

# 9 Contribution of Stable Light Isotopes to Paleoenvironmental Reconstruction

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## Abstract

In this chapter, we focus attention on the potential linkages between hominin evolution and environmental change in Africa, as shown by the stable light isotope evidence. We begin with an overview of the principles and the materials typically available to produce this kind of stable isotope data. Carbon isotope analyses of faunal enamel, soils, and ostrich eggshells provide good evidence for the emergence of  $C_4$  grasses ca. 5–8 Ma, broadly concordant with hominin bipedalism. Although  $C_4$  grasses remained a modest yet variable component of the vegetation for millions of years, the associated biomass may have quickly become an important foraging resource for hominins. Rather than a climate-driven “pulse” ca. 2.4–2.8 Ma, evidence from East and South Africa suggests a significant change to more open, grassy ecosystems ca. 1.8 Ma, broadly concordant with the emergence of early *Homo*. On present evidence, there appears to be only a weak overall aridification trend for the entire period from ca. 4 Ma. Speleothem and other evidence points to deep-rooted cyclicity in floral and rainfall shifts, which suggest that obliquity and precessional orbital cycles were important drivers of environmental variability. In relation to climate and environmental influences on hominin evolution, a revised “Savanna” hypothesis may yet be compatible with the “variability selection” hypothesis.

## 9.1 Introduction

It is widely accepted that understanding the environments that hominins inhabited provides important information for understanding evolutionary trends. First, and perhaps most obvious, we need this contextual information to tell us about the kinds of opportunities available for the basics of life—food,

water, and shelter, and the biological and perhaps cultural responses used to obtain these things. Second, there are questions about how environmental and climate shifts might have influenced the course of hominin evolution and, similarly, that of other coeval fauna. Here, paleoenvironmental studies must take a broader, more long-term view. Large-scale, global climate shifts are very often invoked as major influences on evolutionary pathways, but in practice demonstrating the links is not at all straightforward (Feibel 1997). This is partly because of the nature of the environmental evidence on land, which is patchy in time and space and often poorly dated, and partly because climate is just one of a number of forces acting on landscapes.

One of the ways to address this problem is to take a broad, continent-based perspective that can "subtract" more local environmental influences. At the same time, we must bear in mind that behavioral (and biological) responses of hominins occur at the local level, which is the most important for understanding the lives of individuals. In other words, scale is important, depending on the question that is being asked. In this chapter, we focus our attention on paleoenvironments of Africa for the obvious reason that much of early hominin evolution occurred there.

A whole range of investigative tools is available for reconstructing paleoenvironments at the site level. Standard methods rely on geological context, faunal abundances, and in some cases floral indicators such as woody materials or pollen. None of these approaches on its own is sufficient because each has its own set of advantages and disadvantages. For instance, methods based on vertebrate faunal-abundance data have to rely on what is deposited, preserved and found in a site so that the fossil bones represent a highly filtered representation of the original vertebrate fauna. Furthermore, in interpreting abundance data as environmental proxies, one has to rely on knowledge of the habitat requirements of various animals, and this is difficult for unfamiliar, extinct taxa. In fact, we very often do not understand enough about the habitat requirements of their modern relatives (Cerling et al. 2003; Sponheimer et al. 2003). Stable isotope approaches can help to provide this complementary evidence.

There are even greater challenges in reconstructing evolving continental climates and landscapes *beyond* the site level to regional or global contexts. They are partly related to the enormous heterogeneity of continental environments, and partly to the rarity of long, continuous records on land. To this is tied a problem of chronological control. Global climate changes are mainly understood from marine sediment cores that provide an oceanic perspective on climate evolution (Zachos et al. 2001), but it is not always clear how these changes have affected continental African environments. Moreover, it is unclear whether

large-scale climate shifts are synchronous across the continent; between the north and south, and east and west, many recent and ancient climate fluctuations are thought to be opposite (or antiphased) (Nicholson and Entekhabi 1986; Partridge et al. 1997; Tyson et al. 2002). Continuous marine sediment records near continental margins have provided some direct information about African climates. For instance, episodes of windblown dust off North Africa indicate increasing Saharan aridity from ~2.6 to 2.8 Ma (deMenocal 1995), and entrained pollen indicates the pattern of contraction and expansion of West African equatorial forests in the Late Pleistocene (Dupont 1999). These patterns, however, are not necessarily representative of trends for East and southern Africa, where most of the hominin sites are found. Thick sedimentary sequences with diatomites and other organic derivatives from continental lake systems provide good proxies for lake histories and salinity, but they are extremely discontinuous in space and time. For instance, deep, old, but discontinuous lake systems are known from the East African Rift, while none occur in southern Africa. Lake formation is dependent both on basin formation, defined by tectonic activity, as well as on a positive precipitation/evaporation balance, controlled by climate (Trauth et al. 2005). Other land-based clues come from pollen (Bonnefille 1983, 1995) and faunal abundance data considered regionally (Vrba 1985, 1988; Behrensmeyer et al. 1997; Reed 1997; Bobe et al. 2002). Vrba's "turnover-pulse" hypothesis that postulates a direct link between evolutionary trends in bovids and climate shifts at ~2.4–2.6 Ma (Vrba 1985) was based on bovid abundances, while studies that tested or disputed this idea were based on consideration of radiations among a broader range of fauna (Behrensmeyer et al. 1997; Bobe et al. 2002).

Stable light isotope tools can help to address some of the gaps. These biogeochemical tools have several advantages, because once the principles of isotope fractionation in biogeochemical pathways are understood, they may be broadly applied to past ecosystems to produce quantitative, repeatable results. Stable light isotope applications to paleoenvironmental reconstruction have been extensively reviewed in the literature and the field is broad (for a global review see Koch 1998). Given the breadth of the topic, our intention here is to restrict discussion to some of the key examples that we believe have made, or look set to make, substantive contributions to understand the environments associated with hominin evolution. These contributions lie principally in the context of shifts in floral composition (such as the relative abundance of  $C_4$  grasses in the flora, and implications for climate) and climate indicators including temperature, aridity, and seasonality. The nature of longer-term climate evolution can be deduced from these data. We concentrate on examples reliant on materials from hominin or paleontological sites, or from sequences that are closely associated in space and time.

