by 1450 huge swaths of desert were abandoned, including areas that had been witness to over 1,500 years of canal irrigation.

To understand the ecology of the Hohokam is to understand their canal systems, the lifeblood to their society, around which they organized their communities and farms. Historical photographs and archaeological excavations indicate that the canals were hand-excavated and well designed in terms of their engineering properties, such as channel geometry and gradient. Canal channels were parabolic to trapezoidal in form, with widths ranging from 1 to 10 m; the largest canals supported up to 10 m^3 per second of flow. Main canals connected to a series of smaller distributary and field lateral channels through a series of stone and brush-constructed water control structures (Masse 1991). Unfortunately, historical agriculture followed by modern urbanization has effaced over 99 percent of the prehistoric canal systems over the past 150 years. Nonetheless, the middle to lower dimensions of these linear features remain intact beneath plowed fields and city streets in the Phoenix Basin. The city of Phoenix is currently the second fastest growing city in the United States, and development projects over the past 20 years have provided archaeologists an opportunity to study the subsurface remains of these relict canal systems. These irrigation features are unlike most archaeological features in that they are linear and usually extend beyond the borders of a given project area. Moreover, they are defined solely by sediments and are amenable for geoarchaeological analysis. An investigation of prehistoric canals is by default an analysis of sediments and stratigraphy.

A recurrent question regarding Hohokam canals is the degree to which they were resilient or susceptible to environmental fluctuations such as floods and droughts. Indeed, a combination of geologic data (Huckleberry 1995; Waters & Ravesloot 2001), and archival records of historic canals (Ackerly 1989; Huckleberry 1999a) suggests that Hohokam canal systems were vulnerable to frequent floodplain dynamics associated with large floods, resulting in headgate destruction and siltation within channels. These canals had to be maintained and rebuilt regularly, which required large pools of human labor. If periods of recurrent flood damage combined with alternating periods of drought, a probable outcome would be collapse of the canal systems and consequent food stress.

Dendrohydrological reconstructions of annual runoff on the major rivers supplying the canals suggest that increased runoff variability (i.e., flood and drought) coincided with the decline of the Hohokam, starting in the late 1300s (Nials et al. 1989; Gregory 1991). If the decline of the Hohokam was due in part to increased canal system instability caused by increased flood frequency and magnitude, then there should be recurrent sedimentological evidence for uncontrolled flooding within the fill of the abandoned canals. Such evidence should be manifested in the grain sizes of canal sediments and changes in mean grain size and sorting within a depositional sequence. Ostensibly, sediments deposited in canals through normal operation and controlled water flow should be dominated by silt and clay, and should be relatively well sorted. In contrast, flood-damaged canal headgates allow large, erosive volumes of water to penetrate the system, depositing coarser-textured sediments dominated by sand and possibly fine gravel.

Over 20 years, numerous archaeological investigations in the Phoenix area have resulted in the collection of granulometric data on many prehistoric canals. Whereas these sediments do provide insights into past canal operation and flow history, several limitations are recognized. One is that much, if not most, of the canal has been destroyed by historical plowing and more recent urban mixing, such that only the middle to lower dimensions are preserved. Also, short canal alignment segments far from the system headgate are usually sampled with little understanding of their specific context within the larger irrigation system. In general, only an approximate distance from the headgate can be estimated. It is important to know exact distances from headgates, because high-energy alluvium produced through flooding ostensibly decreases in mean grain size down the canal channel, and it is thus difficult to compare mean grain-size values between different channels without knowing where within each system the segments are located. Despite these limits, sediment samples collected during these investigations should allow you to estimate whether or not canal deposits are reflective of high-energy, flood-like conditions, or more controlled, lower-energy flow regimes.

