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Radiocarbon dating of minute gastropods and new constraints on the timing of late Quaternary spring-discharge deposits in southern Arizona, USA

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Abstract

Gastropod shells are commonly preserved in Quaternary sediments, but are often avoided for radiocarbon dating because some taxa incorporate ^{14}C-deficient carbon during shell formation. Recently, Brennan and Quade [(1997) Quat. Res. 47, 329–336] found that some minute taxa (*Vallonia*, *Pupilla*, and *Succineidae*) appear to yield reliable ^{14}C ages for late Pleistocene samples. A more rigorous evaluation of the ^{14}C inventory of minute gastropods is presented here, which involved measuring the ^{14}C activity of specimens collected live in two geologic settings that maximize the potential for ingestion of 'old' carbon: (1) alluvium dominated by Paleozoic carbonate rocks, and (2) adjacent to extant springs with highly ^{14}C-deficient water present at the surface. We found that several minute taxa, including *Vallonia*, incorporate significant and variable amounts of old carbon (~2 to >30%) during shell formation. The ^{14}C activities of the land snails *Pupilla blandi* and *Euconulus fulvus*, however, are indistinguishable from the ^{14}C activity of live plants. The ^{14}C activity of the semi-aquatic gastropod *Catinella* sp. (Family: *Succineidae*) deviates from modern values in the presence of ^{14}C-deficient water by an amount equivalent to ~10% of the local carbon-reservoir effect. These results imply that at least some minute gastropods can provide reliable ^{14}C ages even when ^{14}C-deficient carbon is readily available. To demonstrate an application of our findings, we ^{14}C-dated shells from *P. muscorum*, *E. fulvus*, and *Succinea* sp. (Family: *Succineidae*) recovered from the Coro Marl, a late Pleistocene spring-fed marsh deposit exposed at the Murray Springs Paleoindian site in the San Pedro Valley of southern Arizona, USA. Radiocarbon ages obtained from the minute gastropods show that the unit was deposited between ~25000 and 13000 ^{14}C years ago. The marl is situated >15 m above the modern water table at Murray Springs, and is similarly positioned in discontinuous outcrops along a ~150-km stretch of the San Pedro Valley. Thus, the ^{14}C ages of minute gastropods presented here may be used to infer the timing of high water-table levels throughout the valley.

Keywords: ^{14}C dating; gastropods; ground water; marl; carbon-reservoir effect; wetlands

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1. Introduction

1.1. Radiocarbon dating of minute gastropods

Radiocarbon ages derived from terrestrial mollusks (Class Gastropoda) are often anomalously old because they incorporate ^{14}C-deficient carbon during shell formation. Numerous studies have demonstrated that the magnitude of the ^{14}C-age anomaly can be highly variable between taxa and among individuals of the same species, and may approach $\sim$3000 ^{14}C years (e.g. Rubin et al., 1961; Tamers, 1970; Evin et al., 1980; Goodfriend and Stipp, 1983; Goslar and Pazdur, 1985; Yates, 1986; Goodfriend, 1987; Zhou et al., 1999). Consequently, terrestrial gastropod shells are not widely used for radiocarbon dating.

Radiocarbon studies have traditionally focused on larger taxa and the observed ^{14}C deficiencies were thought to apply to all gastropods, large and small. Recently, Brennan and Quade (1997) suggested that reliable ^{14}C ages could be obtained from a previously overlooked group of mollusks – minute gastropods. ('Minute' is a term commonly used in the malacological literature to refer to small ($\sim$3–10 mm) gastropods, and does not embrace specific taxonomic groups, life habits, or shell morphologies.) Minute taxa such as *Vallonia*, *Pupilla* and *Succineidae* returned ^{14}C ages that, in most cases, agreed with ^{14}C ages obtained from associated late Pleistocene organic material (Brennan and Quade, 1997). These taxa are common in modern settings and the fossil record (e.g. Ashbaugh and Metcalf, 1986; Quade, 1986; Quade et al., 1998) and hold great potential for constraining the ages of Quaternary sediments, provided they actually yield reliable ^{14}C ages.

To determine the suitability of minute gastropods for ^{14}C dating, we measured the ^{14}C activities of specimens collected live in two geologic settings that maximize the potential for ingestion of old carbon and thus provide worst-case scenarios for potential age anomalies: (1) alluvium dominated by carbonate rocks, and (2) adjacent to extant springs with highly ^{14}C-deficient water present at the surface. Collecting live gastropods in their modern settings provides a more rigorous test of dating reliability than the comparisons of fossil material discussed in Brennan and Quade (1997) for several reasons. First, differences between ^{14}C ages of fossil shell carbonate and organic material can arise through bioturbation and reworking of older shells, chemical alteration of the shell carbonate, and/or contamination of the organic material by humic acids or rootlets. Second, collecting live snails constrains the timing of shell formation to within a single year for species having an annual life cycle. This is especially important when evaluating the ^{14}C activity of shell carbonate of live gastropods because the ^{14}C activity of the atmosphere (which ultimatly is the source of carbon in shell carbonate) has decreased exponentially since cessation of above-ground testing of nuclear weapons (Manning et al., 1990; Meijer et al., 1995). Finally, collecting live snails allows observations to be made regarding their habitat, lifespan, and diet. Unlike many of their larger counterparts, the life histories of minute gastropods are not well known.

