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A 15 000-year record of climate change in northern New Mexico, USA, inferred from isotopic and elemental contents of bog sediments

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ABSTRACT: Elemental (C, N, Pb) and isotopic (δ^{13}C, δ^{15}N) measurements of cored sediment from a small bog in northern New Mexico reveal changes in climate during the Late Pleistocene and Holocene. Abrupt increases in Pb concentration and δ^{13}C values ca. 14 420 cal. YBP indicate significant runoff to the shallow lake that existed at that time. Weathering and transport of local volcanic rocks resulted in the delivery of Pb-bearing minerals to the basin, while a ^{13}C-enriched terrestrial vegetation source increased the δ^{13}C values of the sedimentary material. Wet conditions developed over a 300 a period and lasted for a few hundred years. The Younger Dryas period (ca. 12 700–11 500 cal. YBP) caused a reduction in terrestrial productivity reflected in decreasing C/N values, δ^{15}N values consistently greater than 0‰ and low organic content. By contrast, aquatic productivity increased during the second half of this period, evidenced by increasing δ^{13}C values at the time of highest abundance of algae. Dry conditions ca. 8 000–6 000 cal. YBP were characterised by low organic carbon content and high Pb concentrations, the latter suggesting enhanced erosion and aeolian transport of volcanic rock. The range in δ^{13}C, δ^{15}N and C/N values in the sedimentary record fall within the range of modern plants, except during the periods of runoff and drought. The sedimentary record provides evidence of natural climate variability in northern New Mexico, including short- (multi-centennial) and long-(millennial) term episodes during the Late Pleistocene and Holocene. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS: lead; isotopic analyses; Late Pleistocene; Younger Dryas; Southwest, USA.

Introduction

Records of climate change during the Late Pleistocene and Holocene are relevant to understanding natural climate variability, improving our ability to predict the anthropogenic influence that is superimposed on natural conditions. Particularly important is variability in precipitation and temperature, given recent drought conditions (Quiring and Goodrich, 2008), predictions of dust bowl conditions in the near future (Seager *et al.*, 2007) and the need to better assess the links to external forcing from the Atlantic and tropical Pacific (Cole *et al.*, 2002; Seager *et al.*, 2008). Records spanning the Late Pleistocene and Holocene across the Southwest have revealed changes in climate such as periods of increased effective precipitation, extreme drought and/or warmer or cooler temperatures than presently occur (Benson *et al.*, 1990; Spaulding, 1991; Menounos and Reasoner, 1997; Allen and Anderson, 2000; Holliday, 2000; Reasoner and Jodry, 2000; Forman *et al.*, 2001; Huckleberry *et al.*, 2001; Menking and Anderson, 2003; Polyak *et al.*, 2004; Poore *et al.*, 2005; Holmgren *et al.*, 2006; MacDonald *et al.*, 2008; Wurster *et al.*, 2008). These climate changes have not been consistent in timing and/or intensity across different sites. In addition, few continuous records of climate change span the important postglacial transition from the Late Pleistocene into the Holocene in New Mexico (Allen and Anderson, 2000; Armour *et al.*, 2002; Asmerom *et al.*, 2007; Anderson *et al.*, 2008; Jiménez-Moreno *et al.*, 2008). In this paper, we present a climate record that expands on

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previous work by Anderson *et al.* (2008) and provides new insights into periods of climate change during the Late Pleistocene and Holocene in northern New Mexico. We extend the published records of C/N, δ^{13}C and δ^{15}N values to ca. 15 500 cal. YBP and increase the resolution during the Younger Dryas period (ca. 12 700–11 500 cal. YBP). In addition, we report organic carbon concentrations and Pb concentrations (extractable form), the latter providing a reliable proxy for local climate changes that affect weathering and transport of volcanic rocks in this region. We also present C/N, δ^{13}C and δ^{15}N values in contemporary plant material to better interpret the values observed in the sedimentary record. The new data presented here allowed us to identify periods of climate change in northern New Mexico, including: (1) a multi-centennial period of increased effective precipitation during the Late Pleistocene (beginning ca. 14 420 cal. YBP); (2) decreased terrestrial productivity and enhanced aquatic productivity during the Younger Dryas period; and (3) enhanced erosion and aeolian transport during the early to middle Holocene (ca. 8000–6000 cal. YBP), confirming a millennial-scale period of extreme dry climate.