To test for the presence of flood stratigraphy in prehistoric canals, I compiled 363 sediment samples from 45 Hohokam canal segments excavated in the Phoenix metropolitan area in the 1980s and 1990s for which granulometric data exist (Huckleberry 1999b). These canals are the vestiges of approximately 1,500 years of water diversions from the lower Salt River. In most cases, only percentages of sand, silt, and clay are available, thus precluding the ability to construct detailed cumulative frequency distributions and statistical measures of graphical mean and sorting. Instead, I focused on characterizing the general texture of individual deposits and how they change from the bottom to

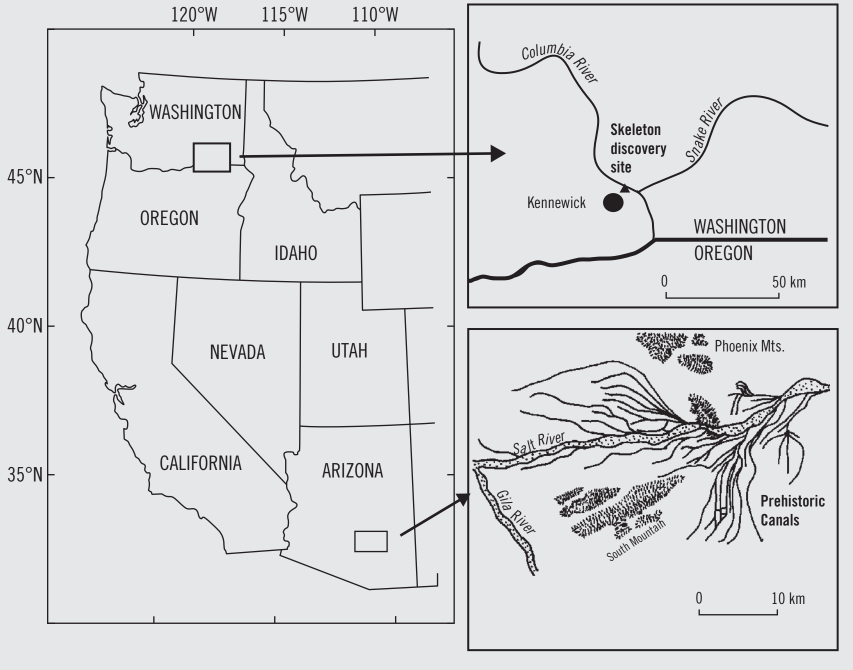
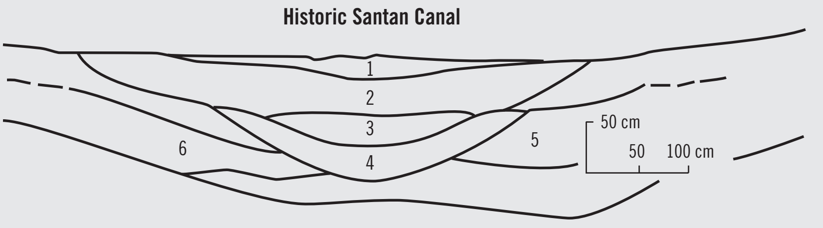


Figure 12.1 Two case study project areas in the western USA. Case study 1 is located in the Phoenix Basin of south-central Arizona. Case study 2 is located on the banks of the Columbia River in the town of Kennewick, Washington.

the top of the extant channels. I divided a simple ternary textural triangle into four areas and developed indices (e.g., clay-dominant = 1, silt dominant = 2, loamy sand = 3, and sand-dominant = 4). Each integer was used to assign an overall texture to each deposit and allowed for analysis of bedding sequences (e.g., coarsening versus fining upwards). Statistical calculations including Markov chain analysis indicated that no recurrent depositional cycle is evident, and that overall, most canal fill sequences are silt-dominant and relatively uniform, with a few exceptions. Some large, main canals located within the floodplain of the Salt River clearly contain high-energy, coarse-textured sediments in the upper part of the channel. On the basis of archival accounts of Anglo-European earthen canals from the late nineteenth and early twentieth centuries, uncontrolled floods would deposit sediment along most of the canal alignment. By reasonable hypothesis, the resulting depositional sequence should be relatively coarse (flood) sediment overlying relatively fine (canal operation) sediment, and such relative textural changes should be evident several kilometers from the headgate. However, the granulometric analysis of 45 Hohokam canals failed to identify this in more than just a few cases. Canal depositional sequences capped by relatively coarse-textured sediments are generally rare.

