

Correcting and Using Carbon-14

Whereas the last lecture covered the principles of Carbon-14 dating, this lecture will deal with actual Carbon-14 dates and their use. Measuring age with Carbon-14 is rather more involved than one might expect, and numerous factors must be accounted for in order to obtain an accurate age estimate of prehistoric objects. Only with due consideration of all possible problems can Carbon-14 dating shed light on important archaeological questions, such as the controversy surrounding when and how people first arrived in the New World.

1 Actual Carbon-14 Dates

The basic procedure for obtaining Carbon-14 dates was described briefly in the last lecture. However, if we want to discuss actual Carbon-14 dates, we need to go into a little more detail into how these measurements are made.

1.1 The raw (uncalibrated) Carbon-14 Dates

Carbon-14 has (almost) the same chemical properties as ordinary carbon. Therefore, all living organisms that exchange carbon with the atmosphere should pick up and give off Carbon-14 atoms as easily as the other forms of carbon. The **Carbon-14 fraction** (the fraction of carbon atoms in the form of Carbon-14) of any such organism should therefore be the same as the Carbon-14 fraction of the atmosphere. If the fraction of the Carbon-14 atoms in the atmosphere has remained a constant in time, then all (land-dwelling) organisms should have had the same Carbon-14 fraction while they were alive. After the organism dies, the Carbon-14 atoms decay with a well-defined half life of about 5700 years. The Carbon-14 fraction therefore falls at a predictable rate (The Carbon-14 fraction is half its original value after 5700 years, a quarter its original value after 11,400 years, and so on). The time when the organism died can therefore be calculated, given the original and current Carbon-14 fractions.

The current Carbon-14 fraction of a once-living object can be measured directly using the radioactivity of the Carbon-14 or the AMS methods discussed in the last lecture. On the other hand, the original Carbon-14 fraction must be estimated by various means. As a practical matter, standard Carbon-14 dates estimate the original Carbon-14 fraction using a contemporary reference sample, which has a known Carbon-14 content relative to a bunch of sugarbeets that lived in 1950. This procedure therefore provides an estimate the number of years between when the organism died and 1950. Carbon-14 dates are therefore given in terms of “years BP”, where BP means “Before 1950” (The letters originally stood for “Before Present”, but they have since been reinterpreted as “Before Physics”).

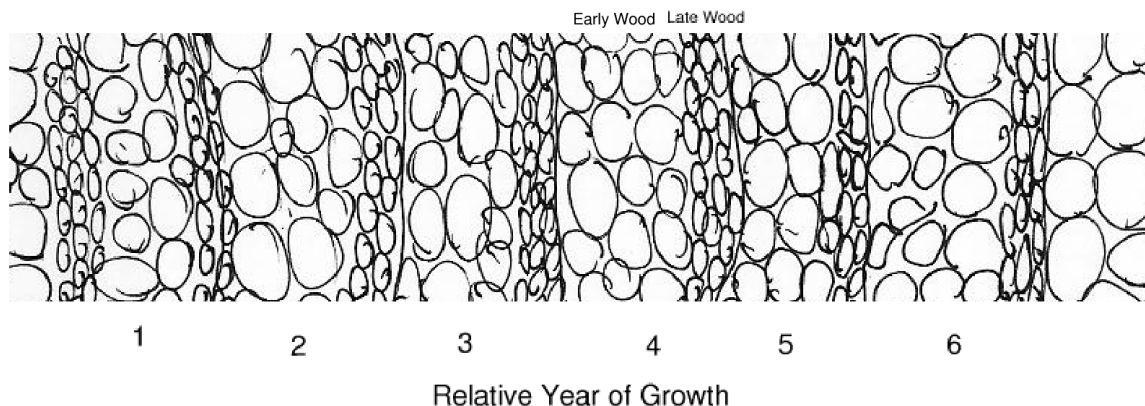


Figure 1: Tree rings. Each year, the wood produced by the tree starts out with an open structure to allow maximum water flow up from the roots to the growing leaves, while later in the year the material becomes denser as the need for water declines. This pattern repeats every year

This conventional estimate of the Carbon-14 age has the practical advantage that it is derived from a clearly defined procedure and the only uncertainty in the number derives from the statistical uncertainties in the measurement itself. However, this number only provides an accurate estimate of the real age of the object if the living organism had the same Carbon-14 fraction as the reference sugarbeets did. This is not true in general, and a variety of corrections must be applied to the estimated Carbon-14 dates to derive accurate measurements of the time since any given organism died.

1.2 Dendrochronology and Carbon-14

Perhaps the most important factor which impacts the accuracy of Carbon-14 age estimates is how the atmospheric Carbon-14 fraction changed with time. If this fraction was different at some time in the past, then the original Carbon-14 fraction of all organisms at this time would be different from that of the reference sugarbeets, and the estimated ages would be systematically off.