## 9.2 Isotopic environmental indicators

This section provides a brief overview of the main isotopic environmental indicators and the sample materials that are used to provide indications of prevailing conditions. It is important to understand these principles as they apply to each potential archive, as they are all likely to provide slightly different perspectives, and in order to evaluate the quality of the evidence.

### 9.2.1 Basis of stable isotope tools

The stable light isotopes of principal interest as environmental proxies are the isotopes of hydrogen, carbon, nitrogen, and oxygen. In all cases, the chemistry of the different isotopes of an element remains the same as chemical properties are controlled by electron configuration. Among these light isotopes, the mass difference owing to one or two extra neutrons is sufficient to cause a small, but predictable, difference in the rates of chemical reactions or physical processes. If the starting materials and the products of a reaction are partitioned in some way, observable isotopic fractionation occurs.

#### 9.2.1.1 Hydrogen (D/H) and oxygen ( $^{18}\text{O}/^{16}\text{O}$ ) isotope fractionation

Fractionation of hydrogen (D/H) and oxygen ( $^{18}\text{O}/^{16}\text{O}$ ) isotopes<sup>1</sup> in nature follows similar patterns because their isotope effects are dominated by the processes undergone by water evaporation, condensation, and freezing. The magnitude of fractionation is controlled largely by temperature in both cases, but isotope effects are much higher for hydrogen because of the greater relative mass difference between deuterium (D or  $^2\text{H}$ ) and hydrogen ( $^1\text{H}$ ) compared to oxygen ( $^{18}\text{O}$  and  $^{16}\text{O}$ ). Water vapor evaporates largely from low- to midlatitude ocean surfaces, and sea surface temperature (or latitude as a proxy) of the oceanic source influences isotopic ratios of moisture-laden weather systems (Dansgaard 1964). Further influences on the isotopic composition of rainfall occur during subsequent

<sup>1</sup>Isotope ratios are expressed by convention in the  $\delta$  notation, in parts per thousand (‰) relative to a standard:  $\delta X (\text{‰}) = (R_{\text{sample}} - R_{\text{ref}}) / R_{\text{ref}} \times 1000$ , where  $R$  is the isotopic ratio. V-SMOW (Standard Mean Ocean Water) is used as the reference for D/H and  $^{18}\text{O}/^{16}\text{O}$  in water, V-PDB (Pee Dee Belemnite) for  $^{18}\text{O}/^{16}\text{O}$  and  $^{13}\text{C}/^{12}\text{C}$  in carbonates and organic materials, and atmospheric  $\text{N}_2$  (AIR) for  $^{15}\text{N}/^{14}\text{N}$ .

transport of these weather systems across continents, related to factors such as the distance traveled, mountains crossed, and height and temperature of rainclouds (Dansgaard 1964; Rozanski et al. 1993). A further effect in arid landscapes is due to evaporation. Soil- and groundwater isotope values reflect this history, as do carbonates precipitated from these waters, with the additional influence of local temperature as fractionation during carbonate precipitation is temperature dependent. This is the basis of the familiar "temperature equation" applied to many carbonates (e.g., forams, corals, and speleothems) (McCrea 1950). In addition, isotope effects also occur in plants. A large isotopic enrichment occurs during daytime evapotranspiration in plants under hot, dry conditions (Yakir 1992).

#### 9.2.1.2 Carbon ( $^{13}\text{C}/^{12}\text{C}$ ) isotope fractionation

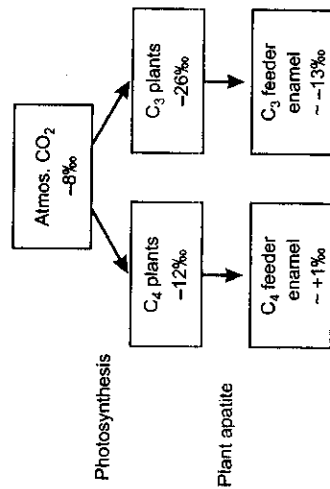
Carbon ( $^{13}\text{C}/^{12}\text{C}$ ) isotope fractionation provides fundamental information about pathways in the terrestrial carbon cycle (see also Sponheimer and Lee-Thorp Vol. 1, Chapter 17). A large depletion in  $^{13}\text{C}$  occurs during assimilation of atmospheric  $\text{CO}_2$  in photosynthesis, but to different degrees depending on the photosynthetic pathway (Smith and Epstein 1971).  $\text{C}_3$  plants (trees, shrubs and forbs, and temperate or shade-adapted grasses) are more depleted in  $^{13}\text{C}$  and have low  $\delta^{13}\text{C}$  values, while  $\text{C}_4$  plants (mainly tropical grasses) are less depleted (Figure 9.1). A smaller group of succulent plants follow the Crassulacean acid metabolism (CAM) pathway, which essentially alternates use of these two pathways by night and day, and depending on conditions, so that their isotopic compositions vary considerably. These plant values are archived in slightly different ways in a range of sample materials (Figure 9.1).