By itself, the paucity of flood-like sediments argues against floods reeking havoc on the Hohokam canals. Nonetheless, it is possible that canal flooding was a recurrent problem but did not produce the expected depositional sequence, or that the flood sequence is missing because only the middle to lower dimensions of the canals are preserved. Some sort of calibration was needed whereby relict canals known to have been flood damaged and abandoned could be sedimentologically analyzed and characterized. Toward that end, I performed granulometric analysis on sediments from abandoned main canal segments located along the Gila River (Figure 12.1), which are documented to have been destroyed by large floods in the early twentieth century (Huckleberry 1999a). In this case, I performed detailed granulometric analysis such that cumulative frequency curves and statistical measures could be calculated. The granulometric data confirmed that most flood-damaged, main canal segments located close to the system headgate do contain a coarsening-upward depositional sequence (Figure 12.2), but the overall textures are quite variable, ranging from silt to coarse sand. Gravel is generally not present. Moreover, because the canals may be partly filled with sediments from normal operation, flood sedimentation may be limited to the uppermost parts of the channel. In the case of most prehistoric canals, such sequences will have been removed by historical plowing. Thus flood damage to canals cannot be ruled out as a contributing factor to the collapse of the Hohokam, despite the paucity of flood-like stratigraphy. Flood deposits far removed from headgates might be dominated by relatively low-energy silt, or flood deposits may not be preserved. Sediment analysis of both partially preserved prehistoric and fully preserved historic canals thus provides insight into the depositional processes that form these features.



Stratum	Graphic mean (ϕ)	Graphic mean (mm)	Sorting (ϕ)	Skewness (ϕ)	Sand (%)	Silt (%)	Clay (%)
1	1.0	0.51	1.6	0.0	94	3	3
2	2.3	0.20	2.2	0.2	87	7	6
3	2.5	0.18	1.5	0.5	90	4	6
4	4.1	0.06	1.9	0.6	65	28	7
5	3.5	0.09	1.7	0.4	72	22	6
6	4.9	0.03	3.3	0.3	44	39	17

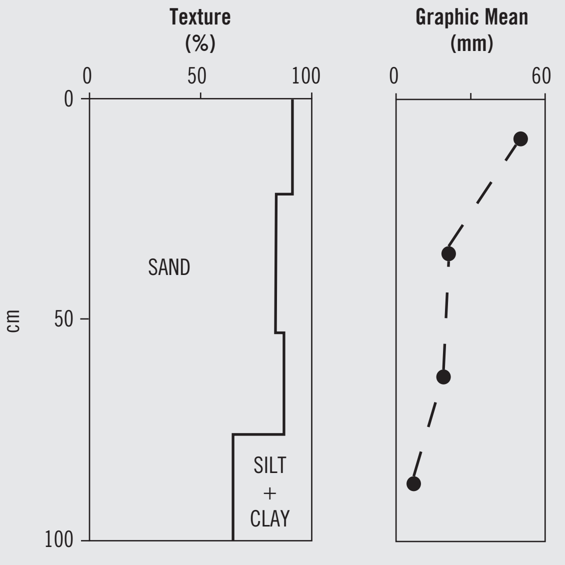


Figure 12.2 The profile and granulometric data for the relict canal located on the Gila River, south-central Arizona (canal profile reproduced from Huckleberry 1999b: fig. 4).

Case Study 2

Kennewick Man, Washington State, USA

Sedimentological analysis has also contributed to resolving a much more contentious issue regarding the appropriate disposition of a 9,000-year-old set of human remains. In the summer of 1996 in the town of Kennewick, Washington (Figure 12.1), two young men found a human skull in shallow water along the shore of Lake Wallulla, a dammed segment of the Columbia River. Little did they know that this skull and associated bones represented the oldest well-preserved skeleton in the Pacific Northwest, or that its discovery would set in place a high-profile lawsuit pitting scientists against Native Americans and the US Federal Government (Downey 2000; Thomas 2000; Chatters 2001). A coalition of Native American tribes requested that the skeleton be returned to them for reburial, following their interpretation of a federal law known as the *Native American Graves Protection and Repatriation Act* (NAGPRA). This law has several statutory components, one of which states that all human remains and associated materials (e.g., funerary objects) recovered from public land that are found to be Native American are to be turned over to culturally affiliated tribes. However, many scientists and their supporters argue that these remains are too old to be culturally affiliated with modern tribes and, given their scientific importance, that they should be archived for future study. The conflict is multifaceted, involving components of science, religion, law, and politics, the details of which go far beyond the scope of this chapter (see “Resources” and also Chapter 2). Of interest here is how sediment analysis played a role in the investigation of the skeleton.

