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Late Quaternary paleohydrological conditions in the drylands of northern Mexico: a summer precipitation proxy record of the last 80 cal ka BP

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A B S T R A C T

We present a late Quaternary multi-proxy record from the paleolake Babicora in order to understand the influence of North American Monsoon (NAM) and westerly winter storms on the paleohydrological budget of the drylands of northern Mexico. Stratigraphy, ^{14}C chronology, mineral magnetism and geochemistry of the 976 cm long sediment core were used to reconstruct the hydrological conditions over the last 80 cal ka BP. The inverse relationship between the proxy records of runoff into Babicora and winter precipitation in southwestern USA indicate the minimal influence of westerly winter storms at 29°N during the Last Glacial period. Westerly winds transported minimally chemically altered sediments from the dry watershed during the cold stadials and the basin received more than average runoff as a result of a stronger NAM during the warm interstadials. The highest pluvial discharge occurred prior to 58 cal ka BP and terrestrial plants became the major contributor to organic matter deposited between 71 and 53 cal ka BP. Over the last 40 cal ka BP, the high amplitude fluctuations in runoff and lake water salinity mirrored an unstable summer rainfall regime.

1. Introduction

The North American Monsoon (NAM) or Mexican Monsoon refers to the system that brings summer precipitation to arid and semi-arid northwestern Mexico and southwestern USA. Its greatest influence is along the western slopes of the Sierra Madre Occidental, where it contributes ~70–80% (northern Mexico) of total annual precipitation; in Arizona and New Mexico (USA) the contribution is ~40–50% (Douglas et al., 1993; Stensrud et al., 1995). Due to the increasing population of the drylands of Mexico and USA and the associated developments, summer precipitation is currently receiving increased attention from the regional hydrometeorology community (Xu et al., 2004; Englehart and Douglas, 2010). The onset of the NAM is associated with a surface wind reversal which is relatively weak compared to the Asian monsoon system (Krishnamurti, 1971; Badan-Dangon et al., 1991). The mid-tropospheric air flow shifts from dry westerly in May and June to moister easterly and southeasterly during July. The trade winds off the Caribbean Sea and Gulf of Mexico provide moist air to eastern Mexico, whereas the strong southeasterly flow from the eastern tropical Pacific and Gulf of California (at low levels) are the major sources of moisture for northern and northwestern Mexico and the southwestern USA (Hales, 1974; Douglas et al., 1993; Stensrud et al., 1995; Amador et al., 2006). A range of factors are known to affect the strength and extent of the NAM, including the state of the tropical Pacific (Douglas et al., 1993; Magaña et al., 2003). The northern NAM area, covering the north of Mexico and into the southwest USA, crosses a significant climatic boundary between the southern region where La Niña-like conditions result in more summer rain (stronger monsoon) and the northern region where El Niño-like conditions cause more winter

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rain (weaker summer monsoon) (Magaña et al., 2003; Pavia et al., 2006).

Contrary to the modern day meteorological observations, most published late Quaternary proxy based paleoclimatic records from this region have related humid periods to increased winter precipitation (COHMAP members, 1988; Thompson and Anderson, 2000; Lozano-García et al., 2002; Metcalfe et al., 2002; Enzel et al., 2003; Polyak et al., 2004; Cheshire et al., 2005; Castiglia and Fawcett, 2006; Asmerom et al., 2007). The increase in effective moisture during the Last Glacial period was associated with the southward displacement of the subtropical high pressure zone in the eastern Pacific and more frequent westerly storm tracks with the possible absence of summer precipitation (Thompson and Anderson, 2000). Enzel et al. (2003) related the growth and co-existence of various lakes in the Mojave river basin (southwestern USA) during the Last Glacial Maximum (LGM) to increased river discharge into the lakes due to higher winter precipitation and reduced evaporation. The atmospheric circulation models suggested that the winter storm tracks possibly migrated into northern Mexico during the LGM (Kutzbach and Wright, 1985; Manabe and Broccoli, 1985; Kutzbach et al., 1998). Asmerom et al. (2007) associated the middle Holocene wet conditions in New Mexico (Guadalupe Mountains) to El-Niño like conditions and an increase in the winter rainfall. Castiglia and Fawcett (2006) also attributed the periods of lake- highstands in northern Mexico (paleolake Fresnal) during the early and mid Holocene to frequent winter rainfall associated with El-Niño like conditions.

However, two proxy records suggest the persistence of the NAM into the southwestern USA during the Last Glacial period (Kirby et al., 2006; Holmgren et al., 2006a). The prevalence of summer flowering annuals and C_4 grasses during certain intervals in the midden records representing the last 46 cal ka BP from the USA and Mexico borderlands (Peloncillo Mountains, Playa Valley, Sacramento Mountains and Hueco Mountains) and the absence of C_3 desert shrubs suggested that the geographical extent of the NAM during the glacial period was similar to today (Betancourt et al., 2001; Holmgren et al., 2003, 2006a, 2006b). Holmgren et al. (2006a) estimated that summer precipitation was at least half or possibly comparable to the modern values and that some intervals of the last glaciation were characterized by wet summers and warmer winters. Comparing the paleohydrological record of Baldwin Lake and summer–winter insolation at 30°N, Kirby et al. (2006) argued that the NAM expanded to the coastal southwestern USA during the intervals of higher summer insolation and the increased summer rainfall along with winter precipitation led to permanent lakes at 57 and 33 cal ka BP.