#### 9.2.1.3 Nitrogen ( $^{15}\text{N}/^{14}\text{N}$ ) isotope ratios

Nitrogen ( $^{15}\text{N}/^{14}\text{N}$ ) isotope ratios reveal pathways in the nitrogen cycle, but since the pathways are complex, the values observed between different ecosystems are highly variable. Nitrogen enters the terrestrial foodweb via  $\text{N}_2$ -fixing bacteria in soils or plants to form nitrates or ammonium ions that are utilized by plants. The net effect of this biological nitrogen fixing and subsequent nitrogen loss is a slight enrichment in  $^{15}\text{N}$ , but the balance and mode of fixing and loss is strongly affected by environmental conditions (Heaton 1987). In a global survey, Handley et al. (1999) found a negative correlation between moisture availability and both leaf and soil  $\delta^{15}\text{N}$ . Stepwise trophic enrichment of about 3–5‰ occurs in animals because there is an ~3‰ fractionation between diet and tissues. The trophic

■ Figure 9.1

A model depicting typical carbon isotope pathways in a modern savanna ecosystem. The values given in the boxes are typical mean values for each material, expressed relative to the international standard V-PDB. We have used values for tooth enamel as this is the tissue most commonly analyzed in fossils; other tissues would show a similar separation, although different absolute values. In fossils, tooth enamel values tend to be slightly more positive, i.e., fossil enamel tends to be slightly enriched in  $^{13}\text{C}$  in comparison with modern specimens. Typical values for  $\delta^{13}\text{C}$  in pedogenic carbonates or speleothems from pure  $\text{C}_3$  or  $\text{C}_4$  habitats are similar, but again slightly enriched



effect, however, can be surpassed by enrichment associated with environmental aridity (Heaton et al. 1986; Sealy et al. 1987; Johnson et al. 1997), effects that are certainly related to raised leaf and soil values in arid areas (Heaton 1987). The effect is very marked in animals living in areas with  $<400\text{-mm}$  rainfall/annum, so  $\delta^{15}\text{N}$  can be an indicator of aridity.

## 9.2.2 Sample materials

The sample materials most often used as environmental indicators in sites associated with hominin activities consist largely of bones and soils in close chronostratigraphic association with those sites. Fossil ostrich eggshell and cave speleothems represent promising but more rarely explored sources of paleoenvironmental and climate information.

### 9.2.2.1 Bones and teeth

Bones are abundant in most sites where conditions are conducive to preservation. They conserve information about many of the processes and conditions to which the animal was subjected when it was alive, which can be accessed via their stable light isotope compositions. Bones and dentine consist of about 25% (by weight)

of a fibrous protein, collagen, and about 75% embedded bioapatite mineral. Collagen can be relatively easily purified and analyzed for  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ . However, it tends to decompose over time so that by about 10–20 Ka collagen has all but disappeared from bones and teeth in most African sites (preservation is better in cool Eurasian sites). The mineral is composed of calcium phosphate crystals with many other ions substituted into the structure (LeGeros 1991) that tend to increase their reactivity and solubility. One exception is fluoride, which enhances stability. Substitutions also affect how well bones and teeth are preserved as fossils. Enamel is far more stable than bone apatite (Lee-Thorp and van der Merwe 1987) and consequently most isotopic studies of fossil fauna have relied on enamel as sample material. The component ions of interest are phosphate ( $\text{PO}_4^{3-}$ ) and carbonate ( $\text{CO}_3^{2-}$ ), with the latter occurring in small amounts (3–6%) as a substitution. Therefore, the isotopes available for study in this system are carbon and oxygen isotopes, and the latter may be extracted from either  $\text{PO}_4^{3-}$  or  $\text{CO}_3^{2-}$ .

Bioapatite phosphate  $\delta^{18}\text{O}$  has been developed as a paleotemperature tool, based on the rationale that body water  $\delta^{18}\text{O}$  ( $\delta^{18}\text{O}_{\text{bw}}$ ) in mammals is related to environmental or drinking water ( $\delta^{18}\text{O}_{\text{w}}$ ), which can in turn be correlated with latitude and temperature effects on rainfall (Longinelli 1984; Luz and Kolodny 1985, 1989). In low- to midlatitudes, temperature effects are far less important than storm-track and amount effects on  $\delta^{18}\text{O}$  of environmental water plus isotope effects on plant waters. We now know that animal behavior, related to drinking patterns and/or thermophysiology, can modulate these environmental signals considerably (Bocherens et al. 1996; Kohn et al. 1996; Sponheimer and Lee-Thorp 1999b, 2001) and that these patterns are conserved in fossil assemblages. Ayliffe and Chivas (1990) found a correlation between  $\delta^{18}\text{O}_{\text{PO}_4}$  and relative humidity in non-obligate drinking animals—in their case, kangaroos, so that these behaviors might still provide useful environmental data. In order to circumvent the problems of variable responses to climate factors, many authors have relied upon “well-behaved,” obligate drinking species such as equids for extracting paleoclimate proxies (Sánchez-Chillon et al. 1994; Bryant et al. 1996).

Stable carbon isotope ( $\delta^{13}\text{C}$ ) analysis of herbivore tooth enamel (or collagen) indicates the relative amounts of  $\text{C}_3$  plants and  $\text{C}_4$  grasses consumed. The calculations are based on our understanding of typical plant values today and how they might be affected by climate variables, and by the difference between diet and enamel  $\delta^{13}\text{C}$  values (or  $\Delta_{\text{diet-en}}$ ). There is a little “play” here, since  $\text{C}_3$  plants may be slightly enriched in  $^{13}\text{C}$  under hot, arid conditions, and vice versa.  $\text{C}_3$  plants in dense forests, where a “canopy effect” with recycling of  $\text{CO}_2$  and low light prevails, are typically depleted in  $^{13}\text{C}$  (van der Merwe and Medina 1989, 1991). Alterations in the species composition of  $\text{C}_4$  grasses, in response to conditions, may shift their average  $\delta^{13}\text{C}$  value slightly (by perhaps 1‰).

In addition,  $\Delta_{\text{diet-en}}$  is not *precisely* established; some authors observe +12‰ (Lee-Thorp and van der Merwe 1987), while others have observed up to +14‰ (Cerling and Harris 1999).

Still, these small differences make no practical difference to distinguishing between  $C_3$  and  $C_4$  consumers since these  $\delta^{13}C$  distinctions are large (● *Figure 9.1*). The presence of  $C_4$  grazers in an assemblage allows us to deduce presence of tropical  $C_4$  grasses in a landscape. Although this information alone may be useful, for instance, if a shift between cold- and warm-season rain patterns is suspected (Lee-Thorp and Beaumont 1995), in practice we need to take this process further. Usually we require information about how closed or open vegetation cover was. A  $C_3/C_4$  index has been developed to reflect the relative openness of an environment from  $\delta^{13}C$  data in a faunal assemblage (Sponheimer and Lee-Thorp 2003) (see below).

