Dynamic response of desert wetlands to abrupt climate change

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Desert wetlands are keystone ecosystems in arid environments and are preserved in the geologic record as groundwater discharge (GWD) deposits. GWD deposits are inherently discontinuous and stratigraphically complex, which has limited our understanding of how desert wetlands responded to past episodes of rapid climate change. Previous studies have shown that wetlands responded to climate change on glacial to interglacial timescales, but their sensitivity to short-lived climate perturbations is largely unknown. Here, we show that GWD deposits in the Las Vegas Valley (southern Nevada, United States) provide a detailed and nearly complete record of dynamic hydrologic changes during the past 35 ka (thousands of calibrated ^{14}C years before present), including cycles of wetland expansion and contraction that correlate tightly with climatic oscillations recorded in the Greenland ice cores. Cessation of discharge associated with rapid warming events resulted in the collapse of entire wetland systems in the Las Vegas Valley at multiple times during the late Quaternary. On average, drought-like conditions, as recorded by widespread erosion and the formation of desert soils, lasted for a few centuries. This record illustrates the vulnerability of desert wetland flora and fauna to abrupt climate change. It also shows that GWD deposits can be used to reconstruct paleohydrologic conditions at millennial to submillennial timescales and informs conservation efforts aimed at protecting these fragile ecosystems in the face of anthropogenic warming.

climate change | groundwater discharge deposits | Las Vegas Valley | paleohydrology | drought

Desert wetlands are critical, groundwater-dependent ecosystems in arid environments that support a wide array of endemic, threatened, and endangered species. Conservation efforts to protect desert wetlands must prepare for a range of possible responses to changing hydrologic conditions (1, 2). It is imperative, therefore, to understand how these systems responded to past episodes of abrupt climate change to inform policy decisions in the face of anthropogenic warming.

Desert wetlands form where water tables approach or breach the ground surface and are expressed as a variety of hydrologic settings, including seeps, marshes, wet meadows, spring pools, and flowing streams. Over time, eolian and alluvial sediments become trapped by dense vegetation and wet ground conditions, resulting in a unique combination of clastic sediments, chemical precipitates, and organic matter that are collectively referred to as groundwater discharge (GWD) deposits (3).

GWD deposits are preserved globally in the geologic record, contain information on the timing and magnitude of past changes in water table levels, and are a source of paleohydrologic and paleoclimatic information (4–10). Previous studies have shown that desert wetlands in the southwestern United States responded to climate change at glacial to interglacial timescales (e.g., refs. 5, 11, and 12). However, GWD deposits have not been used for high-resolution paleohydrologic studies because they are stratigraphically complex and inherently discontinuous, which has limited our understanding of how desert wetlands responded to past episodes of abrupt climate change.

During the late Quaternary, the Las Vegas Valley of southern Nevada supported a series of extensive and diverse wetlands analogous to modern spring ecosystems with helocrene (wet meadows and marshes), rheocrene (flowing streams), and limnocrene (spring-fed pools) discharge regimes (13) (Fig. 1). Wetlands were distributed along the length of the valley axis and supported a diverse flora and fauna (14). The resulting GWD deposits blanket much of the valley floor, particularly in the Upper Las Vegas Wash, where they appear as light-colored, fine-grained sedimentary sequences that exhibit distinct badland topography.

Here, we establish stratigraphic and chronologic frameworks for fossil-bearing GWD deposits in the Las Vegas Valley on the basis of detailed geologic mapping, stratigraphic principles, and ^{14}C dating. The sedimentary sequence was dated absolutely and independently before comparison with northern hemispheric climatic proxy data, thus avoiding pitfalls associated with tuning to other records (15). Overall, we show that a combination of aggrading wetland sediments, incipient soils (Aridisols), and erosion associated with cessation of spring discharge provides a nearly complete record of the rapid hydrologic response of desert wetlands to abrupt climate change during the past 35 ka [thousands of calibrated ^{14}C years before present (BP)], including the presence of atmospheric teleconnections between the southwestern United States and Greenland during the late Quaternary. This paleohydrologic record is a harbinger for the future of desert wetlands in the face of a warming climate.

