Quaternary Paleoclimate of the Colorado Plateau

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Goals of the paper

To give an overview of the climate history of the Colorado Plateau, and the various proxies used to reconstruct it, and to relate the regional climate to the global Pliestocene-Holocene climate.

Introduction

The global climate of the past 800,000 years have been dominated by 100,000 year glacial-interglacial cycles followed by an abrupt sequence of global climatic events which ended the Pleistocene glacial period 11,700 years ago and culminated in the current warm Holocene climate (Figure 2c). While the global climate record of this time period is relatively well understood, regional climate patterns await further investigation. Due to the key role the Colorado Plateau plays in the North American Monsoon, learning about its climate history can teach us a great deal about past regional and even global atmospheric circulation patterns.

The Colorado plateau is a unique physiogeographic province located between the Rocky Mountains to the east and north, and the Basin and Range province to the west and south. It extends through parts of the states of Utah, Arizona, Colorado and New Mexico, and covers an elevational range between 360 m and 3850 m. The current climate of the Colorado Plateau is dominated by the North American Monsoon, a seasonal change in atmospheric circulation that results in a pronounced increase in summer precipitation following a hyperarid spring season. Topographic disparities of the North American continent leads to a differential heating of its surface which results in the development of a summer atmospheric low pressure zone over the southwest United States. This thermally induced low-pressure zone invites moisture-filled atmospheric jet streams from the pacific and Bermuda high-pressure zones (Wright et al., 2001).

The climate history of the Colorado Plateau is poorly understood. Much of what we know about the global climate of the last 400,000 years comes from marine sediments and ice core data from Greenland and Antarctica. Locally, however, the semiarid climate of the Colorado plateau inhibits sediment accumulation and preservation which results in a scarce paleoclimate archive for the region. The short, discontinuous, and difficult-to-interpret record we have of the paleoclimate of the plateau comes from plant fossils preserved in 10,000-20,000 year old packrat middens (trash piles) found throughout the region.

Packrats (neotoma spp.) collect anything from tree leaves, twigs and needles to animal bones within a 30 m radius, and pile it up to 10 ft. high in front of their dens. These middens serve a climate-control purpose preserving moisture in the dens, and as protection from larger animals. The viscous packrat urine readily crystallizes cementing the content together and preserving it for up to 50,000 years. The plant macrofossils from these middens can be used to learn about the prevalence of different plant species and their spatial and temporal migration patterns.

Literature synthesis

Anderson et al. (2000) used packrat middens, alluvial and lake sediments from forty-six site localities across the 337,000 km^2 region in order to reconstruct vegetation and climatic patterns during the last glacial maximum. Their results show that during 27,5000-50,000 BP, areas that are today forests of ponderosa pine were thickly-forested with a mixed assortment of different conifers, including subalpine species such as

Engelmann spruce which today only grow at the highest elevations; thousands of feet above their former range. Later, during 14,040-23,000 BP, boreal forests, primarily Engelmann spruce, replaced the mixed conifer association (figure 1). This temporal vegetation pattern can be climatically interpreted as an estimated mean annual temperature of 3-4 ºC cooler during 27,5000-50,000 BP, and 5 ºC cooler during 14,040-23,000 BP.

