Quaternary Research 77 (2012) 87–95

Contents lists available at SciVerse ScienceDirect

Quaternary Research

journal homepage: www.elsevier.com/locate/yqres

Cool, wet conditions late in the Younger Dryas in semi-arid New Mexico

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ARTICLE INFO

Article history:
Received 8 April 2011
Available online 3 December 2011

Keywords:
Mollusks
New Mexico
Ostracodes
Pollen analysis
Scholle wet meadow
Stable carbon isotopes
Younger Dryas

ABSTRACT

A thick alluvial sequence in central New Mexico contains the Scholle wet meadow deposit that traces upstream to a paleospring. The wet meadow sediments contain an abundant fauna of twenty-one species of freshwater and terrestrial mollusks and ten species of ostracodes. The mollusks and ostracodes are indicative of a local high alluvial water table with spring-supported perennial flow but without standing water. Pollen analysis documents shrub grassland vegetation with sedges, willow, and alder in a riparian community. Stable carbon isotopes from the wet meadow sediments have $\delta^{13}C$ values ranging from −22.8 to −23.3‰, indicating that 80% of the organic carbon in the sediment is derived from C_3 species. The wet meadow deposit is AMS dated 10,400 to 9700 ^{14}C yr BP, corresponding to 12,300 to 11,100 cal yr BP and overlapping in time with the Younger Dryas event (YD). The wet meadow became active about 500 yr after the beginning of the YD and persisted 400 yr after the YD ended. The Scholle wet meadow is the only record of perennial flow and high water table conditions in the Abo Arroyo drainage basin during the past 13 ka.

Introduction

Wet meadows were once more common in alluvial valleys in the arid and semi-arid American Southwest, as indicated by the presence of wetland deposits exposed in arroyo cutbanks. Wet meadows are saturated grounds along perennial streams where water from spring and groundwater discharge moves over the surface without ponding. Desert streams may also include ciénegas that are small marshes with standing water supported by seeps and springs, often with aquatic life such as cattails and small fish (Hendrickson and Minckley, 1984). Wet meadows and ciénegas alike are especially sensitive to local ground water conditions: they thrive with high water tables but may dry when the water table is lowered. The sediments that accumulated at Scholle wet meadow document late-glacial paleoenvironments that contrast with conditions today in semi-arid New Mexico.

The Scholle wet meadow formed in the upper Abo Arroyo drainage, western Torrance County, central New Mexico, and is named for the nearby abandoned community of Scholle (Fig. 1). A weather station at Mountainair at the upper end of the Abo Arroyo watershed records a mean annual temperature of 10.8°C (51.5°F) and a mean annual precipitation of 360 mm (14.2 in) at an elevation of 1987 m (6520 feet); 66% of the rainfall occurs in April–September (data from NOAA, 2008).

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Methods

The alluvial sediments of the Scholle wet meadow are well exposed in an arroyo bank, facilitating field description and sample collection (Fig. 2). The sediments were analyzed by the Milwaukee Soil Laboratory for sand (1Φ), silt, clay, carbonate (chittick method) and organic carbon (Walkley–Black method). Sediment samples for AMS radiocarbon dating by Beta Analytic, Inc. were collected from 7- to 10-cm stratigraphic intervals and pre-treated with HCl to remove carbonate. The $\delta^{13}C$ values were determined during AMS radiocarbon dating by Beta Analytic. Mollusks were recovered by hand-picking from the outcrop as well as water screening of approximately 9 kg of matrix with a 0.6-mm mesh wire sieve. Matrix for ostracode analysis was sampled at 5-cm intervals; the samples were processed by methods described in Palacios-Fest (1994). Preliminary pollen analysis was conducted on two 5-cm samples from the lower and upper zones of the wet meadow deposit. Pollen samples were processed by HCl, sieving, sodium hexametaphosphate, decanting in water, HF, heavy density separation in lithium polytungstate, acetolysis, and alcohol with the residue stored in glycerol. A *Lycopodium*-spore spike was initially added to the weighed pollen sample. Inspection of the mollusk, ostracode, and pollen material did not yield plant macrofossils. Samples for iridium analysis were collected at 2-cm intervals below the Scholle wet meadow deposits and were analyzed by Becquerel Laboratories.

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doi:10.1016/j.yqres.2011.10.005