Significance

A paleohydrologic record from the Las Vegas Valley (southern Nevada, United States) shows that desert wetlands were extremely sensitive to rapid climatic changes during the past 35,000 years and exhibit temporal congruence with the Greenland ice core record. Wetlands in the valley expanded and contracted many times in response to climatic events during this period, including Dansgaard–Oeschger cycles and other millennial and submillennial climatic perturbations. Widespread erosion occurred when entire wetland systems collapsed during exceptionally dry times. Drought-like conditions typically lasted for a few centuries, which highlights the threat of anthropogenic warming to endemic fauna and flora that depend on desert wetlands to provide a consistent source of water in an otherwise arid landscape.

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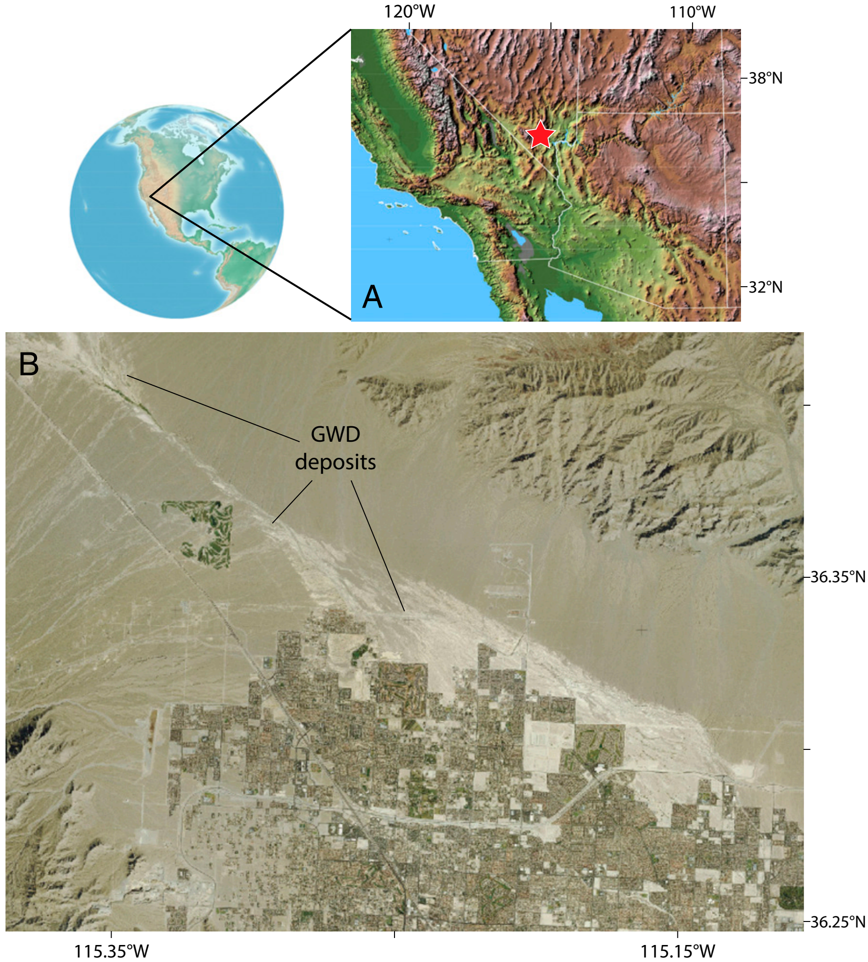

Fig. 1. (*A*) Site location map for the Las Vegas Valley GWD deposits. (*B*) Aerial photograph of light-colored GWD deposits that are exposed in the northern portion of the valley.

Results and Discussion

The depositional environments represented by the GWD deposits in the Las Vegas Valley are both spatially complex and time-transgressive, with disparate sedimentological facies related to discharge regime and topographic position in the valley. Diverse lithologies of the GWD deposits often host vertebrate fossils and include organic-rich black mats and light-green to white fine-grained sediments representing valley-bottom marshes and wet meadows, tufa-filled outflow streams, well-sorted light-brown silts representing phreatophyte flats (areas adjacent to the former marshes), and poorly sorted coarse-grained alluvial sediments representing peripheral xeric landscapes (Fig. 2). A detailed examination of the GWD deposits throughout the Las Vegas Valley, in conjunction with targeted ^{14}C dating of charred vascular plants (and to a lesser extent small, terrestrial gastropod shells), allowed us to establish a composite stratigraphic section and high-resolution chronology from ~35 ka to the present (Fig. 3) (see *SI Appendix* for details).

