CHAPTER 6: LATE NEOGENE PALEOCLIMATE OF THE GRAND CANYON

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INTRODUCTION

The climate history of the Grand Canyon and Colorado Plateau is a history of progressively increasing aridity over the last several million years, culminating in the desert landscape present today. Local climate is influenced by large-scale climate circulation patterns, such as the North American monsoon, active in the southwestern US in the summer, which developed and intensified starting in the late Miocene, around 6 million years ago (Ma), and has continued to the present. Winter precipitation on the Colorado Plateau is sourced instead from the central North Pacific, increasing isolation from moisture source and a continental effect. These regional climate patterns are overprinted by regional responses to climate modulation from further afield, such as the El Niño/Southern Oscillation, an inter-annual climate cycle originating in the equatorial Pacific Ocean (Chapin, 2008). Elevation also strongly affects precipitation patterns, so the elevation and uplift history of the Colorado Plateau since the late Miocene also plays a strong role in determining the resultant climate history during this time period.

This chapter will focus on the climate history of the Grand Canyon and Colorado Plateau during the last 6 million years. Several lines of evidence help to constrain ancient climate patterns, but an unequivocal history of climate processes in this region is still emerging. The record of ancient climate and its cumulative contribution to modern processes, ecology, and landforms is fundamental to developing an understanding of long-term climate and environmental change in the region, and is thus of key importance to conservation scientists and land managers.

PALEOCLIMATE PROXIES

Reconstructing climate conditions during ancient times requires an understanding of the effect of climate processes on the environment. Direct, measured records of climate parameters such as temperature or rainfall do not extend back more than a few hundred years. As a result, scientists seeking to reconstruct ancient climate must employ a proxy: an environmental parameter that is recorded as a physical or chemical signal in the geologic record. Direct proxies, such as the fossil remains of animals or plants, can be easily interpreted as the presence of these organisms in an appropriate habitat during the time that they were alive. In the area in and around the Grand Canyon, direct proxies of ancient plant communities include fossil pollen, fossil plant remains as collected and preserved in packrat middens, and whole fossilized trees. Structures within sedimentary rocks also record unique conditions during the time a rock was deposited; sedimentary rocks characteristic of lakes, rivers, and alluvial fan landforms are all examples of direct proxies for ancient environments.

Other climate proxies, such as geochemical signals in sedimentary rocks, require a more thorough knowledge of the relationship between the environmental or climate processes occurring and the environmental chemistry, since the latter is preserved in the rock record.

Analyses of traces of strontium in calcium carbonate rocks document a signal of the geographic origins of a modern or ancient watershed. The strontium isotopic composition of bedrock geology varies considerably with the age and origin of the rocks, and is distinct from a unique strontium isotope value in seawater. Strontium isotope analyses are thus used in conjunction with sedimentary structures to distinguish whether a package of sedimentary rocks was deposited under freshwater runoff from continental precipitation or deposited in a marine setting.

The stable oxygen isotope ratio in sedimentary rocks is dictated by the oxygen isotope ratio of water during deposition. These values reflect a combination of hydrologic processes, including both the atmospheric source of precipitation and the effects of evaporation after rainfall. The physical process of progressive distillation within rainclouds yields a very negative, depleted oxygen isotope value for precipitation very distant from the initial moisture source, the ocean, and so seasonal shifts in moisture source between the north Pacific (winter) and the summer monsoons (Gulf of California), are reflected in these isotopic signatures. Localized evaporation overprints this signal by producing a more positive, enriched oxygen isotope value in a body of water, which is then typically preserved in the chemistry of limestone rocks as a function of this value and temperature. Oxygen isotope records are thus utilized to interpret both large-scale climate circulation patterns and regional patterns of aridity.

Stable hydrogen isotope (deuterium) ratios in water are also determined by the combined effects from climate and hydrologic processes. However, since hydrogen is not readily incorporated into the mineral structure of sedimentary rocks, a hydrogen isotope record of climate processes is less readily determined. Some biological materials do preserve a record of hydrogen isotope values from which ancient climate processes can be reconstructed, as discussed in detail below.

The biological process of carbon fixation by plants fractionates stable carbon isotopes into different chemically distinct pools, and is determined by the metabolic pathway utilized by the plant. Since different groups of plants utilize distinctive metabolic pathways, carbon isotope values as preserved in fossil material can be utilized to reconstruct the relative abundance of different plant functional types on the landscape. These reconstructions provide insight into plant ecological interactions with environmental controls and hydrology in the past, and thus stable carbon isotope values serve as an additional indirect proxy for paleoclimate.

