Stable carbon and hydrogen isotopes from bat guano in the Grand Canyon, USA, reveal Younger Dryas and 8.2 ka events

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ABSTRACT

We inferred climate change through the Pleistocene-Holocene transition from δ¹³C and δD values of bat guano deposited from 14.5 to 6.5 ka (calendar ka) in Bat Cave, Grand Canyon, Arizona. The δ¹³C and δD values generally covaried, indicating that regional late Pleistocene climate was relatively cool and wet, and early Holocene climate gradually became warmer with increased summer precipitation until ca. 9 ka, at which time the onset of modern North American Monsoon–like conditions occurred. During the Younger Dryas event, δ¹³C values decreased, whereas δD values increased, indicating a cool and possibly drier period. We also observed a distinct isotopic anomaly during the 8.2 ka event, at which time both δ¹³C and δD values decreased. The δ¹³C values abruptly increased at 8.0 ka, suggesting a rapid change in atmospheric circulation and greater influence from convective storms originating from the south. Deposits of bat guano represent a largely untapped source of paleoenvironmental information that can provide continuous and long-term continental archives of environmental change.

Keywords: arid, precipitation, vegetation, paleoclimate, North American Monsoon.

INTRODUCTION

The climate of the interior continental southwestern United States is currently dominated by the North American Monsoon, a seasonal change in atmospheric circulation that results in elevated summer precipitation following a hyperarid spring (Adams and Comrie, 1997; Wright et al., 2001). Large-scale circulation patterns, forced by differential heating of the North American continent in summer, result in the development of a thermal low over the southwest United States and northward displacement of the Pacific and Bermuda highs (Wright et al., 2001). During the last glacial period, it is thought that there was greater effective moisture in the region due to a southerly shift in the jet stream and an increase in associated frontal precipitation from the west (Thompson et al., 1993). However, beyond such generalities, the climate history of this region is poorly understood because semiarid climates are generally not conducive to the preservation of depositional archives of climate change (Des Marais et al., 1980; Anderson et al., 2000; Metcalfe, 2006). Some of the questions that remain concern the timing of the initiation of the current North American Monsoon system (Poore et al., 2005), and whether the southwest United States experienced climate anomalies during the Younger Dryas (YD) and 8.2 ka events (e.g., Anderson et al., 2000; Cole and Arundel, 2005; Metcalfe, 2006).

A long-term climate archive may be found in bat guano deposits that have accumulated over thousands of years (Des Marais et al., 1980; Mizutani et al., 1992a, 1992b). Cave guano deposits of substantial depth are found throughout tropical (e.g., McFarlane et al., 2002; Bird et al., 2007), subtropical (e.g., Mizutani et al., 1992a, 1992b; Wurster et al., 2007), and temperate regions (e.g., Maher, 2006). Some guano deposits extend at least beyond the Last Glacial Maximum (LGM) (Bird et al., 2007), but guano deposits have as yet been only superficially exploited as climate archives. Herein, we report results from a deposit located in Bat Cave, a maternity roost for Mexican free-tailed bats (Tadarida brasiliensis) that migrate from Mexico to Arizona each summer (Mizutani et al., 1992a) (Fig. 1). Because of the substantial elevation gradient of the Grand Canyon and its proximity to the limit of the current North American Monsoon system, which lead to a variable precipitation and temperature regime that immediately impacts plant distributions, Bat Cave is sensitively placed to record past climate change (Cole and Arundel, 2005; Poore et al., 2005).

Tadarida brasiliensis is an opportunistic feeder, consuming local insects in proportion to their diversity and abundance (Lee and McCracken, 2002). Because insect tissue δ¹³C and δD values reflect
insect diet (Schimmelmann et al., 1993; Webb et al., 1998) and insect abundance is largely determined by available local vegetation (e.g., Pinder and Kroh, 1987; Warren and Gaston, 1992), stable-isotope assays of guano accumulated in thick deposits provide a long-term record of changes in δ13C and δD values of local vegetation, which are in turn dependent on local climatic conditions (Mizutani et al., 1992b; McFarlane et al., 2002; Wurster et al., 2007).