In this study, we present the geochemical and mineral magnetic characteristics of a 976 cm long lacustrine sequence collected from the paleolake Babicora in order to understand the influence of the NAM and westerly winter storm tracks on the hydrological cycle of the drylands of northern Mexico over the last 80 cal ka BP. Geochemical characteristics of lacustrine sediments such as total organic carbon (TOC), total inorganic carbon (TIC), carbon to nitrogen ratio (C/N), multi-element geochemistry and magnetic susceptibility are used as proxies of productivity, hydrological changes (dry and wet conditions), provenance of clastic as well as organic matter and chemical alteration of the deposited sediments. The runoff record is compared with stable isotope records from the Greenland ice core (NGRIP project members, 2004) and speleothem from the Cave of the Bells (Wagner et al., 2010), a proxy-record of summer precipitation from the northwestern Mexico (Roy et al., 2010) and variations in the solar insolation at 30°N latitude (Berger and Loutre, 1991) to estimate the influence of summer as well as winter precipitation on the hydrological budget of the basin.

2. Modern day climate and geology of study area

The drylands of northern Mexico belong to the Sonora and Chihuahua Deserts. The Chihuahua Desert of Mexico extends from the state of Chihuahua in the north to San Luis Potosi in the south. It also includes parts of the states of Coahuila, Durango and Zacatecas (Fig. 1). As described above, the summer precipitation associated with the NAM is the dominant source (60–80%) of rainfall in the region (Douglas et al., 1993; Xu et al., 2004), while the winter rainfall (November–March) constitutes 10–20% of annual precipitation (Fig. 2A). Between AD 1941 and 2005, the Chihuahua Desert received between 327 mm (Coahuila) and 946 mm (San Luis Potosi) of average annual precipitation. The states of Chihuahua, Durango and Zacatecas received mean annual precipitation of 423, 500 and 518 mm, respectively (source: CONAGUA, Mexico).

Paleolake Babicora (29°15′–29°30′N, 107°45′–108°W and 2140 m a.s.l.) is located in an endorheic tectonic basin in the eastern foothills of the Sierra Madre Occidental in the western part of the Chihuahua Desert (Fig. 1). The basin is surrounded by ~2500–3100 m a.s.l. high hills comprised of Tertiary and Quaternary volcanic and sedimentary rocks (Fig. 1). The geology of the watershed consists of dominant mafic and felsic volcanic extrusive rocks, with minor exposures of conglomerate and sandstone (Servicio Geológico Mexicano, 1997, 1998, 1999, 2000). In the northeastern margin of the basin, ~2–5 m thick aeolian sand deposits are present. Today, the basin receives mean annual precipitation of ~550 mm. It remains dry for almost 8 months in a year and maintains a shallow water column (few cm deep) in the central part during rest of the year. A meteorological station located ~10 km east of the paleolake (at Gomez Farias, source: CONAGUA, Mexico) recorded total annual rainfall varying between 350 and 770 mm between AD 1958 and 1986 (Fig. 2B). More than 70% of the annual precipitation occurs during the warmer months (June–September: average temperature of 17–20 °C), whereas the winter (November–March: average temperature of 4–8 °C) precipitation constitutes less than 30% (Fig. 2C and D). Even during the El Niño years with increased winter precipitation, summer rainfall is still the major influence on the hydrological budget of the basin. In one of the strongest El Niño years on record (i.e. AD 1982–83), the basin still received more than 60% of its annual precipitation during the summer. Due to its location at the boundary between the subtropics and middle latitudes, the sediments of the basin have been previously studied for sedimentology, mineral magnetism, ostracode, diatom and pollen (Metcalfe et al., 1997; Urrutia-Fucugauchi et al., 1997; Ortega-Ramírez et al., 1998; Metcalfe et al., 2002; Palacios-Fest et al., 2002; Roy et al., 2012a). Except for the work of Metcalfe et al. (2002), all other records are based on short cores (<300 cm). In a 467 cm long sediment sequence collected from the northern part of the basin (Fig. 1B), Metcalfe et al. (2002) reconstructed the fluctuating lake water column and surrounding vegetation over the last 65 ka. However, this record was limited by the poor preservation of fossil pollen in the sediments of the last 24 cal ka BP and absence of diatom in the sediments deposited over a major part of the Holocene.

3. Material and methods

A 976 cm long sediment core was collected from the central-eastern part of the paleolake using an Eijelkamp soil corer and transparent polycarbonate tubes. The sequence is chronologically constrained by 9 AMS ^{14}C dates on bulk organic matter present in the sediments at depths of 17, 37, 47, 89, 183, 273, 375, 409 and 457 cm (see Table 1). Magnetic susceptibility was measured at intervals of 0.5 cm in a Bartington MSE High Resolution Surface Scanning Sensor at 2 kHz. Magnetic mineralogy, grain size and