1.2. Coro Marl

We ^{14}C dated the most promising minute gastropods to improve constraints on the timing and rate of deposition of a late Pleistocene spring-fed marsh deposit in the San Pedro Valley of southern Arizona (Fig. 1). A series of arroyos on the east flank of the Huachuca Mountains (31.57°N, 110.18°W) has exposed a nearly complete sequence of late Pleistocene and Holocene deposits, including the Murray Springs Paleoindian site (Haynes, 1968, 1974, 1987). Included in the depositional sequence is the Coro Marl (formerly the upper member of the Boquillas Formation and also known as Unit E; Haynes, 1968), which is a white calcareous marl that is $\sim$1–2 m thick. The Coro Marl contains a large number of minute gastropods (Mead, 1979; this study) that lived in and around a shallow, spring-fed paleomarsh that developed at the site in the late Pleistocene. Discontinuous outcrops of the Coro Marl have been identified along a $\sim$150-km stretch of the San Pedro Valley and therefore determining the age of the marl at the Murray Springs locality would allow us to infer the timing of high water-table levels throughout the valley.

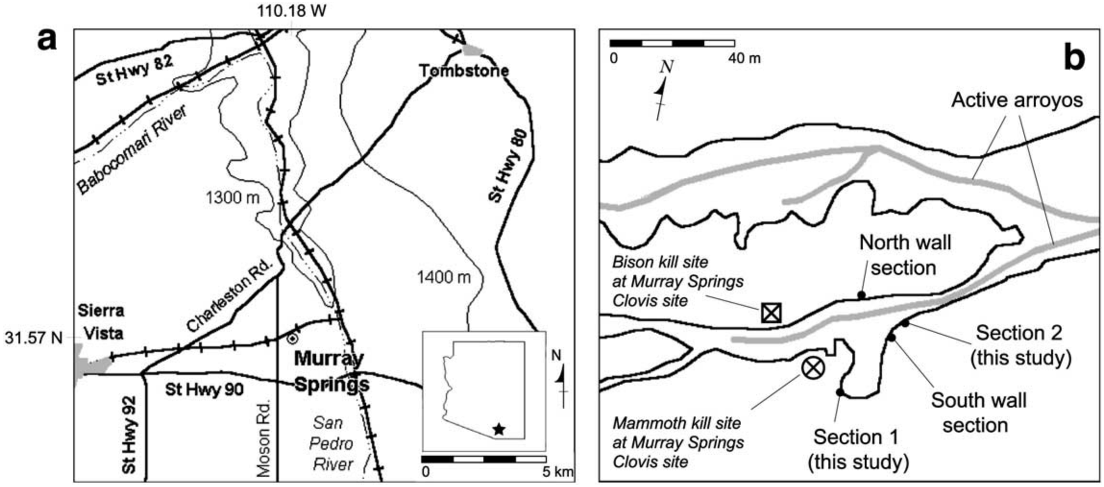

Fig. 1. (a) Location of the Murray Springs Paleoindian site in the San Pedro Valley, southern Arizona. (b) Location of sections at the Murray Springs site.

The upper age of the marl at Murray Springs is constrained by ages of 12 940 ± 390 ^{14}C yr BP (charcoal; Tx-1406) and 12 820 ± 450 ^{14}C yr BP (unidentified snail shells; SMU-190) recovered from an overlying channel-fill deposit. No reliable dates have been obtained from the marl itself because of the lack of organic macrofossils within the unit. Radiocarbon ages from marl carbonate fall between 12 310 ± 170 and 21 200 ± 500 ^{14}C yr BP (Table 1a). However, the accuracy of these dates is questionable because of two important uncertainties: (1) the potential for incorporation of old carbon from ground water during marl precipitation (i.e. carbon-reservoir effects), and (2) post-depositional alteration and isotopic exchange of the fine-grained marl. ^{14}C ages obtained from diffuse organic matter occluded in the Coro Marl range from 13 980 ± 190 to 19 650 ± 1400 ^{14}C yr, excluding one anomalously old sample (SMU-37; Table 1b). The occluded organic matter, however, likely contains a significant aquatic component, and may also be subject to carbon-reservoir effects. Improving constraints on the age of the Coro Marl would allow comparison with other well-dated paleoclimatic records to better understand the causes and timing of hydrologic changes in the southwestern USA during the late Pleistocene.

Table 1
Previous ^{14}C ages of Coro Marl unit at Murray Springs

(a) North wall of main channel[a]			(b) South wall of main channel[b]		
Sample ID	Depth (cm)	Sample age (^{14}C yr BP)	Sample ID	Depth (cm)	Sample age (^{14}C yr BP)
I-4562	0–5	12 310 ± 170	SMU-34	0–10	13 980 ± 190
I-4564	50–55	19 620 ± 380	SMU-35	10–20	18 060 ± 150
A-897	90–95	21 200 ± 500	SMU-36	50–60	16 810 ± 420
			SMU-37	90–100	27 560 ± 2300[c]
			SMU-38	110–120	19 650 ± 1400

[a] ^{14}C ages obtained from marl carbonate.
[b] ^{14}C ages obtained from diffuse organic matter occluded in marl carbonate. Samples were subject to pyrolysis and hydrolysation in HCl to remove carbonates prior to the ^{14}C measurement.
[c] Anomalously old ^{14}C age.

2. Field and laboratory methods

2.1. ^{14}C activity of the atmosphere

We collected leaves of *Ostrya knowltonii* and *Quercus gambeli* in the Spring Mountains of southern Nevada at Cold Creek and Deer Creek, respectively (Fig. 2), to determine the atmospheric ^{14}C value during the time of shell formation for gastropods collected in 2001. Both sites are located far from the influence of urban and industrial activities. Leaf growth for these species is fastest in the spring and decreases beginning in early- to mid-summer, similar to the observed life cycles of the minute gastropods studied here. Thus, the ^{14}C activity of the leaves represents the ^{14}C activity of the atmosphere integrated over the period of shell formation. We also collected plant detritus (rotting leaves, twigs, etc.) from under the most heavily populated limestone boulders at the Deer Creek locality to determine if the diet of the minute land snails includes decaying vegetation.