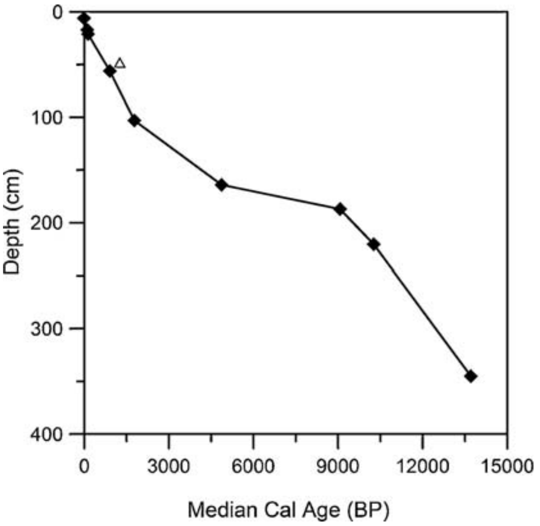

Figure 1 Age–depth curve for Chihuahueños Bog. Ages (diamonds) are graphed as the median probability of calibrated radiocarbon years. Triangle is Beta-176475, which was considered too old and not used in construction of curve. (Original figure from Anderson et al., 2008, copyright Elsevier, reproduced by permission of Elsevier)

Study site and methods

Chihuahueños Bog (basin area < 2 km^2) is located in northern New Mexico (36° 02′50″ N, 106° 30′30″ W) at an elevation of 2925 m. A climate-induced succession of environments occurred at this site over the last ca. 15 500 cal. YBP. These are described in Anderson *et al.* (2008) as pollen zones I–IV (see Fig. 4), corresponding (from Late Pleistocene to present) to shallow lake then wetland phases, followed by a dry period, and finally succeeded by a wetland to bog environment.

A 465 cm long core was retrieved from the centre of the basin (area < 2 km^2) as described by Anderson *et al.* (2008). The upper ~171 cm of the core alternates between sedge peat and peaty clay; sediments between 171 and 235 cm are similar but mottled. Below 235 to 300 cm, sediments have increasing clay content, and from ~300 to 406 cm sediment is clayey silts with fine sands. Coarser sands and gravels are found below 422 cm (Anderson *et al.*, 2008). Details on core sampling and analyses of pollen, charcoal, plant macrofossils, magnetic susceptibility and previous C/N, δ^{13}C and δ^{15}N analyses can be found in Anderson *et al.* (2008) and Allen *et al.* (2008).

The chronology of the core was based on ^{137}Cs and ^{210}Pb ages for the upper 21 cm of the core and seven ^{14}C dates downcore (Table 1; Anderson *et al.*, 2008). Maximum ^{137}Cs deposition (i.e. AD 1963–1964) occurred at 6 cm depth. Downcore to ~21 cm we used the ^{210}Pb age relationship (0.146 cm a^{-1}). All seven ^{14}C ages (except for Beta-176475), occurred in stratigraphic order (Table 1 and Fig. 1). Therefore, our chronology for most of the core consists of linear interpolation between adjacent radiocarbon dates (except Beta-176475, which was not used), using the median value of the calibrated age of the date, with extrapolation in the core deposited prior to ca. 13 800 cal. YBP.

Modern plants were collected from the surface and immediate surroundings of the bog. We collected the most representative species in and near the basin to provide a range of elemental and isotopic values with which to compare values in the sedimentary record. Values in the sedimentary record outside the range of values in modern plants helped us identify periods when different species dominated and/or other climate regimes prevailed.

Following identification to species, plant and sediment samples (at 5–10 cm depth intervals) were oven dried (60°C),

Table 1 Radiometric ages for the Chihuahueños bog core[a]

Laboratory Number	Depth (cm)	Age (^{14}C a BP, ^{210}Pb, ^{137}Cs, Historic)	SD (±)	^{13}C/^{12}C (‰)	Cal. YBP (2 SD)	Median probability (used for graphing)	Calibration	Date type	Material
USC Geology	6	AD 1963	N/A	N/A	−13	−13	N/A	^{137}Cs	Sediment
USC Geology	17	AD 1890	N/A	N/A	60	60	N/A	^{210}Pb	Sediment
USC Geology	21	AD 1865	N/A	N/A	85	85	N/A	^{210}Pb	Sediment
Beta-176475[b]	48–51	1 320	40	−24.7	1 176–1 302	1 254	CALIB 5.0	AMS[c]	Charcoal
Beta-202658	54–58	990	40	−26.1	795–964	902	CALIB 5.0	AMS	Peat, chitin
Beta-160243	101–105	1 840	70	−25	1 601–1 927	1 773	CALIB 5.0	Bulk	Peat
Beta-160244	162.5–166.1	4 290	70	−25	4 783–5 047	4 864	CALIB 5.0	Bulk	Peat
Beta-176476	188–189	8 130	40	−22.3	8 996–9 139	9 070	CALIB 5.0	AMS	Charcoal
AA-39836	217.7–222.9	9 100	61	Unknown	10 177–10 425	10 262	CALIB 5.0	AMS	Sediment
Beta-114177	340–350	11 850	80	−25	13 471–13 876	13 711	CALIB 5.0	Bulk	Peat

[a] From Anderson et al. (2008), copyright Elsevier, reproduced by permission of Elsevier.