The skeleton had apparently eroded out of the stream bank in the spring of 1996 and lay in shallow water for several months. Over 90 percent of the skeleton was recovered along the shore (Chatters 2000), but it was unclear where in the stream bank the skeleton was originally contained. A preliminary, noninvasive geologic study of the shoreline was commissioned by the US Army Corps of Engineers, the agency in charge of the land where the skeleton was found. Performed in December 1997, this study, which was submitted to the US Army (Wakeley et al. 1998), provided important information regarding the general stratigraphic context of the skeleton as well as general geomorphic setting. Stratigraphic profiles, soil descriptions, and sediment samples were collected; sediment analysis included granulometry, petrography, and pH. In addition, several samples of organic sediment from the stream bank and subsurface vibracores were ^{14}C dated.

The stream bank marks the edge of an early Holocene Columbia River terrace and provides a less than 2 m exposure of deposits (Figure 12.3). The upper unit, Lithostratigraphic Unit I, is composed of loose to friable fine sand to very fine sand, and ranges from 25 cm to 80 cm in thickness. Many of the larger quartz sand grains are frosted, suggesting eolian transport. Mazama tephra, dated at 7,600 BP, is discontinuously

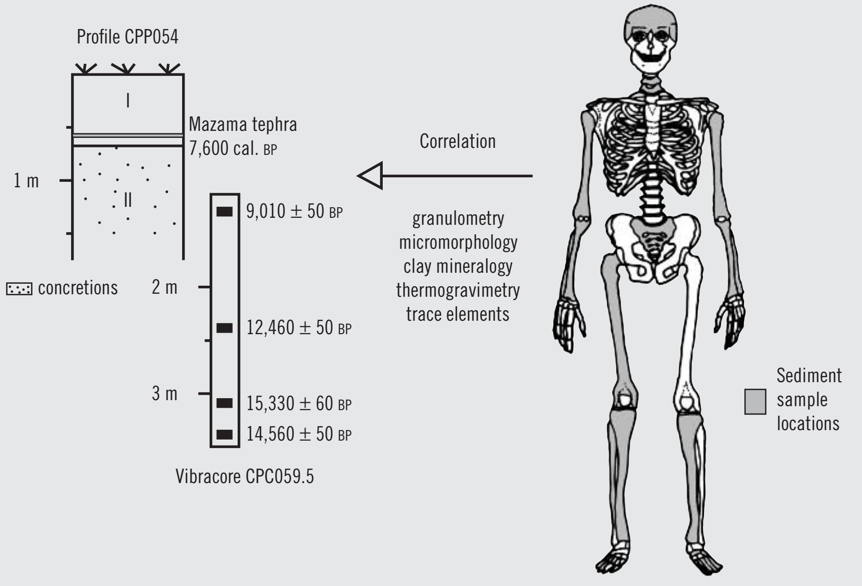


Figure 12.3 Skeleton sediment sample locations and geochronology at the Kennewick Man discovery locality. Physical and chemical tests of sediments were used to correlate the skeleton to the upper part of Lithostratigraphic Unit II, thus supporting the early Holocene age of the human remains (skeleton reproduced from Huckleberry et al. 2003: fig. 3).