### 9.2.2.2 Ratite eggshells

The eggshells of ostriches and earlier ratite taxa are durable and often abundant in paleontological and archeological sites. The shells consist of a protein matrix and inorganic calcium carbonate. Eggshells can yield  $\delta^{13}C$ ,  $\delta^{15}N$ , and  $\delta^{18}O$  proxy information reflecting conditions during the short egg-laying season. Ostriches are mixed feeders that prefer tender plants, which can include succulents as well as annual grasses and forbs in their diets; hence  $\delta^{13}C$  data can indicate presence of both  $C_4$  grasses and CAM plants (Stern et al. 1994; Ségalen et al. 2006). The  $\delta^{15}N$  values are thought to reflect mean annual rainfall (MAP) (Johnson et al. 1997) in the same way as mammals in arid regions with under 400-mm rain/year (Sealy et al. 1987).  $\delta^{18}O$  data also reflect aridity but from a slightly different perspective; since ostriches are drought-tolerant animals that do not need to drink free water,  $\delta^{18}O$  primarily reflects leafwater enrichment due to evapotranspiration under hot, dry conditions (Lee-Thorp and Talma 2000). Because of the high variability in  $\delta^{18}O$  and  $\delta^{15}N$  data, large numbers of analyses are required (Lee-Thorp and Talma 2000). To date, only one study has produced a sequence, extending beyond the Holocene based on all three proxies (Johnson et al. 1997).

### 9.2.2.3 Soils

A history of overlying vegetation may be preserved for long periods in remnant organics and pedogenic carbonates in paleosols (Cerling et al. 1991). The principles are by now familiar: carbon isotopes in both the organic and inorganic components

of soils systematically reflect differences between vegetation following the  $C_3$  and  $C_4$  pathways, allowing estimations of the relative mix of woody and grassy plants on the landscape.  $\delta^{13}C$  of paleosol organic matter, where preserved, is a reasonably direct reflection of the mean isotopic composition of the vegetation, with a small enrichment in  $^{13}C$  owing to decomposition and associated processes (Cerling et al. 1991). Pedogenic carbonate nodules are formed about 0.5–1 m below the active soil horizon from soil-respired  $CO_2$  (Cerling and Quade 1993). There is a net enrichment in  $^{13}C$  of 14–17‰ due to combined effects of diffusion and isotopic fractionation during carbonate precipitation, causing increases of 4.4–5‰, and 9.5–12.5‰, respectively (Cerling et al. 1988, 1991; Cerling and Quade 1993). Pedogenic carbonates have a relatively restricted distribution; for one, nodule formation is associated with semiarid to arid conditions. An important constraint is the identification of “true” pedogenic nodules formed well below the active, identifiable soil horizon, where diffusion enrichment is complete and there is no mixing with atmospheric  $CO_2$  (Cerling et al. 1988; Cerling and Quade 1993).

### 9.2.2.4 Cave speleothems

Cave flowstones and stalagmites are composed of calcium carbonate formed from  $CO_2$ -rich seepage water dripping into cave systems, degassing, and precipitating as carbonate. Their  $\delta^{13}C$  and  $\delta^{18}O$  values reflect the proportions of  $C_3$  and  $C_4$  plants in overlying vegetation, and the isotopic composition of the water, in a similar manner to pedogenic carbonates. Speleothems have some decided advantages. For one, a closed cave system is a protected environment, where averaged annual temperatures are maintained year-round, along with high relative humidity. In a closed cave system equilibrium conditions are more likely, meaning that greater confidence can be placed in the isotopic data as sound indicators of environmental conditions. Very importantly, they are incremental structures and can be precisely dated using thorium–uranium disequilibrium or lead isotopes. Ages are more difficult to obtain for older Pliocene- or Miocene-age speleothems, but paleomagnetic and lead–uranium methods are being developed (Hopley 2004). So, where the right material can be located and the ages determined, speleothems can be sampled at small intervals to yield continuous, high-resolution records of a quality unlike any of the other proxies discussed here. Continuous sequences like this are invaluable because they can be compared with other dated continuous records, and they allow us to check trends and the scales of variability.

The following section describes some important applications of isotopic tools to paleoenvironmental and -climate problems.

### 9.2.3 Emergence of C<sub>4</sub> grasses

One important application has been to document the global expansion of C<sub>4</sub> grass systems between ~8 and 5 Ma (Cerling et al. 1997; Jacobs et al. 1999). Since both biochemical and fossil evidence suggest that our common ancestor with chimps lived at about this time, this important environmental shift might well have had some direct impact on the origins of the hominin lineage. The phenomenon was first detected in pedogenic carbonate nodule isotope studies from East Africa and Pakistan (Cerling et al. 1988; Quade et al. 1989; Cerling and Quade 1993). In East Africa, Cerling et al. (1988) observed the first appearance of C<sub>4</sub> grasses in the Turkana Basin ca. 7 Ma. This pattern of first appearance of significant amounts of C<sub>4</sub> has been mirrored in  $\delta^{13}\text{C}$  of fossil fauna in Africa, North and South America, and Pakistan (Cerling et al. 1997), although Fox and Koch (2003) have suggested earlier presence of minor amounts of C<sub>4</sub> biomass in the North American Great Plains, based on pedogenic carbonate evidence. Kingston et al. (1994) and Morgan et al. (1994) have argued that modest proportions of C<sub>4</sub> grasses were present earlier in the Mid-Miocene of East Africa, based respectively on continuous heterogeneity in a pedogenic carbonate sequence from the Tugen Hills and several slightly enriched faunal values from early Tugen Hills sites. The argument hinges largely on the weight of evidence, since the results for the Tugen Hills pedogenic sequence have not been replicated elsewhere in Africa. The values used to demarcate the certain presence of C<sub>4</sub> in fauna also differ as Morgan et al. (1994) used a value of -10‰ as the cut-off point, above which they deduced presence of C<sub>4</sub>, whereas Cerling et al. (1997) used a more conservative -8‰.