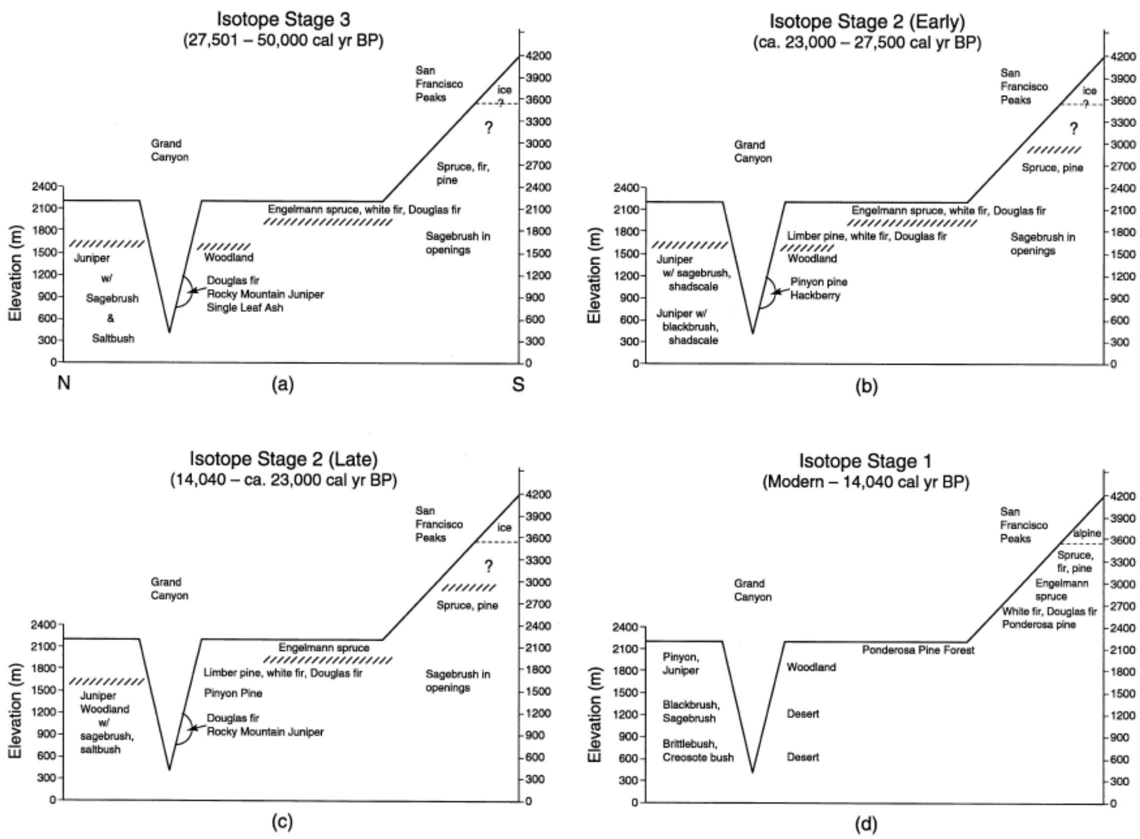

Figure 1: Inferred elevational distribution of vegetation on the southern Colorado Plateau, in a line running from the Grand Canyon to the San Francisco Peaks (a) inferred vegetation during 27,501–50,000 cal. yr BP; (b) inferred vegetation between during 23,000–27,500 cal. yr BP; (c) inferred vegetation during 14,040–23,000 cal. yr BP); (d) inferred vegetation for during present–14,040 cal. yr BP.

The content of these middens can also be analyzed for carbon isotopes and their temporal variation for a quantitative approach of deciphering the paleoclimatic signal. Plant species photosynthesize using different metabolic pathways known as C3, C4, and

CAM. These metabolic pathways fractionate carbon isotopes differently, making the plants that use them have a characteristic carbon isotope ratio (Fraquhar et al., 1989). The $\delta^{13}C$ ratios of plant tissues resulting from the predominant C3 pathway are much lower than those produced through C4 or CAM pathways. Cole and Arundal (2005) measured carbon isotopes ($\delta^{13}C$) in packrat fecal pellets from middens collected from the Grand Canyon, Arizona. The $\delta^{13}C$ signature of the pellets reflects the abundance of cold-intolerant C4 and CAM plant species relative to main C3 vegetation in the packrat diet. This $\delta^{13}C$ signature was then compared to the abundance of the cold-intolerant Utah Agave plant middens of the same age. By knowing current winter minimum temperatures for the Utah Agave, they were then able to use its temporal change in the middens as a proxy for paleotemperatures. Their results suggest that temperatures were ~8 ºC below modern during the Last Glacial Maximum (19,000-20,000 and 26,500 BP). They also showed that temperatures in the Colorado Plateau shifted in accordance with the global temperature ice core record, clearly reflecting two main global climatic events (Bølling/Allerød warming and Younger Dryas cooling) that were previously considered restricted to the North Atlantic region (Figure 2).