[b] Sample not used in the construction of the chronology.

[c] Accelerator mass spectrometry.

milled and homogenised. C/N, δ^{13}C and δ^{15}N analyses were performed on 2–3 mg of plant material and 4–52 mg of sediment (depending on organic carbon content) using an elemental analyser interfaced to a continuous-flow isotope ratio mass spectrometer. No pretreatment of the sediment samples to remove the carbonate fraction was performed as prior X-ray diffraction analysis indicated the samples were carbonate free. δ^{13}C and δ^{15}N values are expressed as the deviation per mil (‰) of the heavy to light isotope ratio of the sample with respect to that of the standard Pee Dee Belemnite (PDP) and atmospheric air, for carbon and nitrogen respectively. Precision of the measurements was better than 0.5%, 0.1‰ and 0.4‰ for C/N values, δ^{13}C and δ^{15}N, respectively.

Extractable Pb was quantified in sediment samples at the same depth intervals used for C and N analyses. We used partial dissolution according to USEPA method 3051A. Briefly, oven-dried (105°C) and homogenised sediments (0.1–0.2 g) were microwave digested at 175°C for 10 min with 10 mL of concentrated HNO_3. Pb extracts were diluted and analysed for total Pb concentration using inductively coupled plasma mass spectrometry. Precision of the measurement was ±1 p.p.b. based on repeated analyses of SRM 1640.

Statistical analyses were performed using the statistical software Minitab. The tests used included Pearson correlations and one-way analysis of variance using Tukey's method.

Our interpretations of δ^{13}C, δ^{15}N, C/N, organic carbon and Pb profiles in the sedimentary record were guided by the following criteria:

1. An increase in δ^{13}C values can be driven by either enhanced aquatic productivity (Hodell and Schelske, 1998; Brenner *et al.*, 1999; Meyers, 2003) or greater inputs from C4 plants and/or plants with higher water use efficiency.
2. High δ^{15}N values can result from increased aquatic relative to terrestrial inputs and/or enhanced aquatic productivity (Wada and Hattori, 1976; Boyle, 1993; Hodell and Schelske, 1998; Brenner *et al.*, 1999) in the absence of cyanobacteria.
3. Increasing C/N values suggest a relative increase of terrestrial inputs over aquatic (e.g. wetland plants, algae) (Meyers, 2003), though algae species such as *Pediastrum* and *Botryococcus* can also contribute to high C/N values due to their high carbon content (Banerjee *et al.*, 2002; Metzger and Largeau, 2005).
4. Organic carbon content is proportional to the extent of terrestrial and/or aquatic productivity given a constant rate of inorganic inputs.
5. Increases in Pb concentration result from both aeolian and fluvial deposition occurring during very dry or very wet conditions, respectively.

Results and discussion

The suite of modern plants collected comprised 31 species (Table 2), including 14 from wetland habitat, 10 from dry habitat and seven from mixed habitat (plants that grow in both environments). Wetland species differed significantly ($P < 0.05$) from dryland species in the former having higher δ^{15}N values and lower C/N values, while there was no difference among plants from the three habitats with respect to their δ^{13}C values (Fig. 2). The range of δ^{13}C, δ^{15}N and C/N values in the sedimentary record for the most part fell within the range measured for modern plants (Fig. 3). The rather stable pattern in these proxies over the last ca. 4000 cal. YBP relative to the rest of the record, particularly in δ^{13}C values, is consistent with the period of establishment of the modern plant species assemblage, as observed in the pollen record (Fig. 4; Anderson *et al.*, 2008). Throughout the core, the patterns in δ^{13}C, δ^{15}N and C/N values reflect the succession of habitats that occurred at the site, from a shallow lake to a wetland to a bog (pollen zones I, II and IV). Values outside the range of modern plant values were observed in the sedimentary record for δ^{13}C ca. 14 000 cal. YBP and during the Younger Dryas period, and for δ^{15}N and C/N ca. 8000–6000 cal. YBP.

