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An enhanced role for the Tropical Pacific on the humid Pleistocene–Holocene transition in southwestern North America

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A B S T R A C T

Climate effects on landscape evolution during the Late Pleistocene–Holocene transition (~14.6–8 ka) in southwestern North America traditionally are linked to the activity of the North American Monsoon and to vegetation change related to a decrease in winter precipitation acting in response to orbital cyclicity. We performed an integrated analysis of regional alluvial fan, lacustrine and paleobotanical records for the area comparing them with hemispheric and regional paleoclimate proxies. Our focus was on the potential role the Tropical Pacific has as a synoptic pattern modulator and moisture source for hydrogeomorphic activity in the region.

Our analysis indicates that the onset of alluvial fan aggradation in most of the region at ~13.5 ka could have been a response to semi-permanent El Niño-like conditions in the Tropical Pacific, which enhanced the frequency of winter frontal storms as well as increased penetration of tropical cyclones in the region. The North American Monsoon was restricted in extent and intensity until ~7 ka and probably was not a major factor in alluvial fan aggradation. A second stage of alluvial fan aggradation from 11.5 to ~9 ka was dominated by hyper-concentrated flows and sheet-flood sedimentation, along with deposition in fluvial settings. Storms were probably were linked to landfall of enhanced water vapor bands in the leading edge of winter extra-tropical cyclones with moisture advected directly from the Tropical Pacific. At ~8 ka, favorable conditions for the occurrence of these storms waned and storm tracks shifted northward.

Analysis of modern analogs for storm types described above as prevalent during this period indicates that changes in circulation patterns across the Tropical Pacific can affect storm properties enough to explain the observed geomorphic effects, regardless of other factors traditionally considered of large impact like vegetation change. Our results suggest that the Tropical Pacific plays a larger role than currently thought in landscape evolution of the region.

1. Introduction

Climate in southwestern North America (comprising NW Mexico and the SW USA) varied significantly during the Late Quaternary, with periods of drought alternating with periods of enhanced effective moisture relative to present-day conditions (e.g., Asmerom et al., 2007; Kirby et al., 2007; Li et al., 2008). The latest event of higher effective moisture that most proxies in the region have recorded is the late Pleistocene to Holocene transition (LPH, between ~14.6 ka, the start of the Bølling–Allerød warming event and ~8 ka), with enhanced effective moisture recorded across a wide area. This resulted in permanent occupation of now ephemeral lake basins (Metcalfe et al., 1997, 2000; Davis, 2003; Wells et al., 2003; Negrini et al., 2006) and sedimentation in alluvial fans (Spelz et al., 2008; Miller et al., 2010). This humid period was followed by widespread aridity during the warm mid Holocene (Anderson, 1993; Ortega-Ramírez et al., 1998; Murillo De Nava et al., 1999; Weng and Jackson, 1999; Metcalfe et al., 2000; Davis, 2003; Bacon et al., 2006; Masters, 2006; Negrini et al., 2006; Anderson et al., 2008; Ortega-Rosas et al., 2008). Despite the fact that southwestern North America is one of the most studied arid regions in the world, there is still uncertainty regarding the source of the moisture feeding precipitation during the LPH. Evidence from different proxies supports hypotheses in favor of increases in winter precipitation (Van Devender and Spaulding, 1979; Van Devender, 1990a, 1990b; Rhode, 2002; Kirby et al., 2005; Spelz et al., 2008), summer precipitation (Spaulding and Graumlich, 1986; Li et al., 2008), or both (Kirby et al., 2007; Miller et al.,

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2010). Each of these hypotheses describes possible synoptic scenarios linked broadly to the actual processes responsible for observed effects on hydrological systems, geomorphology and ecosystems.

The consequences of resolving the mechanisms increasing effective moisture during the LPH reach far beyond paleoclimate and paleohydrology analyses, affecting fundamental conceptual models in arid zone geomorphology dealing with the timing and style of hillslope erosion and deposition in alluvial fan environments (Bull, 1991; Miller et al., 2010; Antinao and McDonald, 2013). Conceptual models of hillslope-alluvial fan response to climate normally are framed against a particular climate variation, and key roles have been assigned to the effects of rainfall intensity and duration on sediment detachment and transport from mountain basins and associated alluvial fan aggradation (or channel incision) (Harvey et al., 1999; McDonald et al., 2003), or to a changing vegetation cover in response to climate change (Bull, 1991). Aggradation on alluvial fans in North American deserts has been suggested to be related to either increased channel flow due to winter Pacific frontal storms in a wetter climate (Harvey and Wells, 1994; Harvey et al., 1999) or to increases in the activity of short but intense summer convective storms (Bull, 1991; Reheis et al., 1996, 2005; Miller et al., 2010) in the transition to a more arid climate with decreasing vegetation cover. The latter model was suggested to be driven mainly by activity of the North American Monsoon (NAM), although recently attention has been directed to rainfall associated with eastern Pacific tropical cyclones (e.g., McDonald et al., 2003; Bird and Kirby, 2006; Kirby et al., 2007). Analysis of available data for the geomorphically active LPH offers a reasonable chance to discriminate effects of these possible source systems linked to contemporaneous global and regional climate change, in contrast to the analysis of present day geomorphic and hydrologic conditions in southwestern North America or other arid zones, which are not conducive to aggradation on alluvial fan surfaces.