Most evidence, however, still suggests that C<sub>4</sub> grasses first began their expansion in lower latitudes at ca. 7–8 Ma, expanding over the next few million years to midlatitudes (Cerling et al. 1997). The timing is unclear in southern Africa. Ratite eggshell data document emergence of C<sub>4</sub> and differentiation of the  $\delta^{13}\text{C}$  records between the southern and northern Namib about 5 Ma (Ségalen 2003; Ségalen et al. 2006). A large undated, collapsed cone speleothem in the Makapansgat Limeworks in South Africa indicates relatively invariant C<sub>3</sub> vegetation cover from the  $\delta^{13}\text{C}$  record, suggesting that it was formed prior to C<sub>4</sub> grasses reaching this region at ~27° S (Hopley 2004). A notable exception to the general picture of C<sub>4</sub> expansion is the 5-Ma-year-old site of Langebaanweg in the southwestern Cape of South Africa (Franz-Odenaal et al. 2002), where faunal  $\delta^{13}\text{C}$  data show that a winter-rainfall, Mediterranean-type ecosystem was already in place in this region in the Late Miocene and Early Pliocene. In the northeastern interior, faunal evidence suggests a minor presence of C<sub>4</sub> vegetation by ~4 Ma or earlier from the Rodent Corner at Makapansgat Limeworks (Hopley et al. 2006), while the modest proportion of pure C<sub>4</sub> grazers in the Makapansgat Member 3

faunal assemblage indicates clear presence by ~3 Ma (Sponheimer and Lee-Thorp 1999a).

The expansion of C<sub>4</sub> grasslands across large parts of the world must have a global driver but the exact causes have remained curiously elusive. Cerling et al. (1997) and Ehleringer et al. (1997) proposed that plummeting CO<sub>2</sub> levels in the Late Miocene, to a level below 500 ppm, favored C<sub>4</sub> plants. The hypothesis is based on the known tolerance of C<sub>4</sub> plants for lower levels of pCO<sub>2</sub>. But evidence from marine cores suggests that CO<sub>2</sub> levels were already low prior to this period (Pagani et al. 1999). This, along with  $\delta^{13}\text{C}$  data from fossil ratite eggshells in Namibia that closely track the marine-derived trends in pCO<sub>2</sub> for the Miocene (Ségalen et al. 2006), has led to a reconsideration of the possible drivers. The emergence and spread of C<sub>4</sub> may reside in a combination of tectonic and solar insolation forces that rearranged the earth's global heat budget, both spatially and seasonally. Resolution of the problem likely requires a good deal of more detailed evidence from the transition period, spread across different regions of Africa and elsewhere.

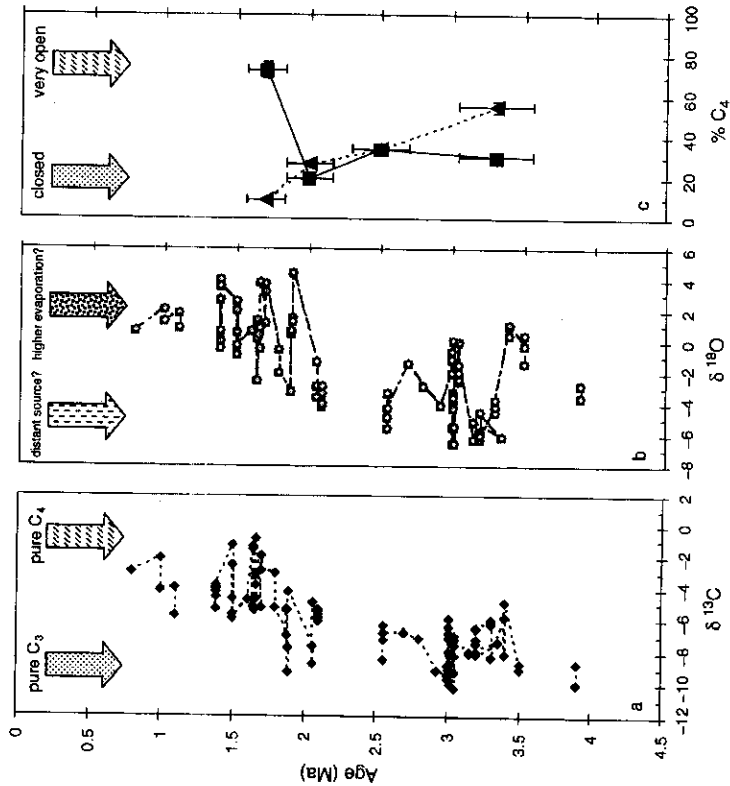
### 9.2.4 Evolution of open African environments

A great deal of interest has been shown in issues related to the decline of large-scale forests and opening up of the African landscape. Some years ago, the "Savanna hypothesis" held that forest shrinkage/savanna expansion in Africa was a primary driver of hominin bipedalism because it was thought that these two trends occurred at about the same time. This hypothesis fell from favor once it became apparent that bipedalism emerged before 5 Ma among relatively wooded habitats (WoldeGabriel et al. 2001). Nevertheless, there have undoubtedly been important and influential changes in the vegetation structures across Africa. Vrba's turnover-pulse hypothesis relied on the observed radiation of open-country grazing bovids to draw inferences about shifts to more open landscapes in the Pliocene and Pleistocene, which could be linked to hominin evolutionary changes (Vrba 1980, 1985, 1988). This approach is not entirely straightforward because the habitat preferences of extinct bovids, or indeed of any extinct animals, are not always clear. Vrba proposed that a shift to bovid lineages with open-country preferences between about 2.4 and 2.6 Ma was associated with the onset of Northern Hemisphere glaciation observed from marine oxygen isotopes in marine sediment core records (Shackleton et al. 1984). But the nature of the climate trigger is not clear. The idea of a pulse in faunal change has been challenged, although it is acknowledged that faunal changes occurred between 2 and 3 Ma (Behrensmeyer et al. 1997; Bobe et al. 2002).