During the Late Pleistocene and Holocene, Pb inputs to the Chihuahueños basin were likely dominated by natural sources given its remote location and the abundance of Pb-bearing volcanic rocks in the region. Pb concentrations in the Chihuahueños bog core are typical of igneous rocks in general (2–30 p.p.m.; Adriano, 2001), although Pb concentrations in the nearby Bandelier tuff can range from 50 to 85 p.p.m. (Self *et al.*, 1996). One instance of relatively high Pb concentrations in the Chihuahueños record occurred ca. 14 420 cal. YBP (Fig. 3). At that time, Pb concentration increased from 14 to 24 p.p.m. over a 300 a period, lasted another 200–400 a and was accompanied by an equally short-lived and significant increase in δ^{13}C values (from −25‰ to −19‰, Fig. 3). Synchronous with these changes in the Chihuahueños record was a significant increase in effective precipitation and consequent runoff in the nearby area of White Rock Canyon to the east (which hosts the Rio Grande) ca. 14 410 cal. YBP (12 400 ^{14}C a BP) (Dethier and Reneau, 1996). Consistent with this evidence of relatively wetter climate, several pluvial lakes in the Southwest experienced high levels around that time (Benson *et al.*, 1990, 1997; Allen and Anderson, 2000; Bacon *et al.*, 2006; Garcia and Stokes, 2006). At the Chihuahueños Bog site, we thus interpret the abrupt increase in Pb concentration and δ^{13}C values as further evidence of conditions of enhanced precipitation in the region ca. 14 420 cal. YBP. The increase in Pb concentrations and δ^{13}C values suggests significant runoff that delivered Pb-bearing minerals from the weathering and transport of local volcanic rocks and ^{13}C-enriched organic material from a vegetation source to the shallow lake that existed at that time. A synchronous spike in magnetic susceptibility (Anderson *et al.*, 2008) supports the scenario of increased delivery of clastic material.

The increased ^{13}C-enriched organic material in the sediment probably resulted from a plant assemblage different from that of today. At that time, pollen evidence suggests *Artemisia* was more prominent in the environment (Anderson *et al.*, 2008, Fig. 4). The only modern *Artemisia* identified around the bog (*A. ludoviciana*, white sagebrush) has a low δ^{13}C of ∼−29‰ (Table 2). However, modern *Artemisia* collected at lower elevations has δ^{13}C values around −23‰ (unpublished data). It cannot be determined whether these higher values are typical of a specific sagebrush species or whether they reflect increased water use efficiency under present environmental conditions. Poaceae species were also abundant in the Late Pleistocene, some of which might have been C4 species with higher δ^{13}C values, though wetter conditions at the time would have favoured C3 grasses. Because the Late Pleistocene plant community was very different from the modern plant suite, we cannot unequivocally interpret the δ^{13}C signal during this period. Alternatively, higher δ^{13}C values could be attributed to higher aquatic productivity, which would be supported by the high δ^{15}N values at that time (Fig. 3). However, abundant algal remains started to appear only later (from ca. 14 000 cal. YBP; Anderson *et al.*, 2008, Fig. 4) and organic carbon content did not increase substantially during this period of high δ^{13}C values, suggesting low aquatic productivity.

Conditions of enhanced precipitation at ca. 14 400 cal. YBP likely facilitated the full establishment of the shallow lake and

Table 2 δ^{13}C, δ^{15}N and C/N values in modern plants collected at the Chihuahueños bog site. See Fig. 2 for statistical analyses by habitat