preserved at or near the base of Unit I. The lower deposit, Lithostratigraphic Unit II, is exposed in the lower part of the terrace edge, although vibracores were used to provide additional subsurface information. Unit II is a finer-grained deposit, which is characterized by weakly preserved, horizontally bedded, very fine sand and silt. In places, very fine, centimeter-scale graded bedding is evident in the upper deposit, but most of the primary bedding is not preserved in the upper 1 m due to bioturbation. Bedding becomes more distinct below 2 m and consists of several more distinct coarse-to-fine graded and cross-bedded sequences. The upper part of Unit II contains numerous calcitic concretions formed through soil formation, that match similarly described concretions on the exterior of post-cranial elements on Kennewick Man. This suggested that the skeleton likely came from the upper part of Unit II, which would match the ~ 9,000-year-old ^{14}C age of the skeleton (Taylor et al. 1998). Although scientists recommended that further testing be done (Wakeley et al. 1998), the US Army Corps of Engineers buried the site with tons of earth and rock debris, citing concerns of further erosive damage.

While the case was tied up in court, the federal government elected to perform a series of nondestructive tests on the skeleton in 1998, in order to better determine the applicability of federal law to these remains. Specifically, the federal government needed to confirm that these remains were “Native American” in order to fall under the jurisdiction of NAGPRA. They elected to use a chronological criterion for Native American status:

if the skeletal remains predate the year 1492, they are to be interpreted as "Native American." A single ^{14}C date indicated that the remains were approximately 9,000 years old, and the geologic study at the discovery site suggested that the remains predate a volcanic eruption dated at 7,600 BP. However, given the importance of this lawsuit, the government wanted additional chronological information, preferably without performing more ^{14}C dating, which would require additional destructive sampling of the skeleton, something opposed by most Native Americans. In an effort to better correlate the bones to the geologically dated levels at the discovery site, the government elected to perform a nondestructive analysis of sediments adhering to the skeleton. Although the preliminary geologic study of the site suggests that the skeleton came from the upper part of Unit II (confirming a pre-7,600 BP age), and an independent sediment analysis by Chatters (2000) correlated the skeleton to a more specific depth within the upper part of Unit II, the government wanted to test that hypothesis and affirm the early Holocene age of Kennewick Man. Interestingly, the requested sedimentological study is similar to those performed in forensic geology, whereby sediments are used to link a suspect to a crime scene (Murray & Tedrow 1992). In this case, the physical and chemical properties of sediments on the skeleton were to be compared to sediments from the stream cut in an effort to better define the provenance of the original skeleton. I was asked by the federal government to participate in the investigation. My colleagues and I selected laboratory tests including granulometry, thin-section and micromorphology analysis, X-ray diffraction (clay mineralogy), thermogravimetry (loss on ignition), and trace element analysis (Huckleberry et al. 2003). Unfortunately, detailed sampling at the discovery site for control was not possible because of its recent burial by the federal government. Consequently, sediments collected at the skeleton recovery site during the 1997 study were analyzed for comparison. These sediments were from stream bank profiles and a vibracore that sampled subsurface shoreline sediments (Figure 12.3). Granulometry data compiled by James Chatters (2000) during his original study of the site was also used in the analysis.

The main hypothesis to test was whether or not sediments located on the surface of post-cranial bones and within the cranium match those from the upper part of Lithostratigraphic Unit II (60–150 cm depth) containing the calcite concretions (Figure 12.3). Thermogravimetric analysis is a detailed measure of weight loss as a sediment sample is progressively heated to temperatures at which organic matter and calcite oxidize. It allows for an analysis of both components, and in this case demonstrated nicely that concretions from both the skeleton and Unit II are chemically similar (Table 12.3), further supporting a correlation. Another goal was to determine whether vertical changes in the physical and chemical properties of Unit II were sufficiently distinct to discern the depth of burial within a range of 20–30 cm. Chatters (2000) used granulometric data to indicate that sediments on the skeleton best match terrace sediments at depths of 80–85 cm and 135–140 cm. However, our analyses indicated that differences in grain size and sorting within Unit II are statistically insignificant, a likely result of bioturbation

Table 12.3 Organic matter and calcite data from (a) the Kennewick study site and (b) the skeleton (Huckleberry et al. 2003).

