

# Paleoenvironment of the Folsom archaeological site, New Mexico, USA, approximately 10,500 <sup>14</sup>C yr B.P. as inferred from the stable isotope composition of fossil land snail shells

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## Abstract

Well-preserved aragonitic land snail shells (*Vallonia*) from late Pleistocene Eolian sediment in the Folsom archaeological site in New Mexico exhibit an overall decrease of  $\delta^{18}\text{O}_{\text{PDB}}$  from maximum values of +2.7‰ (more positive than modern) to younger samples with lower average values of about –3.6‰ (within the modern range). The age of the samples (approximately 10,500 <sup>14</sup>C yr B.P.) suggests that the decrease in  $\delta^{18}\text{O}$  may manifest climatic changes associated with the Younger Dryas. Some combination of increased relative humidity and cooler temperatures with decreased  $\delta^{18}\text{O}$  of precipitation during the times of snail activity can explain the decrease in shell  $\delta^{18}\text{O}$ . A well-known Paleoindian bison kill occurred at the Folsom site during this inferred environmental transition.

Average  $\delta^{13}\text{C}$  values of the aragonite shells of the fossil *Vallonia* range from –7.3 to –6.0‰ among different archaeological levels and are not as negative as modern values. This suggests that the proportion of C<sub>4</sub> vegetation at the Folsom site approximately 10,500 <sup>14</sup>C yr B.P. was greater than at present; a result which is consistent with other evidence for higher proportions of C<sub>4</sub> plants in the region at that time. © 2004 University of Washington. All rights reserved.

**Keywords:** Oxygen isotopes; Carbon isotopes; Land snails; Paleoenvironment; Folsom site; C<sub>4</sub> plants; Younger Dryas

## Introduction

The Folsom archaeological site, located along Wild Horse Arroyo in the northeastern corner of Colfax County, New Mexico (Fig. 1), was discovered in late 1908 with the exposure, in a newly formed arroyo, of large mammal bone from what later proved to be an extinct species of bison (*Bison antiquus*) (Meltzer, 1983; Meltzer et al., 2002). The discovery of the site in 1908 was followed by three seasons of excavations in the late 1920s that yielded a substantial number of bison skeletal remains as well as some two dozen projectile points (Folsom fluted points), several of which were found embedded between bison

skeletal elements (Cook, 1927; Figgins, 1927). Renewed investigations at Folsom began in the late 1990s, and involved several seasons of excavations, along with a reanalysis of collections made in the 1920s. This investigation demonstrated that 32 bison were trapped and killed and that their remains occur in two areas of the site: the paleochannel of Wild Horse Arroyo, and a steep-sided tributary that fed into it. Patterns of bison dental eruption and wear suggest that the kill occurred in the fall. Multiple radiocarbon assays on bone amino acids from different individuals in the bison herd indicate an average age of approximately 10,500 <sup>14</sup>C yr B.P. (Meltzer et al., 2002).

Land snail shells (dominantly *Vallonia*) are also present in the quaternary sediments of the Folsom site and could be important sources of information about the site. Brennan and Quade (1997) demonstrated that fossil shells of *Vallonia*

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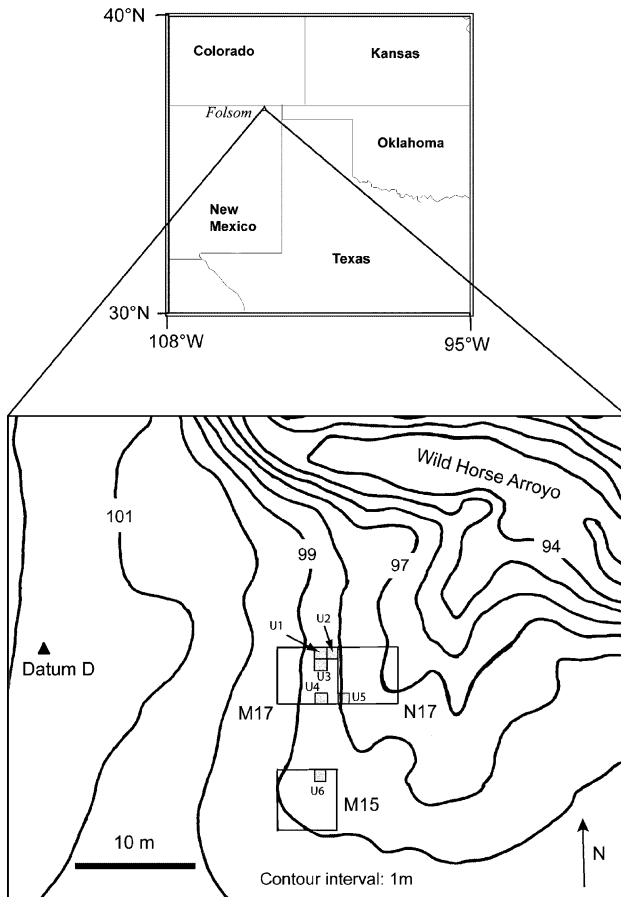


Figure 1. Location of the Folsom archaeological site with details of the present topography and sample grids. Larger open squares are “blocks” labeled M17, N17, and M15. In each block, smaller labeled and shaded squares represent the “units” from which the samples of this study were collected (see text and Appendix). A value of “100” for a contour line corresponds to an elevation of 2109 m (sea level datum; see Meltzer et al., 2002). Contour intervals are 1 m. Datum “D” is a local reference datum used in the original archaeological study to assign the relative elevation numbers of levels in each excavated unit (see text and Meltzer et al., 2002).

spp. may be reliable sources of  $^{14}\text{C}$  dates (however, see Pigati et al., 2004). Stable oxygen isotopes in land snail shells appear to reflect a combination of local variables: (1) temperature, (2) relative humidity, (3) isotopic composition of local rainfall, and (4) isotopic composition of ambient water vapor at the time of snail activity (e.g., Balakrishnan and Yapp, 2004). This dependence of shell  $\delta^{18}\text{O}$  values on a variety of active season environmental parameters arises from the evaporative loss of water from the body fluid of land snails (Balakrishnan and Yapp, 2004; Yapp, 1979). Stable carbon isotopes in the aragonite shells, on the other hand, are related to the isotopic composition of organic matter (i.e.,  $\text{C}_3$  vs.  $\text{C}_4$ ) ingested by the snails (Balakrishnan and Yapp, 2004; Goodfriend and Ellis, 2002; Metref et al., 2003; Stott, 2002). However, varying contributions of carbon from local “limestone” carbonate may contribute to scatter in the relationship (e.g., Goodfriend and Hood, 1983; Yates et al., 2002). Stable isotope data from various genera of fossil snail shells (including *Vallonia*) have been used to

deduce paleoenvironmental conditions in Utah (Yapp, 1979), Israel (Goodfriend, 1988, 1990, 1991, 1992; Magaritz and Heller, 1980), Switzerland (Kaiser and Eicher, 1987), Argentina (Bonadonna et al., 1999), South Africa (Abell and Plug, 2000), and Texas (Goodfriend and Ellis, 2000).

The renewed archaeological activity at the Folsom site yielded samples with well-preserved fossil *Vallonia* shells and some soil carbonate nodules. The excellent preservation suggested that the shells had not experienced significant sedimentary transport (Meltzer, in review). Thus, the *Vallonia* shells represented an opportunity to use stable isotopic analysis to enhance our understanding of the environmental conditions extant at the time of ancient human occupation of the Folsom site. The results of an isotopic study of these shells are presented herein.

## Samples and experimental procedures

### The site and samples

The Folsom site is located at an elevation of 2109 m (sea level datum). The local bedrock is Smoky Hill shale of Cretaceous age (Scott and Pillmore, 1993). The shale is unconformably overlain by late quaternary sediments. These quaternary sediments (shown schematically in Fig. 2) are the Folsom formation (*f*); overlain by the McJunkin formation (*m*); and the Wild Horse formation (*w*). The sediments are described in detail by Anderson and Haynes (1979), Meltzer et al. (2002), and Meltzer (in review). The Folsom formation consists of three distinct strata. The oldest of the three strata,  $f_1$  (dated at about 12,400  $^{14}\text{C}$  yr B.P.), is comprised of silt containing eroded shale fragments. The  $f_2$  stratum lies conformably over  $f_1$  and is composed predominantly of silty clay (hereafter termed “silt”), likely of Eolian origin, deposited approximately between 11,500 and 10,000  $^{14}\text{C}$  yr B.P. (Meltzer et al., 2002). The silt  $f_2$  is succeeded by the  $f_3$  gravel, which rests unconformably on  $f_2$ . The  $f_3$  gravel consists of eroded fragments of the Smoky Hill shale and was deposited in episodes of slope wash between 10,000 and 9800  $^{14}\text{C}$  yr B.P. (Meltzer et al., 2002). The Folsom-age artifacts and the main area of the bison bone bed are concentrated in a tributary head cut, where the remains were rapidly buried by, and are confined to, the  $f_2$  sediments. The bones have an age of approximately 10,500  $^{14}\text{C}$  yr B.P. (Meltzer et al., 2002). A small number of bison remains have also been recovered in the  $f_3$  stratum within a paleochannel, but these elements show clear evidence of having been transported subsequent to their initial deposition and thus are not in primary context (Meltzer et al., 2002; Meltzer, in review). All samples discussed here came from the bone bed area of the tributary head cut, where there is little or no evidence of sediment reworking. In this head cut, the contact between the silt ( $f_2$ ) and gravel ( $f_3$ ) occurs at depths from