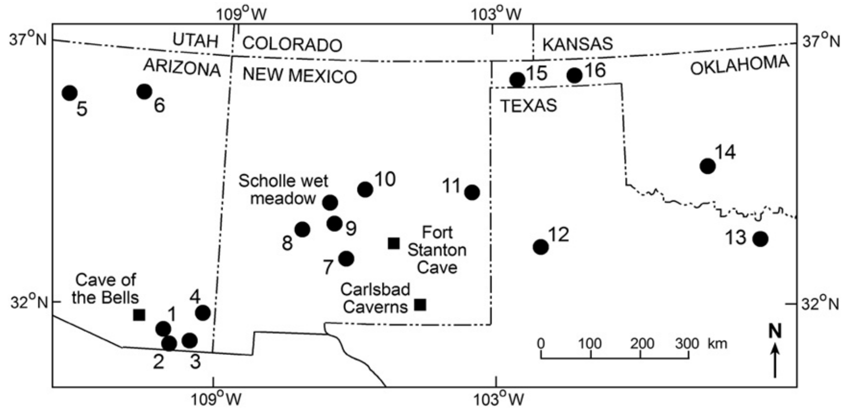

Figure 1. Selected Younger Dryas-age localities with high water table-related wetland deposits, many associated with Paleoindian sites: 1, Murray Spring site (Haynes and Huckell, 2007); 2, Lehner site (Haury et al., 1959; Haynes and Haury, 1982); 3, Naco site (Haury et al., 1953); 4, Wilcox Playa (Haynes et al., 1987); 5, Kaibito Plateau (Cyr, 2004); 6, Red Peak Valley (Karlstrom, 1986); 7, Salt Creek marsh (Love et al., 2011); 8, Water Canyon site (Dello-Russo et al., 2010); 9, Mockingbird Gap site (Holliday et al., 2009); 10, Pounds Playa (Haynes, 2008); 11, Blackwater Draw Clovis site (Haynes, 1995; Haynes et al., 1999); 12, Lubbock Lake site (Holliday, 1985; Haas et al., 1986); 13, Aubrey site (Ferring, 2001; Waters and Stafford, 2007); 14, Domebo site (Leonhardy, 1966); 15, Nall site (LaBelle et al., 2003); 16, Bull Creek site (Bement et al., 2007). Modified from Haynes (2008).

Scholle wet meadow

Scholle wet meadow was a small area of spring-fed moist ground that formed at the end of the Pleistocene (Fig. 2). The wet meadow deposit extends about 50 m across the narrow valley floor and can be traced downstream at least 850 m from the springhead, the point from which the wet meadow originated. Beyond that distance, the wet meadow deposit dips below the modern channel fill and is not exposed in arroyo banks. From the springhead, it has a downvalley slope of 0.009 m/m, slightly greater than the slope of the modern channel in that stretch of the arroyo. The wet meadow deposit is about one meter thick and thins slightly downstream. It is distinguished from other local alluvium by its dark reddish-brown color and abundant shells of freshwater and terrestrial snails and ostracodes. The springhead of the wet meadow deposit is exposed in the present-day arroyo bank and is a mass of carbonate-cemented coarse gravel overlying a bedrock bench formed by a resistant red sandstone bed of the Abo Formation (Permian) (Fig. 3). The paleospring is inactive today and is buried by Holocene alluvium. Wet meadow-related deposits do not occur upstream from the springhead. Abo Arroyo, especially in the upper reaches where Scholle wet meadow deposits are exposed, is today an ephemeral stream and is usually dry. Downstream, several present-day springs support intermittent flow in Abo Arroyo where it passes through Abo Canyon. However, a modern analog of the late-glacial-age Scholle wet meadow does not occur in the broad area today.

Stratigraphy and sediments

The Scholle wet meadow deposit is exposed at 577 to 667 cm depth in the measured section of an 8-m-thick alluvial sequence along Abo Arroyo. The wet meadow sediments are dark reddish brown to reddish brown (2.5YR 3-4/4) clayey silt with less than 15% sand. The color of the wet meadow and associated alluvial deposits is due to the presence of reddish-brown sandstone and shale of the Abo Formation in the drainage basin (Scott et al., 2005). The wet meadow deposit is subdivided into a lower and upper zone in the field based on the darker color of the upper zone. At the measured section, the wet meadow sediments exhibit twenty-three beds of alternating dark reddish-brown and reddish-brown beds ranging from 0.5 to 13 cm thickness (Fig. 4). The thin beds are massive without internal structures except for a reddish-brown bed at 641–645 cm depth, which is weakly laminated. The upper and lower boundaries of the thin beds are irregular and diffuse, probably a consequence of

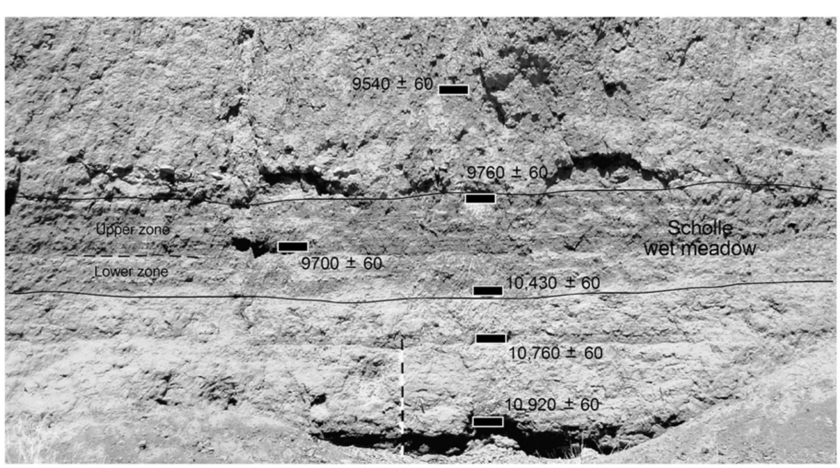

Figure 2. Measured section at Scholle wet meadow deposit, Abo Arroyo, southwestern Torrance County, New Mexico; located at latitude 34°25.69′N, longitude 106°24.28′W, elevation 1783 m (5851 feet); 1 m scale. Dates expressed as ^{14}C yr BP.

https://doi.org/10.1016/j.yqres.2011.10.005 Published online by Cambridge University Press