Between 35 and 24 ka, pervasive episodes of spring discharge accompanied the highest water table levels achieved in the valley (Fig. 3). Within this period, spring discharge was interrupted episodically by widespread desiccation when water table levels were depressed as indicated by soil development and disconformities. More specifically, vigorous rheocrene discharge (outflow streams) yielded to pronounced limnocrene ponding shortly after 35 ka. Between 34.2 and 31.7 ka, spring discharge terminated and aridity ensued at least twice as evidenced by Aridisol formation and strongly oxidized lithologies (Fig. 3). These breaks in discharge reflect widespread drying events that correspond in time to Dansgaard–Oeschger cycles (D-O) 6 and 5. Spring discharge renewed at 31.7 ka and reached its zenith shortly thereafter with geographically widespread wetland development as the water table breached the ground surface, resulting in extensive valley-wide wet meadows and marshes that prevailed through 24.5 ka. Within this interval, a short-lived discharge event preserved in the marginal facies of the GWD deposits occurred at 27.6 ka and is bounded above and below by two prominent Aridisols that are likely correlative with D-O 4 and 3. The timing of these Aridisols and the D-O cycles is offset slightly, but correlation is permissible given the uncertainties within this interval of the GICC05 chronology (~0.8 ka) (16) and the charcoal ^{14}C age obtained between the two soils (~0.2 ka; *SI Appendix*, Table S2).

Prominent carbonate caps and benches that are resistant to erosion are important marker beds in the full-glacial sequence and form broad, topographically extensive flats. The caps/benches form at the ground surface or very shallow subsurface via capillary migration of groundwater through the vadose zone (5). We attribute their formation to abrupt warming that intensified evaporative effects and depressed the water table leading to desiccation of the wetlands and carbonate precipitation. For example, a prominent carbonate bench found throughout the valley corresponds in time to D-O 4 and 3. Similarly, following wetland formation between 25.9 and 24.5 ka, a second widespread carbonate cap represents a

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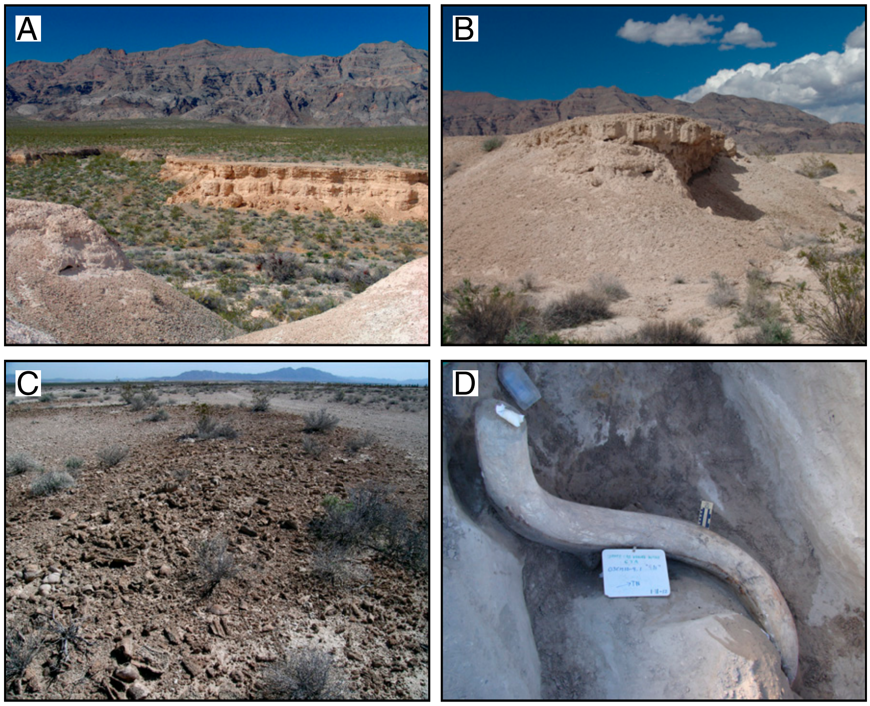

Fig. 2. Representative lithologies of the GWD deposits in the Las Vegas Valley (see *SI Appendix* for additional examples). (*A*) Badland topography (axial) of the Upper Las Vegas Wash GWD deposits; multiple individual stratigraphic sections were used to compile the composite stratigraphy used to decipher the hydrologic conditions in the Las Vegas Valley over the last 35 ka (Fig. 3); (*B*) geographically extensive carbonate cap representing aridification and wetland collapse during Dansgaard–Oeschger events 4–3; (*C*) phytoclast tufa representing a Younger Dryas-age rheocrene outflow stream; and (*D*) Columbian mammoth tusk in discharge deposits from outflow streams dating to the Bølling warm period.

period of warm temperatures and relatively low water tables associated with D-O 2, which marks the collapse of the full-glacial wetlands (Fig. 3).