USDA scientific name	Common name	Functional group	Family	Habitat	δ^{13}C (‰)	δ^{15}N (‰)	C/N (‰)
Artemisia ludoviciana Nutt. *ssp. mexicana* (Willd. ex Spreng.) Keck	White sagebrush	Forb/herb	Asteraceae	Dryland	−29.24	−1.55	24.2
Unknown Asteraceae species		Forb/herb	Asteraceae	Dryland	−29.71	1.20	17.0
Brassicaceae species	Mustard species	Forb/herb	Brassicaceae	Dryland	−30.38	−0.86	19.5
Bromus ciliatus L.	Fringed brome	Graminoid	Poaceae	Dryland	−29.20	0.84	22.9
Picea pungens Engelm.[a]	Blue spruce	Tree	Pinaceae	Dryland	−23.35	−1.47	33.1
Abies concolor (Gord. & Glend.) Lindl. ex Hildebr.	White fir	Tree	Pinaceae	Dryland	−28.50	−3.57	43.5
Pseudotsuga menziesii (Mirbel) Franco var. glauca (Beissn.) Franco	Rocky Mountain Douglas fir	Tree	Pinaceae	Dryland	−27.93	−1.49	43.0
Populus tremuloides Michx.	Quaking aspen	Tree	Salicaceae	Dryland	−28.78	−1.60	36.9
Populus virginiana L. var. *melancocarpa* (A. Nels.) Sarg.	Black Chokecherry	Tree/ shrub	Rosaceae	Dryland	−27.61	0.32	17.1
Juniperus communis L. var. *depressa* Pursh[b]	Common juniper	Tree/ shrub	Cupressaceae	Dryland	−27.52	−2.32	58.6
Achillea millefolium L. var. *occidentalis* DC.	Western yarrow	Forb/herb	Asteraceae	Mixed	−29.90	−1.42	11.9
Taraxacum officinale G.H. Weber ex Wiggers	Common dandelion	Forb/herb	Asteraceae	Mixed	−28.92	2.64	10.3
Elymus elymoides (Raf.) Swezey ssp. *brevifolius* (J.G. Sm.) Barkworth, comb. nov. Ined.	Squirreltail	Graminoid	Poaceae	Mixed	−29.96	−0.14	27.2
Agrostis scabra Willd.	Rough bentgrass	Graminoid	Poaceae	Mixed	−29.08	0.55	17.7
Poaceae species	Unknown grass species	Graminoid	Poaceae	Mixed	−27.95	0.69	16.6
Dasiphora floribunda (Pursh) Kartesz, comb. nov. Ined.[b]	Shrubby cinquefoil	Shrub	Rosaceae	Mixed	−27.41	−0.63	56.0
Populus × *acuminata* Rydb. (pro sp.) [*angustifolia* × *deltoides*]	Lanceleaf cottonwood	Tree	Salicaceae	Mixed	−28.12	−2.11	13.0
Mentha arvensis L.	Wild mint	Forb/herb	Lamiaceae	Wetland	−29.46	0.25	19.9
Polygonum amphibium L. var. *Stipulaceum* Coleman	Water smartweed	Forb/herb	Polygonaceae	Wetland	−29.17	−1.18	9.8
Rumex acetosella L.	Common sheep sorrel	Forb/herb	Polygonaceae	Wetland	−29.24	2.98	12.7
Potentilla norvegica L. ssp. *monospeliensis* (L.) Aschers. & Graebn.	Norwegian cinquefoil	Forb/herb	Rosaceae	Wetland	−27.61	1.51	12.2
Veronica americana Schwein. ex Benth.	American speedwell	Forb/herb	Scrophulariaceae	Wetland	−29.82	−0.97	19.6
Carex utriculata Boott	Northwest Territory sedge	Graminoid	Cyperaceae	Wetland	−26.16	2.05	20.9
Carex utriculata Boott	Northwest Territory sedge	Graminoid	Cyperaceae	Wetland	−26.81	2.31	20.0
Carex utriculata Boott	Northwest Territory sedge	Graminoid	Cyperaceae	Wetland	−26.84	3.46	24.4
Carex aquatilis Wahlenb. var. Aquatilis	Water sedge	Graminoid	Cyperaceae	Wetland	−27.27	−1.01	15.6
Carex species	Unknown sedge	Graminoid	Cyperaceae	Wetland	−25.86	1.75	23.8
Glyceria borealis (Nash) Batchelder[c]	Small floating mannagrass	Graminoid	Poaceae	Wetland	−27.77	11.80	18.4
Poa palustris L.	Fowl bluegrass	Graminoid	Poaceae	Wetland	−26.48	−0.73	22.8
Deschamsia caespitosa (L.) Beauv.	Tufted hairgrass	Graminoid	Poaceae	Wetland	−28.23	−0.66	21.6
Sparganium emersum Rehmann	European bur-reed	Graminoid	Sparganiaceae	Wetland	−27.32	2.11	18.5

[a] Outlier in the observed range of δ^{13}C values.
[b] Outlier in the observed range of C/N values.
[c] Outlier in the observed range of δ^{15}N values.

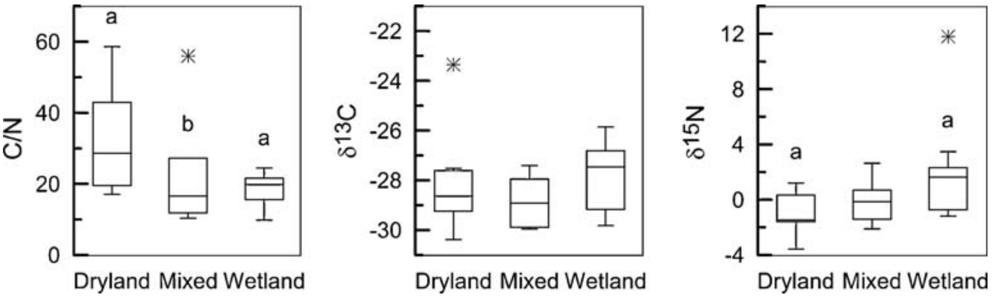

Figure 2 Range of C/N, δ^{13}C and δ^{15}N values in modern plants collected at the bog site (see Table 2 for a list of species). The median is indicated by line inside the boxes and outlier values by asterisks. Boxes labelled 'a' indicate a statistically significant ($P < 0.05$) difference. Boxes labelled 'b' indicate a statistically significant difference if outliers are removed