Discrimination of the sources of rainfall affecting this area during the LPH also bears on assessments of future climate change impacts for the region. The deserts of southwestern North America receive a considerable proportion of their annual precipitation during the summer from either tropical storms and their remnants or from monsoonal precipitation (e.g., Higgins et al., 1997, 1998; Englehart and Douglas, 2001; Gutzler, 2004; Díaz et al., 2008; Corbosiero et al., 2009), both having a substantial impact on the hydrologic balance (Saarinen et al., 1984; Smith, 1986), as well as on ecosystem equilibrium and human occupation (Webb and Betancourt, 1992; Webb et al., 2008). Precipitation derived from these tropical sources can increase in the near future under anthropogenic global warming scenarios predicting enhanced drought conditions for southwestern North America (Seager et al., 2007; Weiss et al., 2009; Asmerom et al., 2010; Wagner et al., 2010). Possible changes in tropical cyclone occurrence and intensity (Webster et al., 2005; Emanuel et al., 2008; Yu et al., 2010), or in ENSO teleconnections (An et al., 2008; Yang and Zhang, 2008) under a warmer climate may impact the variability of summer precipitation in southwestern North America. Therefore, although not a direct analog for anthropogenic climate change, study of the effects of LPH climate change will provide alternate, testable hypotheses about causal linkages affecting geomorphological, hydrologic, and ecological systems and will enable a more accurate assessment of prediction uncertainties in this region of high susceptibility to environmental stress and rapid population growth.

2. Objective and approach

Our objective is to review multiple proxy evidence supporting the different hypotheses that have been proposed to explain the humid LPH in southwestern North America, contrasting paleobotanical, paleohydrological and paleoclimatic variability with the observed geomorphic constraints. The focus of the discussion is on clarifying the hydroclimatic conditions that lead to alluvial fan deposition in the region. Given the breadth of data sources and emphasis on summarizing records, our approach does not discuss in detail the many interpretations that different authors have proposed for similar records. Therefore, we do not imply that this review is a definitive resource for assessment or discussion of all different topics. Our arguments are based more on common points that can be identified in the different proxies rather than on one preferred interpretation. We tried to avoid stating conclusions derived from single records or localities. In some specific subject areas this criterion lead to conclude that more research is warranted.

Our analysis emphasizes on trends rather than on a precise correlation of events. Therefore, we have made no attempt to harmonize or tune the data in semi-continuous records (marine or lacustrine cores) to a particular calibration or model. Single ages used to describe aggradation in alluvial fan settings or in analysis of earlier data for midden records have been recalibrated from the original published datasets based on the most recent calibration schemes. A few specific geochronology datasets required further statistical treatment for an updated interpretation, as noted in the text.

The approach stated above allowed us to interpret two different stages in the LPH, which we describe based upon evolution of the geomorphic, hydrologic and ecologic systems in a global and regional climate variability framework. We show that climate conditions during the LPH were appropriate for generation of unique regional precipitation patterns that have no modern day analogs. Atmosphere–ocean conditions were favorable to development of a larger amount of moisture over the Tropical Pacific, available to be transported the entire year by either extra-tropical or tropical cyclones. These storms facilitated landward transport of tropical moisture, which delivered more and more frequent intense precipitation events across the region compared to present day conditions. We conclude that current models explaining arid-region alluvial fan sedimentation need refinement, through full incorporation of millennial tropical variability and its effects on landscape evolution.

3. Present day weather patterns affecting southwestern North America

Southwestern North America is currently under the influence of different weather systems (Fig. 1), all of which create precipitation events that under specific circumstances may cause runoff, erosion and transport of sediment and eventually aggradation in alluvial and fluvial settings (Webb and Betancourt, 1992; Huckleberry, 1994; Enzel and Wells, 1997; Lino Escobedo, 2006; Griffiths et al., 2009; Bacon et al., 2010). These systems persisted partially or completely and with varying degrees of geomorphic relevance during the Late Quaternary. Here we provide a description of their present-day sources, effects, and variability.

3.1. *Winter extra-tropical cyclones*

The North Pacific winter cyclonic storm track (Fig. 1) is modulated by the position and strength of the polar jet stream, with dominantly zonal advection of moisture from the North and Central Pacific by extra-tropical cyclones (Carlson, 1991). These storms derive directly from regions south of the Aleutian Low, bringing wide (>1000 km) precipitation fronts that can penetrate deeply into the western portion of the continent, with rain and snow