The longest and most significant hiatus in the Las Vegas Valley GWD record followed D-O 2 and lasted more than three millennia as evidenced by extensive erosion of the older deposits. Between 21.0 and 18.0 ka, wetland development was reestablished and several distinct discharge episodes are evident on the basis of characteristic lithologies and inset/cross-cutting relationships (Fig. 3). In opposition to full-glacial flow regimes, discharge after 21.0 ka is dominated by rheocrene flow emanating from spring conduits that produced braided fluvial channels containing microbially mediated, ambient-temperature tufas. Remnants of braided fluvial tufa and stromatolitic tufa are preserved as surficial lag deposits that mantle the resistant carbonate surface of the flats and as in situ primary sedimentary structures intercalated with inset fluvial channel deposits. Tufa first occurs in the GWD record at 21.0 ka, persists until 10.6 ka, and is always associated with rheocrene flow. Microbially mediated tufa formation is inhibited by colder temperatures (17, 18) and is strikingly absent from the full-glacial deposits. Therefore, the appearance of tufa at 21.0 ka likely suggests that rising temperatures crossed an unspecified threshold at this time.

During the late glacial period, the Las Vegas Valley GWD record supports the "tripartite period of deglaciation" of Broecker et al. (19) that includes the Mystery Interval, Bølling–Allerød, and Younger Dryas (YD). Intense erosion of the full-glacial–aged deposits occurred between 18.0 and 16.1 ka, corresponding with the "Big Dry" portion of the Mystery Interval (20), with no wetland development recorded during this time (Fig. 3). Rheocrene discharge resumed between 16.1 and 15.0 ka, correlative in time with the "Big Wet" (Oldest Dryas) portion of the Mystery Interval. Discharge at the end of this period ended abruptly, as evidenced by intense erosion of these deposits in response to the initiation of the Bølling warm period (D-O 1). In a notably nonlinear response, pulsed fluvial discharge resumed shortly thereafter (14.6–14.3 ka), accompanied by intensified tufa formation. Despite the warm conditions, groundwater levels remained high enough to support rampant rheocrene discharge. Following this discharge episode, a sharp lithologic transition occurred at 14.1 ka and marks the onset of the Older Dryas. Additional discharge events show congruence with global climatic oscillations as the Las Vegas Valley wetlands responded dynamically to changing climate conditions, including limnocrene ponding during the YD cold event (Fig. 3). At the end of the YD, a distinct change from limnocrene discharge to more arid conditions marked by oxidized GWD deposits occurred, which represents the end of sustained GWD in the valley. Oxidized GWD deposits dating to the early Holocene suggest that wetland development at this time was intermittent, with intensified pulses corresponding to pre-Boreal climate oscillations and a final brief pulse of Holocene discharge at ~8.5 ka that is broadly correlative with the 8.2 ka cooling event (21, 22). Widespread erosion and episodic dune formation indicate that arid conditions prevailed in the valley during the remainder of the Holocene.

GWD deposits of the Las Vegas Valley reflect hydrologic conditions comparable to modern spring ecosystems with helocrene, rheocrene, and limnocrene outflow systems (13). The chronology of these deposits for the past 35 ka, coupled with the identification and interpretation of wetland sedimentary facies and depositional hiatuses, presents a previously unrecognized record of hydrologic conditions for this region. Importantly, our record supports the hypothesis that atmospheric teleconnections existed between the southwestern United States and Greenland during the late Quaternary, and shows temporal congruence with rapid warming associated with D-O events (16, 23) that have been observed previously in marine sediments (24–26) and speleothems (27–29).