Variations in the Carbon-14 content of the atmosphere can be measured using objects with a known age. By comparing the real age of these objects with the Carbon-14 estimates, we can look for discrepancies which indicate that the atmospheric Carbon-14 fraction fluctuated in time. The trick is that we need ancient once-living material with ages determined by some method other than Carbon-14. Fortunately, such material exists in the form of tree rings.

Everyone is familiar with the pattern of dark and light rings present in any cut piece of wood. This pattern reflects how the tree grows over the years. The wood is part of the tree's vascular system, which carries water up from the roots to the leaves (see figure 1). Only the outermost layer of tissue actively carries fluids, and layers are constantly being added under the bark to the outside of the tree. In spring, as new leaves are growing, the demand for water is relatively high, and the tissue has a relatively open structure. As the season goes on, the need for water declines and the tissue becomes denser and more structural, with less open spaces for water

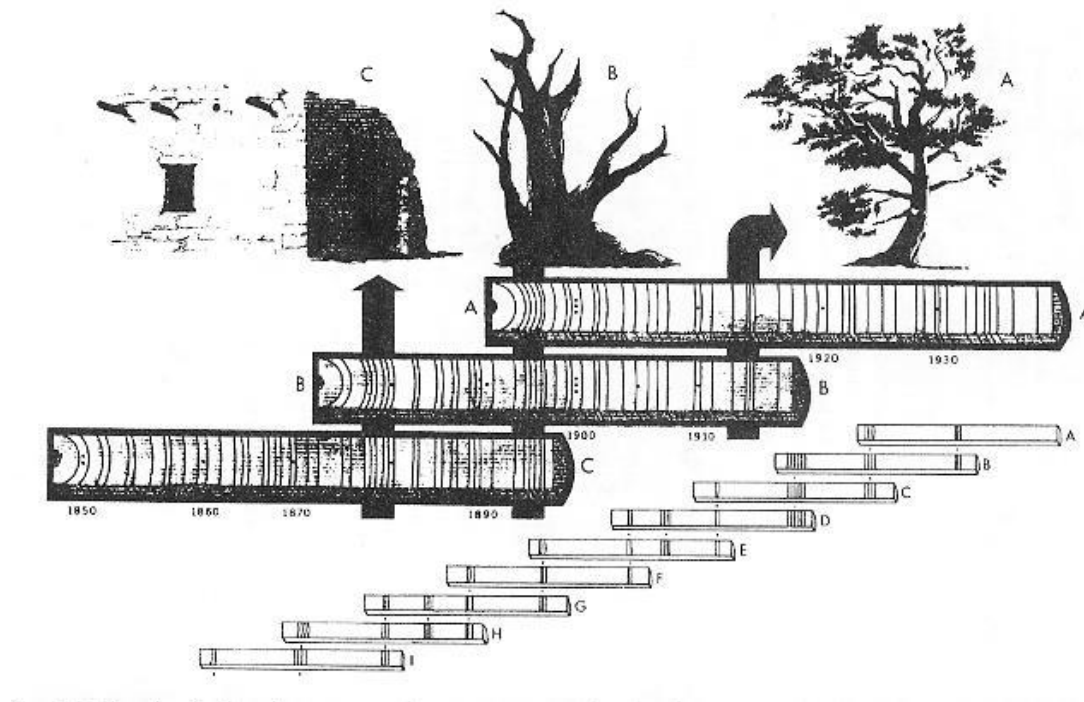


Figure 2: The basic idea of dendrochronology (Taken from Taylor and Aitken's *Chronometric Dating in Archaeology*) Different trees from the same general area produce the same pattern of rings. By matching these patterns, a record on tree-rings can be extended far into the past

to flow through. This continues until winter, when the tree is relatively dormant, and the next spring the cycle starts all over again. Each ring (consisting of a light and dark band) therefore corresponds exactly to one year of growth.

These rings not only provide a way to measure the age of the tree, but also are the basis of **dendrochronology**, which allows us to determine exactly when year each ring in the tree was made, even if the tree has been dead for thousands of years. Depending on local weather conditions, the amount the tree grows varies from year to year. This means the rings have different thicknesses in different years. Since trees growing in the same general area experience similar growing seasons, these variations in the ring thickness are repeated in different trees. By matching the patterns in trees of different ages, we can generate a continuous record of tree-rings, with a specific year assigned to each and every ring (see figure 2). For example, say we have one log of known age, so we know exactly when each and every ring in that log was made. Now we find a second log, with a pattern that partially overlaps with the original log. If the match is correct, we now know when all the rings in that log were made, including those that were made before any of the rings in the first log. Repeating this procedure over and over again yields extremely long sequences of rings, covering thousands of years.