(a)

Location	Depth (cm)	Stratum	Organic matter (%)	$CaCO_3$ (%)
CPP054	10–20	I	2.2	2.8
CPP054	30–40	I	2.1	4.5
CPP054	50–60	I	1.7	6.7
CPP054	70–80	II	1.5	8.7
CPP054	80–90	II	1.0	48.7[a]
CPP054	95–135	II	1.8	5.0
CPC059.5	0–10	II	1.4	35.0[a]
CPC059.5	30–40	II	1.6	1.8
CPC059.5	60–66	II	1.7	1.8

[a] Analysis on concretion

(b)

Location	Element	Material	Organic matter (%)	$CaCO_3$ (%)
Ox coxea	97A.I.17a	Dark sediment	2.3	3.7
Metatarsals	97.L.24 (Mta + Mtb)	Concretion	1.8	18.5
Cranium	97.U.1a	Sediment	1.2	6.7
Unidentifiable fragment	97.I.25c	Concretion	1.2	51.5
Femur	97.R.18a	Sediment	1.3	18.4

(Huckleberry et al. 2003). Likewise, post-depositional processes and consequent homogenization of fluvial beds preclude any distinct matches in organic matter, calcium carbonate, mineralogy, or trace element chemistry at spatial scales of 10–20 cm. Instead, pedogenesis has mixed the originally stratified deposits such that the skeleton can only be correlated to a ~ 90 cm zone in the upper part of Unit II. We were, however, able to distinguish sediment derived from the original burial and darker sediment (e.g., element 97 A.I.17a, Table 12.3) that became attached to the skeleton after eroding out of the bank. We concluded that the skeleton is from a stratum located beneath the Mazama tephra and at an approximate level that ^{14}C dated to 9,010 ± 50 BP. Hence, the early Holocene age of the skeleton is further supported by these tests. Interestingly, the federal government, in an effort to be as certain as possible that Kennewick Man was indeed pre-Columbian in age, later elected to perform further ^{14}C tests of the skeleton, the results of which confirmed the age of approximately 9,000 years.

In sum, analysis performed on sediments attached to Kennewick Man and the original burial site was nondestructive to bone and further supported the hypothesis that the skeleton was derived from the upper part of a geologic unit that was approximately 9,000 years old. This added further credence to the original ^{14}C date on the skeleton, based on the geologic age of the deposits. It was not possible, however, to further distinguish the burial depth of the skeleton, due to insufficient variance of sediment chemistry, texture, and mineralogy with depth. It also remains to be proven whether or not the skeleton was interred in the ground by human hands or buried by flood sedimentation (Chatters 2001; Huckleberry et al. 2003). If the US Army Corps had not buried the site in 1998, more detailed sampling of control sections may have improved the precision of the analysis. Although questions remain regarding the burial context of Kennewick Man, these studies are a good example of how sedimentology can provide useful contextual information that otherwise might not be available for these controversial human remains.

Conclusion

The value of sediment analysis has long been recognized in archaeology, given that sediments and stratigraphy constitute an important environmental and chronological framework for interpreting the material record. To extract the maximum amount of information from archaeological sediments, you should be able to objectively and systematically observe and record sedimentological and stratigraphic features in the field. Indeed, this is probably the most essential skill in geoarchaeology, and one that I emphasize in my class. Beyond that, you need to turn to laboratory methods for confirming field observations and generating and/or testing hypotheses regarding site formation or contextual information for individual objects and features. There are a variety of laboratory methods for analyzing sediments, many of which do not require expensive, high-tech, or elaborate equipment. This chapter has reviewed some common laboratory methods for grain size, pH, organic matter, and phosphorus, and provided two examples where laboratory analyses of sediments helped to address archaeological questions. A proper combination of rigorous field descriptions and prudent laboratory testing can help to bolster interpretations and test hypotheses linking the physical evidence at archaeological sites to the ultimate goal of reconstructing human behavior.

Resources

For contrasting opinions on the Kennewick Man controversy, see www.cr.nps.gov/aad/kennewick/, www.saa.org/repatriation/index.html, www.umatilla.nsn.us/ancient.html, and www.friendsofpast.org

For a chronology of events related to the case, see www.kennewick-man.com/

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