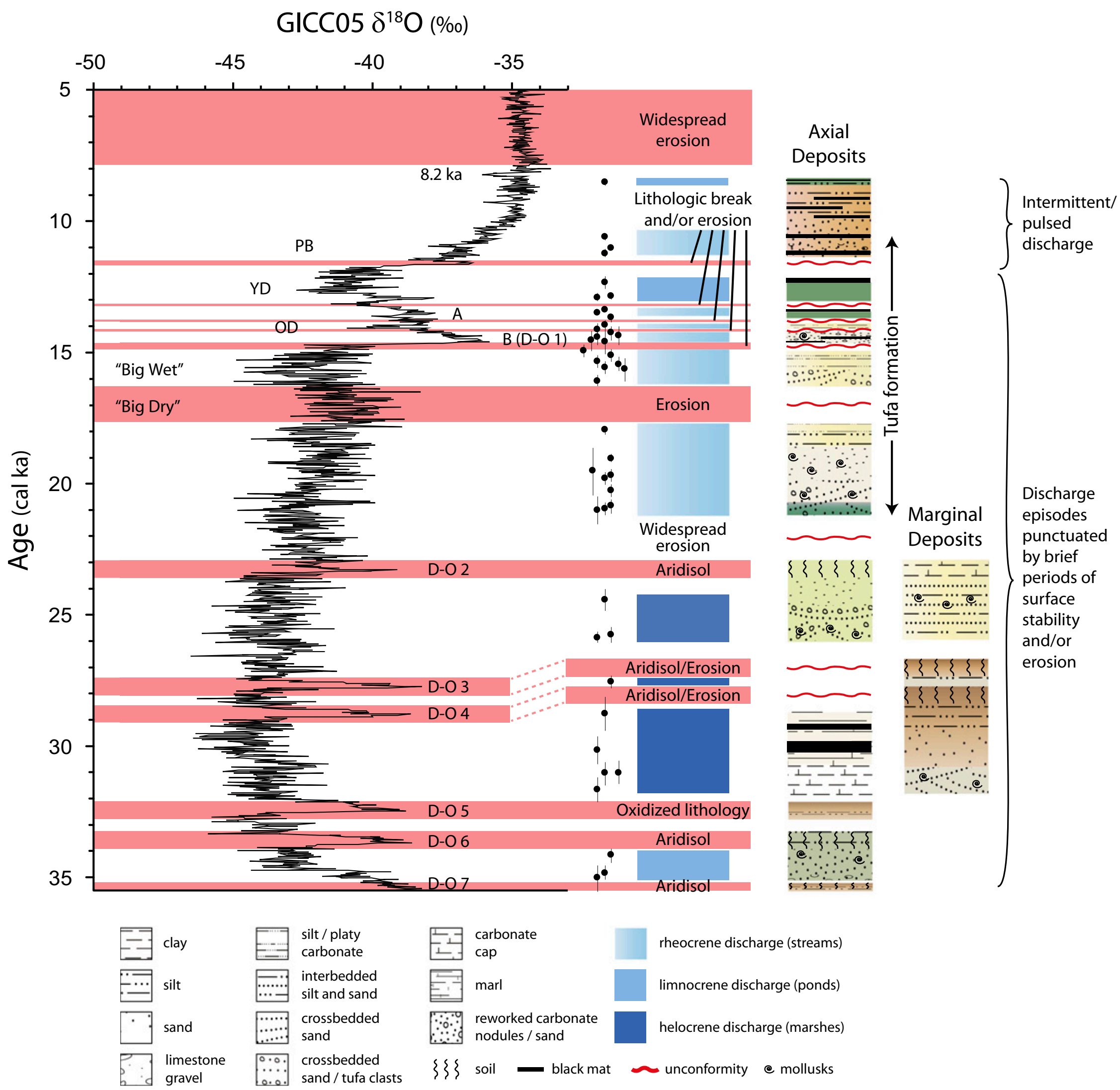

Fig. 3. Composite stratigraphy and chronologic record of GWD deposits in the Las Vegas Valley of southern Nevada compared with $\delta^{18}O$ data from the Greenland ice cores using the GICC05 chronology (16). Filled circles are calibrated radiocarbon ages of the GWD deposits with uncertainties presented at the 95% (2σ) confidence level. Wetland discharge (by type) is shown in graduated shades of blue. Red bars indicate periods of surface stability and/or erosion. A, Allerød; B, Bølling; "Big Wet/Big Dry" after Broecker (20); D-O, Dansgaard–Oeschger cycles; 8.2 ka, 8.2 ka cold event; OD, Older Dryas; PB, pre-Boreal; YD, Younger Dryas.