Using logs preserved in southern Germany and the west coast of the United States, researchers have managed to construct continuous records of tree rings all the back to about 10,000 BCE. Since we know exactly what year each of these rings was made, this record is a perfect collection of material for evaluating whether the Carbon-14

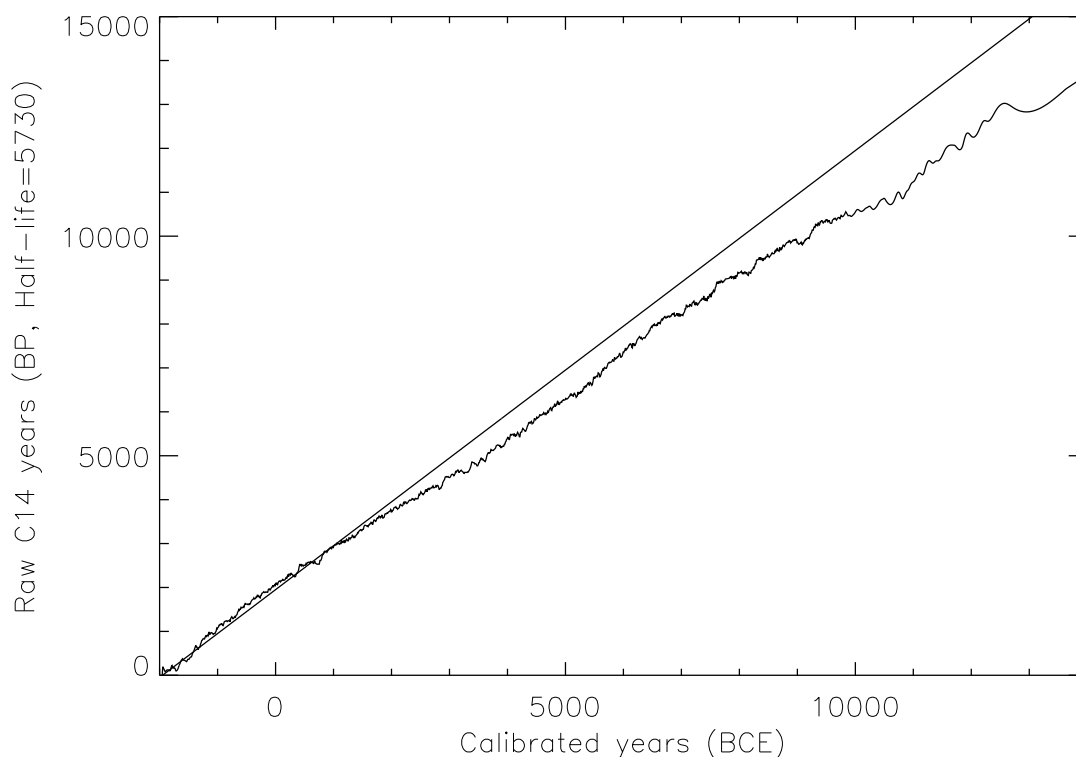


Figure 3: The calibration curve for Carbon-14 dates, as of 1998. This curve gives the derived Carbon-14 age as a function of real years, measured by dendrochronology and other means. If Carbon-14 dating were perfectly accurate, then the data would fall on the straight line. In fact, before 2000 BCE, Carbon-14 dating significantly underestimates the actual age of the specimens.

fraction in the atmosphere has changed with time. (Beyond 10,000 BCE, other yearly phenomenon provide similarly dated materials).

1.3 Calibrating Carbon-14 Dates

Figure 3 is a graph showing the Carbon-14 estimate of age of tree rings and other known-age samples as a function of the actual age of the rings. If the Carbon-14 estimates were accurate, then this data would trace out a straight line. Obviously this is not the case. For samples from before 2000 BCE, the actual curve falls significantly below the expected line. This means that standard Carbon-14 methods **underestimate** the real age of things by a significant amount (as much as 2000 years in the oldest part of the plot).

These variations indicate the Carbon-14 content of the atmosphere has in fact changed over time. In fact, we can use this data to estimate what the relative Carbon-14 content of the atmosphere was at different times. For example, if a Carbon-14 date underestimates the real age of the material by a certain amount, then we know we underestimated the original Carbon-14 content of the material (and the atmosphere) by factor we can calculate. Figure 4 shows the results of these calculations, giving the percent change in the Carbon-14 content of the atmosphere as a function of time.