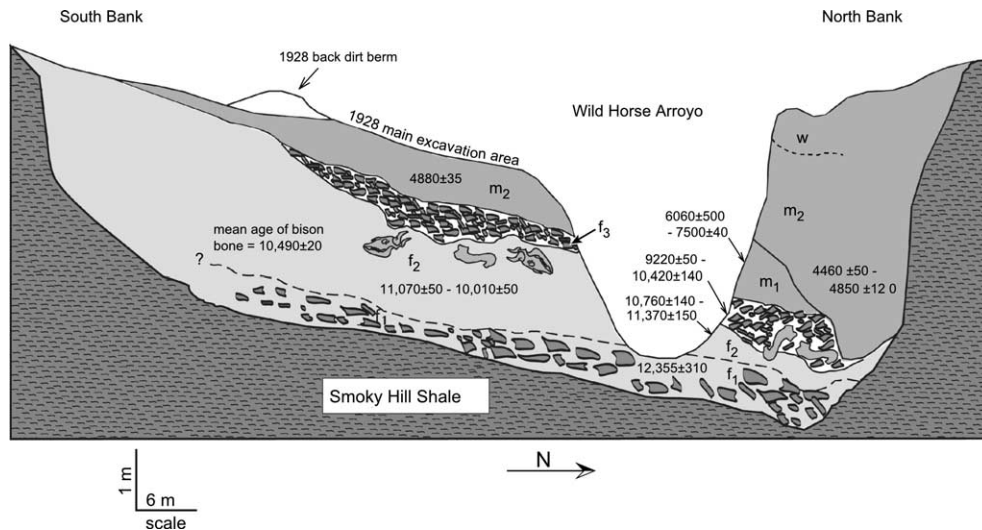


Figure 2. Generalized north–south schematic representation of the stratigraphic profile of Wild Horse Arroyo at the Folsom site (from Meltzer et al., 2002). Location of bison remains and  $^{14}\text{C}$  ages of the sediments are also shown.

approximately 1 to 3 m below the local modern ground surface.

Meltzer et al. (2002) systematically collected sediment samples from all of their archaeological excavations. Because the snail shells analyzed for the current study were taken from these archaeological samples, the system for sample labeling and the sediment descriptions employed by Meltzer et al. (2002) were necessarily also used here. Within the main area of the bone bed in the tributary head cut, a total of twenty-one  $1 \times 1$  m “units” were excavated, from three prescribed  $5 \times 5$  m “blocks,” designated M17, N17, and M15 (Fig. 1). Seventeen of these  $1 \times 1$  m units were from the M17 and N17 blocks, which contained the greatest concentration of bison bone. The remaining units were from the M15 block, which produced very limited archaeological material. Each of the  $1 \times 1$  m units was subdivided into  $50 \times 50$  cm quadrants, which were excavated in vertical “levels.” Individual level numbers (Appendix) were referenced to a local datum used for the entire Folsom site and level numbers increase with depth (Meltzer et al., 2002). Thus, older levels in a unit have progressively larger level numbers. Each level represents a vertical increment of 5 cm. Untreated sediment samples collected from successive levels in excavations of the southwest quadrants of six of the  $1 \times 1$  m units (U1, U2, U3, U4, U5, and U6; see Appendix and Fig. 1) were sources of the snail shells analyzed in this study.

#### Laboratory preparation and analysis

Five of the six units were processed at Southern Methodist University (SMU). Snail shells were extracted from the sixth (U2) at the University of Wisconsin-LaCrosse. Sediments from each level of the SMU-processed units were weighed and sieved with deionized water in the laboratory using a series of nested sieves (4 mm, 710  $\mu\text{m}$ , 420  $\mu\text{m}$ , and

250  $\mu\text{m}$ ). After sieving, snail shells and carbonate nodules were carefully extracted with forceps or a fine brush, thoroughly rinsed with deionized water and allowed to dry in air at room temperature. As an approximate indicator of the change in grain size from the  $f_2$  silt to the  $f_3$  gravel, the sieved sediment samples were also air-dried, and the mass fraction of the sediment with grain size  $>710 \mu\text{m}$  in a particular sample was measured (see Appendix). The sediments from two of the five aforementioned sieved units (U3 and U6) were processed by Kim Arnold (Arnold, 1998, 1999), while the remaining three were processed specifically for this study. The  $>710 \mu\text{m}$  mass fractions for the sediment in the levels of U2 were not determined.

Fossil snail shell material can be altered by dissolution of the shell aragonite and reprecipitation as calcite (Brennan and Quade, 1997). Therefore, the shells analyzed for the current work were carefully hand picked under a stereo microscope and analyzed with X-ray diffraction and scanning electron microscopy (SEM) to look for evidence of recrystallization. It should be noted that extrapolation to sedimentary temperatures yields extremely small values for volume diffusion coefficients of oxygen in carbonates (e.g., Cole and Ohmoto, 1986). Therefore, in the absence of dissolution and recrystallization, significant isotope exchange by solid state self-diffusion of oxygen seems unlikely on the time scales of preservation of the Folsom aragonite shells.

Not all of the levels yielded snail shells, or soil carbonate nodules, and because of the comparatively small amount of sediment analyzed from each level, not all of the levels that did contain snail shells contained sufficient amounts to perform duplicate analyses. To reduce the effect of possible genera-specific isotopic differences, only the shells of the relatively more abundant *Vallonia* were analyzed.

The hand-picked shells were treated ultrasonically in deionized water to remove any adhering particulates that

might derive from associated pedogenic calcite and were thoroughly rinsed. The shells were then gently crushed and treated with 5% reagent grade sodium hypochlorite at room temperature for about 7–8 h to remove organic matter. They were again rinsed thoroughly with deionized water and dried in air at about 40–50°C. This treatment yielded shell fragments for which aragonite was the only XRD-detectable mineral, and SEM imaging showed no evidence of shell recrystallization (Fig. 3). Isotopic analyses were performed only on such “clean” fossil shells.

Samples of shell fragments and the soil carbonate nodules were subsequently reacted overnight in vacuum with 100% H<sub>3</sub>PO<sub>4</sub> at 25°C following the method of McCrea (1950). The CO<sub>2</sub> prepared from the snail shell aragonite and soil carbonate nodules was analyzed for δ<sup>13</sup>C and δ<sup>18</sup>O on a Finnigan MAT 252 mass spectrometer in the stable isotope laboratory at SMU. Analytical uncertainty is about ±0.1‰. The δ values are defined as:

$$\delta^{13}\text{C} \text{ or } \delta^{18}\text{O} = \left[ \left( \frac{R_{\text{sample}}}{R_{\text{standard}}} \right) - 1 \right] \times 1000\text{‰}$$

$R = {}^{13}\text{C} / {}^{12}\text{C}$  or  ${}^{18}\text{O} / {}^{16}\text{O}$ . δ<sup>13</sup>C and δ<sup>18</sup>O are reported relative to the PDB standard (Craig, 1957).

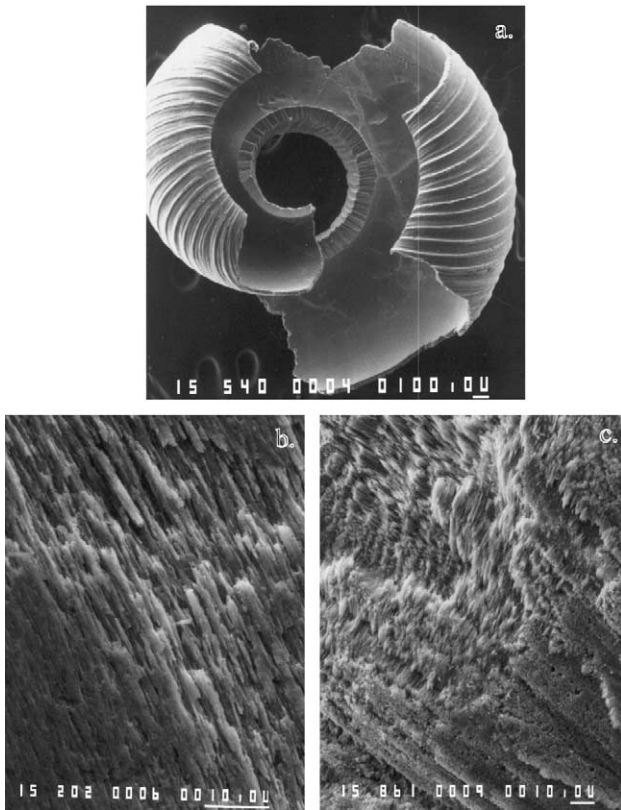


Figure 3. SEM images of a fragment of a *Vallonia gracilicosta* shell from the Folsom, New Mexico, archaeological site. (a) Entire shell fragment showing inner and outer walls (scale bar = 100 μm); (b) outer wall (scale bar = 10 μm); (c) inner wall (scale bar = 10 μm). Note that there is no evidence of recrystallization or secondary overgrowths on either the interior or exterior walls.