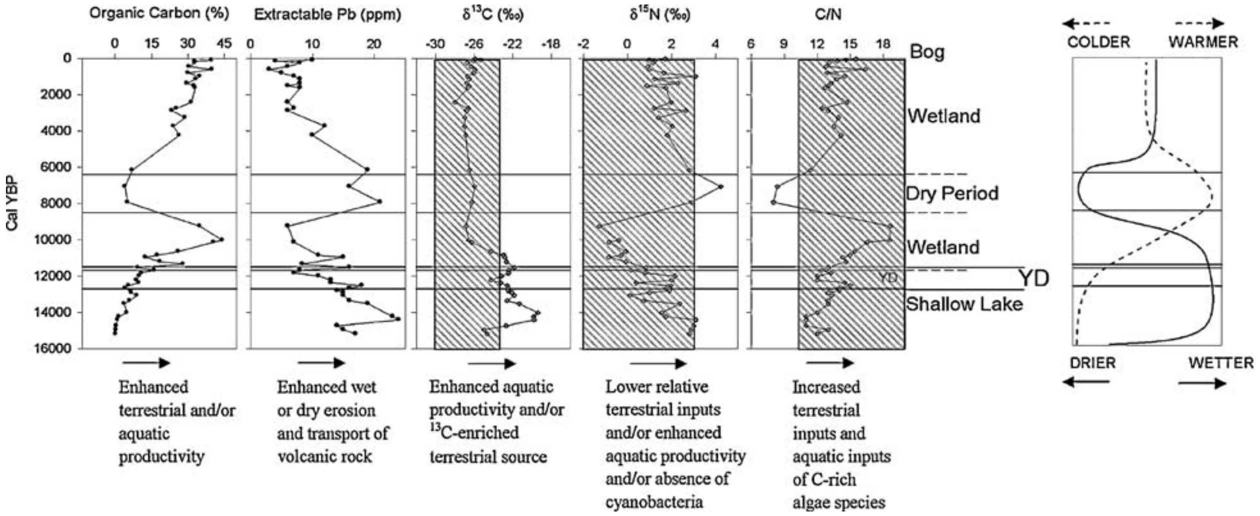

Figure 3 Variables measured in Chihuahueños bog sediments spanning ca. 15 500 cal. YBP (calendar years before present). The boundaries of succession of environments (based on the pollen record, Anderson et al., 2008) and Younger Dryas (YD) period are indicated by horizontal lines. Minimal pollen was preserved during the dry period. Decomposition effects and not those indicated by arrows drove the organic carbon, δ^{13}C, δ^{15}N and C/N values during this period. See text for more detailed explanation of effects. Diagonal lines indicate the range of values in modern plants at the site. Right panel shows inferred relative changes in temperature and precipitation, drier vs. wetter (solid line) and colder vs. warmer (dashed line)

the appearance of *Pediastrum* and *Botryococcus* as recorded in the pollen record (Anderson *et al.*, 2008, Fig. 4). The stronger jet stream relative to present time that prevailed ca. 18 000–12 000 cal. YBP, combined with a strengthening of the westerlies, could have contributed to increased local winter precipitation from the Pacific Ocean (Kutzbach and Wright, 1985; COHMAP Project Members, 1988). In fact, the existence of several pluvial lakes in the Great Basin, western USA, during the Late Pleistocene (before the jet stream retreated north) has been explained by this mechanism (Garcia and Stokes, 2006). Superimposed on this forcing, centennial-to-millennial climatic factors may have driven the water balance of Pleistocene–Holocene pluvial lakes (Allen and Anderson, 1993). Similarly, the Chihuahueños bog record provides evidence for a multi-centennial period of enhanced precipitation in northern New Mexico during the Late Pleistocene.