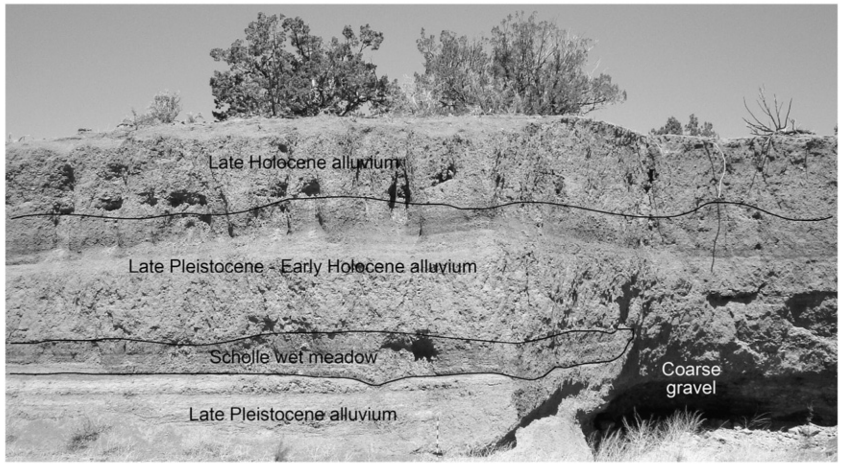

Figure 3. Springhead of Scholle wet meadow associated with coarse gravel overlying sandstone of the Abo Formation (Permian); middle Holocene alluvium is missing at this locality; 1 m scale.

turbation. The significance of the thin beds is not clear, although they may represent alternating episodes of comparatively slow (dark reddish brown bands) versus rapid (reddish-brown bands) aggradation. The wet meadow sediment has organic carbon ranging from 0.42 to 0.66%; the higher amount of organics may contribute to the dark reddish brown color. A hydric soil and redoximorphic features such as iron staining and mottles are absent. The net accumulation rate of the Scholle wet meadow deposit is 0.75 mm/yr.

The wet meadow formed on a flat, sloping alluvial surface in the narrow valley. A channel may not have been present prior to the formation of the wet meadow. However, a narrow, shallow channel was formed or widened through the wet meadow deposit near the springhead during the last stage of wet meadow formation (Fig. 5). The channel may have existed farther downstream but is no longer exposed due to late nineteenth and twentieth century arroyo cutting along Abo Arroyo that has removed a large volume of alluvium from the central axis of the valley (Hall et al., 2009). The channel outline is bowl shaped but narrow at the base and is about 2.9 m across at the top, probably a maximum dimension. At the deepest level of scouring, it extends about 2.4 m below the top of the wet meadow fill and about 70 cm into pre-wet meadow alluvium. The channel fill is laminar-bedded clayey silt, similar to the sediments that make up the wet meadow. Numerous snail shells are scattered throughout the laminar sediments that fill the channel; the shells are not sorted or concentrated in lenses. The channel cuts through the middle and lower wet meadow deposits and tops out at the upper part of the wet meadow, suggesting that the channel was eroded or enlarged at the terminal stage of wet meadow formation. The channel may have been cut towards the end of the wet period accompanying the local lowering of the water table, decrease in spring flow, and drying.

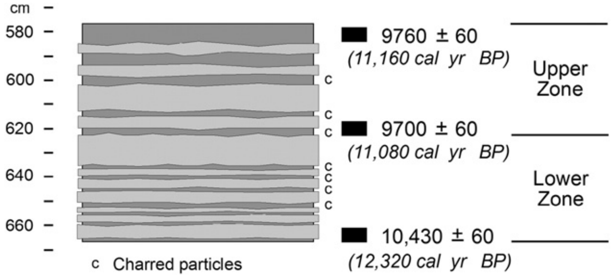

Figure 4. Microstratigraphy of Scholle wet meadow deposit at measured section (Fig. 2), showing alternating thin beds of dark reddish-brown and reddish-brown clayey silt; charred particles indicate fires at the wet meadow occurred in seven of the dark reddish-brown beds.

Chronology

The age of the Scholle wet meadow is determined by three accelerator mass spectrometry (AMS) radiocarbon ages from the wet meadow deposits (Figs. 2, 4) and bracketed by two AMS ages below and four AMS ages above (Table 1). All of the AMS ages are on organics from bulk sediment with the exception of one age on small particles of charcoal. Scholle wet meadow accumulated during the period 10,400 to 9700 ^{14}C yr BP or about 12,300 to 11,100 cal yr BP, spanning 1200 yr (based on IntCal09 calibration data set; Stuiver and Reimer, 1993; Reimer et al., 2009).

Correlation with late Younger Dryas

The accumulation of Scholle wet meadow sediment overlaps in time with the YD event. The YD is a brief episode of late-glacial cold climate and glacier advance, first defined by the classic Fennoscandian moraines and pollen records and in northwest Europe and dated by varves (Zeuner, 1970; Denton et al., 2010). The chronology of the YD in the Greenland ice core GISP2 is concluded to be 12.8 ka to 11.5 ka (Grootes et al., 1993; Stuiver et al., 1995; Alley, 2000a,b) which is equivalent to about 10,900 to 10,000 ^{14}C yr BP (based on IntCal09).

Alluvium about a meter below the base of the Scholle wet meadow deposit is AMS dated 10,920 ± 60 ^{14}C yr BP and coincides with the beginning of the YD; pre-YD alluvial sediments at greater depth are poorly exposed (Fig. 2). However, it is apparent that the Scholle wet meadow did not begin to form until about 500 yr after the beginning of the YD. Furthermore, the wet meadow continued to accumulate sediments for 400 yr after the YD ended. Thus, while deposition at Scholle wet meadow overlapped the YD event by 800 yr, the wet meadow and the YD are chronologically offset, the active wet meadow beginning later and persisting later in time.