## Results and discussions

### Comparisons of land snail shell and soil nodule isotope compositions

The δ<sup>13</sup>C and δ<sup>18</sup>O results for all samples analyzed for this work are reported in the Appendix and plotted in Figure 4. The δ<sup>18</sup>O values of the aragonitic snail shells range from –6.9 to +2.7‰, while the δ<sup>13</sup>C values range from –9.4 to –3.9‰. There is no correlation of snail shell δ<sup>13</sup>C with δ<sup>18</sup>O. For the calcitic soil nodules, δ<sup>18</sup>O values range from –12.1 to –4.2‰ and the δ<sup>13</sup>C values from –16.7 to –3.9‰. The snails and soil nodules from the Folsom site appear to define distinctly separate isotopic populations (Fig. 4). Moreover, although represented by a limited number of data points, there seem to be two different isotopic populations (SN<sub>1</sub> and SN<sub>2</sub>) of the soil nodules.

The range of δ<sup>13</sup>C values of the SN<sub>1</sub> population of nodules (Fig. 4) is comparable to that of the land snails (L). If the land snail shells and soil nodules formed in the presence of CO<sub>2</sub> derived from oxidation of organics with similar δ<sup>13</sup>C values, it is expected that the δ<sup>13</sup>C values of the two forms of carbonate would be similar. This similarity is expected because the mineral-CO<sub>2</sub> carbon isotope fractionation factors for aragonite and calcite differ from one another by only 1.7‰ at sedimentary temperatures (e.g., Mook et al., 1974; Romanek et al., 1992). Moreover, in each case, the ambient CO<sub>2</sub> gas is enriched in <sup>13</sup>C relative to the oxidizing organic matter to about the same degree (approximately 4.4‰) by a diffusive, gas phase, mass transfer process (Balakrishnan and Yapp, 2004; Cerling, 1984). Therefore, the overlap in δ<sup>13</sup>C values of the land snail (L) and SN<sub>1</sub> populations of Figure 4 suggests that the source of carbon for the two populations was similar and may have represented varying contributions of carbon from oxidation of a mix of local C<sub>3</sub> and C<sub>4</sub> plants (e.g., Balakrishnan and Yapp, 2004; Cerling, 1984; Francey, 1983; Goodfriend and Ellis, 2002; Metref et al., 2003; Stott, 2002).

In contrast, there is no overlap of the ranges of δ<sup>18</sup>O values of the SN<sub>1</sub> and the L populations (Fig. 4). The more positive δ<sup>18</sup>O values of the snails probably reflect the fact that they live at the soil–air interface and form shells only during their periods of activity—when the relatively high <sup>18</sup>O rains of the warmer months are further enriched in <sup>18</sup>O by evaporation (e.g., Balakrishnan and Yapp, 2004; Rozanski et al., 1993). The δ<sup>18</sup>O values of the soil nodules of SN<sub>1</sub> on the other hand suggest crystallization in subsurface soil environments with waters lower in <sup>18</sup>O, which were more representative of average annual precipitation (e.g., Cerling, 1984; Rozanski et al., 1993).

The δ<sup>13</sup>C values of –15.3 and –16.7‰ for the samples of population SN<sub>2</sub> (Fig. 4) are, as far as we know, the most negative reported to date for soil nodules (e.g., Ekart et al., 1999). Such negative δ<sup>13</sup>C values are not plausibly explained by invoking, as a sole source of CO<sub>2</sub>, oxidation of commonly observed C<sub>3</sub> plant populations, particularly in

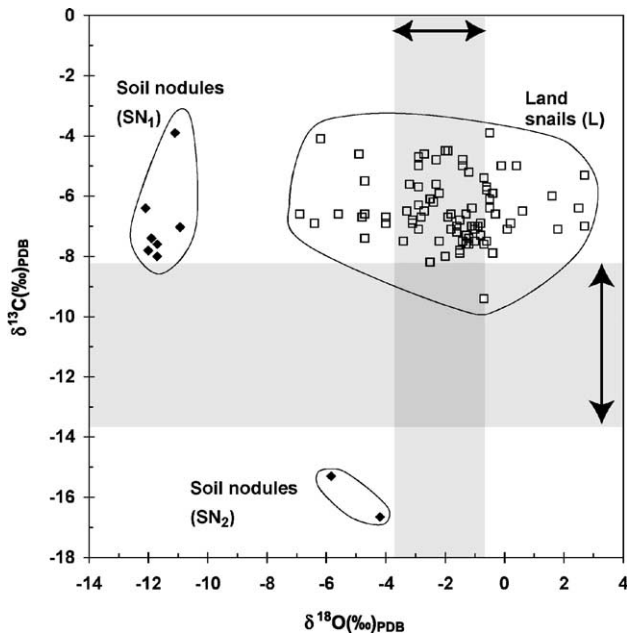


Figure 4. Plot of  $\delta^{13}\text{C}$  against  $\delta^{18}\text{O}$  for all of the ancient aragonitic *Vallonia* shells (L, open squares) and associated calcitic soil nodules (SN, filled diamonds) analyzed for this study from the Folsom archaeological site. The land snail shells and soil nodules appear to define separate isotopic populations. The populations SN<sub>1</sub> and SN<sub>2</sub> are discussed in the text. The arrows and the corresponding shaded areas represent the ranges of  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  of modern snail shells in the area.

the American southwest (e.g., Arens et al., 2000; Cerling, 1984; Cerling and Quade, 1993).

The  $\delta^{13}\text{C}$  values of the SN<sub>2</sub> soil nodules suggest that, at the time and place of their formation, an additional more  $^{13}\text{C}$ -depleted  $\text{CO}_2$  was added to the soil gas. It is noted that the SN<sub>2</sub> nodules were from levels stratigraphically above the base of the bone bed and that the relict bison carcasses are presumed to have been buried in a relatively short period of time as indicated by the quality of bone preservation (Meltzer et al., 2002; Meltzer, in review). Moreover, considerable soft tissue from the bison carcasses was apparently buried with the bone (Meltzer, in review). This suggests the possibility that the low  $\delta^{13}\text{C}$  values of SN<sub>2</sub> nodules may reflect small amounts of  $^{13}\text{C}$ -depleted biogenic methane (perhaps generated by local anaerobic decay of underlying bison tissue) that was oxidized at shallower depths in the soil environment at the time of nodule formation. A simple mass balance calculation suggests that only a relatively small contribution of such  $^{13}\text{C}$ -depleted, methane-derived  $\text{CO}_2$  would be needed. First, it is assumed that without additions of the hypothesized  $^{13}\text{C}$ -depleted  $\text{CO}_2$ , the soil nodules would have had  $\delta^{13}\text{C}$  values of about  $-7\text{‰}$  (e.g., SN<sub>1</sub>; Fig. 4). If so, addition of methane-derived  $\text{CO}_2$  with  $\delta^{13}\text{C}$  values of about  $-65\text{‰}$  (Schoell, 1980) would need to have constituted only about 20% of the total soil  $\text{CO}_2$  to produce soil nodule  $\delta^{13}\text{C}$  values of about  $-16\text{‰}$ .

The  $\delta^{18}\text{O}$  values of the SN<sub>2</sub> nodules overlap the range of snail shell  $\delta^{18}\text{O}$  values (Fig. 4) and are significantly more

positive than the  $\delta^{18}\text{O}$  values of SN<sub>1</sub>. This seems to support the possibility that the SN<sub>2</sub> nodules formed at shallower depths in the soil because higher soil water (and soil carbonate)  $\delta^{18}\text{O}$  values could be expected as a consequence of evaporation at shallow depths (e.g., Cerling, 1984; Cerling and Quade, 1993).

There are only two samples in SN<sub>2</sub>, and none of the other soil nodules stratigraphically above the base of the bone bed (Appendix) exhibit anomalously low  $\delta^{13}\text{C}$  values. Additional detailed analyses of laterally distributed soil nodules from levels above and below the bone bed are needed to look for systematic patterns of spatial distribution that might provide additional insights into the origin of the anomalously low SN<sub>2</sub>  $\delta^{13}\text{C}$  values.

#### *Temporal variations of oxygen and carbon isotopes in fossil Vallonia shells*

##### *Oxygen isotopes*

Units U1, U2, U3, U4, and U5 from the juxtaposed blocks M17 and N17 (Fig. 1) contain bison bones, and the age of the bones (approximately 10,500  $^{14}\text{C}$  yr B.P.; Fig. 2) is known (Meltzer et al., 2002; Meltzer, in review). Therefore, the base of the bone bed may serve as a common time line for units U1, U2, U3, U4, and U5. As discussed previously, in a particular unit, the identifying numbers of excavation levels increase with increasing depth in the sediment and thus represent progressively older samples. Rates of sedimentation in each of these five bone-bearing units are unknown, but proximity of the units to one another (Fig. 1) might favor an assumption that the rates were similar. We make use of three additional observations: (1) that each excavation level has a thickness of 5 cm; (2) that a particular excavation number refers to the same vertical position relative to a common local datum no matter which unit is under consideration; and (3) that the base of the bone bed is at level 149 in each of the units U1, U2, U3, U4, and U5 (Appendix). With these conditions, it was assumed, as a working hypothesis, that excavation levels with the same identifying number in these units were of the same age. It should be emphasized that there are currently no  $^{14}\text{C}$  dates that can be used to establish convincing temporal correlations among the levels in these five units either above or below the base of the bone bed. The few pieces of charcoal and/or humic acid that have been dated are allochthonous and do not necessarily represent the age of the enclosing sediment (Meltzer, unpublished data). Therefore, they are not considered in the current discussion.