Leaves were treated with 10% HCl for 2 h at 25°C to remove carbonate dust, washed repeatedly, sonicated for 5–10 min to remove any adhering HCl, dried using a filter vacuum, and dried

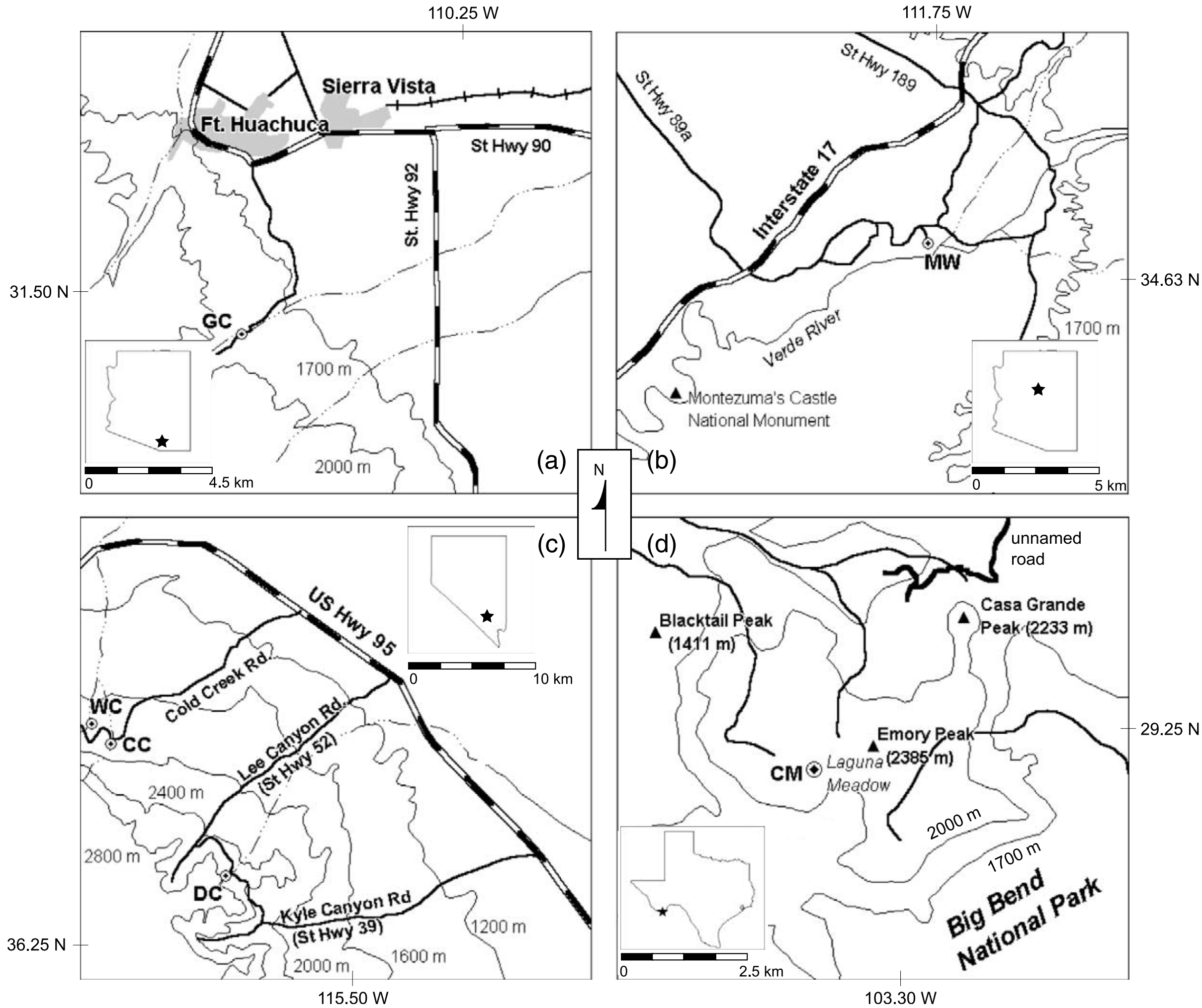

Fig. 2. Sampling locations for live gastropods: (a) Garden Canyon (GC); (b) Montezuma's Well (MW); (c) Cold Creek (CC); Deer Creek (DC); Willow Creek (WC); (d) Chisos Mountains (CM).

further in a vacuum oven at 70°C overnight. The dried leaves were crushed and amalgamated using a mortar and pestle. Approximately 4–6 mg of the crushed leaves were placed in a 6-mm O.D. Vycor tube along with cupric oxide (CuO) and silver foil and combusted at 900°C for 4 h to convert organic carbon to CO_2. The plant detritus sample was also amalgamated using a mortar and pestle and processed in the same manner.

CO_2 was extracted and purified at the University of Arizona's Desert Laboratory using standard cryogenic techniques and split into two aliquots. One aliquot was converted to graphite by catalytic reduction of CO (Slota et al., 1987) and submitted to the National Science Foundation–Accelerator Mass Spectrometry (AMS) facility at the University of Arizona for ^{14}C analysis. The second aliquot was used to measure stable carbon isotope ratios in order to correct the measured ^{14}C value for fractionation. Stable isotope measurements were conducted on a Finnigan Delta-S gas source mass spectrometer and the results are reported in the usual del (δ) notation as the per mil (‰) deviation from the PeeDee Belemnite (PDB) standard. Analytical uncertainties for $\delta^{13}C$ measurements are less than 0.1‰ based on repeated measurements of carbonate standards.

The ^{14}C activity of the atmosphere prior to 2001 was determined by measuring the ^{14}C activity of individual tree rings of *Pinus ponderosa* sampled near Mt. Lemmon in the Santa Catalina Mountains of southern Arizona (T. Lange, unpublished).

2.2. Live gastropods

Sampling locations for live gastropods (Fig. 2) were selected to ensure carbonate rocks and/or highly ^{14}C-deficient water were present at the surface. We searched for gastropods in a variety of microhabitats, from leaf litter and grassy areas to under limestone boulders and rotting wood. Snail density was highest in moist areas with modest leaf cover adjacent to perennial, spring-fed streams. These conditions allow the ground surface to remain continually moist without the threat of flooding.