C4, C3, and Crassulacean acid metabolism (CAM) photosynthetic pathways control the carbon isotopic composition of plants (Ehleringer et al., 1997), and in semiarid regions, the relative abundances of these plant types are strongly tied to local climate conditions (Paruelo and Lauenroth, 1996). In the western United States, C4 vegetation, with δ13C values that average −26%e relative to Vienna PeeDee belemnite (VPDB), tends to predominate under cooler and winter-precipitation-dominated climatic conditions, whereas C3 vegetation, with δ13C values around −13%e, becomes more dominant at higher growing season temperatures with a summer-dominated precipitation regime (Des Marais et al., 1980; Paruelo and Lauenroth, 1996). Notably, shrubby C4 vegetation will replace C3 grasses when there is insufficient monsoonal rainfall for C3 growth (Paruelo and Lauenroth, 1996). CAM vegetation, which has comparable or higher δ13C values to C3 plants, is also a contributor of production in the Grand Canyon (Cole and Arundel, 2005). Wurster et al. (2007) demonstrated a strong correlation between the relative abundance of C4 grasses and δ13C values of modern guano from insectivorous bats from Florida to California. Moreover, they found that δ13C values of guano were most strongly correlated with summer precipitation amount and winter precipitation ratio in the western United States.

Bat guano is largely composed of insect fragments, the structural component of which is chitin. Chitin is a polymeric nitrogen-bearing polysaccharide, and in terrestrial insects, it may be partially deacetylated and covalently bonded with proteins to add structural integrity and preservation potential in the sedimentary record (Gröcke et al., 2006). Insect tissue (particularly chitin) δD values are determined by diet (e.g., Schimmelmann et al., 1993; Miller et al., 1988; Gröcke et al., 2006), which is in turn related to the δD values of local precipitation (e.g., Wassenaar and Hobson, 1998; Miller et al., 1988; Hobson et al., 1999). The δD values of local precipitation are related to temperature, seasonality of precipitation (source), and humidity (e.g., Miller et al., 1988).

We therefore surmised that relative to Pleistocene conditions characterized by cool temperatures and winter precipitation (Thompson et al., 1993), vegetation δD values in a North American Monsoon–dominated climate should be higher due to increases in relative summer precipitation, evaporation, and/or temperature (Wright et al., 2001); moreover, an increase in summer precipitation and/or temperature would increase the relative proportion of C4/CAM vegetation (Wurster et al., 2007), and thus coeval increases in δ13C and δD values of bat guano can be interpreted to indicate the onset of the North American Monsoon. If changes are not coeval, other factors like aridity may be more likely.

METHODS

A continuous guano core, 1 m in length, was collected from the back chamber of Bat Cave (36.0◦N, 113.8◦W, 580 m above sea level [asl]), ~330 m from the entrance and isolated from the currently occupied roost by a boulder collapse and blockage of guano. The core displayed distinct depositional laminae, and the organic component was well preserved by the desiccating environment of the cave (Mizutani et al., 1992a). Abundant skeletal remains of T. brasiliensis in the isolated chamber suggest that the sequence was deposited by this species. Moreover, only T. brasiliensis is known to deposit laminated guano piles of comparable size in the southwest United States.

In the laboratory, the core was opened and sampled at 4 mm intervals from 0 to 260 mm, and every 8 mm thereafter. A greater total organic carbon content from the first 260 mm permitted a higher sample resolution. Core material was homogenized and then suspended in a 2 N HCl-ZnCl2 solution (specific gravity 2.0) for 3 hr to separate organic from mineral fractions and remove carbonate. The supernatant was then rinsed using deionized H2O through a 12 µm metal sieve. Particulates retained on the sieve were washed once in methanol and three times in chloroform:methanol (2:1 v/v) and lyophilized. Stable isotope values and elemental composition were measured by continuous flow–isotope ratio–mass spectrometry (CF-IR-MS) using a ThermoFinnigan Conflo III coupled to a Delta Plus XP mass spectrometer. The δ13C values were combusted using a Flash 1112 Elemental Analyzer, and they are reported relative to VPDB. Replicate analyses of internal laboratory standards yielded an external reproducibility better than ±0.2‰. Samples for determination of δD values and weight percent hydrogen (H%) were pyrolyzed using a ThermoFinnigan High-Temperature Conversion Elemental Analyzer (TC/EA). The δD values of nonexchangeable hydrogen are reported relative to the Vienna standard mean ocean water–Vienna standard light Antarctic precipitation (VSMOW-VSLAP) scale, after correction using grasshopper “chitin” and fresh bat guano “chitin” working standards and the comparative equilibration procedure (Wassenaar and Hobson, 2000, 2003). Replicate analyses of internal laboratory standards and 10 replicate measurements on selected subsamples analyzed approximately 1 yr apart yielded an external reproducibility better than ±3‰.