$\delta^{18}\text{O}$  values of the snail shells from U1, U2, U3, U4, and U5 are plotted collectively in Figure 5 against their respective excavation levels. Samples collected from the silt ( $f_2$ ) are represented by solid diamonds, while those found in the overlying gravel ( $f_3$ ) are depicted as shaded diamonds (Fig. 5).  $\delta^{18}\text{O}$  values of the individual measurements range from  $-6.9$  to  $2.7\text{‰}$ . For comparison,  $\delta^{18}\text{O}$  values of modern land snail shells in the study area range

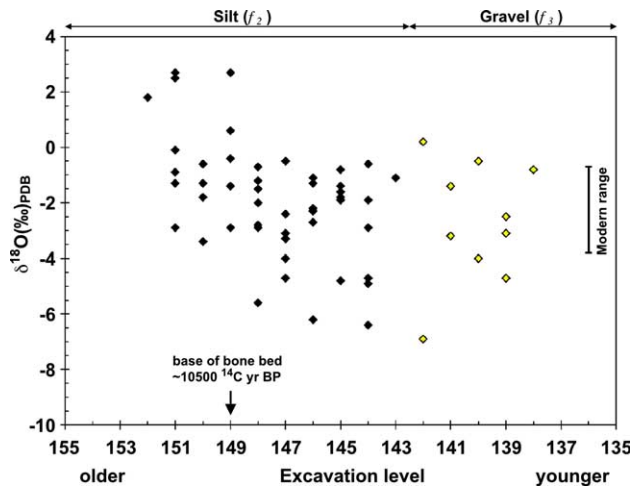


Figure 5. Measured  $\delta^{18}\text{O}$  values of *Vallonia* shell aragonite for units U1, U2, U3, U4, and U5 of the M17 and N17 blocks in the Folsom archaeological excavation are plotted with respect to their corresponding designated archaeological excavation level (see text for explanation of levels). These five units contain the bison bone bed, the base of which is assumed to be of the same age (approximately 10,500  $^{14}\text{C}$  yr B.P.) in each of these units (Meltzer et al., 2002). Also, in each of these five units, excavation level 149 is the base of the bone bed (Appendix).

from  $-3.8$  to  $-0.7\text{‰}$  (Balakrishnan et al., in press). In the silt ( $f_2$ ), the most positive  $\delta^{18}\text{O}$  value measured for shells from the younger levels (143 through 148) is  $-0.5\text{‰}$  (Fig. 5). In contrast, at the base of the bone bed (level 149) and in older levels (to level 152),  $\delta^{18}\text{O}$  values range up to  $2.7\text{‰}$ . The absence of such positive  $\delta^{18}\text{O}$  values in the younger levels and their occurrence in the older levels suggests that the snail shells may preserve evidence of a temporal change in local paleoenvironmental conditions. Although there are relatively few analyses represented in some of the levels, the overall pattern of such change might be better represented

by snail shell  $\delta^{18}\text{O}$  values averaged for each level among the five units.

Average  $\delta^{18}\text{O}$  values for land snails from levels with two or more analyses among the five bone-bearing units are plotted in Figure 6b against excavation level. Among the five units, there is only one analysis each available from levels 152, 143, and 138 (Appendix), and these are not included in the plot of average values in Figure 6b. To provide some context, the transition from silt to gravel in unit U3 is illustrated in Figure 6a by a plot of the mass fraction of sediment grains with particle size  $>710\ \mu\text{m}$  at different levels. As seen in Figure 6b, the average  $\delta^{18}\text{O}$  values exhibit an overall decrease from  $0.0\text{‰}$  at level 151 to  $-3.6\text{‰}$  at level 144. Over this same interval, the host sediment is the silt of  $f_2$  (Fig. 6a). In the overlying gravel ( $f_3$ ), average  $\delta^{18}\text{O}$  values of *Vallonia* shells range from  $-3.4$  to  $-2.3\text{‰}$  (Fig. 6b). The change in depositional environment from the lower transport energies represented by the silt of the  $f_2$  stratum to the higher transport energies of the gravels in the  $f_3$  stratum (Fig. 6a) is consistent with a shift in precipitation regime from lower to higher amounts and/or intensities of precipitation. However, this difference in transport and depositional environment is not manifested in systematic changes in the  $\delta^{18}\text{O}$  values of the *Vallonia* shells.

In unit U6 (Fig. 1), which contains no bone bed,  $\delta^{18}\text{O}$  values of *Vallonia* shells show a decrease of  $2.8\text{‰}$  early in the record (filled diamonds, Fig. 7) from a value of  $1.6\text{‰}$  at level 154 to a value of  $-1.2\text{‰}$  at level 152. From level 152 to level 140, there is a  $\delta^{18}\text{O}$  range of  $2.0\text{‰}$  (from  $-2.5$  to  $-0.5\text{‰}$ ), but no evident monotonic variation (Fig. 7). This overall pattern of temporal variation of  $\delta^{18}\text{O}$  values in U6 (Fig. 7) is similar to that observed in Figure 6b, but the early decrease in  $\delta^{18}\text{O}$  does not occur at the same excavation

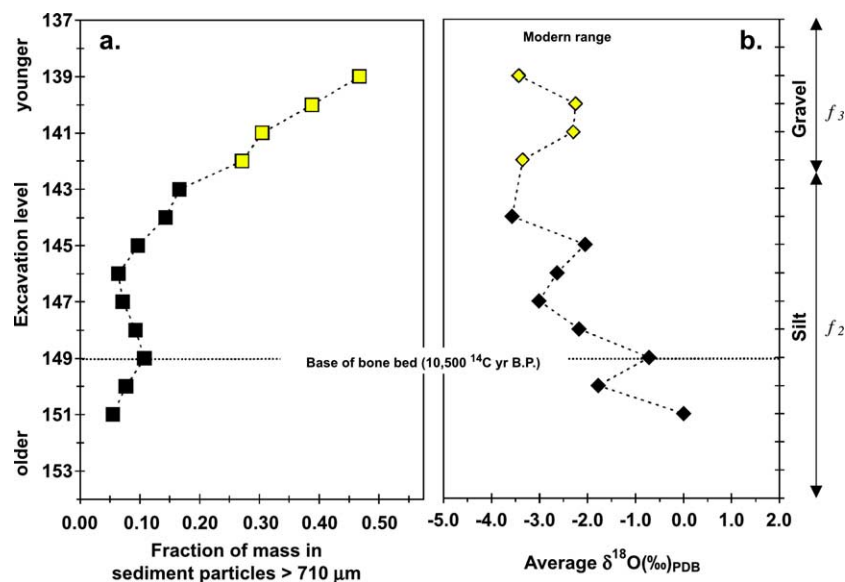


Figure 6. Folsom site. (a) Fraction of the sediment mass contained in grains with diameters  $>710\ \mu\text{m}$  plotted with respect to excavation level for unit U3. (b) Average  $\delta^{18}\text{O}$  value of *Vallonia* shells from units U1, U2, U3, U4, and U5 plotted with respect to excavation level (see text). The labeled arrows indicate the vertical extent of silts ( $f_2$ ) and gravels ( $f_3$ ) in which the shells occurred.

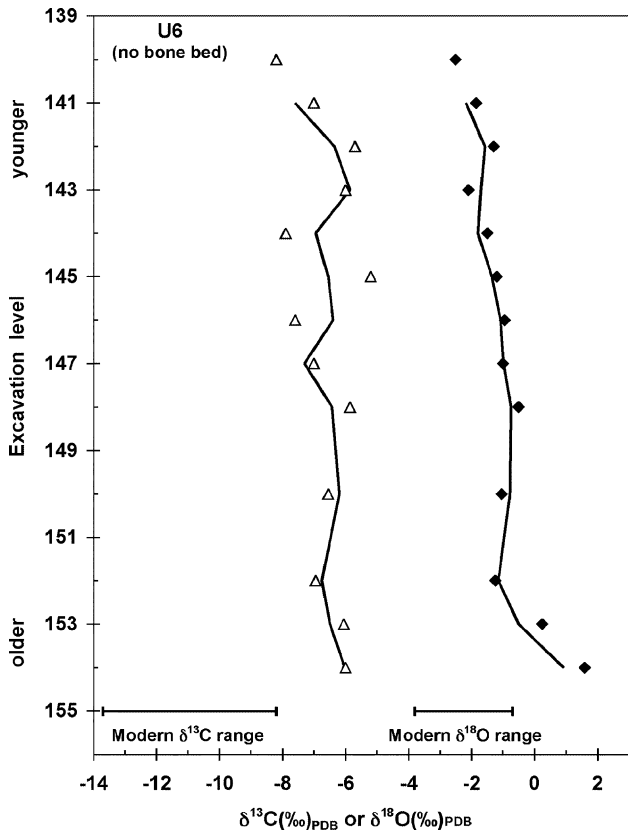


Figure 7. Folsom site.  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  of *Vallonia* shells from unit (U6), which contains no bone bed. The irregular lines represent two-point moving averages of the  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values plotted against the older excavation level in each average. Filled diamonds:  $\delta^{18}\text{O}$ . Open triangles:  $\delta^{13}\text{C}$ .

levels in U6. As noted, there is an absence of reliable  $^{14}\text{C}$  ages that might be used for a temporal correlation of levels in U6 with those of the bone-bearing beds. However, the similarity in the patterns of temporal variation of the  $\delta^{18}\text{O}$  values in the two categories of units (those with and those without a bone bed) suggests that the *Vallonia* shells in both may record a common local environmental change.

