PALEOCLIMATIC INVESTIGATIONS AT THE PUEBLO CHEMICAL Depot
PUEBLO COUNTY, COLORADO

Prepared for
Pueblo Chemical Depot
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## Contents

**Introduction** ........................................................................................................................................... 1  
**Study Area** ............................................................................................................................................... 2  
  - Groundwater and Fens .............................................................................................................................. 4  
  - Regional Climate ..................................................................................................................................... 5  
**Field Methods** ........................................................................................................................................ 8  
**Laboratory Methods** ............................................................................................................................ 8  
  - Loss on ignition and bulk density .................................................................................................................. 9  
  - Colorimetric peat humification analyses .................................................................................................... 10  
  - Accelerator mass spectrometry (AMS) $^{14}$C sample preparation ................................................................ 11  
**Results** .................................................................................................................................................... 11  
  - AMS dating, age-depth models and lithology ............................................................................................ 11  
  - Peat humification, organic matter and bulk density ..................................................................................... 15  
  - Data Processing and Display ...................................................................................................................... 19  
**Discussion** .............................................................................................................................................. 22  
  - Periods of Warmer (ca. 850-700 BC, 2800-2650 BP), and Cooler (ca. 425-650 BC, 2375-2600 BP) Temperatures ...................................................................................................................... 22  
  - Terminal Archaic Drought (ca. 50 BC-AD 375, 2000-1575 BP) .................................................................. 24  
  - Audubon Advance? (ca. AD 525-660, 1425-1290 BP) .............................................................................. 26  
  - Medieval Warm Period (ca. AD 975-1250, 1025-700 BP) ...................................................................... 27  
  - Little Ice Age (ca. AD 1250-1860, 700-90 BP) ....................................................................................... 28  
  - Recent Climate Change (ca. AD 1860-present) ...................................................................................... 29  
**Conclusions** .......................................................................................................................................... 37  
**Acknowledgments** ................................................................................................................................. 38  
**References Cited** ................................................................................................................................... 39
List of Figures

Figure 1. Location of the fen locations mentioned in the text .............................................. 2
Figure 2. Location of PCD-3, PCD-5 and PCD-6 ................................................................. 3
Figure 3. View looking north of PCD-5 ............................................................................ 3
Figure 4. Hypothesized formation processes of Chico Creek fens ...................................... 4
Figure 5. Annual precipitation in southeastern Colorado ..................................................... 5
Figure 6. Map of the extent of the effect of the North American Monsoon on summer precipitation in the American Southwest ...................................................... 5
Figure 7. Geopotential height patterns associated with the five wettest and driest summers in Arizona ................................................................. 7
Figure 8. Linear interpolation age-depth model, stratigraphic description and bulk density for PCD-5 ............................................................................. 13
Figure 9. Linear interpolation age-depth model, stratigraphic description and bulk density for PCD-6 ............................................................................. 13
Figure 10. Polynomial age-depth models for the PCD cores .............................................. 14
Figure 11. Percent organic matter, grams organic matter, and bulk density for PCD-5........ 16
Figure 12. Percent organic matter, grams organic matter, and bulk density for PCD-5........ 16
Figure 13. Relationship between bulk density and mineral and organic content of peat at Church Camp Fen ................................................................. 17
Figure 14. Relationship between bulk density and grams mineral and grams organic content of peat at PCD-6 ................................................................. 18
Figure 15. Relationship between percent organic material and bulk density in the sediments from PCD-6 ................................................................. 18
Figure 16. Organic material curve for PCD-5. ................................................................... 20
Figure 17. Percent transmittance (corrected) and organic material curves, PCD-6.............. 21
Figure 18. Percent transmittance (corrected) and organic material curves for PCD cores, with paleoclimatic episodes ......................................................... 23
Figure 19. The summed probability distribution curve (proxy population) and cultural chronology for the Arkansas River Basin, compared with paleoclimate ................................................................ 25
Figure 20. Summer (June, July and August) precipitation and temperature for instrument data from Pueblo, Colorado for the years 1888-2005 ........... 31
Figure 21. Instrument records for summer precipitation and temperature with above the mean and below the mean for Pueblo, Colorado....................... 32
Figure 22. Five-year running averages for Pueblo summer precipitation and temperature for the years 1888-2005, compared with the upper 120 years (extrapolated) of the PCD-5 and PCD-6 cores ............ 33
Figure 23. Inverse polynomial relationship between summer temperature and precipitation in the instrument data from Pueblo, Colorado ...................... 35
Figure 24. Inverse power relationship between humification and percent organic material in the sediments from PCD-6 ......................................................... 35
Figure 25. Inverse polynomial relationship between humification and percent organic material from Church Camp Fen ......................................................... 36
List of Tables

Table 1. PCD-5 AMS Dates........................................................................................................12
Table 2. PCD-6 AMS Dates........................................................................................................12
Introduction

RMC Consultants, Incorporated (RMC), performed paleoecological investigations, under contract W9125F-05-P-0044, for Pueblo Chemical Depot (PCD). Field work was performed by Kevin P. Gilmore and Don Sullivan on May 12, 2005.