This study is unique in using GWD records as a high-resolution paleohydrologic proxy to document synoptic-scale climate patterns that operated in the southwestern United States during the late Quaternary.

Our study also documents that desert wetlands in the Las Vegas Valley collapsed repeatedly during the late Quaternary, a time that was relatively cool/wet compared with today, which indicates that desert wetlands are highly sensitive to changes in climate and may be more vulnerable to submillennial-scale droughts than previously recognized. Flora and fauna that were dependent on springs and wetlands for water in an otherwise arid landscape were likely stressed or extirpated from the valley when the wetlands went dry.

Desert wetlands serve as keystone ecosystems in arid environments worldwide and support a high species biodiversity including endemic, threatened, and endangered biotas. They are also loci for human and megafaunal activities and underpin the association of archeological and paleontological materials with GWD deposits that, with robust chronologic control, can reveal much about changing climates and ecosystem responses over time (14, 30, 31). Wetlands are an invaluable resource for flora and fauna, and compose ∼0.3% of the total land cover of deserts in the southwestern United States (32). They are also common features in the deserts of South America, Asia, Africa, and Australia (ref. 10 and references therein). Conservation efforts aimed at maintaining extant desert wetlands, therefore, should be viewed through the unique geological lens that is afforded by GWD deposits when evaluating and planning for the potential response of these fragile ecosystems to future climate warming.

Methods

This study was conducted from 2008 to 2014 on ∼11,000 acres of federal land managed by the Bureau of Land Management (BLM), Southern Nevada District Office. Work was performed under Grant L08AC13098 entitled "The Upper Las Vegas Wash Conservation Transfer Area, Clark County, NV: Treatment, Protection, and Interpretation of Heritage Paleontological Resources through Public Involvement." Paleontological resources are protected under several federal statues, most recently and broadly, the Omnibus Public Land Management Act of 2009 (also called the Paleontological Resources

Preservation Act). All work was conducted under BLM Permit N85806 and Field Work Authorizations, which were renewed annually.

Standard geological and stratigraphic practices were used during the course of the study. Multiple stratigraphic sections throughout the upper Las Vegas Wash were described and measured, and then used to construct the composite stratigraphy reported herein. Sediment samples were collected and curated at the San Bernardino County Museum. All sites, including radiocarbon dating localities and stratigraphic sections, were photo-documented, and their positions were recorded with handheld GPS units. All physical and digital data reside at the San Bernardino County Museum (Redlands, CA).

Radiocarbon (^{14}C) dating of charred vascular plants and, to a lesser extent, small terrestrial gastropod shells was used to establish the chronologic framework of the Las Vegas Valley GWD deposits. A few aliquots of charred plant material were identified to genus level by PaleoResearch Institute (Boulder, CO), although most were not (*SI Appendix*, Table S2). Charcoal samples were treated using either the standard acid–base–acid treatment or acid–base–wet oxidation methods before combustion online in the presence of excess high-purity oxygen.

Clean, dry gastropod shells were broken and examined under a dissecting microscope to ensure that the interior whorls were free of secondary carbonate and detritus. Fossil shells that were free of detritus were etched with dilute HCl to remove ∼15–20% of the total mass before hydrolysis. We selected several shells at random for X-ray diffraction analysis to verify that only shell aragonite remained before preparation for ^{14}C analysis. None of the shells that we analyzed contained measurable quantities of calcite. Shell carbonate was converted to CO_2 using American Chemical Society reagent-grade 85% by weight H_3PO_4 under vacuum at 50 °C until the reaction was visibly complete (∼1 h).

For all samples, water and other contaminant gases (including SO_x, NO_x, and halide species) were removed using a combination of cryogenic separation and high-temperature fine-wire copper and silver wool traps. The resulting pure CO_2 gas was measured manometrically and split into two aliquots. One aliquot was converted to graphite using an iron catalyst and the standard hydrogen reduction process and submitted for ^{14}C analysis by accelerator mass spectrometry. The second aliquot was submitted for $\delta^{13}C$ analysis to correct the measured ^{14}C activity of the shell carbonate for isotopic fractionation. All ^{14}C ages were calibrated using the IntCal13 dataset and CALIB 7.0 (33, 34). Ages are presented in calibrated years BP (0 y BP = 1950 A.D.), and uncertainties are given at the 95% (2σ) confidence level.

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