Such conditions took place during the Bølling period, coinciding with observations of wet conditions in nearby sites (Polyak *et al.*, 2004; Jiménez-Moreno *et al.*, 2008), and in contrast to arid climate during Bølling and Ållerød periods in other southwestern regions (Holmgren *et al.*, 2006). Wet conditions at the Chihuahueños bog site during these periods are also evident in the pollen and spore record (Fig. 4). In addition, low organic carbon content during the Late Pleistocene suggests low terrestrial and aquatic productivity relative to younger time periods recorded in the core, which in turn suggests relatively cold conditions. Low terrestrial productivity may have contributed to low fire event frequencies (Allen *et al.*, 2008) at that time. The predominance of *Artemisia* during the Late Pleistocene is also indicative of relatively cold conditions. This is consistent with cold conditions known to have prevailed in the Sangre de Cristo Mountains (east of the Chihuahueños bog site), during this period (Armour *et al.*, 2002; Jiménez-Moreno *et al.*, 2008).

Evidence of the Younger Dryas interval (ca. 12 700–11 500 cal. YBP) is equivocal in the Chihuahueños bog pollen record (Anderson *et al.*, 2008, Fig. 4), but is observed in the δ^{13}C, C/N and organic carbon profiles (Fig. 3). Proxy evidence

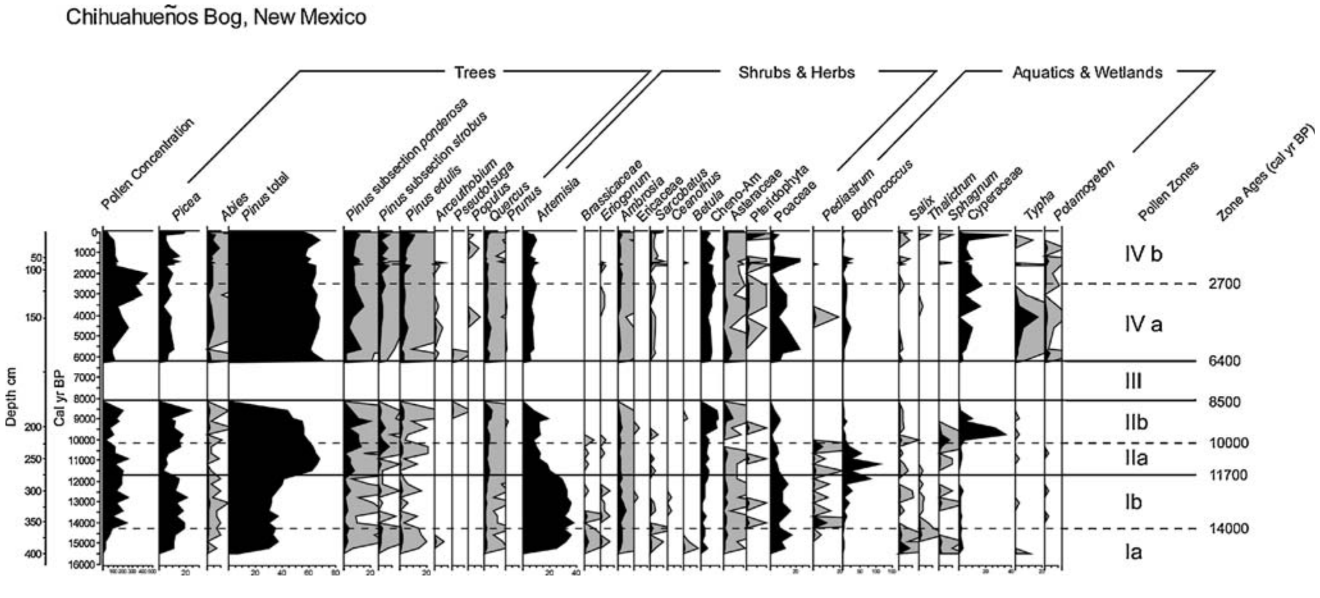

Figure 4 Summary pollen percentage data from Chihuahueños Bog core. Silhouette is percentage × 10. Pollen zones Ia–IVb are shown on the right. (Original diagram from Anderson et al., 2008, copyright Elsevier, reproduced by permission of Elsevier)

for the Younger Dryas period, aside from pollen records, has also been observed in records from the Sangre de Cristo Mountains (Armour *et al.*, 2002; Jiménez-Moreno *et al.*, 2008) and other regions (MacDonald *et al.*, 2008). Following our criteria for the interpretation of the proxies measured in the Chihuahueños record, we observe that except for the Younger Dryas interval, organic carbon content, δ^{13}C, δ^{15}N and C/N values suggest increasing terrestrial productivity at the site, starting ca. 14 000 cal. YBP through ca. 10 000 cal. YBP (Fig. 3). Particularly high terrestrial productivity following the Younger Dryas interval is in agreement with the synchronous establishment of a mixed conifer forest at this site (Anderson *et al.*, 2008, Fig. 4). These trends are interrupted during the Younger Dryas period, with δ^{13}C values increasing by 2‰, C/N values decreasing from 15 to 12, and δ^{15}N values consistently greater than 0‰. Aquatic productivity, on the other hand, seems to have been enhanced during the second half of the Younger Dryas, based on the increase in δ^{13}C values concomitant with the time of highest abundance of *Botryococcus* and presence of *Pediastrum* (Anderson *et al.*, 2008, Fig. 4). In addition, δ^{15}N and C/N values are consistent with predominantly aquatic inputs during the second half of this interval (Fig. 3).