Figure 8 depicts a three-point moving average (including levels with single analyses) of the average  $\delta^{18}\text{O}$  values of the Folsom snails from the bone-bearing units (U1, U2, U3, U4, and U5) plotted against the level of the youngest sample in the average. Although some information is lost in calculating moving averages, such averages remove high frequency “noise” in favor of displaying longer term trends. The curve for oxygen isotopes in Figure 8 emphasizes the significance of the overall decrease in snail shell  $\delta^{18}\text{O}$  values at about 10,500  $^{14}\text{C}$  yr B.P. Furthermore, the moving average indicates that even if the single analysis at level 152 ( $\delta^{18}\text{O} = 1.8\text{‰}$ ) were excluded from consideration, the pattern of decreasing  $\delta^{18}\text{O}$  values early in the record would remain.

*Carbon isotopes*

$\delta^{13}\text{C}$  values of modern land snail shells in the study area range from  $-13.7$  to  $-8.2\text{‰}$  and indicate that  $\text{C}_3$  plants are

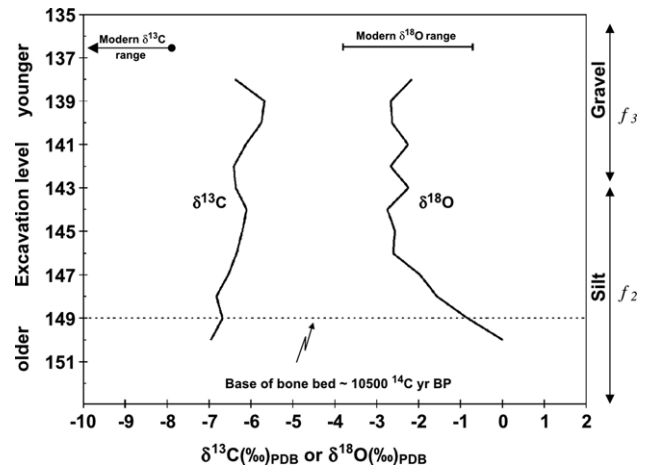


Figure 8. Three-point moving averages of the average  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values of *Vallonia* shells from each of the excavation levels in units U1, U2, U3, U4, and U5 at the Folsom site plotted against the youngest excavation level in each average. Level 149 is the base of the bison bone bed, which has an age of approximately 10,500  $^{14}\text{C}$  yr B.P. This diagram emphasizes the “long-term” patterns of isotopic variation in the *Vallonia* data. A relatively large decrease in  $\delta^{18}\text{O}$  values is evident early in the record (see text) and is recorded in snails from the silt ( $f_2$ ) of the Folsom Formation.  $\delta^{13}\text{C}$  values are more positive than modern over the length of this record.

the primary constituents of snail diets (Balakrishnan et al., in press). In contrast, with one exception, the  $\delta^{13}\text{C}$  values of the fossil *Vallonia* shells of the Folsom site are more positive than the modern snails. The fossil  $\delta^{13}\text{C}$  values range from  $-9.4$  to  $-3.9\text{‰}$  (Fig. 9 and Appendix). These more positive  $\delta^{13}\text{C}$  values probably indicate a higher proportion of  $\text{C}_4$  plants in the snail diet (Balakrishnan and Yapp, 2004; Balakrishnan et al., in press; Goodfriend and Magaritz, 1987; Goodfriend and Ellis, 2002; Metref et al., 2003; Stott, 2002), which suggests that the local plant ecology about 10,500  $^{14}\text{C}$  yr B.P. was different from modern.

The presence of a higher percentage of  $\text{C}_4$  vegetation in the American Southwest at a variety of altitudes at the end of the late Pleistocene is indicated by other proxy data.  $\delta^{13}\text{C}$

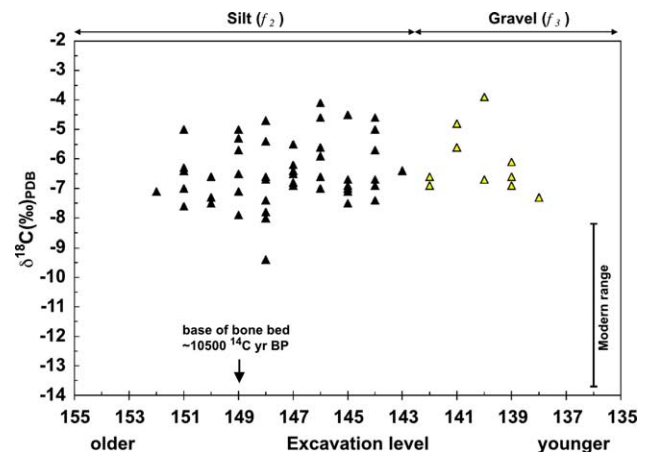


Figure 9. Folsom site. Measured  $\delta^{13}\text{C}$  values of *Vallonia* shells plotted with respect to the excavation level from which the shells were recovered for units U1, U2, U3, U4, and U5 (see text). Level 149 is the base of the bison bone bed, which has an age of approximately 10,500  $^{14}\text{C}$  yr B.P. (Appendix).

values of tooth enamel of *Bison* spp. and *Mammuthus* spp. indicate a C<sub>4</sub>-dominant diet from about 12,000 to 10,000 <sup>14</sup>C yr B.P. in the Southern High Plains (Connin et al., 1998).  $\delta^{13}\text{C}$  values of organic carbon from soil sequences in the Southern High Plains (Holliday, 2000) and South Central Texas (Nordt et al., 2002) also indicate a higher percentage of C<sub>4</sub> vegetation between 11,000 and 10,000 <sup>14</sup>C yr B.P. Moreover, a higher proportion of C<sub>4</sub> plants between 20,000 and 10,000 <sup>14</sup>C yr B.P. has been deduced from isotopic studies of soil carbonates in Arizona (Liu et al., 1996) and New Mexico (Cole and Monger, 1994; Monger et al., 1998).

The  $\delta^{13}\text{C}$  values of *Vallonia* shells from U6 (no bone bed) in silt  $f_2$  are plotted in Figure 7 (open triangles) and range from  $-8.2$  to  $-5.2\text{‰}$ . These  $\delta^{13}\text{C}$  values lie within the range of values measured for shells from the bone-bearing units (U1, U2, U3, U4, U5; Fig. 9). Therefore, the  $\delta^{13}\text{C}$  data from U6 are also consistent with an interpretation of a higher proportion of C<sub>4</sub> plants in the diet of these ancient *Vallonia* at the time of deposition of the silt ( $f_2$ ).

A plot of three-point moving averages of level-average  $\delta^{13}\text{C}$  values of *Vallonia* shells from bone-bearing units U1, U2, U3, U4, and U5 at the Folsom site (Fig. 8) hints at a possibly small, overall increase in shell  $\delta^{13}\text{C}$  values over much of this record (each moving average value is plotted against the youngest level in the average). However, the scatter in the  $\delta^{13}\text{C}$  data of Figure 9 makes an interpretation of a secular variation of  $\delta^{13}\text{C}$  values problematic.

#### Paleoclimatic inferences

Comparison of <sup>230</sup>Th and <sup>14</sup>C ages in corals (Bard, 1998) with data from the Greenland ice cores (e.g., Johnsen et al., 2001) suggests that the Younger Dryas (YD) cold interval persisted over the interval from approximately 11,000 to 10,000 <sup>14</sup>C yr B.P. As noted, the silt ( $f_2$ ) of the Folsom Formation was deposited approximately between 11,500 and 10,000 <sup>14</sup>C yr B.P., whereas the gravel ( $f_3$ ) was deposited approximately between 10,000 and 9800 <sup>14</sup>C yr B.P. (Meltzer et al., 2002). Therefore, the entire temporal record in Figure 5 is encompassed in an interval of about 1700 yr. The <sup>14</sup>C “age plateau,” which is part of this interval, adds uncertainty to the assessment of the actual number of years that might be represented by the Folsom Formation record (Bard, 1998). However, the age of the bison bones (approximately 10,500 <sup>14</sup>C yr B.P.) suggests that much, if not all, of the temporal variation of  $\delta^{18}\text{O}$  values of *Vallonia* analyzed for this work (Fig. 8) occurred during the YD.

The Younger Dryas (YD) interval appears, in general, to have been a time of significant, often rapid, global climate change (e.g., Alley et al., 2003; Denton and Hendy, 1994; Kuhry et al., 1993; Thompson et al., 1995). The onset of the YD was marked by a rapid decrease in  $\delta^{18}\text{O}$  values of Greenland ice with subsequent relatively high frequency oscillations of  $\delta^{18}\text{O}$  (e.g., Dansgaard et al., 1993; Dansgaard et al., 1984, 1989; Johnsen et al., 2001; Stuiver et al., 1995).