PALEOHYDROLOGY AND UPLIFT HISTORY (6 MA TO 1 MA)

The late Miocene to Pliocene Bouse Formation occupies the modern basin of the lower Colorado River (Figure 1), and consists of fine-grained limestone rocks, including marls and tufa, interbedded with siltstone and more coarse sandstones, with rare conglomerates. This formation was initially interpreted as marine in origin, based on the presence of marine planktonic foraminifera and other fossils (Metzger, 1968; Metzger et al., 1973). Outcrops of the Bouse Formation are currently at 400-700 m elevation (Spencer and Patchett, 1997), so a marine incursion from the Gulf of California into the Lower Colorado River trough requires a significant amount of subsequent uplift during Pliocene-Pleistocene time (4 Ma--present). This interpretation has major implications for the timing of uplift of the Colorado Plateau and incision of the Grand Canyon (Gross et al., 2001; Karlstrom et al., 2008). The Hualapai Limestone of the Muddy Creek Formation, upstream from the Bouse Formation and more proximal to the ancestral Colorado River, provides a clear record of lacustrine conditions prior to 6 Ma (Lopez

Pearce, 2010). The Hualapai is directly overlain by coarse gravels of the ancestral Colorado River and marks the arrival of Colorado River drainage in this region, either via climate/hydrologic processes or via tectonic activity (see Longinotti, this volume).

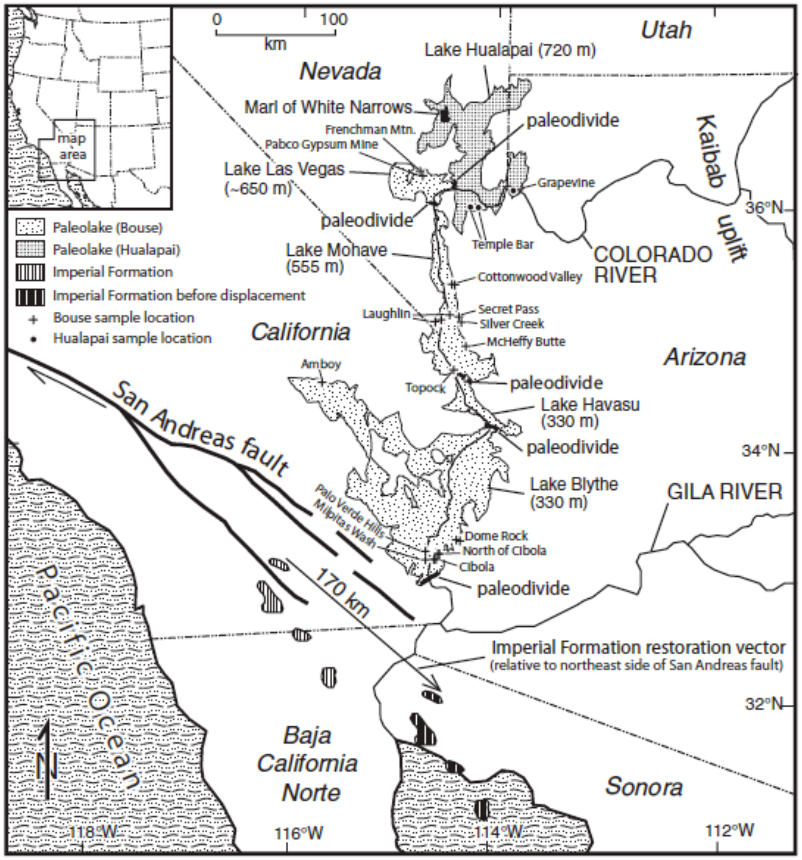

Figure 1. Regional map showing outcrop of the late Miocene to Pliocene lacustrine deposits in proximity to the lower Colorado River. From Roskowski et al., 2010.