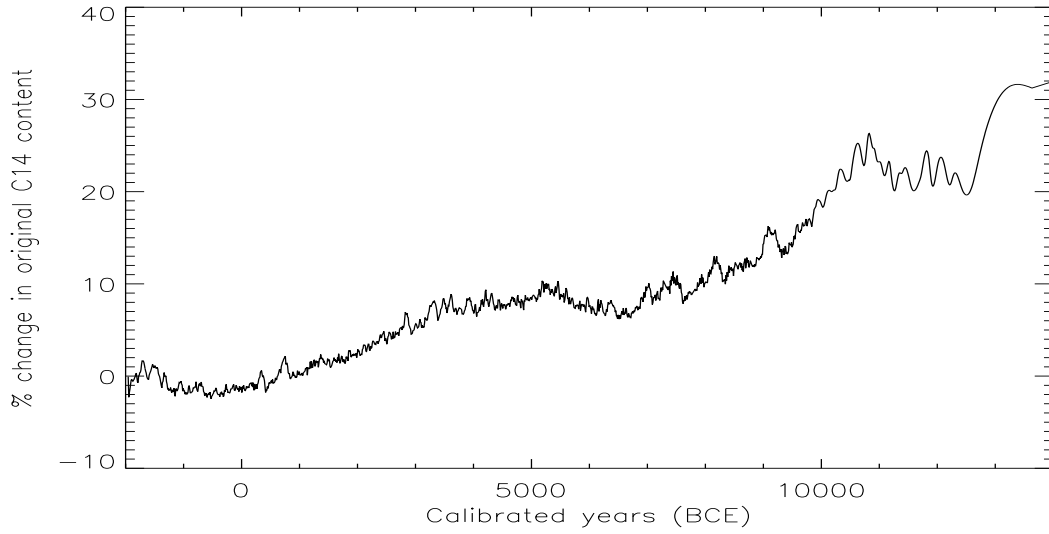


Figure 4: The variations in the calibration curve of the Carbon-14 (see figure 3 can be understood as variations in the original Carbon-14 content of the atmosphere. Here we give the percentage change in Carbon-14 fraction as a function of time. Note that in the past, the atmosphere had more Carbon-14 than it does today.

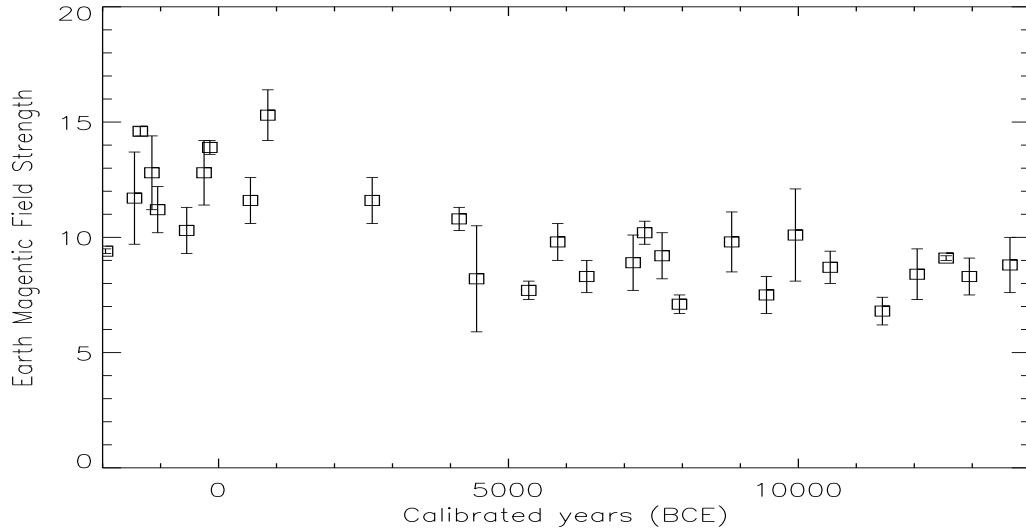


Figure 5: The variations in the earth's magnetic field as a function of time, measured using lava flows in Hawaii (data from Carlos Laj et al, *Earth and Planetary Sciences* 200 (2002), 177-190). Note that the about 2000 BCE, the strength in the earth's magnetic field was lower, which explains why the Carbon-14 content in the atmosphere was higher at this time.

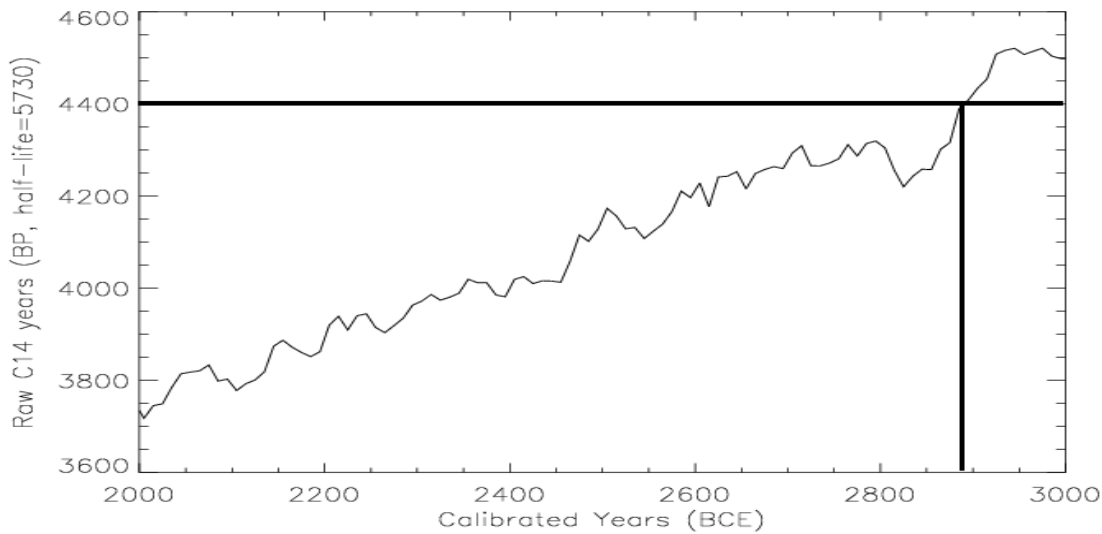


Figure 6: Using the tree ring dates to calibrate Carbon-14 data. Here we show a small portion of the curve illustrated in figure 3. Say we get a Carbon-14 date of 4400 BP, then we can draw a horizontal line across the plot and find where that line intersects the curve. Then we go down and find the age of the sample in real years