Such isotopic instability in precipitation at high latitudes suggests that the apparently rapid decrease in  $\delta^{18}\text{O}$  values of *Vallonia* shells from the mid-latitude Folsom site (Figs. 5, 6b and 8) could be a result of local environmental changes at the times of snail activity during the YD.

Evidence for the expression of the YD in other parts of North America is present in proxy data from the following: (1) the North Atlantic continental margins (e.g., Björk et al., 1996; Peteet et al., 1993; Shemesh and Peteet, 1998); (2) Western North America (Gosse et al., 1995; Mathews et al., 1993; Reasoner et al., 1994); (3) East-Central Missouri (Denniston et al., 2001); and (4) the north slope of Alaska (Epstein, 1995). The decrease of 3.6‰ in the average  $\delta^{18}\text{O}$  values of Folsom *Vallonia* shells from 0.0‰ at level 151 to  $-3.6\text{‰}$  at level 144 (Fig. 6b) is similar to a decline in  $\delta\text{D}$  values of about 40‰ observed in cellulose in <sup>14</sup>C-dated plants (approximately 10,800 <sup>14</sup>C yr B.P.) from the north slope of Alaska (Epstein, 1995). However, a subsequent rapid rise in  $\delta\text{D}$  values observed by Epstein (1995) is not matched by a corresponding increase in the  $\delta^{18}\text{O}$  values of the *Vallonia* shells from the Folsom site (Fig. 6b). The current lack of knowledge of the <sup>14</sup>C ages of the various excavation levels at the Folsom site precludes a more detailed comparison of the temporal relationships of the Alaskan tree and New Mexico snail shell data sets.

Closer to the Folsom locality, a glacial event, possibly related to the YD, is postulated for the Colorado Rockies based on shifts of the alpine tree line (Reasoner and Jodry, 2000) and for the southern Sangre de Cristo Mountains, New Mexico, based on magnetic susceptibility studies of sediment cores from alpine bogs (Armour et al., 2002). It is also possible that a brief interval of higher water levels in Lake Estancia, New Mexico, at ca. 10,000 <sup>14</sup>C yr B.P. (Allen and Anderson, 2000) represents climatic changes associated with the YD.

Temperature affects the magnitude of the equilibrium oxygen isotope fractionation factor between aragonite and water (Grossman and Ku, 1986). If a 3.6‰ decrease in the average  $\delta^{18}\text{O}$  value of the fossil *Vallonia* shells was solely a result of changing ambient temperatures, it would require an increase in temperature of approximately 16°C. If temperatures had risen 16°C above temperatures that were initially similar to modern (approximately 21°C), they would have been above the thermal range (10–27°C) within which land snails might commonly be expected to thrive (Thompson and Cheny, 1996). Moreover, such high temperatures (approximately 37°C) in the Younger Dryas have not been reported elsewhere in the region. Therefore, the effect of temperature alone on the equilibrium aragonite–water fractionation factor does not plausibly explain a range of 3.6‰ in the average  $\delta^{18}\text{O}$  values of the fossil *Vallonia* shells.

On the other hand, lower  $\delta^{18}\text{O}$  values of *Vallonia* shells might arise from lower  $\delta^{18}\text{O}$  values of rain at the times of snail activity (“active period”). Lower  $\delta^{18}\text{O}$  values of active period rain, in turn, could be associated with lower temperatures (e.g., Rozanski et al., 1993). If  $\delta^{18}\text{O}$  values



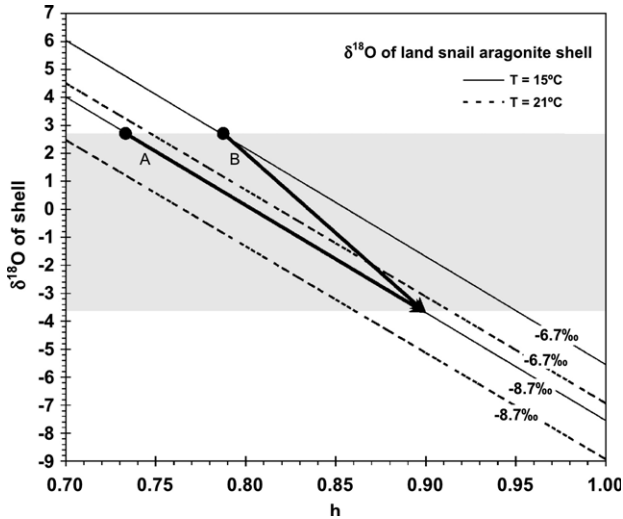


Figure 10. Calculated curves of land snail shell  $\delta^{18}\text{O}$  as a function of active period relative humidity (RH). Calculated for two temperatures ( $15^\circ$  and  $21^\circ\text{C}$ ) and rainfall  $\delta^{18}\text{O}$  values ( $-8.7$  and  $-6.7$ ‰). The shaded region depicts a specified range of  $\delta^{18}\text{O}$  values characterizing fossil *Vallonia* shells from the Folsom site in New Mexico (see text). For a temperature of  $15^\circ\text{C}$ , the arrows illustrate two hypothetical trajectories of decreasing  $\delta^{18}\text{O}$  values of snail shells as a result of increasing RH (arrow A) and both increasing RH and decreasing  $\delta^{18}\text{O}$  of active period rain (arrow B, see text).

of active period rain decreased by approximately  $0.58$ ‰ for each decrease in temperature of  $1^\circ\text{C}$  (e.g., Rozanski et al., 1993), the active period temperature of the Folsom site would have needed to decline by approximately  $6^\circ\text{C}$  to produce a  $\delta^{18}\text{O}$  decrease of approximately  $3.6$ ‰. However, such a temperature decrease increases the equilibrium fractionation factor between aragonite and water (approximately  $0.23$ ‰/°C; Grossman and Ku, 1986). In this simple scenario, the effects of temperature on rainfall  $\delta^{18}\text{O}$  and the fractionation factor would be partially offsetting. Thus, given the preceding conditions, the  $\delta^{18}\text{O}$  of snail shells would be expected to decrease approximately  $0.35$ ‰ for each decline in temperature of  $1^\circ\text{C}$ . If so, all other things being equal, a decrease in shell  $\delta^{18}\text{O}$  of  $3.6$ ‰ would imply a decline in active season temperature of approximately  $10^\circ\text{C}$ . Modern average temperatures in the area during periods of snail activity are approximately  $21^\circ\text{C}$  (Balakrishnan et al., in press). A  $10^\circ\text{C}$  decrease in active period temperatures from  $21^\circ$  to  $11^\circ\text{C}$  would put the temperature near the aforementioned lower thermal limits observed in some common land snails (Thompson and Cheny, 1996). If this thermal limit is applicable to *Vallonia*, a decline in temperature of approximately  $10^\circ\text{C}$  in the Folsom area might have precluded the presence of active *Vallonia*.

Increases in amounts of summer precipitation at continental sites in temperate climatic regimes have also been associated with decreases in  $\delta^{18}\text{O}$  values of rain (the amount effect of Dansgaard, 1964). Comparison of modeled and measured relationships between isotopic composition and precipitation intensity for tropical islands indicated a range of  $5$ ‰ for average monthly precipitation  $\delta^{18}\text{O}$  values with lower

values in general corresponding to higher precipitation intensities (Yapp, 1982). Moreover,  $\delta\text{D}$  values of nonexchangeable hydrogen in cellulose from two trees in Alaska and British Columbia exhibited an antithetical correlation with monthly average amounts of summer precipitation (Yapp and Epstein, 1985). The range of  $\delta\text{D}$  values in the two trees was approximately  $25$ – $30$ ‰, which corresponds to a  $\delta^{18}\text{O}$  range of  $3$ – $4$ ‰. This range of values represented intervals of a few decades. Such a relationship might be postulated to explain some of the variation in the  $\delta^{18}\text{O}$  values of the snail shells. However, the most obvious evidence for possible increases in rainfall at the Folsom site is the onset of deposition of the gravel bed ( $f_3$ ). This gravel was deposited after the interval of the approximately  $3.6$ ‰ decrease in the average  $\delta^{18}\text{O}$  values of the snail shells (Figs. 6a and b).

A decrease in  $\delta^{18}\text{O}$  values of the water vapor transported into the Folsom region could also account, in part, for a decrease in  $\delta^{18}\text{O}$  values of precipitation. Three possible causes of change in the  $\delta^{18}\text{O}$  of input water vapor are as follows: (1) changes in vapor source region; (2) changes in condensation history during transport; and (3) no geographic change in the oceanic source region, but decrease in  $\delta^{18}\text{O}$  of the source water. Yu and Wright (2001) concluded that the Gulf of Mexico was the predominant source of summer moisture to the Southern Plains region of North America throughout the Pleistocene–Holocene transition. This suggests that decreases in the  $\delta^{18}\text{O}$  values of the surface waters of the Gulf of Mexico might be responsible, in part, for a decrease in  $\delta^{18}\text{O}$  values of the input vapor. Such a decrease could have resulted from melting of the low- $^{18}\text{O}$  North American ice sheet and its subsequent runoff into the Gulf of Mexico (e.g., Aharon, 2003).