Recently, researchers have interpreted strontium isotope values of the Bouse Formation deposits to be derived from runoff from continental rocks (Poulson and John, 2003; Roskowski et al., 2010; Spencer and Patchett, 1997), instead of marine in origin. In this alternate interpretation, the Bouse Formation was deposited in a lake or chain of lakes derived from an ancestral Colorado River. Strontium isotope analyses of carbonate rocks, in conjunction with a mixing model for strontium concentration during deposition, suggest no marine influence during deposition (Spencer and Patchett, 1997). Oxygen isotope analyses of the same carbonates yield a wide range of values, and suggest water sourced from continental precipitation overprinted by a strong signal of evaporation (Poulson and John, 2003). Subsequent re-examination of indicator fossils previously interpreted as marine in origin suggests that these taxa are present during "high-salinity" or evaporative intervals, and that the presence of these organisms is tied to local water chemistry rather than an incursion of marine waters at sea level. Fossils that are unequivocally marine in origin may have been transported inland by migrating birds, and subsequently survived in high-salinity environments (Spencer and Patchett, 1997).

Evidence of large freshwater lakes during the deposition of the Bouse and Hualapai Formations in the Late Miocene (~6 Ma) could be interpreted as a paleoenvironment much wetter than the modern arid environment. However, the still-water sedimentary rocks in the Bouse Formation directly overlay alluvial fan conglomerates and other coarse deposits characteristic of high-energy environments with sparse, episodic sediment deposition consistent with an arid environment and flash flooding. This abrupt initiation of deposition of the Bouse Formation suggests a tectonic, non-climatic source for freshwater. The laterally discontinuous lake deposits, in conjunction with the evaporative signal recorded in oxygen isotope values, suggest instead a history of episodic precipitation, impoundment of freshwater into lakes, and subsequent evaporation (Roskowski et al., 2010).

Inherited hydrologic connections

The dissolution of limestone rocks by slightly acidic rainwater produces distinctive dissolution features and topography known as karst. Characteristic landforms include underground cave systems that can be laterally extensive, following the presence of limestone units within bedrock, and surface dissolution features such as sinkholes and vertical drainage pathways. The Paleozoic Muav and Redwall Limestones form the most continuous, sub-horizontal calcium carbonate units within the Grand Canyon region of the Colorado Plateau (see Kercher, this volume). Today, this karst system forms the Muav-Redwall aquifer in northern Arizona, and the distribution and morphology of this cave system is controlled primarily by whether or not the aquifer is saturated with water (Hill and Polyak, 2010; Huntoon, 2000).

Filling and recharge of the Muav-Redwall aquifer system has a variable recharge time that averages climate processes over perhaps many thousands of years. A record of precipitation and climate variability is thus averaged across longer timescales. This karst system is very well-developed, and has been proposed as an initial underground source of drainage from the Colorado Plateau beginning around 6 Ma (Hill et al., 2008), and potentially impacted incision of the Colorado River and subsequent deposition of downstream lacustrine units.

PALEOENVIRONMENT: GLACIAL TO HOLOCENE (100 KA TO PRESENT)

During the last 0.8 million years, global climate has been dominated by glacial/interglacial cycles with a recurrence of ~100 thousand years (ka). While a high-resolution picture of global climate evolution during this interval is derived from ice cores and deep-sea sediment records, records of the local response to climate on the Colorado Plateau are discontinuous and often difficult to interpret unequivocally. In part, this is due to the episodic sedimentary record in a terrestrial environment; it is also a function of the low deposition rate of sediment in an arid environment, as well as the low population density and sparse human development in the remote Colorado Plateau region.

Paleo-hydrologic features

The modern hydrology of the Grand Canyon is determined by an inherited history from a wetter glacial climate during the last glacial cycle and glacial maximum (25 ka). Enhanced rainfall in the headwater catchment basin of the Grand Canyon resulted in an increase in aggradation and downcutting within the canyon (Anders et al., 2005). This process has continued well into the current interglacial; the lag time is a function of the delayed response of the smaller catchment basins of Colorado River tributaries (see Selander, this volume).

The most prominent physical record of paleo-hydrology during glacial/interglacial climate cycles in the Grand Canyon is the dramatic, thick deposits of travertines, which are layered calcium carbonate deposits associated with springs. Calcium and carbonate are dissolved from surrounding bedrock, often during the karstification of limestone as described above. These waters transport calcium and carbonate ions via underground aquifers and, upon arrival at the surface in artesian springs, become oversaturated, and calcium carbonate is spontaneously deposited. The deeply incised Grand Canyon provides a unique cutaway into local Colorado Plateau bedrock (Figure 2), so the intersection of the Muav and Redwall Limestones, as well as other Paleozoic carbonate units, with the canyon wall provides a discharge point for springs, where many of these distinctive travertine deposits are found.