Alluvium below and above Scholle wet meadow

About 1.5 m of yellowish-red (5YR 4/6) silt to sandy silt alluvium underlies the wet meadow deposit. The alluvium is soft and generally massive but with discontinuous beds of thin clayey silt. The sediment contains an occasional ostracode shell and four species of land snails (*Pupoides albilabris*, *Helicodiscus eigenmanni*, *Hawaiia minuscula*, and *Gastrocopta procera*) that occur in both dry lowland and moister montane habitats in eastern and central New Mexico (Metcalf and Smartt, 1997). The early YD-age alluvium that predates the wet meadow does not contain evidence for high water table or wet conditions. Twenty samples for iridium analysis were collected at 2-cm increments between 735 and 813 cm depth centered on the 10,920 ± 60 yr age.

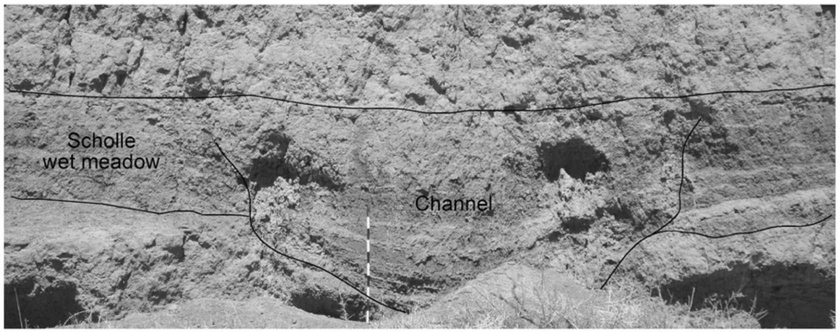

Figure 5. A small channel in Scholle wet meadow deposits in the upstream area about 30 m downstream from the springhead; 1 m scale.

The iridium content of the sampled alluvium has only background values ranging from <0.05 to 0.11 ppb and does not show an iridium spike.

The Scholle wet meadow deposit is overlain by 5.8 m of late Pleistocene–early Holocene and late Holocene alluvium at the measured section. Downstream, the valley fill consists of middle Holocene gravel and thick sections of fine-textured late Holocene alluvium. The late Holocene alluvium includes thick, massive beds of sandy silt that accumulated slowly on the valley floor. The fine-textured beds largely accumulated by over bank and sheet flow on the alluvial canyon floor but lack evidence of a high water table, saturated ground, or perennial stream flow.

Paleoecology of Scholle wet meadow

Mollusks

One species of pill clam, nine species of aquatic to semi-aquatic snails, and eleven species of terrestrial snails were recovered from Scholle wet meadow sediments, collected mostly from the shell-rich upper zone (Table 2). The shells are scattered throughout the wet meadow deposit and are not concentrated in lenses. Some of the specimens exhibit a darkening of the shell material such as is formed when shell is burned, consistent with the evidence discussed below, that the wet meadow vegetation burned several times.

All of the Scholle mollusks are extant in the Southwest today (Taylor, 1980; Metcalf and Smartt, 1997), and most have been reported as well from late Pleistocene faunas (Metcalf, 1967; Leonard and Frye, 1975; Ashbaugh and Metcalf, 1986), including other YD-age wetland deposits throughout the region (Cheatum and Allen, 1966; Quade et al., 1998; Meade, 2007). All of the freshwater species are consistent with perennial aquatic or semi-aquatic habitats, and most of the terrestrial snails are indicative of moist habitats where the ground is wet or saturated by a high water table. Exceptions are *P. albilabris* and *P. hordaceous* that commonly inhabit dry places; their shells may have washed onto the wet meadow from the adjacent hillslope. While the species that constitute the terrestrial snail fauna inhabit a variety of places and elevations in New Mexico, the species *H. minuscula*, *H. eigenmanni*, and *Vallonia gracilicosta* are more prolific above 2100 m (7000 feet) in the nearby Sacramento Mountains, about 350 m in elevation above Scholle wet meadow (Dillon and Metcalf, 1997). The slightly higher range of these species indicates a cooler climate at the time of Scholle wet meadow. The fauna includes a record of *Gastrocopta tappaniana*, distinct from *G. pellucida*, which is rare in the Southwest. Further discussion of nomenclature and ecology of the Scholle fauna can be found in Metcalf (2011).

Ostracodes

Ten species of ostracodes from among 1800 shells were recovered from Scholle wet meadow sediments (Fig. 6). Ostracode density ranges from 0.1 to 5.9 shells/g of sediment with greater concentration of shells in the upper zone. The fauna is composed of extant species and all are found today in perennial wetland environments with flowing but not standing water. Three species, *Eucypris meadensis*, *Cypridopsis vidua*,

Table 1
Radiocarbon ages from Scholle wet meadow and associated alluvium, central New Mexico.