Note that over 4000 years ago, the Carbon-14 fraction in the atmosphere is 10-20% higher than it is today.

Carbon-14 is manufactured in the atmosphere by cosmic rays, thus a change in the Carbon-14 content of the atmosphere implies that the cosmic ray flux on earth has changed with time. It turns out that this change has less to do with the astronomical sources of cosmic rays than with the geology of the earth.

Cosmic rays are charged particles, so some of them are deflected by earth's magnetic field. We know that the earth's magnetic field has changed with time because we have volcanic rocks that provide a record of the history of the earth's magnetic field. These rocks contain small grains of material that are magnetic. These grains have a magnetic moment proportional to the strength of the earth's magnetic field when they and their parent rock solidified. In places like Hawaii, where there are many layers of volcanic rocks, we have a record of the magnetic field strength as a function of time, as shown in figure 5. (We will learn about how the age of these rocks can be measured next time). These records shows that the magnetic field was significantly weaker before 2000 BCE than it was after 2000 BCE. A weaker magnetic field means more cosmic rays will reach earth and there will be more Carbon-14 produced in the atmosphere, as we observe.

In addition to the long term trend in the curve shown in figure 3, there are a number of bumps and wiggles on shorter time scales. These features reflect both short time scale variations in earth's magnetic field and other phenomena, such as changes in solar activity and ocean currents. Clearly the standard Carbon-14 age estimates alone do not give accurate estimates of the real age of living material. However, this curve allows us to convert or **calibrate** the raw Carbon-14 age estimates into accurate measurement of real age in years. All we need to do is find the Carbon-14 age on the

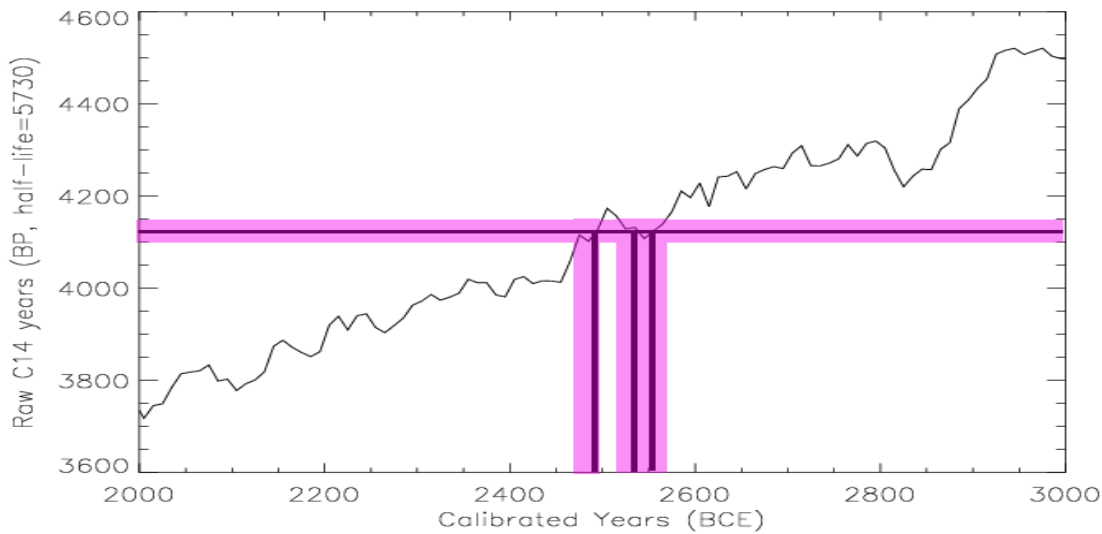


Figure 7: How the wiggles in the curve complicate Carbon-14 estimates of the age. Say the Carbon-14 date was 4125 BP, then there are three points where the lines cross and three possible values for the age of the sample. If this measurement has a error indicated by the shaded bar. Then the calibrated age can have a larger uncertainty than might be expected.

vertical axis and draw a horizontal line across the plot, find where the curve intersects that line, and find the real age in years that corresponds to that intersection. (see figure 6). This curve can therefore be regarded as a **calibration curve** to convert any Carbon-14 age estimate into the real age of the material.