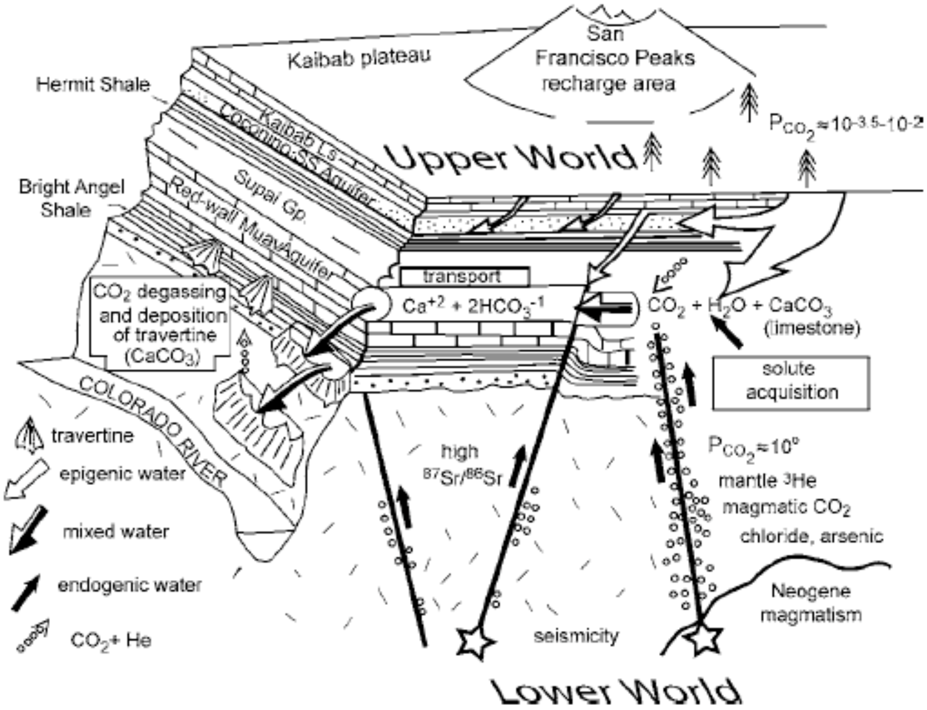

Figure 2. Schematic diagram of karst aquifers outcropping as springs in Grand Canyon walls, producing travertine deposits. Geochemical end-members of precipitation (epigenic) and deep-crust-derived waters are shown as potential contributors to travertines. From Crossey et al., 2006.

Several researchers have presented different hypotheses to explain the origin of these travertine spring deposits. Deposition is tied closely to hydrologic activity and thus to rainfall and climate, although variation in aquifer recharge times complicates a direct interpretation of enhanced rainfall from enhanced spring activity. Some researchers have interpreted oxygen isotope values in travertine limestones to record a climate signal from the last 10,000 years (O'Brien et al., 2006). They interpret rhythmically banded deposits as evidence of climate cyclicity, and compute paleo-temperatures during mineral formation based on oxygen isotope equilibrium expressions (e.g., O'Brien et al., 2006). Other researchers argue that the volume of travertine deposited is unlikely to have been derived from dissolution of Paleozoic limestones alone, and invoke additional sources of carbonate to produce these spring deposits. Geochemical analyses of spring water and travertines suggest the influence of some waters derived from deep within the earth's crust (Crossey et al., 2006). Migration of these old waters along old, deep faults could produce mixing with water derived from recent precipitation to produce oversaturated subsurface water within aquifers and produce travertines with observed chemistry (Crossey et al., 2006; Crossey et al., 2009). The influence of additional crustal waters complicates interpretation of a climate signal from travertine geochemistry.