Depth (cm)	Lab no.	Material dated	Measured radiocarbon age[a]	$\delta^{13}C$ (‰)	Corrected radiocarbon age	2-sigma calibrated age[b]
Post-wet-meadow alluvium						
310–320	Beta-288966	Bulk sediment	9160 ± 50	−20.9	9230 ± 50	10,250–10,520 (.99) 10,537–10,546 (.01)
350–360	Beta-288967	Bulk sediment	9340 ± 50	−21.4	9400 ± 50	10,507–10,747 (1.0)
390–400	Beta-287190	Bulk sediment	9270 ± 50	−21.8	9320 ± 50	10,300–10,320 (.02) 10,344–10,349 (.003) 10,377–10,681 (.98)
470–480	Beta-248012	Charred particles	9540 ± 60	−24.9	9540 ± 60	10,673–11,126 (1.0)
Scholle wet meadow						
570–580	Beta-248006	Bulk sediment	9720 ± 60	−22.8	9760 ± 60	10,872–10,946 (.06) 11,074–11,273 (.94)
622–629	Beta-248007	Bulk sediment	9670 ± 60	−23.1	9700 ± 60	10,791–10,966 (.29) 11,002–11,027 (.02) 11,065–11,236 (.69)
657–667	Beta-248008	Bulk sediment	10,400 ± 60	−23.3	10,430 ± 60	12,095–12,543 (1.0)
Pre-wet-meadow alluvium						
698–708	Beta-248009	Bulk sediment	10,730 ± 60	−22.9	10,760 ± 60	12,557–12,804 (1.0)
770–780	Beta-248010	Bulk sediment	10,890 ± 60	−23.3	10,920 ± 60	12,617–12,968 (1.0)

[a] AMS, Beta Analytic, Inc., Miami, Florida; Libby half-life.
[b] IntCal09 calibration data set; Stuiver and Reimer (1993); Reimer et al. (2009); relative area of calibration in parentheses.

https://doi.org/10.1016/j.yqres.2011.10.005 Published online by Cambridge University Press

Table 2
Mollusks from Scholle wet meadow, central New Mexico.

Pelecypod	Terrestrial snails
Pisidium casertanum	*Carychium exiguum*
Freshwater snails	*Gastrocopta tappaniana*
Fossaria parva	*Hawaiia minuscula*
Fossaria dalli	*Helicodiscus eigenmanni*
Fossaria modicella	*Helicodiscus singleyanus*
Fossaria obrussa	*Oxyloma* sp., cf. *O. retusum*
Fossaria techella	*Pupoides albilabris*
Gyraulus parvus	*Pupoides hordaceus*
Physella virgata[a]	Succineid, sp. indet.
Stagnicola caperata	*Vallonia gracilicosta*
Stagnicola elodes	*Vertigo ovata*

Note: Shells are housed in the Department of Biological Sciences, University of Texas at El Paso, El Paso, Texas.
[a] This is the only living freshwater mollusk found in Abo Arroyo in 2008; may be a junior synonym of *Physella acuta* (Dillon et al., 2005).

and *Cypridopsis okeechobei*, strongly support a spring origin of the wet meadow. Water chemistry and temperature are the main variables affecting ostracode presence and abundance. The faunal assemblage indicates hard water with total dissolved solids 300 to 800 mg/L but seldom exceeding 1000 mg/L. This compares with the present-day chemical composition of water from downstream Abo Arroyo with a pH of 8.3 and total dissolved solids 1910 mg/L, more than half sulfates (Plummer et al., 2004). Evidently the water in Scholle wet meadow and its associated spring was less alkaline than in lower Abo Arroyo today. The ostracode species have a wide range of temperature tolerance. The abundant species *Ilyocypris bradyi* has a more restricted temperature requirement of 6 to 18°C (43 to 64°F) that overlaps the median annual temperature of surface waters in the region today, including the Abo Arroyo watershed (Blakey, 1966). Additional information on the ecology of the Scholle ostracode fauna is in Palacios-Fest (2011).

Pollen analysis

The Abo Arroyo drainage basin occurs in the transition of short-grass prairie and mixed grama-juniper vegetation at the western edge of the Plains of eastern New Mexico (Donart et al., 1978). Preliminary pollen analysis of Scholle wet meadow sediments yielded well-preserved assemblages dominated by Cheno-am (chenopod-amaranth), Asteraceae (aster family), *Pinus* sp. and *Pinus edulis* (pinyon pine), *Juniperus* (juniper), and Poaceae (grass) pollen with low percentages of *Quercus* (oak) and *Artemisia* (sagebrush) (Fig. 7). Trace amounts of Cyperaceae (sedge), *Salix* (willow), and *Alnus* (alder) are present. The pollen is consistent with a local plant community dominated by shrubs and grasses with some pinyon pine and juniper in the region. The presence of sedge, willow, and alder is indicative of the riparian environment at Scholle wet meadow. Plant macrofossils were not observed in the wet meadow sediments, although a small fragment of wood charcoal was collected from the pre-wet meadow alluvium and identified as *Pinus* sp.

Fire history

The dark reddish-brown color of the thin beds and the high organic content may be related to the presence of many charred particles. The particles are not charcoal from cellulose of woody plants; instead they are fine particles such as produced from burned herbaceous plants. The concentration of charred particles indicates that the wet meadow, and probably the vegetation surrounding the valley, burned at least seven times during its 1200-yr history (Fig. 4). A number of snail shells show evidence of burning, as well. Studies of fire-scarred trees in the Southwest have shown that pre-AD 1900 fire frequency is one fire event in 5 to 15 yr (Allen et al., 1996; Swetnam and Baisan, 1996). A review of charcoal and pollen records from the past 15 ka in the western US indicates that wildfire frequencies during the YD are similar to that of the Holocene (Marlon et al., 2009). If the field evidence for seven local wildfires at Scholle wet meadow is accurate, it represents one fire event per 170 yr, a low frequency that may reflect the comparatively wet YD-age climate. Nevertheless, charred particles and burned snail shells indicate that the wet meadow occasionally burned. The fire events may have occurred during a drought year when the wet meadow was dry.