Unfortunately, the various wiggles in the curve mean that sometime the Carbon-14 age does not correspond to a single real age, so there are multiple possibilities for the exact age of the sample (see figure 7). These wiggles can also amplify the uncertainty in an age measurement. For example, in figure 7, a 50 year uncertainty in the Carbon-14 date yields a true age estimate with an uncertainty of about 100 years. These wiggles therefore impose limits on how precisely carbon-14 dates can constrain age, which must always be kept in mind when using these dates.

This correction for variations in the Carbon-14 content of the atmosphere is only one of several factors that are included to convert Carbon-14 age estimates into real measurements of time. Other corrections for things like fractionation effects and reservoir effects will not be dealt with here due to lack of time, but the curious reader can find relevant discussions in the references. Even after applying all the relevant corrections, there are still other factors to consider: the sample could be contaminated so that the Carbon-14 date is unreliable, or the Carbon-14 date could measure the age of something other than the age of the object or event of interest. Rather than giving a tedious laundry list of possible problems with Carbon-14 dates we need to look out, let us turn now to the question of when and how people first reached the New World from Asia, which will demonstrate the importance of these issues.

2 Carbon-14 and the peopling of the New World

2.1 Of land bridges and ice-free corridors

It is generally accepted that people came to the Americas from northeast Asia through Alaska and the Bering strait during the end of the last Ice Age. (Although other routes have been suggested, they are very speculative and have not found wide acceptance.) Much more uncertainty surrounds exactly why and how this migration occurred. For some time, theories about the initial colonization of the Americas have centered on the people who made the distinctive “Clovis points” (named after a site in New Mexico), found throughout North America. These stone tools are easily recognized by their large size and the characteristic “flute” at their base (which only rather skilled modern flintknappers can replicate). These are spear points which were used in hunting mastodons. We know this because Clovis points have been found with the remains of mastodons, or even embedded in mastodon bones. These associations clearly demonstrate that the people who made them were early. Indeed, Carbon-14 dates show that these points were used about 11,000 BP, or 13,000 calibrated years ago. (In this section, dates given with BP are standard uncalibrated Carbon-14 dates—the).

This timing is important, because it corresponds to the very end of the last great Ice Age. During the Ice Age, large amounts of water was locked up in glaciers, which meant that sea levels were low and a land bridge (called Beringia) connected Northeast Asia and Alaska. However, these glaciers covered almost all of Canada and were a significant barrier for people to move further on into the New World. However, these glaciers began to melt around 18,000 BP, and around 11,500 BP there was an ice-free corridor between two glaciers which opened up a path through Canada to the United States (see figure 8).

The makers of the Clovis points appear reasonably soon after the corridor appeared, and several important sites with Clovis points are mastodon kills in the plains near the southern end of the corridor. These facts led some people to suggest a model for how people entered the New World. In this model, the first Americans were big game hunters which pursued mammoths down the ice-free corridor into the plains of the western United States. These people spread rapidly over the entire the entire New World in pursuit of large animals, leaving behind their distinctive fluted points. The large animals died out due to combination of the climatic changes brought on by the end of the ice age and perhaps over-hunting, and the people now scattered all over North and South America began to settle down and use more local resources.

This picture is almost certainly a gross oversimplification of what actually happened, but given the limited data, it was a reasonable enough model, which could be checked against additional data. One important prediction of this model is that there should not be any people in the Americas much before 11,500 BP, since the ice-free corridor did not open until that time.

2.2 People before the Clovis points? Meadowcroft

Over the years, a number of people have claimed to find sites in the Americas that pre-date the Clovis sites, and thus disprove this model. None of these sites have escaped