Uncertainties about the precise temporal equivalence of  $^{14}\text{C}$  ages from the Folsom site and  $^{14}\text{C}$  dates for planktonic foraminifera from the Gulf of Mexico preclude a robust assessment of the possible role of glacial melt-water in producing a decrease in the  $\delta^{18}\text{O}$  values of the summer rain at the Folsom site. However, it is speculated that transient decreases in  $\delta^{18}\text{O}$  of surface water in the Gulf of Mexico of approximately  $1$ – $2$ ‰ (Aharon, 2003) may have produced corresponding decreases in  $\delta^{18}\text{O}$  of active period rain at Folsom that could explain part of the approximately  $3.6$ ‰ decrease in the average  $\delta^{18}\text{O}$  values of the *Vallonia* shells (Figs. 6b and 8).

The oxygen isotope flux balance model of Balakrishnan and Yapp (2004) indicates that changes in ambient relative humidity (RH) can have a significant effect on the  $\delta^{18}\text{O}$  of land snail shells. Roads (1978) suggested that RH increases with decreasing climatic temperature. Such an increase in RH would not necessarily imply larger amounts of rainfall at any particular location. According to the flux balance model of Balakrishnan and Yapp (2004), an increase in RH of  $0.01$  (RH expressed as a decimal fraction) corresponds to a decrease of about  $0.4$ ‰ in the  $\delta^{18}\text{O}$  value of the shell (all other things being equal). Therefore, if changes in RH were the only cause of the  $3.6$ ‰ decrease in average  $\delta^{18}\text{O}$  values

of *Vallonia* (from 0.0 to  $-3.6\text{‰}$ ; Fig. 6b), active period RH would have needed to increase by approximately 0.09. The apparent sensitivity of the snail shell  $\delta^{18}\text{O}$  values to RH (Balakrishnan and Yapp, 2004) suggests that variations of RH were an important part of what was probably a combination of some of the aforementioned possible changes in environmental variables. Two hypothetical scenarios are illustrated in Figure 10.

A specified range of  $\delta^{18}\text{O}$  values for ancient *Vallonia* shells from the Folsom site is shown in Figure 10 (shaded area). For purposes of discussion, a relatively conservative value of  $-3.6\text{‰}$  was chosen as the lower limit of the range by using the most negative average  $\delta^{18}\text{O}$  value for a level shown in Figure 6b. In contrast, the upper limit of the specified range in Figure 10 represents the most positive  $\delta^{18}\text{O}$  values ( $+2.7\text{‰}$ ) measured for *Vallonia* shells from among the various individual excavation levels in the Folsom site (see Fig. 5). Extremum individual (rather than average)  $\delta^{18}\text{O}$  values were used to represent the upper limit in Figure 10 because these and other similarly positive individual analyses are a distinguishing feature of only the earlier portion of the record (levels 149, 151, 152) and are not found in shells from either the younger archaeological excavation levels (138–148) or modern samples (Fig. 5). Moreover, these more positive  $\delta^{18}\text{O}$  values would not result from undetected contamination of the shells with the calcite of the low- $^{18}\text{O}$  soil nodules (SN<sub>1</sub>; Fig. 4). This latter condition adds to the significance of the most positive values. Therefore, a shell  $\delta^{18}\text{O}$  range of  $6.3\text{‰}$  is delineated in Figure 10.

To examine the possible paleoenvironmental significance of the temporal shift in  $\delta^{18}\text{O}$  values of the ancient *Vallonia* shells (Figs. 5, 6b and 8), model  $\delta^{18}\text{O}$  values of snail shells were calculated with the steady-state flux balance equation of Balakrishnan and Yapp (2004) for no liquid output (i.e.,  $\theta = 0$ ) and with the assumption that ambient water vapor was in isotopic equilibrium with the rainfall (for an explanation of the assumptions, definitions of terms, etc., see Balakrishnan and Yapp, 2004). The calculations were performed for two temperatures ( $T$ ): a modern active period  $T$  of  $21^\circ\text{C}$  and a possible late Pleistocene active period  $T$  of  $15^\circ\text{C}$ . For each  $T$ , two different  $\delta^{18}\text{O}$  values were assumed for active period rain: a modern  $\delta^{18}\text{O}$  of  $-6.7\text{‰}$  (Balakrishnan et al., in press) and a Younger Dryas (YD)  $\delta^{18}\text{O}$  of  $-8.7\text{‰}$  (see previous discussion). With these input parameters, the shell  $\delta^{18}\text{O}$  values were calculated for a range of RH values from 0.70 to 1.00 (Fig. 10). The lower limit for RH of 0.70 was chosen because snails are commonly inactive (i.e., no shell formation) at values of relative humidity less than 0.70 (e.g., Van der Schalie and Getz, 1961, 1963).

The arrows (A and B) in Figure 10 depict two possible trajectories (at  $15^\circ\text{C}$ ) of changing  $\delta^{18}\text{O}$  values of land snail shells: (1) arrow A illustrates decreasing shell  $\delta^{18}\text{O}$  values as a function of increasing RH for an active period YD rainfall  $\delta^{18}\text{O}$  value of  $-8.7\text{‰}$ ; (2) arrow B depicts decreasing shell  $\delta^{18}\text{O}$  as a result of a combination of increasing RH and

decreasing  $\delta^{18}\text{O}$  of active period rain. The starts of the arrows are the intersections of the most positive shell  $\delta^{18}\text{O}$  value ( $+2.7\text{‰}$ ) with the two reference lines calculated for  $T = 15^\circ\text{C}$  and rain with  $\delta^{18}\text{O}$  values of  $-8.7$  and  $-6.7\text{‰}$ . The arrows terminate at the intersection of the minimum average shell  $\delta^{18}\text{O}$  ( $-3.6\text{‰}$ ) with the curve calculated for  $15^\circ\text{C}$  and Younger Dryas rain with  $\delta^{18}\text{O} = -8.7\text{‰}$ .

For the  $\delta^{18}\text{O}$  range of  $6.3\text{‰}$ , the increases of RH depicted by the hypothetical trajectories in Figure 10 are from approximately 0.74 to 0.90 (arrow A) and approximately 0.79 to 0.90 (arrow B). These predicted changes in RH values would be characteristic of the times when the snails were active (i.e., times of shell formation, usually nighttime and/or after rain events). The extent to which variations in the values of RH,  $T$ , and rainfall  $\delta^{18}\text{O}$  at the times of snail activity are correlated with variations in the values of these parameters for seasonally averaged daily values has yet to be established. Knowledge of any such correlations is essential to a more robust climatic interpretation of variations in shell  $\delta^{18}\text{O}$  values.

It should be emphasized that the trajectories depicted in Figure 10 are not uniquely constrained but are intended to illustrate an approach to understanding the paleoclimatic implications of  $\delta^{18}\text{O}$  values of fossil land snail shells. Nevertheless, some combination of higher relative humidity, lower active period temperature, and lower  $\delta^{18}\text{O}$  of active period rain could explain the observed temporal decrease in  $\delta^{18}\text{O}$  values of the *Vallonia* shell (Figs. 5, 6b and 8). An increase in the amount of active period precipitation is not required to explain this decrease.

Holliday (2000) associated episodes of Eolian sediment deposition during the late Pleistocene and early Holocene with dry conditions in the Southern Plains at that time. Polyak et al. (2004) concluded from uranium series dating of speleothems in caves in the Guadalupe mountains of New Mexico that the Younger Dryas in the southwestern United States consisted of drier conditions during its early stages followed by wetter conditions that persisted into the early Holocene. It is speculated that the decrease in  $\delta^{18}\text{O}$  values recorded by snail shells in the Eolian silt ( $f_2$ ) at the Folsom site (Figs. 6b and 8) may reflect a reorganization of atmospheric circulation (manifested by increases in active period RH and decreases in  $\delta^{18}\text{O}$  of rainfall) leading up to the generally wetter conditions discussed by Polyak et al. (2004). The overlying gravel ( $f_3$ ), which suggests high-energy environments of deposition and more runoff, as well as the persistence of lower  $\delta^{18}\text{O}$  values of *Vallonia* shells in the gravel, appears to be consistent with a subsequent increase in precipitation.

## Conclusion

Scatter in the isotopic data for well-preserved fossil *Vallonia* shells from the Folsom archaeological site probably reflects the type of natural variation observed in modern land

snail populations in a locale. However, average values of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  appear to provide useful insights into environmental conditions at the site during the Younger Dryas. Average  $\delta^{18}\text{O}$  values of the shells declined relatively rapidly from 0.0‰ to a minimum of  $-3.6\text{‰}$  about 10,500  $^{14}\text{C}$  yr B.P. Explanation of the  $\delta^{18}\text{O}$  decrease favors some combination of an increase in relative humidity, a decrease in  $\delta^{18}\text{O}$  values of precipitation, and cooler temperatures during the periods of snail activity. The extent to which the values of these parameters at the times of snail activity are correlated with the overall averages of those variables during the warmer season at a locale remains to be established. It is of interest that a well-known Paleoindian bison kill (with a  $^{14}\text{C}$  age of approximately 10,500 yr B.P.) occurred at the time of the decrease in snail shell  $\delta^{18}\text{O}$  values.