Stable carbon isotopes

Stable carbon isotopes from soil A horizons and alluvium provide information on whether the local plant communities represented by those sediments are dominated by C_3 or C_4 species. Low-elevation

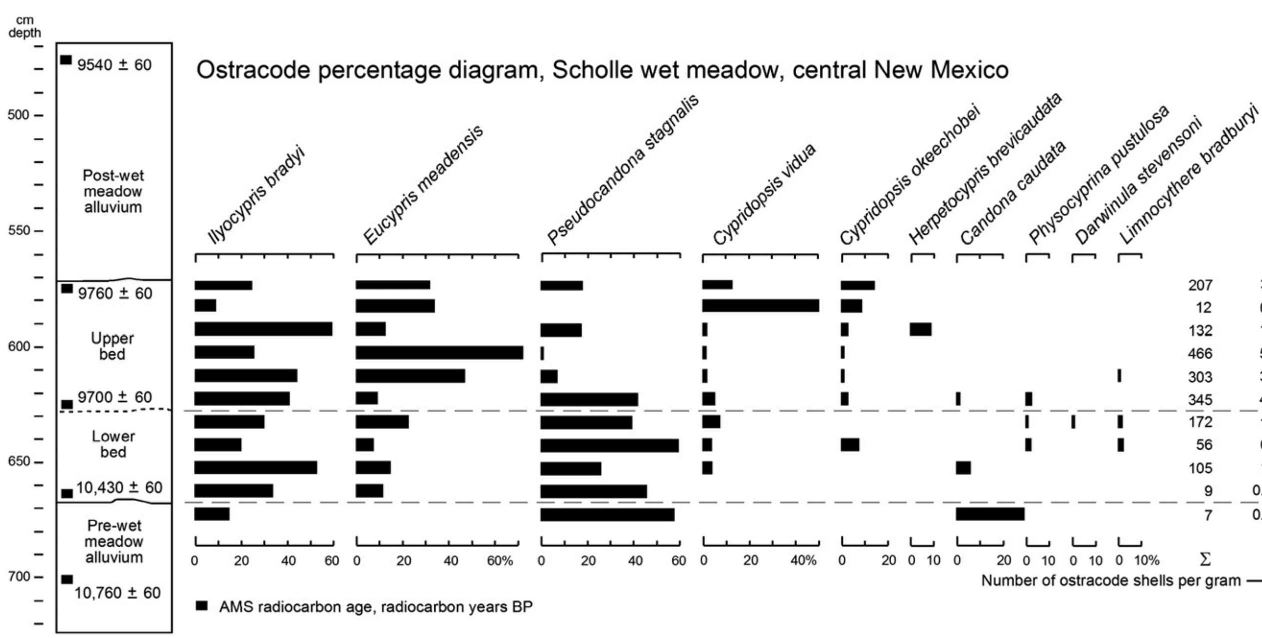

Figure 6. Ostracode percentage diagram from Scholle wet meadow alluvium; samples from measured section (Fig. 2). Dates expressed as ^{14}C yr BP.

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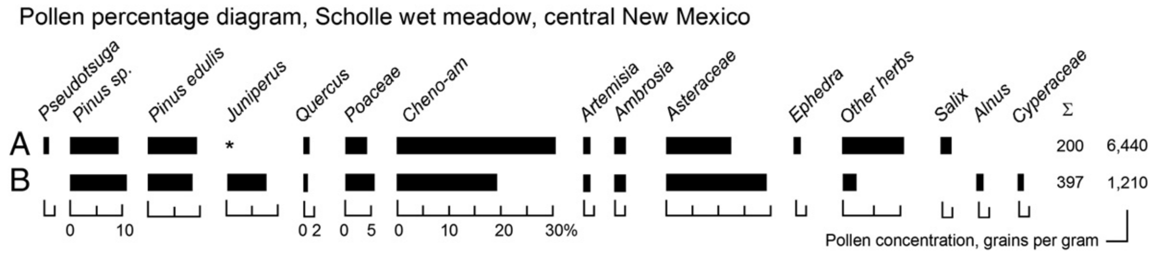

Figure 7. Preliminary pollen diagram from Scholle wet meadow alluvium; spectrum A is from 600 to 605 cm and spectrum B is from 640 to 645 cm depth in the measured section (Fig. 2). **Juniperus* pollen overwhelmed the pollen count in A; the grains were all fresh, indicating contamination of the pollen sample in the field when it was collected; accordingly, *Juniperus* counts are excluded from the pollen sum.

plant communities in the Southwest are generally a mix of C_3 (cool season grasses, forbs, shrubs, trees) and C_4 (warm season grasses) species, and they all contribute to the organic carbon found in soils and alluvial sediments. The proportion of C_3 and C_4 species represented by organic matter in sediment can be estimated from the $\delta^{13}C$ value of the organic carbon. From studies in the Great Plains, it was found that $\delta^{13}C$ values less (more negative) than −19‰ represent C_3-dominated vegetation and that $\delta^{13}C$ values greater (less negative) than −19‰ represent C_4-dominated plant communities (Nordt et al., 2007, 2008). The $\delta^{13}C$ values also correspond to mean July temperature where low temperatures correlate with low $\delta^{13}C$ values and greater proportion of C_3 species in the vegetation (Teeri and Stowe, 1976; Nordt et al., 2007).