We restricted our sampling to members of Order Stylommatophora (Subclass Pulmonata), which are minute, lung-breathing snails that are common in extant and paleo-wetland systems worldwide. Gastropods were routinely identified to genus and, when possible, to species using Chamberlain and Jones (1929), Hibbard and Taylor (1960), Taylor (1960), Burch (1962), Evans (1972), and Burch and Van Devender (1980). We collected live *Discus whitneyi*, *Euconulus fulvus alaskensis*, *Pupilla blandi charlestonensis*, and *Vallonia cyclophorella* from alluvium dominated by Paleozoic carbonate rocks in the Spring Mountains of southern Nevada (Deer Creek locality), and *Cochlicopa lubrica* and *Oreohelix concentrata* from Paleozoic carbonate bedrock and alluvium in the Huachuca Mountains in southern Arizona (Garden Canyon locality). We obtained specimens of *Gastrocopta pellucida hordeacella* and *Vallonia perspectiva* collected live in 1971 from carbonate alluvium in the Chisos Mountains of Texas, and *Vitrina alaskana* collected live in 1976 from the Willow Creek locality in the Spring Mountains. All gastropods were collected either directly from or adjacent to limestone clasts to maximize the potential for ingestion of old carbon. Finally, we collected live *Catinella* sp. (Family: *Succineidae*) near extant springs at the Cold Creek and Montezuma's Well localities.

After collection, specimens were drowned and the soft parts removed from the larger taxa (*Succineidae*, *Oreohelix*) using forceps. The soft parts of the smaller taxa were removed after drying and breaking the shell. Shells were not powdered during pretreatment to minimize the potential for adsorption of atmospheric ^{14}C (Samos, 1949). We amalgamated a large number of specimens whenever possible to ensure the results of the ^{14}C measurements represented the average activity of the population.

Shell carbonate was treated with 6% NaOCl for 48–72 h to remove organic matter, washed repeatedly, sonicated for 5–10 min, dried using a filter vacuum, and dried further in a vacuum oven overnight at ~70°C. Shell fragments were examined under a 25×-dissecting microscope to ensure the interior whorls were free of carbonate and organic detritus. We also selected shells at random for X-ray diffraction analysis using a Siemens Model D-500 diffractometer to verify that only shell aragonite remained prior to preparation for ^{14}C analysis. There was no evidence of primary or secondary calcite in any of the modern or fossil shells analyzed.

Shell aragonite was converted to CO_2 using 100% H_3PO_4 under vacuum at 50°C. Extraction and purification of the resulting CO_2, and conversion to graphite, were completed as described above. Measured ^{14}C values for all gastropod shells were corrected for isotopic fractionation as described in Pigati (2003).

2.3. Fossil gastropods

We measured and collected sediment and fossil shells from the Coro Marl at two sections at Murray Springs (Fig. 1b). Section 1 was located in a recently eroded headcut ~25 m south of the main channel (Curry Draw) cutting through the site, and Section 2 was located on the south wall of the main channel. The marl was too indurated to allow separation of gastropod shells in the field, so we collected blocks of sediment in 10-cm increments from each of the two sections for lab processing.

Calcareous sediment from each section was sonicated in 4-L beakers for at least 24 h to soften it enough to pass it through 100-μm sieves without destroying the gastropod shells. We recovered the terrestrial snails *Pupilla*, *Euconulus*, *Gastrocopta*, and *Vertigo*, the semi-aquatic snail *Succinea* sp. (Family: *Succineidae*), the aquatic snails *Fossaria* and *Gyraulus*, and the aquatic bivalve *Pisidium*. This assemblage is similar to that found by Mead (1979). Shells were separated by taxa, and those chosen for radiocarbon analysis were prepared for AMS analysis in the same manner as their living counterparts.

2.4. Data analysis

Uncertainties for ^{14}C values associated with the blank correction (Donahue et al., 1990) and the AMS measurement (counting statistics and random machine error) were fully propagated using the law of combination of errors, neglecting covariance terms (Bevington and Robinson, 1992). We also fully propagated all errors associated with the $\delta^{13}C$ measurement, including the individual measurement error, and the daily and long-term variability of the mass spectrometer.

All weighted mean values were calculated using $1/\sigma_i^2$ weighting, where σ_i is the analytical error associated with the individual sample measurement (Bevington and Robinson, 1992, eq. 4.17). We calculated both the standard error of the weighted mean (Bevington and Robinson, 1992, eq. 4.19) and the weighted average variance of the data (Bevington and Robinson, 1992, eq. 4.22), and took the square root of the larger of the two as the uncertainty associated with the weighted mean. The standard error of the mean represents the total analytical (internal) error, whereas the weighted average variance represents the scatter of the data (external error). All uncertainties are reported at the 1σ confidence level unless otherwise noted.

3. Results

3.1. Vegetation

The ^{14}C results of leaves collected live in 2001 at the Cold Creek and Deer Creek localities in southern Nevada have a weighted mean of 1.0919 ± 0.0039 (Table 2). The ^{14}C activity of plant detritus collected under and adjacent to limestone clasts at the Deer Creek locality was

Table 2
^{14}C results of live vegetation

Sample ID	Locality	Taxa	Date collected	$\delta^{13}C_{pdb}$	^{14}C activity
AA45596	Cold Creek	*Quercus gambeli*	15-Oct-01	−27.5	1.0946 ± 0.0052
AA45597	Deer Creek	*Ostrya knowltonii*	15-Oct-01	−29.9	1.0888 ± 0.0057
				Weighted mean	**1.0919 ± 0.0039**
AA45598	Deer Creek	Plant detritus	15-Oct-01	−27.9	1.1724 ± 0.0059

1.1724 ± 0.0059. This value is equivalent to the atmospheric value in the late 1980s (T. Lange, unpublished data), which indicates plant litter persists in the local environment for > 10 years. The large difference between the ^{14}C activities of live and decaying vegetation allows us to determine whether minute gastropods feed exclusively on live vegetation. This is an important consideration when ^{14}C dating fossil gastropod shells in arid regions because snails feeding on long-dead carbon could yield anomalously old ^{14}C ages.