Paleoecology and vegetation

Plants are sensitive indicators of water availability, and so the combined paleoenvironmental records from plant fossils and related ecological indicators yield a clearer picture of the response of local ecosystems to shifts in climate regime since the last glacial maximum (25 ka). Dune deposits in the nearby Canyonlands region of Utah provide a record of Aeolian, or wind-dominated, processes, alternating with wetter, soil-forming intervals (Reheis et al., 2005). These deposits preserve a record of variable aridity from the last glacial maximum to the present. In particular, there is evidence of an abrupt climate ~8,500 years ago in response to both a regional an intensification of the summer monsoon and an abrupt global climate shift at 8,200 yr. Combined carbon and hydrogen isotope analyses of bat guano also document a dramatic shift in vegetation (carbon isotopes) and hydrology (hydrogen isotopes) at ~8,500 years ago (Wurster et al., 2008), and clearly document a regional ecological change in response to the global climate anomaly at 8,200 yr.

Vegetation records from packrat middens in the Grand Canyon preserve a history of plant diversity in a very localized area around the point source, the midden (e.g., Coats et al., 2008; Cole and Arundel, 2005). Some plant remains are identifiable to the genus or species level, enabling researchers to reconstruct the diverse plant community that existed in response to past climate conditions in the Grand Canyon (Coats et al., 2008). Carbon isotope analyses of material from packrat middens provide a measure of the relative proportion of C3, C4, and CAM plants. Because many species of C4 and CAM plants are cold-intolerant, these results can also be used indirectly as a paleotemperature proxy (e.g., Cole and Arundel, 2005).

A reconstruction of climate shifts on finer timescales, and the ecological responses of plant communities, can be recovered from lacustrine sediments. Analysis of pollen and plant macrofossils from lake cores on the Kaibab Plateau provide additional evidence for climate shifts since the last glacial maximum (25 ka) and intensification of the North American monsoon in the early Holocene (Weng and Jackson, 1999). Lake records have an additional advantage over other climate proxies because of their high resolution, but the continuous presence of lakes in arid environments is rare, and sedimentation may be discontinuous.

High-resolution records

Many paleoclimate archives preserve records of climate variability on multi-annual or decadal timescales, and the absolute dating of these records, while excellent for the instrumental precision available, retains large error bars. The combined evidence from many paleoclimate proxies provides a clear picture of general climate trends in the past, but is of limited utility to land managers seeking to use this information in resource allocation to better accommodate current and predicted future climate conditions.

Dendrochronology, or the analysis of tree rings, is a unique paleoclimate proxy that provides a record with annual resolution. Trunk growth in sensitive indicator tree species responds strongly to moisture availability, and thus tree ring thickness is a clear proxy for precipitation in a year or growing season. Oxygen isotope analyses of wood cellulose can augment ring thickness with additional information about paleo-precipitation. The real utility of tree ring analyses is the ability to cross-correlate spatial patterns in the annual record of living trees with spatial patterns in fossil trees. On a regional scale, tree rings from many different individuals growing in the same climate regime have been cross-correlated, and the Colorado Plateau record now extends back ~1300 years, with annual-scale resolution (Meko et al., 2007).

Because the time span of the tree ring record overlaps with modern climate records of measured temperature and precipitation, tree ring analyses can be directly correlated with instrumented meteorological records over the last ~100 years (e.g., Woodhouse and Lukas, 2006). This provides a direct link between the paleoclimate proxy and absolute climate measurements, a feature not available from other proxies that are more indirect. The Colorado Plateau record of climate and hydrology, as reconstructed from tree ring records, provides unequivocal evidence of large-scale droughts over the last ~1300 years. Severe droughts, lasting several years to decades, are prevalent throughout the records (D'Arrigo and Jacoby, 2001). Frequently, these droughts appear to have been more severe than droughts recorded by instrumented gages in the 1950s (Woodhouse and Lukas, 2006). A drought during the globally-recorded Medieval warm period was characterized by a low-flow regime for up to 6 decades in the 1100s (Meko et al., 2007).

LAND MANAGEMENT DECISIONS

The ecosystems and physical geology of the Grand Canyon are a product of development within an arid climate, and are thus a product of a long-term history of aridity. However, resource allocation and ecosystem management issues have traditionally been made based on the gaged, instrumented climate record. In particular, water allocation for western states was based on a recent interval of climate history with exceptionally high regional precipitation (D'Arrigo and Jacoby, 2001). Recent interactions between paleoclimatologists and resource managers have begun to influence the long-term view of resource management in the Grand Canyon (e.g., Rice et al., 2009; Woodhouse and Lukas, 2006). A better understanding of the climate history of the Grand Canyon and Colorado Plateau on geologic timescales, and increased communication between paleoclimate researchers and land managers, will provide crucial long-term context to influence future management decisions.

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