Eight AMS dates on bulk sediment from Scholle wet meadow and associated alluvium have $\delta^{13}C$ values ranging from −23.3 to −20.9‰ (Fig. 8; Table 1). During the YD and the formation of the wet meadow at Abo Arroyo, $\delta^{13}C$ values indicate that about 80% of the carbon is derived from C_3 species. After the end of the wet meadow, $\delta^{13}C$ values increase, indicating a slight decrease in the abundance of C_3 species and an increase in C_4 species, although still predominantly C_3 vegetation. The presence of C_3 vegetation is consistent with a comparatively cool YD-age climate in the region, and the shift to higher $\delta^{13}C$ values after the end of the wet meadow may represent a change in climate to less cool temperatures.

Discussion

Exposures of late Pleistocene alluvium are uncommon in the American Southwest, having been removed by erosion or still buried deep in valley fill. Many of the sequences that have been reported are associated with Paleoindian archeology (Fig. 1). Scholle wet meadow

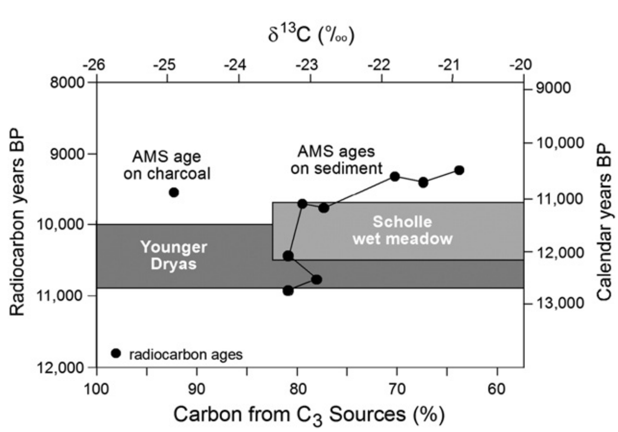

Figure 8. Stable carbon isotopes from Younger Dryas-age alluvium, Scholle wet meadow sediments, and associated alluvium; from measured section (Table 1); the proportion of C_3 plants follows Nordt et al. (2008). Left axis, radiocarbon dates as ^{14}C yr BP; right axis, cal yr BP.

correlates in part with the black mat at the Murray Springs Clovis site in southeastern Arizona (Haynes and Huckell, 2007), a wet meadow deposit at the Water Canyon site in west-central New Mexico (Dello-Russo et al., 2010), and with wet meadow or ciénega mud deposits recovered from cores along Chupadera Draw near the Mockingbird Gap site in central New Mexico (Holliday et al., 2009). It also correlates broadly with other cases of wetland deposits at early man sites across the continent, especially in the Great Plains and American West (Haynes, 2008) (Fig. 1).

Speleothems

Sequences of oxygen isotope ratios ($\delta^{18}O$) from speleothems in Fort Stanton Cave, New Mexico, and Cave of the Bells, Arizona, show that the YD interval was characterized by greater rainfall than the period before or after (Asmerom et al., 2010; Wagner et al., 2010). Another case of a late-glacial wet interval is also documented by stalagmites in the Carlsbad Caverns area of southeastern New Mexico (Polyak et al., 2004). Although the U-series ages and growth rates have large sigmas of uncertainty, Polyak and others found that stalagmite growth began about 12.5 ka and ended by 10.5 ka. The period of stalagmite growth overlaps the YD event, starting 300 yr after the YD began and continuing 1000 yr after the YD ended. It is not known why the Carlsbad stalagmite growth records lag the YD while $\delta^{18}O$ sequences at Fort Stanton Cave and Cave of the Bells have a closer correlation with the YD event.

Paleo-hydrology

The speleothem record of greater precipitation during the YD coincides with evidence for increased groundwater discharge in the San Pedro Valley in southeastern Arizona. A sequence of paleo-spring and groundwater discharge deposits formed during the period 50 ka to 15 ka. After 15 ka the water table dropped, coinciding with the Bølling-Allerød warm period. The regional water table rebounded briefly during the YD cold event; no further evidence of groundwater highstands was found after the YD (Pigati et al., 2009).

Alpine glaciation

The Sangre de Cristo Mountains of northern New Mexico were glaciated during the late Pleistocene (Ellis, 1935; Ray, 1940; Richmond, 1965). Wesling (1987, 1988) mapped various moraines near Santa Fe Baldy (3847 m elevation) and assigned them relative ages based primarily on soil development and clast weathering properties. Wesling obtained a late Holocene radiocarbon age 3570 ± 145 ^{14}C yr BP on charcoal from the base of a 16-cm deposit of eolian silt overlying a moraine with a well-defined Bt horizon, the only radiocarbon age associated with the glacial deposits in the area at that time and later mistakenly cited as evidence for Neoglaciation (Armour et al., 2002). Sediment cores from nearby bogs were radiocarbon dated, and thin zones of sand in the cores have been equated with periods of glacial and periglacial activity during the YD and Neoglacial (Armour et al., 2002). In a new investigation, cosmogenic ^{10}Be dating of boulders from the moraines previously thought to be YD and Neoglacial are instead pre-YD in age (Davis et al., 2009). Consequently, YD and Neoglacial moraines in the Sangre de Cristo Mountains of New Mexico, if they exist, are yet to be discovered.