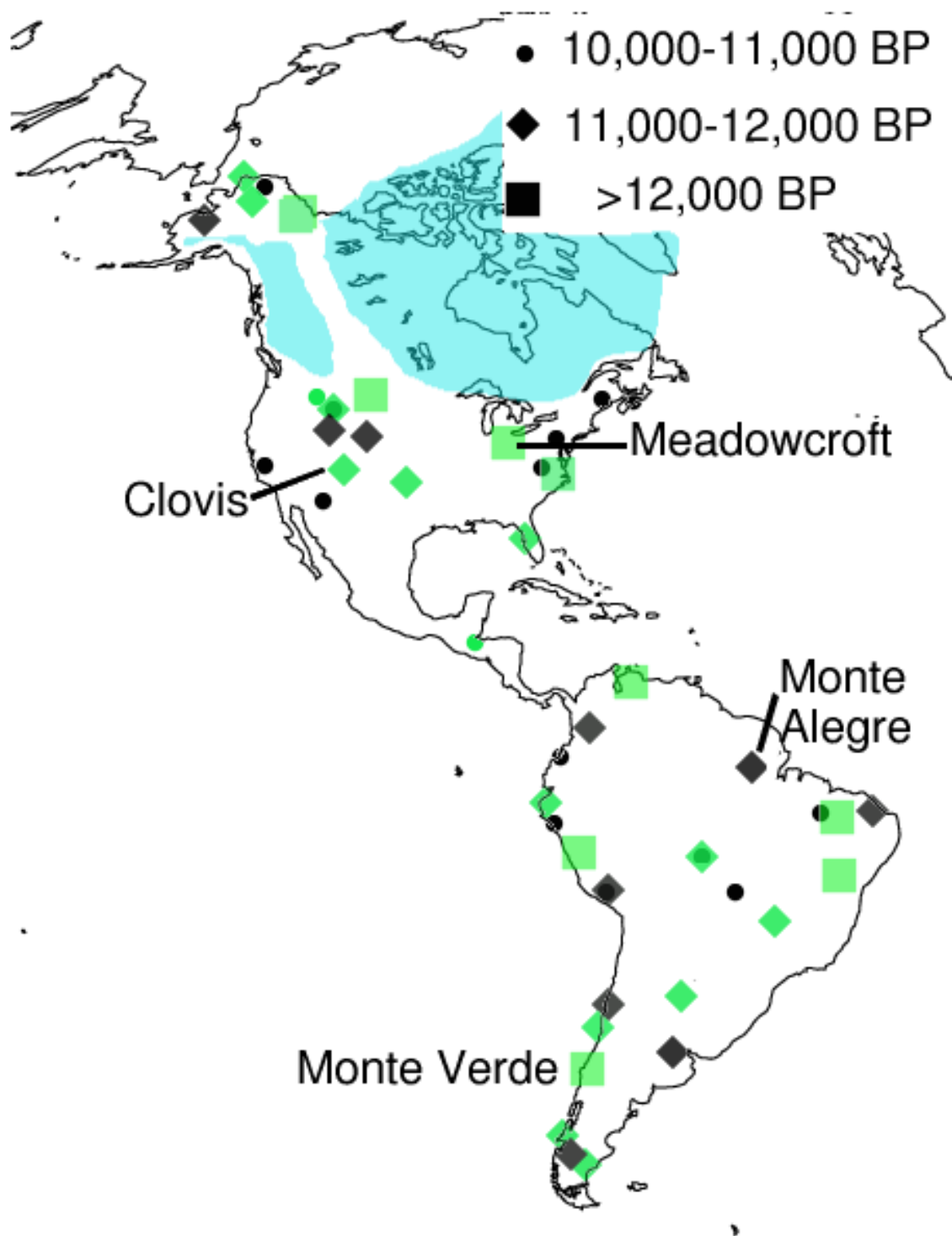


Figure 8: Early Sites in the Americas (based on Roosevelt et al. 2002) different shapes correspond to different ages. Green (light gray) symbols are ones with uncertain or contentious dates. The blue shaded regions show the extent of the glaciers at 12,000 BP. All dates are in uncalibrated radiocarbon years. Sites mentioned in the text are labeled

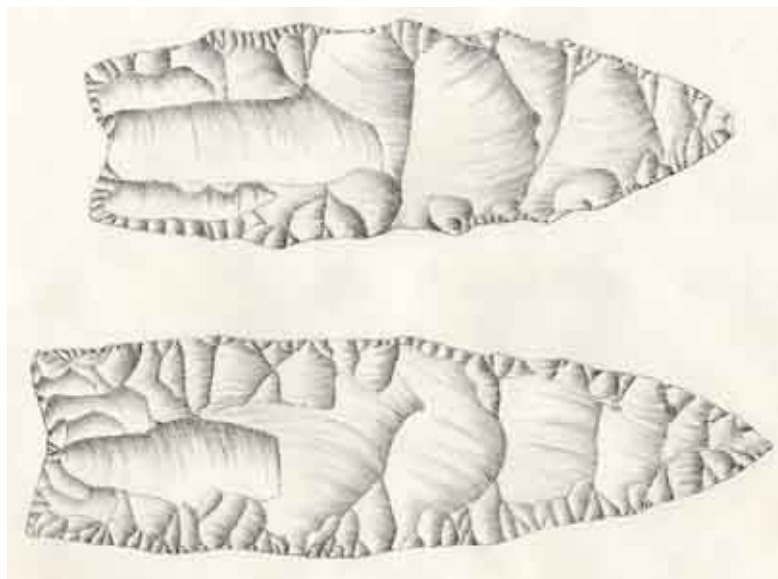


Figure 9: Examples of Clovis points, note the distinctive “flute” at the base

controversy, and since the better-supported claims all rely on Carbon-14 dates, the controversy always centers on the interpretation and reliability of these dates.

For example, consider the Meadowcroft Rockshelter in western Pennsylvania. This place was occupied intermittently for a long time, and there are many layers with indications of human activity, including stone tools and campfires. When this site was carefully excavated in the late 1970's, charcoal from the fires in the lower levels of the sites had Carbon-14 dates around 15,000 BP. This would put it people at this place well before the Clovis points were made and the ice-free corridor was opened. However, these dates are still controversial even after twenty years.