3.2. Live terrestrial snails

The ^{14}C activities of *Pupilla blandi charlestonensis* (1.0893 ± 0.0064) and *Euconulus fulvus* (1.0864 ± 0.0044) are indistinguishable from the ^{14}C value of live plants, which suggests that these taxa do not incorporate limestone or other sources of old carbon during shell formation (Table 3; Fig. 3). Although the effects of ingestion of a small amount of old carbon could be offset by ingestion of plant detritus with a relatively high ^{14}C activity, such a fortuitous offset is unlikely based on the number of specimens amalgamated in each AMS measurement, 23 specimens for *P. blandi* and 7 for *E. fulvus*. In terms of application to the fossil record, these results indicate that both taxa can provide accurate ^{14}C dates provided multiple shells are amalgamated for each AMS measurement.

Other minute land snails appear to be ^{14}C deficient to varying degrees. The ^{14}C activity of *Cochlicopa lubrica* (1.0719 ± 0.0047) is slightly lower than the atmospheric ^{14}C activity, which suggests that ~2% of the shell carbon was derived from limestone. Incorporation of even this small amount of ^{14}C-deficient carbon is problematic for dating late Holocene deposits (Fig. 4). However, *C. lubrica* can provide maximum ^{14}C ages that deviate from the true age by < 2% for samples older than ~10 000 ^{14}C yr assuming that the amount of ^{14}C-deficient carbon consumed by these specimens is similar to that consumed at other localities.

The ^{14}C activity of *Discus whitneyi* (1.0223 ± 0.0047) and *Vallonia cyclophorella* (1.0075 ± 0.0076) indicate that ~6–8% of the shell carbon for each of these taxa is derived from limestone. These taxa provide maximum ^{14}C ages that deviate from the true age by ~4% even after 20 000 ^{14}C yr (Fig. 4). This is in contrast with the results

Table 3
^{14}C results of live gastropods

Sample ID	Locality[a]	Taxa	Type[b]	Date collected	Number of specimens	$\delta^{13}C$ (‰ pdb)	^{14}C activity[c]
AA43963	CM	*Gastrocopta pellucida hordeacella*	T	09-Jun-71	15	*nc*[d]	0.9591 ± 0.0049
AA43964	CM	*Vallonia perspectiva*	T	09-Jun-71	12	*nc*[d]	1.3093 ± 0.0075
AA44285	WC	*Vitrina alaskana*	T	02-May-76	2	−7.5	1.3444 ± 0.0060
AA43958	CC	*Catinella sp.*	SA	23-Jun-01	1	−8.5	1.0528 ± 0.0049
AA46072	CC	*Catinella sp.*	SA	23-Jun-01	1	−9.6	1.0577 ± 0.0044
AA43962	DC	*Discus whitneyi*	T	23-Jun-01	1	−9.5	1.0223 ± 0.0047
AA43961	DC	*Euconulus fulvus alaskensis*	T	23-Jun-01	7	−8.5	1.0864 ± 0.0044
AA43960	DC	*Pupilla blandi charlestonensis*	T	23-Jun-01	23	−9.4	1.0893 ± 0.0064
AA43959	DC	*Vallonia cyclophorella*	T	23-Jun-01	13	−8.2	1.0075 ± 0.0076
AA46070	GC	*Cochlicopa lubrica*	T	04-Aug-01	4	−9.4	1.0719 ± 0.0047
AA46069	GC	*Oreohelix concentrata*	T	04-Aug-01	1	−5.4	0.7826 ± 0.0039
AA44286	MW	*Catinella sp.*	SA	07-Aug-01	4	−10.9	0.9682 ± 0.0057
AA46071	MW	*Catinella sp.*	SA	07-Aug-01	6	−12.6	1.0156 ± 0.0043

[a] Abbreviations: CC, Cold Creek, Nevada; CM, Chisos Mountains, Texas; DC, Deer Creek, Nevada; GC, Garden Canyon, Arizona; MW, Montezuma's Well, Arizona; WC, Willow Creek, Nevada.
[b] Abbreviations: SA, semi-aquatic; T, terrestrial.
[c] ^{14}C activities were corrected for fractionation as described in Pigati (2003).
[d] Not corrected for fractionation because sufficient material was not available for stable isotope analysis.

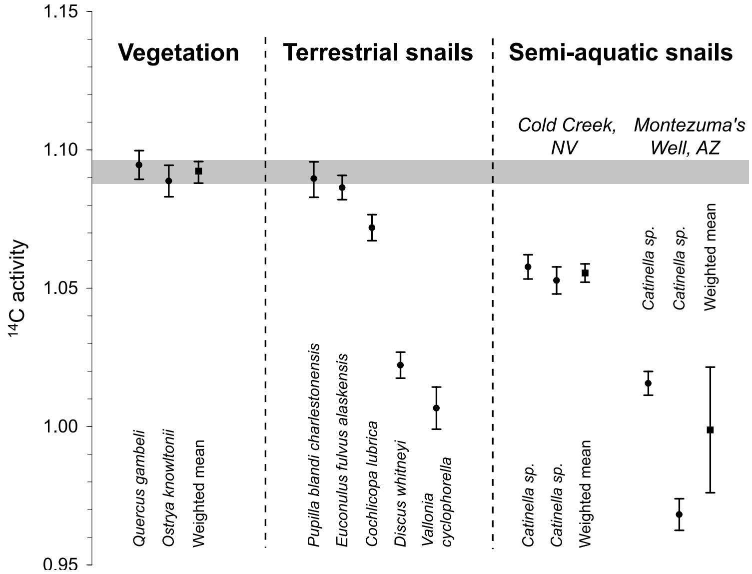

Fig. 3. ^{14}C activities of minute gastropods collected live in 2001. Gray band denotes weighted mean of ^{14}C activity of live plants collected in 2001.

of Brennan and Quade (1997), which suggested *Vallonia* provide accurate radiocarbon ages for the late Pleistocene. The measured ^{14}C activity of *Oreohelix concentrata* (0.7826 ± 0.0039) deviated significantly from the atmospheric value, by ~30%. This is similar to the upper limit of the percentage of limestone-derived carbon observed by Goodfriend and Stipp (1983).