Pluvial lakes

Late Pleistocene lacustrine deposits in the large New Mexico lake basins that correlate with the YD are uncommon or poorly dated. A noteworthy record, however, is a 3-m-thick marsh deposit along Salt Creek at the north end of old Lake Otero in the Tularosa Basin. The bedded gypsiferous deposits contain freshwater snails, bones of fish and amphibians, and many ostracodes and foraminifera; radiocarbon ages indicate that the marsh deposits are restricted to the YD interval (Love et al., 2011). Except for the Salt Creek marsh, lacustrine deposits at Lake Otero are absent after ca. 18.8 ka (Allen et al., 2009). In the Estancia Basin, the last perennial stand of Lake Estancia ended about 13.9 ka, although a poorly dated lacustrine phase may have occurred between ca. 12.9 and 11.5 ka, tentatively placing it in the YD until its age can be better constrained (Allen and Anderson, 2000; Anderson et al., 2002; Allen, 2005). In all of these cases, middle Holocene deflation has removed the upper levels of most paleolake sediments, truncating the lacustrine record in most large and small lake basins alike. Accordingly, if YD-age lake deposits were once widespread, they are now largely missing due to wind erosion. Farther north, YD-age lacustrine deposits associated with the Gilbert shoreline have been reported from the Bonneville basin of Utah (Hart et al., 2004; Oviatt et al., 2005).

Eolian sand sheets

Eolian processes of deposition and non-deposition are shaped by vegetation and climate, and it is reasonable to expect that a period of wet conditions, such as observed during the YD, would produce a hiatus in eolian sequences. However, based on OSL chronologies of large sand sheets in the region, eolian sand deposition continued across the YD interval without interruption. Eolian sand accumulated steadily in the Mescalero sand sheet from 18 to 5 ka (Hall and Goble, 2006, 2011) and in the Bolson sand sheet from 24 to 5 ka (Hall et al., 2010). Either greater rainfall during the YD was insufficient to increase ground cover and curtail sand supply in low-elevation areas, or the duration of the YD was too brief to have a noticeable effect on eolian processes and sand-sheet accumulation.

Pollen records

An *Artemisia* grassland characterized the regional lowland vegetation during the last glacial maximum but was not present in the vicinity of Scholle wet meadow during the YD (Hall and Valastro, 1995; Hall, 2001, 2005). At the end of the YD, however, a sagebrush grassland was present farther south at Hueco Tanks, Trans-Pecos Texas (Hall and Riskind, 2010). Pollen records from the Sangre de Cristo and Jemez mountains in northern New Mexico also document an *Artemisia*-dominated interval during the late glacial but provide little or no indication of changes in alpine vegetation related to cooler conditions during the YD (Anderson et al., 2008; Jiménez-Moreno et al., 2008). At Black Mountain Lake in the San Juan Mountains of Colorado, however, pollen accumulation rates of *Pinus*, *Picea*, and *Abies* decreased during the YD, indicating a down-slope shift in tree populations in response to cooler climate (Reasoner and Jodry, 2000). At Tiago Lake in northern Colorado, the YD was characterized by a subalpine plant community with spruce, representing a minimum of 200 m lowered vegetation over today (Jiménez-Moreno et al., 2011). The YD event is the coldest in the 14.5 ka record at Tiago Lake and was preceded by warm conditions during the Bølling-Allerød. While lowered alpine vegetation during the YD cold event is documented in Colorado mountains, a vegetation response to the YD is not yet observed farther south in New Mexico.

Conclusions

The spring-fed Scholle wet meadow resulted in the slow accumulation of a meter of organic-rich silt on the narrow valley floor of Abo Arroyo. A high water table and perennial spring flow promoted saturated ground that supported a diverse and abundant fauna of mollusks and ostracodes. Ostracodes indicate that the spring water was perhaps less alkaline than the modern stream in lower Abo Arroyo. Pollen analysis documents shrub grassland vegetation with sedges, willow, and alder in a riparian community. The dominance of C_3 species in the vegetation and the presence of some land snails with modern distributions at higher elevation suggest a comparatively cool climate at Scholle wet meadow. The wet meadow formed during the late YD and persisted 400 yr after the YD ended. The cool, moist environment of the brief YD event evidently did not impact alpine glaciation, alpine forest vegetation, or eolian sand sheets in New Mexico. The YD influence on fluvial environments, however, was pronounced and widespread. Increased precipitation, as documented by speleothems from caves in the region, resulted in higher alluvial water tables, greater spring flow, and the formation of cumulic soils and wet meadow deposits in a number of alluvial valleys.

Acknowledgments

We thank Bill Pohl for permission to study the alluvial deposits containing Scholle wet meadow on his land. We thank Nicholas Parker and Robert Dell-Russo for assistance in the field, Pamela McBride for identifying *Pinus* sp. from a small piece of charcoal, and Steven Simpson for facilitating the iridium analysis. We especially thank BNSF Railway for supporting this study and for granting access to their right-of way property through Abo Canyon. Robert Dello-Russo made helpful suggestions to an earlier version of the manuscript; we thank Vance Holliday, Jay Quade, and two anonymous reviewers for their helpful comments.

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