Further perspectives on the appearance of savanna landscapes have emerged from several isotope studies. Although  $C_4$  grasses appeared in the Late Miocene and persisted with fluctuations through the Pliocene (Cerling et al. 1988; Cerling 1992; Kingston et al. 1994; WoldeGabriel et al. 2000; Wynn, 2004), importantly, they did not become a consistently dominant part of the floral biomass until  $\sim 1.8$  Ma (Figure 9.2). A shift in  $\delta^{18}O$  also occurs at about 1.8 Ma, suggesting that the source area and vapor transport pathway changed (Figure 9.2)

Figure 9.2

Isotopic indicators of open, grassy environments from the Koobi Fora Basin and from the South African hominin sites, showing small but variable presence of grasses prior to 1.8 Ma, and a distinctive shift to open habitats after this time. The sequences are as follows: (a) pedogenic carbonate  $\delta^{13}C$ , (b)  $\delta^{18}O$  from the Koobi Fora Basin, shown alongside, and (c) calculations for the percentages of browsers and grazers from Makapansgat and Sterkfontein. The arrows provide some guidance about the predicted ranges for pure  $C_3$  and  $C_4$  for (a) and (c), and some pointers to interpretations of the record in (b). Data for (a) and (b) are from Cerling et al. (1988), and they are expressed relative to an age model calculated relative to depth data in the same source. The data for (c) comes from Sponheimer and Lee-Thorp (2003), and Luyt and Lee-Thorp (2003)



(Cerling et al. 1988). The  $\delta^{13}C$  and  $\delta^{18}O$  sequences for the Turkana basin shown in Figure 9.2 also illustrate the variability of the results for each period, indicating a rather broad view of vegetation structure. Additional data sets from a wider range of regions and periods have been completed (Kingston et al. 1994; Sikes et al. 1999; WoldeGabriel et al. 2000). These data show a rather complex and variable overall mix of wooded terrain that tends to deemphasize the contributions of  $C_4$  grass to the overall mix.

Isotopic studies of fossil faunas, on the other hand, can be designed to investigate the various components of ancient flora. A number of isotopic data sets are now available for Pliocene and Pleistocene faunas that demonstrate presence or absence of  $C_4$  grasses in East and South Africa, (Morgan et al. 1994; Cerling et al. 1997; Sponheimer and Lee-Thorp 1999; Lee-Thorp et al. 2000; van der Merwe et al. 2003), and in Chad (Zazzo et al. 2000). In the Chad case, the faunal isotopic data demonstrated significant grassy vegetation from the Late Miocene through the Pliocene (Zazzo et al. 2000). In East Africa, faunal isotope data have in some cases run counter to the perspective afforded by pedogenic studies. At Olduvai, for instance, the isotope data from fauna suggest a greater  $C_4$  biomass (van der Merwe et al. 1999) than suggested by the soil carbonates. Another contradiction occurs in the Awash of Ethiopia, where de Heinzelin et al. (1999) suggest a wooded environment at  $\sim 2.5$  Ma based on presence of certain key fauna (*Colobus* and *Tragelaphus*) and soil isotope values, but faunal isotope analyses suggest a significant proportion of  $C_4$  grazers (Levin et al. 2004). These discordances suggest that different parts of the ecosystem are being sampled. The advantage of faunal isotope data is that they are abundant in the actual sites associated with hominin activity, and because we can follow first principles to establish abundance of  $C_4$  without assumptions about dietary preferences.

No pedogenic carbonate isotope record exists for the regions associated with the South African hominin sites, and the sites are not as old as many in East Africa. The nature of the karstic infill sites present serious challenges for determining the nature of long-term vegetation change. Faunal  $\delta^{13}C$  data from all the more important sites analyzed to date (Makapansgat, Sterkfontein, Swartkrans, Kromdraai) have shown that  $C_4$  grasses were present from the earliest periods associated with hominins, about 4 Ma or earlier, onward (Lee-Thorp and van der Merwe 1987; Sponheimer et al. 1999; van der Merwe et al. 2003; Hopley et al. 2006). On their own, these data demonstrate presence of  $C_4$  but are not very informative about changes in proportions of woody or grassy cover. A " $C_3/C_4$  index" has been developed, which is essentially an isotopic expression of the "acelaphine+antelope" index developed by Vrba (1980); it is based on the proportions of genera (Sponheimer and Lee-Thorp 2003), or individual specimens (Luyt and Lee-Thorp 2003), falling into one of the grazer, mixed feeder or

browser categories as determined by  $\delta^{13}\text{C}$ . The underlying idea is that browsers will be favored in a closed habitat with many trees, while grazers will be favored in open, grassy landscapes (Sponheimer and Lee-Thorp 2003). When applied to a series of sites to construct a sequential view, the results suggest that the most significant shift toward open, grassy landscapes occurred about 1.6–1.8 Ma (● Figure 9.2) rather than at ~2.4–2.6 Ma.

Isotopic data from the Buffalo Cave speleothem, in the Makapansgat Valley, provides more detailed information about vegetation change in this important time period. The speleothem is dated by independent means to between 2 and 1.5 Ma (Hopley 2004). The detailed  $\delta^{13}\text{C}$  sequence shows cyclical fluctuations in the proportions of  $\text{C}_4$  grass, with a dominant variability at ~40 Ka, indicating that the major control is the angle of the Earth as it orbits the Sun, and known as the obliquity cycle. Precessional cycles clustered around 20 Ka, due to the Earth's "wobble", are also visible. This sequence shows a ~1.7 Ma shift to higher proportions of  $\text{C}_4$  as before, but importantly, that this was but part of a cyclical pattern. The entire speleothem shows a slight long-term trend toward grassier conditions. Variability in the  $\delta^{18}\text{O}$  (reflecting rainfall) seems to be most strongly controlled by precessional cycles, in good agreement with those shown for the Tswaing Crater Lake Late Pleistocene sequence (Partridge et al. 1997), and for some Pliocene East African lakes (Trauth et al. 2005). Other stalagmite isotope data from Botswana (Holmgren et al. 1995) and Cold Air Cave in the Makapansgat Valley (Holmgren et al. 2003; Lee-Thorp 2004) hint at considerable floral and rainfall fluctuations but these records are too intermittent or too short to demonstrate precessional cycles. Although both  $\delta^{13}\text{C}$  (reflecting vegetation) and  $\delta^{18}\text{O}$  (reflecting rainfall) in the Buffalo cave speleothem are orbitally controlled, the differences in dominant orbital forcing modes between them emphasize the complexities of climate and environment, and the need for multiple sources of evidence.