The ^{14}C activity of *Vitrina alaskana* (1.3444 ± 0.0060) collected live from the Willow Creek locality in 1976 is slightly lower than the atmospheric ^{14}C activity during the year of collection (1.37 ± 0.01). Thus, *V. alaskana* can provide maximum ^{14}C ages that deviate from the true age by < 2% for samples older than ~10 000 ^{14}C yr (Fig. 4). Specimens of *Vallonia perspectiva* and *Gastrocopta pellucida hordeacella* collected live in 1971 from the Chisos Mountains in Texas yielded ^{14}C activities of 1.3093 ± 0.0075 and 0.9591 ± 0.0049, respectively. These values are significantly lower than the atmospheric ^{14}C activity (1.55 ± 0.01) during the time of shell formation and suggest *V. perspectiva* and *G. pellucida* provide maximum ^{14}C ages that deviate from the true age by ~4% and 13%, respectively, even after 30 000 ^{14}C yr (Fig. 4).

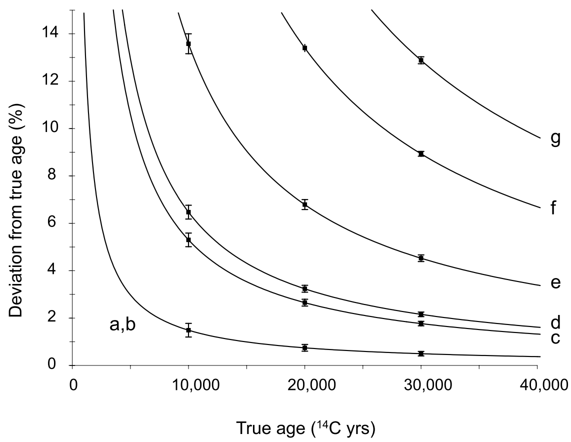

Fig. 4. Maximum predicted deviation from the true ^{14}C age caused by incorporation of ^{14}C-deficient carbon during shell formation (based on live-collected gastropods). Predicted radiocarbon ages obtained from *Pupilla blandi* and *Euconulus fulvus* are indistinguishable from the true ^{14}C ages at any time. (a) *Cochlicopa lubrica* and (b) *Vitrina alaskana* deviations are essentially identical; (c) *Discus whitneyi*; (d) *Vallonia cyclophorella*; (e) *Vallonia perspectiva*; (f) *Oreohelix concentrata*; (g) *Gastrocopta pellucida*. Error bars are included at 10 000, 20 000, and 30 000 ^{14}C yr for comparison.

3.3. Live semi-aquatic snails

Catinella sp. (Family: *Succineidae*) is considered to be semi-aquatic and may be subject to carbon-reservoir effects. Specimens of *Catinella* sp. were collected live from grassy areas adjacent to ^{14}C-deficient surface waters at Cold Creek, Nevada (76.0 ± 0.1 percent modern carbon (pMC); Thomas et al., 1991; Thomas, unpublished data) and Montezuma's Well in central Arizona (6.46 ± 0.42 pMC; Damon et al., 1964). Specimens were collected at each locality within 5–10 cm of the water's edge on wet ground with minimal leaf litter and few carbonate clasts. The weighted mean of the Cold Creek specimens (1.0555 ± 0.0033) and those collected at Montezuma's Well (0.9988 ± 0.0227) indicate *Catinella* incorporates old carbon during shell formation. Based on their proximity to the highly ^{14}C-deficient surface water, we suspect the primary source of old carbon in the *Catinella* shells is the water itself, rather than limestone, as in the case of the other terrestrial snails. If this is true, we can calculate the magnitude of the carbon-reservoir effect for *Catinella*.

Assuming only live, non-aquatic vegetation is consumed (i.e. no plant detritus), the fraction of old aqueous carbon ($f_{aqueous}$) incorporated in the shell of *Catinella* is given by:

$$A_{shell} = A_{aqueous} f_{aqueous} + A_{modern} f_{modern} \quad (1)$$

where A_x is the ^{14}C activity of the shell, water, and modern carbon, and f is the fraction of carbon derived from each. The modern carbon source represents carbon obtained from both the atmosphere and live terrestrial vegetation (they can be grouped together because their ^{14}C activities are identical). The ^{14}C activity of the water at Cold Creek and that at Montezuma's Well differ by an order of magnitude, yet the fraction of old carbon incorporated in *Catinella* shell carbonate is similar, $11.0 \pm 1.8\%$ at Cold Creek and $9.1 \pm 0.6\%$ at Montezuma's Well. Thus, it appears *Catinella* can provide reliable ^{14}C ages if a correction of $\sim 10\%$ of the local carbon-reservoir effect is applied. In most natural settings, the magnitude of this correction will be much smaller than the ~ 200 and 2200 ^{14}C yr required for *Catinella* at the Cold Creek and Montezuma's Well localities, respectively, because surface waters are typically at or near equilibrium with atmospheric carbon-14. The spring water emerging from deeply circulating carbonate aquifers sampled in this study makes these examples worst-case scenarios.