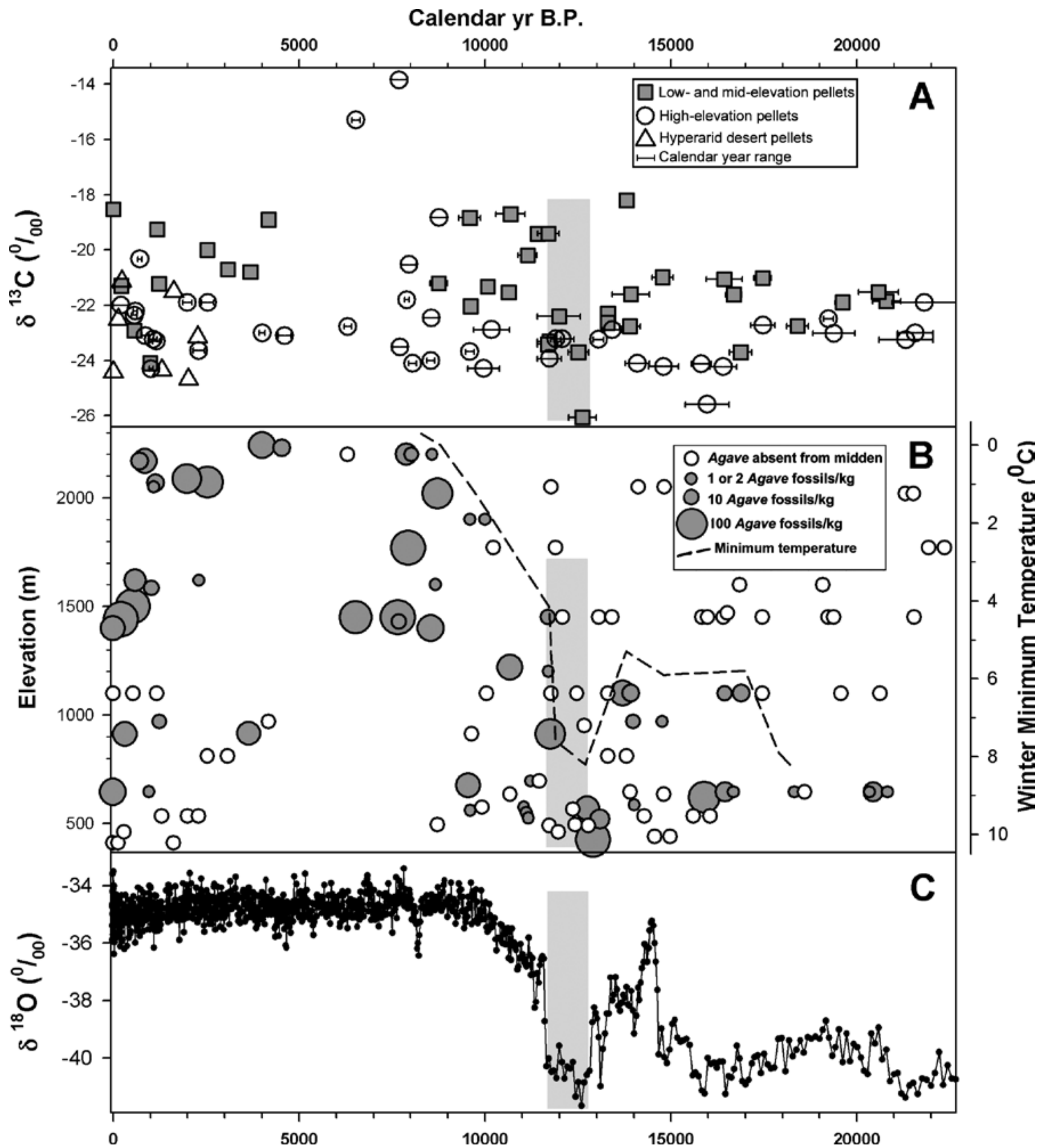

Figure 2: Comparison of carbon isotope and Utah agave chronologies from Grand Canyon with oxygen isotope chronology from Greenland. Younger Dryas period is shown in gray. A: $\delta^{13}C$ values from packrat pellets from low to mid-elevation middens (450-1200m; grey squares), high elevation middens (145-2250 m; open circles), and late Holocene hyperarid desert middens (<550 m, <2.5 ka; triangles). B: concentration of Utah agave in fossil packrat middens in Grand Canyon. Size of circles reflects the concentration of agave plants in a middens. Dashed line shows departure from modern minimum winter temperatures inferred from upper limit of Utah agave. C: $\delta^{18}O$ isotope values from Greenland Ice Sheet Project 2 ice core (Cole and Arundal 2005).

The Younger Dryas (YD) event was also documented in carbon and hydrogen isotopes of bat guano deposits from the Grand Canyon (Wurster et al., 2008). At 9,000

BP, $\delta^{13}C$ values decreased reflecting an increased abundance of cold-tolerant C3 plants, while δD values increased possibly indicating a drier period. The bat guano record also showed an abrupt decrease of both $\delta^{13}C$ and δD values at 8,200 BP that has never been reported in the region. This is interpreted as a rapid change in atmospheric circulation and a greater influence of southern convective storms.

Oxygen isotopes of travertine cold-water spring deposits have also been used to reconstruct climatic patterns over the Colorado plateau. Water masses that are subjected to different temperatures and evaporation: precipitation ratios fractionate oxygen isotopes differently and consequently have characteristic $\delta^{18}O$ signatures. O'Brien et al. (2006) measured oxygen isotope compositions of modern as well as mid-Holocene (7,400 BP) layered spring sediments. The cyclicity of the $\delta^{18}O$ shows a seasonal variation in the water source that deposited travertine layers extending back to the mid-Holocene. This demonstrates that the monsoonal circulation, which is responsible for the cyclic variation in the water source, have already been established over the Colorado Plateau by 7,400 years ago.