The shift to grassier conditions in South Africa about 1.6–1.8 Ma is entirely concordant with the shift to open ecosystems in East Africa at the same time. This might be one occasion in which environmental shifts are in phase in East and South Africa.

These changes in floral composition, which can be documented using isotopic tools, are important for evaluating competing hypotheses about links between environment and hominin evolution. What does the floral information tell us? For one, the broad correspondence between the emergence (first appearance) of  $\text{C}_4$  grasses and hominin bipedalism *still holds*, in spite of observations that locally, environments may have remained relatively closed. The underlying connection might be dietary rather than locomotor.  $\delta^{13}\text{C}$  data on hominin diets have, almost without exception, shown an involvement with  $\text{C}_4$ -derived foods

(see Sponheimer and Lee-Thorp Vol. 1, Chapter 17, Lee-Thorp et al. 2003). The implication is that early hominins chose to make use of these new food sources, even if  $\text{C}_4$  grass remained a relatively minor component of the ecosystem. We need to test how far back in time this dietary flexibility goes.

There is widespread agreement on the appearance of more open, grassy habitats around 1.6–1.8 Ma. Given the increasing evidence for presence of a fully bipedal hominin equipped with more sophisticated stone tools (including hand-axes) from about this time, it is tempting to draw links between these two occurrences. In this case, we can suggest with some confidence that there is a real environmental "shift," but the exact nature of linkages to hominin behavioral and evolutionary shifts still require further investigation. Finally, the evidence for cyclical floral and moisture changes from the speleothem data, if upheld, requires reappraisal of several interpretations we have made. These have to do with the issue of time-scale and the nature of the fossil record. Most of the existing data rely on material that can, in principle, reflect small time-windows but the chronologies with which we have to work are quite gross. As a result, what emerges is rather a lot of noise and only the really large-scale environmental trends. The speleothem data also forcibly raise the issues of variability and cyclicity, which are crucial to the "variability selection" hypothesis advanced by Potts (1996, 1998).

## 9.2.5 Aridity indices from oxygen isotopes

Africa never experienced the large temperature swings associated with glacial to interglacial shifts at higher latitudes, and the climate variable of most importance and influence seems to have been rainfall. An overall trend toward aridification has been inferred from the visible trends toward more open, grassier African landscapes over the last ~5–6 Ma, as discussed earlier. However, although aridity and forest diminishment may well be linked in certain respects (for example, maintenance of equatorial forests requires high rainfall), the two are not necessarily tightly connected in savanna habitats. In their report on the isotopic data from pedogenic carbonates from Turkana from ~4 Ma, Cerling et al. (1988) note that the *presence* of these carbonates through the sequence is indicative that arid conditions were present from the lower sections. Since the  $\delta^{13}\text{C}$  data of pedogenic carbonates and fauna in the region shows that the proportions of  $\text{C}_4$  grasses remained fairly modest for millions of years after their first appearance, these data suggest strongly that tree density/open landscapes and aridity should be delinked. Studies of modern savanna ecosystems show that lower rainfall often favors more thicket and bushland rather than grass (Scholes and Walker 1993; Owen-Smith 1999). It remains important to establish

*independent* indicators for aridity. A number of isotopic approaches have been, or are, in the process of development.

As illustrated in **Figure 9.2**, the Turkana Basin pedogenic carbonate  $\delta^{18}\text{O}$  sequence suggests that a change in East African rainfall patterning occurred around 1.8 Ma. Since  $\delta^{18}\text{O}$  values prior to this time were more negative, and those thereafter more positive, the suggestion is that the dominant moisture source changed from a distant (perhaps the Atlantic Ocean) to a closer source, likely the Indian Ocean. The  $\delta^{18}\text{O}$  values in the latter period are sufficiently enriched to suggest that processes of evaporation also exerted an influence (**Figure 9.2**). This kind of information, therefore, provides some hints about development of aridity, but little detail.

Isotopic ratios from ostrich or ratite eggshells show great promise as aridity indicators, where the potential is to extract subtle and quantifiable indications of moisture shifts in the past. Johnson et al. (1997) used dual  $\delta^{15}\text{N}$  and  $\delta^{18}\text{O}$  data from ostrich eggshell in the Equus Cave hyena accumulation to document moisture fluctuations associated with Late Glacial to Holocene climate shifts. However, no similar studies have been undertaken for earlier periods of interest for hominin evolution, possibly because of the difficulties associated with the organic fraction in older material. Fortunately, data from modern and Late Pleistocene–Holocene archeological sites show that  $\delta^{18}\text{O}$  alone provides a reasonable aridity index (Lee-Thorp and Talma 2000; Ségalen 2003).  $\delta^{18}\text{O}$  from the eggshells of earlier ratites has been used to show continuously high, but fluctuating aridity in the Namib from the Miocene to the Present (Ségalen 2003; Ségalen et al. 2006). The main constraint is the chronology, which of necessity is based on biostratigraphy and thus provides only rather crude time intervals. A related tool based on fossil tooth enamel is under development (Schoeninger et al. 2003; Levin et al. 2006), which employs  $\delta^{18}\text{O}$  differences between animals that use environmental water, and those that rely on plant water and in turn reflect the influences of relative humidity (and aridity). Both of these tools hold potential but have not yet yielded information of direct consequence for addressing questions about climate trends and hominin evolution.