Throughout the interval of decreases in the average  $\delta^{18}\text{O}$  values of the fossil *Vallonia* shells from the Folsom site, average  $\delta^{13}\text{C}$  values of the shells changed very little and

were significantly more positive than  $\delta^{13}\text{C}$  values of modern land snail shells in the area. This implies that  $\text{C}_4$  plants constituted a higher proportion of the local snail diet ca. 10,500  $^{14}\text{C}$  yr B.P. than at present. An inference of higher proportions of  $\text{C}_4$  plants in the American southwest during the Pleistocene–Holocene transition is supported by studies using other proxies (e.g., Connin et al., 1998; Holliday, 2000; Nordt et al., 2002).

### Acknowledgments

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### Appendix A. Folsom sample levels, $\delta^{13}\text{C}$ , $\delta^{18}\text{O}$ of shells, soil nodules, fraction of grains $>710\ \mu$

Block	Unit coordinates <sup>a</sup>	Unit ID <sup>a</sup>	Level no. <sup>a</sup>	Level of bone bed base	Snail shells		Soil nodules		Mass fraction of sediment $>710\ \mu$
					$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	
M17	N1034E998	U1	137	–	–	–	-6.4	-12.1	–
	N1034E998	U1	138	–	-7.3	-0.8	-7.6	-11.7	–
	N1034E998	U1	139	–	-6.6	-4.7	-8.0	-11.7	–
	N1034E998	U1	140	–	-3.9	-0.5	–	–	0.302
	N1034E998	U1	141	–	–	–	–	–	0.225
	N1034E998	U1	142	–	–	–	–	–	0.600
	N1034E998	U1	143	–	–	–	–	–	0.637
	N1034E998	U1	144	–	-5.0	-2.9	–	–	0.229
	N1034E998	U1	145	–	-7.0	-1.6	–	–	0.486
	N1034E998	U1	146	–	-4.1	-6.2	–	–	0.484
	N1034E998	U1	147	–	-5.5	-4.7	–	–	0.189
	N1034E998	U1	148	–	-6.6	-5.6	–	–	0.006
	N1034E998	U1	149	bone bed base	–	–	–	–	0.006
	N1034E998	U1	150	–	-7.5	-3.4	–	–	0.010
	N1034E998	U1	151	–	-6.3	-2.9	–	–	0.007
M17	N1034E999	U2	139	–	-6.9	-3.1	–	–	–
	N1034E999	U2	140	–	–	–	–	–	–
	N1034E999	U2	141	–	-5.6	-3.2	–	–	–
	N1034E999	U2	142	–	-6.9	0.2	–	–	–
	N1034E999	U2	143	–	–	–	–	–	–
	N1034E999	U2	144	–	-6.7	-1.9	–	–	–
	N1034E999	U2	144	–	-7.4	-4.7	–	–	–
	N1034E999	U2	145	–	-6.9	-0.8	–	–	–
	N1034E999	U2	145	–	-4.5	-1.9	–	–	–
	N1034E999	U2	146	–	-5.9	-2.2	–	–	–
	N1034E999	U2	146	–	-5.6	-2.3	–	–	–
	N1034E999	U2	147	–	-6.9	-4.0	–	–	–
	N1034E999	U2	147	–	-6.2	-2.4	–	–	–
	N1034E999	U2	148	–	-4.7	-2.9	–	–	–
	N1034E999	U2	148	–	-5.4	-0.7	–	–	–
	N1034E999	U2	149	base of bone bed	-6.5	0.6	–	–	–
	N1034E999	U2	149	bone bed	-5.7	-2.9	–	–	–
N1034E999	U2	150	–	-7.3	-1.3	–	–	–	
N1034E999	U2	150	–	-6.6	-1.8	–	–	–	
N1034E999	U2	151	–	-5.0	-0.1	–	–	–	
N1034E999	U2	151	–	-7.0	-0.9	–	–	–	
N1034E999	U2	152	–	-7.1	1.8	–	–	–	

(continued on next page)

## Appendix A (continued)

Block	Unit coordinates <sup>a</sup>	Unit ID <sup>a</sup>	Level no. <sup>a</sup>	Level of bone bed base	Snail shells		Soil nodules		Mass fraction of sediment >710 μ
					δ <sup>13</sup> C	δ <sup>18</sup> O	δ <sup>13</sup> C	δ <sup>18</sup> O	
M17	N1033E998	U3	139	–	-6.1	-2.5	–	–	0.467
	N1033E998	U3	140	–	-6.7	-4.0	–	–	0.388
	N1033E998	U3	141	–	-4.8	-1.4	–	–	0.305
	N1033E998	U3	142	–	-6.6	-6.9	–	–	0.271
	N1033E998	U3	143	–	-6.4	-1.1	–	–	0.167
	N1033E998	U3	144	–	-5.7	-0.6	-16.7	-4.2	0.143
	N1033E998	U3	144	–	-4.6	-4.9	–	–	0.143
	N1033E998	U3	145	–	-7.1	-1.8	–	–	0.097
	N1033E998	U3	145	–	-6.7	-4.8	–	–	0.097
	N1033E998	U3	146	–	-4.6	-2.7	–	–	0.064
	N1033E998	U3	146	–	-6.6	-1.3	–	–	0.064
	N1033E998	U3	147	–	-6.4	-0.5	–	–	0.072
	N1033E998	U3	147	–	-6.8	-3.1	–	–	0.072
	N1033E998	U3	148	–	-6.7	-2.8	–	–	0.093
	N1033E998	U3	148	–	-8.0	-2.0	–	–	0.093
	N1033E998	U3	148	–	-7.4	-1.2	–	–	0.093
	N1033E998	U3	149	–	-5.0	-1.4	-3.9	-11.1	0.108
	N1033E998	U3	149	–	-5.3	2.7	–	–	0.108
	N1033E998	U3	149	–	-7.9	-0.4	–	–	0.108
	N1033E998	U3	150	–	-7.5	-0.6	-7.0	-10.9	0.077
	N1033E998	U3	151	–	-7.6	-1.3	–	–	0.055
N1033E998	U3	151	–	-7.0	2.7	–	–	0.055	
N1033E998	U3	151	–	-6.4	2.5	–	–	0.055	
M17	N1030E998	U4	144	–	-6.9	-6.4	–	–	0.277
	N1030E998	U4	145	–	-7.5	-1.4	–	–	0.200
	N1030E998	U4	146	–	-7.0	-1.1	-7.8	-12.0	0.112
	N1030E998	U4	147	–	-6.5	-3.3	-7.4	-11.9	0.037
	N1030E998	U4	148	–	-7.8	-1.5	–	–	0.048
N17	N1030E998	U4	149	bone bed base	–	–	–	–	–
	N1030E1000	U5	148	–	-9.4	-0.7	-15.3	-5.9	0.172
	N1030E1000	U5	149	bone bed base	-7.1	-2.9	–	–	0.116
	N1030E1000	U5	150	–	–	–	–	–	–
M15	N1024E998	U6	151	–	–	–	–	–	0.120
	N1024E998	U6	140	No bone bed in U6	-8.2	-2.5	–	–	0.202
	N1024E998	U6	140	–	–	–	–	–	0.202
	N1024E998	U6	141	–	-6.5	-2.7	–	–	0.152
	N1024E998	U6	141	–	-7.5	-1.0	–	–	0.152
	N1024E998	U6	142	–	-6.6	-0.3	–	–	0.159
	N1024E998	U6	142	–	-4.8	-2.3	–	–	0.159
	N1024E998	U6	143	–	-4.5	-2.0	–	–	0.150
	N1024E998	U6	143	–	-7.5	-2.2	–	–	0.150
	N1024E998	U6	144	–	-7.9	-1.5	–	–	0.102
	N1024E998	U6	145	–	-5.2	-1.2	–	–	0.105
	N1024E998	U6	146	–	-7.6	-0.7	–	–	0.106
	N1024E998	U6	146	–	-7.6	-1.2	–	–	0.106
	N1024E998	U6	147	–	–	–	–	–	0.127
	N1024E998	U6	147	–	-7.0	-1.0	–	–	0.127
	N1024E998	U6	148	–	-5.8	-0.6	–	–	0.115
	N1024E998	U6	148	–	-5.9	-0.4	–	–	0.115
	N1024E998	U6	149	–	–	–	–	–	0.097
	N1024E998	U6	149	–	–	–	–	–	0.097
	N1024E998	U6	150	–	-6.1	-0.5	–	–	0.090
	N1024E998	U6	150	–	-7.2	-1.6	–	–	0.090
N1024E998	U6	151	–	–	–	–	–	0.047	
N1024E998	U6	152	–	-7.1	-1.0	–	–	0.076	
N1024E998	U6	152	–	-6.8	-1.5	–	–	0.076	
N1024E998	U6	153	–	-7.1	0.1	–	–	0.064	
N1024E998	U6	153	–	-5.0	0.4	–	–	0.064	
N1024E998	U6	154	–	-6.0	1.6	–	–	0.079	

<sup>a</sup> After Meltzer et al. (2002).

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