There are two major reasons why people are skeptical of these dates. For one, the plant remains in the oldest layers of the site are from a deciduous forest, and it seems unlikely that such a forest could exist when the ice sheet covering Canada was less than 50 miles away. The excavators counter this argument by saying the area around the site was sheltered and had a milder climate than more elevated areas.

The second argument has to do with the fact that Pennsylvania is coal country. The entire region is therefore riddled with geological deposits containing remains of truly ancient (300 million years old) carbon, totally lacking in Carbon-14. If any of this material mixed with the charcoal in the fires, it would dilute the Carbon-14 fraction and the dates would be too old. The excavators contend that contamination is not an issue, because dates from different layers of the site are consistent. That is, the dates in any given layer are older than the dates from the layer above it and younger than the dates from the layers below it, whereas contamination would have scrambled the dates. The skeptics then counter that the exact locations of the samples in the sites has not been published, so this consistency may not be true in detail. And so the arguments go on and on. Unfortunately, one can always suggest ways the data could possibly have been contaminated, or construct arguments that “prove” the data are not contaminated. Therefore, without more data from other sites, this argument potentially can continue forever.

2.3 New insights from South America

Fortunately, more data has appeared from South America. When the “Clovis” model was developed the earliest sites in South America were not as well explored as the comparable sites in the north. But now there are numerous sites in South America with well-measured ages. The most famous of these sites is Monte Verde, in Chile. Carbon-14 dates from this site go as far back as 12,500 BP, before the ice-free corridor. Again, there are people who doubt these dates. Again, contamination from old carbon in the area is an issue, but the main concern at this site seems to be the possibility that material could have mixed from various levels, so the Carbon-14 ages of the plant material may not be telling us anything about the age of the stone tools found near them. Again the excavators can defend their interpretations based on the consistency of dates from different parts of the site. Fortunately, this time the discussions of possible problems seem to be more amiable and productive.

“Pre-Clovis” sites like Meadowcroft and Monte Verde attract a lot of attention because if their dates reliable, then people must have reached the Americas before the ice-free Canadian corridor was open. These people must have taken some other route southwards, perhaps along the West Coast of North America.

However, I think the real importance of Monte Verde and other South American sites is that they are yielding new information about how the people lived in the New World during the end of the Ice Age. At this time there weren’t too many people around and they did not leave too much material behind at any one spot. Therefore sites are rare and each one gives us information about only a small part of these people’s lives. For example, the best-known Clovis sites are Mastodon kills, which mainly provide information about how these people hunted large game.

These South American sites are now providing information about other activities carried out by the early Americans. Monte Verde, beyond its potential as a pre-Clovis site, is extremely important because of it preserves vegetable material from this very early time. There are remains of tents and other structures, as well as plant foods such as potatoes. Another site was recently found in the Tropical lowlands of Brazil, which was occupied at almost the exact same time as people was hunting Mastodons with Clovis points in North America. The remains here indicate that these early Amazonians were dining on fruits and nuts, as well as various small animals. There may even be rock-art preserved at this site from this time (although dating rock art is notoriously difficult). This implies that the first colonists of the New World were not just Mastodon-hunters, but that they used a broader range of resources in their environment.

While these new results are extremely encouraging, at present there are still too few sites available and the uncertainties in their ages are too great to piece together a coherent picture of life for the earliest inhabitants of the New World. Hopefully, the discovery of new sites and the refinement of age measurements will continue until one can make precise statements of how people in different areas were using the land and resources, and how these patterns changed with time.

Although Carbon-14 dating is extremely useful for dating events back to maybe 50,000 years, much older and the Carbon-14 content is so low to be difficult to measure and even small amounts of contamination can give rise to serious errors. In we wish to measure the age of objects and events older than this, we need to use different dating

methods. Next time, we will consider the question of when our ancestors first began to walk upright on two legs. Again, a radioactive atom will be useful for figuring out when this happened, but the genetic codes within us and our nearest relatives will also provide crucial information.

3 References

For a general discussion of different methods of measuring age in archaeology, including Dendrochronology and Carbon-14, try:

- R.E. Taylor and M.J. Aitken *Chronometric Dating in Archaeology* (Plenum Press 1997)

For the most-recent agreement for the calibration of Carbon-14 dates, see *Radiocarbon* vol 40 (3) (1998)

An entertaining discussion of the general chaos Carbon-14 dating caused in old-world archaeology can be found in:

- Colin Renfrew *Before Civilization* (Knopf 1973)

A good general work on North American Archaeology is:

- Brian Fagan *Ancient North America* (Thames and Hudson 1995)

Some recent reviews of Clovis, pre-Clovis and other early American sites are

- Stuart J. Fiedel “Initial Human Colonization of the Americas: An overview of the issues and the evidence” in *Radiocarbon* 44 (2002) pp 407-436
- A.C. Roosevelt J. Douglas and L. Brown “The Migrations and Adaptations of the first Americans: Clovis and Pre-Clovis viewed from South America” in *The First Americans* by N.G. Jablonski 2002
- Thomas D. Dillehay *The Settlement of the Americas* (Basic Books 2000)