Results from this study are in agreement with paleobotanical data and other paleoclimate proxies. Anderson et al. (2001) noted that the rapid migration of the Pondarosa pine across the southern Colorado plateau 14,000 years ago might have signaled increased summer precipitation and therefore the initiation of the North American monsoon. Furthermore, eolian and paleosol (ancient soil) deposits from Canyonlands National Park, Utah show rapid formation of soils and an increase in the abundance of trees and grasses at 8,500-12,000 BP corresponding to a wetter period believed to be the peak of monsoonal influence (Reheis et al., 2005). Carbon and hydrogen isotopes measured from 14,500 to 6,5000 year old bat guano deposits from the Grand Canyon showed an increased summer precipitation and warmer climate at 9,000 BP corresponding the onset of modern North American Monsoon.

Summary and Conclusion

Paleobotanical, sedimentary, carbon, hydrogen and oxygen isotopes data from packrat middens, travertine deposits, paleosols, and bat guano deposits have been used to reconstruct the regional climate and atmospheric patterns over the Colorado plateau. The results show a cooler and wetter Pleistocene glacial period over the plateau as well as clear correlation between global and regional climatic events. The Bølling/Allerød warming and Younger Dryas cooling events were reflected in $\delta^{13}C$ values from packrat middens and bat guano deposits. Furthermore, shifts in Holocene vegetation patterns, $\delta^{18}O$ values from monsoon-flooding-fed travertine deposits, and $\delta^{13}C$ and δD values from bat guano deposits show the timing of the initiation of the current monsoonal circulation to be at about 9,000 years ago. Similar changes in climate and atmospheric circulation patterns are expected in the future as well as a similar response of vegetation and precipitation distributions. Plant and water resources should be managed while taking the climate history of the region into consideration.

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