Several studies have revealed relatively wetter conditions in the Southwest during the Younger Dryas period (Benson *et al.*, 1990; Huckleberry *et al.*, 2001; Polyak *et al.*, 2004; Holmgren *et al.*, 2006), while others suggest relatively drier conditions (Benson *et al.*, 1997; Holliday, 2000). At the Chihuahueños bog site, we see evidence for wet conditions in the Late Pleistocene, through the Younger Dryas interval. First, the pollen record suggests that a shallow lake existed at the site, with algae species *Pediastrum* and *Botryococcus* being abundant before, during and after the Younger Dryas (Fig. 4). Second, C/N and δ^{15}N values are consistent with an aquatic environment during these periods (Figs 2 and 3). Third, the observed low charcoal influx rates suggest cool wet conditions (Allen *et al.*, 2008). Lastly, continuation of wet climate throughout the Younger Dryas is in agreement with the observed trend in Pb concentration, which does not suggest a pronounced shift to either relatively drier or wetter conditions.

The drastic reduction in organic carbon ca. 8000–6000 cal. YBP (Fig. 3) confirms the occurrence of a dry period previously inferred from the lack of pollen, increased charcoal deposition, low C/N values and high δ^{15}N values (Allen *et al.*, 2008; Anderson *et al.*, 2008). As indicated in Anderson *et al.* (2008), this was a period of intense decomposition reflected in low C/N and high δ^{15}N values (Fogel and Tuross, 1999; Chen *et al.*, 2003; Kramer *et al.*, 2003). This period conforms to well-recognised drought episodes in several sites in North America ca. 9000–6000 cal. YBP (Holliday, 1989; Spaulding, 1991; Buck and Monger, 1999; Menking and Anderson, 2003; Otvos, 2005). Prolonged drought in the southwestern USA during this interval was attributed to a dominance of La Niña conditions (Forman *et al.*, 2001; Menking and Anderson, 2003), which has also been implicated as a cause for other prolonged droughts in the Southwest and the Great Plains (Seager *et al.*, 2005).

We observe further evidence of intense drought ca. 8000–6000 cal. YBP at the Chihuahueños site from sustained high Pb concentration in the record during this period (Fig. 3). Consistent with observations of extensive aeolian activity as early as ca. 9000 and through ca. 4500 cal. YBP in nearby regions and several other places in North America (Holliday, 1989; Dean, 1997; Forman *et al.*, 2001), high Pb concentrations ca. 8000–6000 cal. a BP in the bog sediments likely resulted from enhanced erosion and aeolian transport of local volcanic rocks. Later episodes of aeolian activity in the Southern High Plains (northwestern Texas, eastern New Mexico and western Oklahoma) during the middle to late Holocene (Forman *et al.*, 2001) were not accompanied by evidence of intense drought (e.g. high Pb concentration sustained for millennia) at the Chihuahueños site, perhaps due to stronger El Niño events and associated wetter climate (Moy *et al.*, 2002; McGregor and Gagan, 2004).

Conclusions

δ^{13}C, δ^{15}N, C/N, organic carbon and extractable Pb measurements in sediments from the Chihuahueños bog in northern New Mexico revealed periods of climate change in the last 15 000 cal. YBP, including the Younger Dryas cold interval. The Chihuahueños record provided evidence for periods of extreme climate during the Late Pleistocene and Holocene, including: (1) enhanced local precipitation ca. 14 420 cal. YBP, likely associated with the stronger jet stream that prevailed during the Late Pleistocene; and (2) enhanced erosion and aeolian transport ca. 8000–6000 cal. YBP, confirming the occurrence of a severe early to middle Holocene drought period at this site. The δ^{13}C, δ^{15}N and C/N values in the sedimentary record fall within values observed in modern vegetation collected at the site from wet, dry and mixed habitats, except during periods of climate change. The cold Younger Dryas interval was characterised by low terrestrial productivity at this site relative to preceding and succeeding periods. By contrast, aquatic productivity increased during this period, particularly during the second half of the Younger Dryas. In addition, wet conditions seem to have characterised the Late Pleistocene through the Younger Dryas interval at this site.

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