3.4. ^{14}C results for Coro Marl

Shells recovered from the Coro Marl were chosen for AMS analysis to accomplish three primary objectives: (1) to determine the local carbon-reservoir effect in order to correct measured ^{14}C ages from *Succineidae*, (2) to constrain the age of the Coro Marl, and (3) to compare the rate of deposition at two nearby sections to determine the degree of continuity of depositional conditions within the paleo-marsh.

3.4.1. Evaluation of the local carbon-reservoir effect

The magnitude of the carbon-reservoir effect was determined by comparing the ^{14}C activity of the land snails *Pupilla muscorum* (0.0408 ± 0.0010) and *Euconulus fulvus* (0.0460 ± 0.0011) and the freshwater bivalve *Pisidium casertanum* (0.0451 ± 0.0010) recovered from the same 10-cm interval (80–90 cm) at Section 1. The ^{14}C activities of *E. fulvus* and *P. casertanum* are indistinguishable. The ^{14}C activity of *P. muscorum*, however, is slightly lower, which is probably due to reworking of older *P. muscorum* shells. However, if this deviation is due to incorporation of old carbon by *P. muscorum* during shell formation, that would suggest that there are differences in terms of limestone consumption within the *Pupilla* genus (*P. muscorum* is closely related to *P. blandi*, which, as shown above, does not incorporate old carbon in its shell).

There are at least three possible reasons for the similar ^{14}C activity values between the aquatic bivalve (*Pisidium*) and terrestrial snail (*Euconulus*): (1) the carbon-reservoir effect at this location is negligible, (2) the aquatic bivalves were living well downstream of the spring outlets, which could have allowed exchange of CO_2 between the water and atmosphere, negating any carbon-reservoir effect originally present, or (3) the similarity is an artifact of the sampling process (i.e. shells were not randomly distributed within the 10-cm sample increment). The presence of at least four major paleo-spring orifices only a few tens of meters upgradient of the sampling sites suggests that there was probably not sufficient opportunity for aqueous $^{14}CO_2$ to attain equilibrium with the atmosphere by the time it reached the sampling sites. The carbon-reservoir effect originally present in the emerging spring waters, therefore, probably would have been recorded in the bivalve shells. The number of shells amalgamated (5 for *Euconulus fulvus* and 9 for *Pisidium casertanum*) makes it unlikely that the similarity in ^{14}C activities is an artifact of sampling. We conclude that the carbon-reservoir effect at this location was minimal, if present at all. The corresponding correction required for Succineidae (~10% of the carbon-reservoir effect) is therefore considered to be negligible.

3.4.2. ^{14}C age of Coro Marl

^{14}C ages of minute gastropods from the top and bottom of each section were measured to constrain the timing of marl deposition. ^{14}C ages of *Succinea* from the top and bottom of Section 1 are 17 860 ± 80 and 24 860 ± 170 ^{14}C yr BP, respectively (Table 4a). ^{14}C ages of *Euconulus fulvus* and *Succinea* from the top of Section 2 are 13 140 ± 60 and 13 680 ± 80 ^{14}C yr BP, respectively (Table 4b). The ^{14}C age of *Succinea* from the bottom of Section 2 is 23 020 ± 200 ^{14}C yr BP. Based on the difference in the upper age between Sections 1 and 2, the top of the marl must have been truncated at Section 1. We conclude that deposition of the Coro Marl at Murray Springs occurred between ~25 000 and 13 000 ^{14}C yr ago. These constraining ages are slightly older and younger, respectively, than the measured ^{14}C ages because it is unlikely we collected the first and last gastropods present in the paleo-marsh

Table 4
^{14}C results of fossil gastropods from the Coro Marl at Murray Springs

Sample ID	Species	Type[a]	Number of specimens	Depth (cm)	$\delta^{13}C$ (‰ pdb)	Sample age (^{14}C yr BP)
(a) Section 1 – Headcut of tributary channel ~25 m south of main channel						
AA39316	*Succinea* sp. (*Succineidae*)	SA	2	0–10	−6.5	17 860 ± 80
AA39317	*Succinea* sp. (*Succineidae*)	SA	8	0–10	−6.5	18 160 ± 80
AA39326	*Succinea* sp. (*Succineidae*)	SA	5	10–20	−5.8	19 380 ± 110
AA39327	*Succinea* sp. (*Succineidae*)	SA	9	20–30	−5.7	21 030 ± 100
AA39319	*Succinea* sp. (*Succineidae*)	SA	7	30–40	−5.7	21 600 ± 120
AA39328	*Succinea* sp. (*Succineidae*)	SA	8	40–50	−5.6	23 570 ± 120
AA39329	*Succinea* sp. (*Succineidae*)	SA	10	50–60	−5.5	23 690 ± 130
AA39330	*Succinea* sp. (*Succineidae*)	SA	7	60–70	−4.8	24 420 ± 140
AA39331	*Succinea* sp. (*Succineidae*)	SA	4	70–80	−5.5	24 980 ± 140
AA39324	*Pisidium casertanum*	A	9	80–90	−7.1	24 890 ± 170
AA47648	*Euconulus fulvus*	T	5	80–90	−6.8	24 740 ± 200
AA47647	*Pupilla muscorum*	T	5	80–90	−6.8	25 700 ± 210
AA39318	*Succinea* sp. (*Succineidae*)	SA	8	80–90	−6.6	24 470 ± 120
AA39333	*Succinea* sp. (*Succineidae*)	SA	2	90–100	−6.2	24 620 ± 140
AA39320	*Succinea* sp. (*Succineidae*)	SA	2	100–110	−6.3	24 310 ± 180
AA39321	*Succinea* sp. (*Succineidae*)	SA	8	100–110	−6.3	24 860 ± 170
(b) Section 2 – South wall of main channel						
AA47649	*Euconulus fulvus*	T	9	0–12	−6.6	13 140 ± 60
AA43399	*Succinea* sp. (*Succineidae*)	SA	4	0–12	−6.0	13 680 ± 80
AA43400	*Succinea* sp. (*Succineidae*)	SA	4	37–49	−5.9	19 780 ± 120
AA43401	*Succinea* sp. (*Succineidae*)	SA	9	73–85	−6.0	23 020 ± 200

[a] Abbreviations: A, aquatic; SA, semi-aquatic; T, terrestrial.

system. Moreover, the measured ^{14}C age represents the mean age of the 10-cm block of sediment from which the gastropods were collected, and therefore is slightly younger (for the basal increment) and older (for the uppermost increment) than the true extreme.