### 9.3 Conclusions

We have attempted to place some of the long-standing questions about the possible linkages between hominin evolution and environmental changes in an isotopic context and on a sound footing. There are a number of principles and constraints that must be considered for these applications or the results will be of limited value. In doing so, we may have rather overemphasized the problems and

constraints. So, in our concluding remarks, we would like to emphasize some of the solid advances that have been made over the last couple of decades.

A great strength of isotopic approaches to paleoenvironments clearly lies in the area of delineating floral changes, most particularly the presence and proportions of  $\text{C}_4$  grasses in the plant biomass. There are a couple of relatively minor disagreements evident from some of the pedogenic versus faunal approaches, but in general, a clear picture emerges.  $\text{C}_4$  grasses emerged about 6–8 Ma, probably earlier at the lower latitudes (Cerling et al. 1997), and they remained a visible, but modest and fluctuating, component of the vegetation for several millions of years. Sometime around 1.8 Ma, grasslands took off to become really major components of many African ecosystems, and this change occurred in both East and southern Africa. It is at this point that we probably best see the birth of a modern “world” complete with the vegetation and faunal distributions that we associate with today’s “typical” African environments. At the same time, new evidence points to the cyclical nature of environmental change for both flora and rainfall, which is strongly related to orbital forcing cycles of obliquity and precession. These cycles appear to have some considerable time depth. Isotopic evidence for aridity and possible aridification trends is at present thin, but the tools for developing these lines of evidence are now available.

What can these trends, shifts, and cycles tell us about hominin adaptations and evolutionary pathways? Are these issues linked, and if so, how? As noted earlier, the Savanna hypothesis fell from popularity sometime ago because the emergence of bipedalism was pushed back in time beyond estimations for the emergence of savannas, and because immediate environments associated with many early hominin sites suggested closed rather than open conditions.  $\delta^{13}\text{C}$  data suggest, however, that the hypothesis might still hold some substance albeit in a rather different sense. For one, the emergence of  $\text{C}_4$  grasses and bipedalism is still broadly concordant. The  $\delta^{13}\text{C}$  data show that these grasses remained relatively modest components of the biomass for a very long time after their first emergence. But the biomass associated with these grasses may have quickly become important to hominins. Without exception, all  $\delta^{13}\text{C}$  studies of hominin diets have shown that significant proportions of their diets contained  $\text{C}_4$ -derived carbon (Lee-Thorp et al. 2003) (see Sponheimer and Lee-Thorp Vol. 1, Chapter 17). The implication is that when grass-related foods became available, hominins chose to make use of these new resources, a development that may be suggested as a defining characteristic of hominins not shared with our closest living relatives (Sponheimer et al. 2005). This hypothesis has yet to be tested on earlier material. On present evidence, it would seem that a link between hominin emergence and environmental change is still there, but it is not quite as we anticipated it would be.

We can also use the isotopic data to evaluate other hypotheses linking climate or environment and evolution. There seems to be no strong isotopic evidence to support the idea of a large climate-driven shift about 2.4–2.8 Ma, as suggested in the turnover-pulse hypothesis (Vrba 1980). Rather, the evidence from  $\delta^{13}\text{C}$  in fauna and pedogenic carbonates from East and South Africa overwhelmingly suggests that the most significant biomass change to more open, grassy ecosystems occurred near 1.8 Ma. All available evidence suggests that this was indeed a big change. It is tempting but nevertheless speculative to suggest that the rise and success of a habitual, fully bipedal, more technologically advanced hominin, viz. *Homo erectus sensu lato*, is in some way connected with this widespread shift in African environments.

The nature of much of the isotopic evidence produced to date does not permit a detailed test of the variability selection hypothesis (Potts 1996, 1998). This is because we tend to produce data averaged in large time chunks, and the variability is mostly hidden. The new speleothem isotope paleoenvironmental data (Hopley 2004), as well as data emerging from East African lakes (Trauth et al. 2005), represent new departures. The Buffalo Cave  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  data sequence suggests orbital control on rainfall and vegetation, respectively, for ~0.5 Ma in the Pliocene and Pleistocene. That the  $\delta^{18}\text{O}$  data show a dominant precessional cycle very similar to the cycles evident from the Tswaing Crater in the last 180 Ka (Partridge et al. 1997) suggest that it is a persistent feature. The difference in cyclicity between  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  underscores the complexity of climate control on environmental variables, where it can be discerned. Above all, and in agreement with the Saharan dust cycles (deMenocal 1995), the data suggest that the obliquity and precessional orbital cycles remained underlying drivers of environmental variability well before the advent of the very large 100 Ka climate swings after ~0.8 Ma. This kind of sequence may at last provide greater land-based substance for testing Potts (1996, 1998) variability selection hypothesis.

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# 10 Chronometric Methods in Paleanthropology

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## Abstract

The aim of archeochronometry is the numeric dating, that is in term of years, of archeological and paleoanthropologic events or processes. The methods that are currently applied with most success are all based on the physical phenomenon of radioactivity. Their development underwent in the last few decades—and still undergoes—rapid progress. It is, in particular, the improvement in time resolution but also the application to novel sample materials as well as the extension of the age range of numeric dating that left a strong impact on modern paleoanthropology. This contribution introduces into the principles of radiometric dating. The most frequently applied dating methods, such as the potassium-argon, the uranium series, the fission track, the luminescence, the electron spin resonance, and radiocarbon techniques, are described. Their potential for paleoanthropology is illustrated using various examples covering the period since human entered the scene few million years ago.

## 10.1 Introduction

In paleoanthropology—as in any historically oriented discipline—time when something happened is the fundamental quantity. Recorded events do not make sense until they are arranged in their correct chronological order. Once such order is known, a mutual, causal relationship between the events may be confirmed or rejected. For instance, the coexistence of Neanderthals with modern humans excludes any hypothesis of simple evolution of the first into the second. Furthermore, a firm chronological database enables assessing the duration and the rate of processes, as is exemplified in the case of the remarkably fast-spreading of *Homo erectus* out of Africa. It is exactly for these reasons that the rapid progress, which chronometric dating experienced during the past few decades, inspired substantially the development of modern paleoanthropology.