It was observed that samples with C:N ratios lower than six tended to have slightly higher δ13C and δD values than adjacent samples. In order to limit isotopic variance related to component rather than environmentally sourced variation, only samples with C:N ratios similar to chitin (between 6 and 8) are considered here (~80% of material analyzed). Because C:N and N:H ratios of subsamples were similar (Kruskal-Wallis, H[2,31] = 5.45), did not covary with δ13C nor δD values, and were close to those expected for chitin, we are confident that δ13C and δD profiles reported here can be interpreted in terms of an environmental rather than diagenetic signal. We report 41 δ13C and 31 δD values of solvent-extracted guano (SEG) samples. Due to the amount of sample recovered, we were unable to measure δD values on all subsamples.

Initially, two accelerator mass spectrometry (AMS) 14C measurements were obtained from Glivice Radiocarbon Laboratory. Subsequently, another seven AMS 14C measurements were obtained from Rafter Radiocarbon National Isotope Laboratory (see the GSA Data Repository1). All radiocarbon analyses were performed on SEG samples. One sample (GdA-695) suggested a slight temporal reversal and was excluded from our age model. Radiocarbon measurements were converted to calendar years using IntCAL04 (Reimer et al., 2004), midpoints of the most probable calendar ages (2σ) between contiguous samples were used to construct a linear depositional age model (Fig. 2), and we discuss all samples in calibrated calendar kiloannum B.P. (ka).

RESULTS AND DISCUSSION

The δ13C and δD values are strongly correlated throughout the record (r = 0.88, p < 0.001, n = 31) (Fig. 2). The δ13C values range from −26.5‰ to −24.0‰; δD values range from −188‰ to −143‰. Overall, the trend in guano δ13C and δD values (Fig. 1) bears similarity to the Greenland Ice Sheet Project 2 (GISP2) δ18O record of North Atlantic climate variability (e.g., Stuiver et al., 1995). A warm Bolling-Allerød (BA) that precedes a cold Younger Dryas is also reflected in the Santa Barbara planktonic δ18O record off the coast of southern California (Kennett and Ingram, 1995; Hendy et al., 2002) and is implied by the δ13C values of packrat fecal pellets (Cole and Arundel, 2005) and guano δ13C values from the Grand Canyon (Fig. 1).

1GSA Data Repository item 2008175, isotopic and C:N ratio results, and radiocarbon results and calendar year conversions, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.
During the Younger Dryas, although others have concluded a cool interpretation that aridity increased at this time since increased summer precipitation coincident with rising summer solar insolation (Van Devender and Spaulding, 1979; Anderson et al., 2000; Metcalfe, 2006).

Perhaps the most interesting aspect of the guano $\delta^{13}C$ and $\delta D$ profiles is a distinct 8.2 ka event, which has been previously unreported in this region. At this time, guano $\delta^{13}C$ and $\delta D$ values display a sustained negative anomaly, indicating a rapid shift to cooler conditions with less summer precipitation. Then, at 8.0 ka, $\delta^{13}C$ values abruptly increase ~1‰ to relatively stable values that are ~0.5‰ higher than values prior to the 8.2 ka anomaly, suggesting an abrupt, albeit slight, increase in $C_3/C_4$ vegetation. We interpret this change as an abrupt reorganization of atmospheric circulation similar to that inferred for the northern Great Plains (Dean et al., 2002). A sudden change in high-latitude surface conditions through the loss of a large portion of the Laurentide Ice Sheet forced the polar front to move its average position northward. Such a shift in the position of the polar front would have abruptly reduced the impact of frontal storms associated with westerlies and increased the frequency of convective storms arriving from the south. The $\delta D$ values also indicate increased North American Monsoon strength, although not abruptly, perhaps reflecting a more regional-scale muted change. The $\delta D$ values appear to mirror changes in insolation that are also apparent in a Gulf of Mexico record, which suggests strong North American Monsoon development during the mid-Holocene (Poore et al., 2005). Unfortunately, comparable mid-Holocene packrat midden sites are exceedingly rare during the early and middle Holocene (Webb and Betancourt, 1990).

CONCLUSIONS

Well-preserved and long-term bat guano deposits provide a means to develop high-resolution climate archives in terrestrial semiarid environments where other long-term continuous depositional climate proxies are rare or nonexistent. Bat guano deposits provide semiarid records that are longer than records derived from tree rings, and they are more continuous and have higher resolution than packrat middens or paleosols. Here, we provide an example from the semiarid Grand Canyon, United States, whereby we infer a cool and possibly drier Younger Dryas, and we describe for the first time a distinct 8.2 ka anomaly for the southwest United States.

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