3.4.3. Deposition rate of Coro Marl

Accurate ^{14}C ages of gastropods recovered from the Coro Marl allow us to evaluate sediment accumulation variability within the deposit. We measured the ^{14}C ages of a number of gastropods to determine the rate of deposition through time,

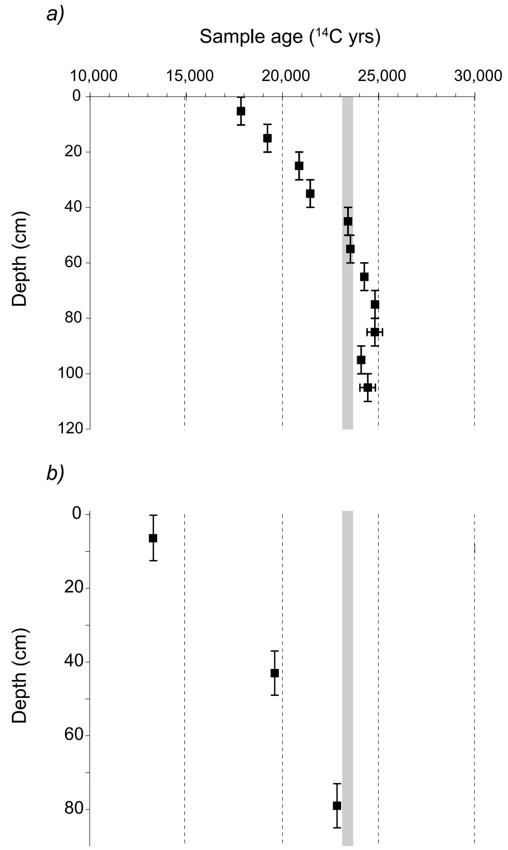

Fig. 5. Depth vs. age of the Coro Marl at (a) Section 1, and (b) Section 2. A weighted mean ^{14}C age was calculated for sampling intervals in which multiple specimens were analyzed. Note the timing of the change in slope for Section 1 (marked by the gray band) is roughly coincident with the onset of deposition at Section 2, perhaps suggesting a change in local hydrologic conditions.

and to check whether the ages remain stratigraphically consistent through the sections (Table 4). There were no major stratigraphic reversals of the *Succineidae* or *Euconulus* ages at either section.

The results indicate that deposition of the lower ~60 cm at Section 1 was initially quite rapid (~0.6 mm/yr), and slowed dramatically after ~23 500 ^{14}C yr ago (Fig. 5). The deposition rate then remained relatively constant at ~0.07 mm/yr until at least 17 900 ^{14}C yr ago. Based on the three ^{14}C dates at Section 2, the deposition rate was ~0.11 mm/yr between 23 000 and 19 800 ^{14}C yr ago, and ~0.06 mm/yr between 19 800 and 13 000 ^{14}C yr ago. Note that the sharp decrease in the deposition rate at Section 1 was quickly followed by the onset of deposition at Section 2. We speculate that this may reflect a local hydrologic change, such as migration of outflow channels within the marsh.

4. Discussion and conclusions

Live minute gastropods are found in a variety of environmental conditions, from marshes and wet meadows to grasslands and high-elevation forested areas. Their distribution in the fossil record is equally diverse. Minute gastropod shells are common in paleo-wetland and alluvial deposits throughout the southwestern and western USA (Bequaert and Miller, 1973; Simcox and Gross, 1983; Lamb, 1989), loess deposits in the Rocky Mountain foothills of Colorado (Roberts, 1935) and the midwestern USA (Muhs et al., 1999, pers. commun., 2002), alluvial sediments in Asia (Margaritz et al., 1981), and numerous archaeological sites worldwide (Evans, 1972; Yapp, 1979). The reliability of *Pupilla*, *Euconulus*, and *Succineidae* for ^{14}C dating, even in settings where highly ^{14}C-deficient carbon is present, demonstrates their potential for dating a variety of Quaternary sediments. Most geologic settings are not as extreme in terms of available ^{14}C-deficient carbon as those chosen for study here. Therefore, minute taxa such as *Cochlicopa*, *Discus*, and *Vitrina* that incorporate small amounts of old carbon when living in carbonate alluvium may potentially yield accurate, rather than maximum, ^{14}C ages in many settings.

Our dating results from the Coro Marl demonstrate the utility of minute gastropods for ^{14}C dating and provide new constraints on the timing of enhanced spring discharge and elevated water tables in the southwestern USA. ^{14}C ages obtained from minute gastropod shells indicate deposition of the marl occurred between ~25 000 and 13 000 ^{14}C yr ago. The Coro Marl is situated > 15 m above the modern water table at Murray Springs, and is similarly positioned in discontinuous outcrops over a ~150-km stretch of the San Pedro Valley. Thus, these ages may be used to infer the timing of elevated water-table conditions throughout the valley.

Deposits similar to the Coro Marl have also been identified in western Texas and southern New Mexico (Ashbaugh and Metcalf, 1986), although the ages of these deposits are not yet known. If synchronous with the Coro Marl, the widespread distribution of the deposits may provide information for the regional hydrology on a scale much larger than the San Pedro Valley, possibly encompassing much of the southwestern USA.

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