This document outlines the collection and analysis of paleoenvironmental data from spring deposits located at PCD, which is situated in the Arkansas River Valley of southeastern Colorado at an elevation of just under 4800 feet (ft) (1463 meters [m]) (Figure 1). Recent work on these spring-fed “pocket fens” at the Depot and elsewhere in eastern Colorado have demonstrated that low elevation records of Holocene climate change are not only available for the semi-arid environment of the Great Plains, but may even be relatively common.

Lakes, ombrotrophic bogs (precipitation fed peatlands), minerotrophic fens (groundwater fed peatlands) and marshes (fens with grass cover with a mineral versus organic substrate) provide an environment in which sediments accumulate over time (Charman 2002; Chambers and Charman 2004). Many lakes and fens contain records of continuous sediment deposition representing thousands and possibly tens of thousands of years. The physical, chemical and biotic characteristics of these sediments reflect the environmental conditions under which they were deposited, thus providing a proxy record of local and possibly regional environment over time. Environments that contain the features that preserve these records are in areas of high precipitation found in either cool high latitudes or high elevations, or in low latitude tropical areas.

Unlike high latitude or high elevation areas where continuous records are usually found, most reconstructions of past environments on the plains are derived from fluvial and eolian sediment records, which can yield valuable information on past conditions, especially episodes of drought (Daniels and Knox 2005; Forman et al. 2001; Madole 1995, Mason et al. 2004), but due to the discontinuous nature of depositional processes and loss of portions of the record due to erosion, these records rarely reflect a complete record of past conditions. However, a limited number of recent studies using data from low elevation lakes on the Northern Plains (i.e., Fritz et al. 1993, 2000; Laird et al. 1996) suggest that these features contain continuous records of climate change. Unfortunately, perennial lakes do not exist on the semi-arid High Plains, so a continuous sediment record was thought to be unavailable for this area prior to the investigation of pocket fens.

Pocket fens are small (25-2500 m$^2$ in size), unassuming features on the landscape that until now have been overlooked. The recent work presented in this report demonstrates that they can provide continuous proxy records of effective moisture and perhaps relative temperature that extend into the middle Holocene (ca. 7800 years Before Present [BP]). The discovery of pocket fens as sources of paleoenvironmental information overcomes several obstacles to examining long-term climate change on the plains such as the general lack of paleoenvironmental data sources specific to the plains and the limited spatial distribution and temporal depth of the records that are available. Obviously, an understanding of lower elevation paleoenvironments and hydrology would be greatly enhanced with data that was collected directly from low
Paleoclimatic Investigations at the Pueblo Chemical Depot, Pueblo County, Colorado

elevation sources. However, prior to this study there is no extant literature that addresses the suitability of small low elevation fens in semi-arid environments as sources for paleoenvironmental data. This report is the first to report on the paleoclimatic records from these features.

Study Area

The Depot is located east of the city of Pueblo, Colorado. This area is within the Piedmont Section of the Great Plains Physiographic province (Fenneman 1931, 1946). The majority of the Depot is situated on a Middle Pleistocene age terrace 170 feet (52 m) above the Arkansas River between Chico Creek on the west and Boone Creek on the east. The three fens that are the subject of this report (PCD-3, PCD-5 and PCD-6) are part of a string of small, closely-spaced wetlands situated on the backslope of the terrace scarp on east side of the valley of Chico Creek in the northwest portion of the Depot (Figure 2). In the area of the fens, the terrace tread is approximately 100 ft (30 m) above Chico Creek, and the fens are situated 50 ft (15 m) above the floodplain.

The fens are all quite small with surface areas between 25-50 m² (Figure 3). They are fed by discharge from a shallow aquifer contained within the Middle Pleistocene age alluvium that consists of unconsolidated stratified deposits that range in texture from sand and gravel to clayey silt (Madole 2003:5). This deposit is 15-30 m thick in the area and rests unconformably on the Cretaceous age Pierre shale. This deposit is correlated to the Verdos alluvium, dated elsewhere to 640,000 years ago (Madole 2003; Scott et al. 1978). Soils in the vicinity of the fens are Otero sandy loam which is characterized as a very deep, well to somewhat excessively drained Aridic Ustorthent formed in alluvium and eolian material (USDA 1979).
Figure 2. Location of PCD-3, PCD-5 and PCD-6. This area is on the North Avondale 7.5 USGS topographic quadrangle (1960, PR 1974).

Figure 3. View looking north of PCD-5 in April 2005. The area of green vegetation delineates the surface of the fen, which is approximately 25 m².
The Middle Pleistocene alluvium is highly permeable and serves as a shallow aquifer that is recharged locally by precipitation. Water flows along the barrier formed by the Pierre shale until it reaches the valley cuts of Chico Creek on the west and Boone Creek on the east where it seeps about midway down the backslope of these valleys. Before cattle grazing ceased at the Depot in 1998, the east side of the Depot in the Boone Creek drainage was the most intensively grazed (Rondeau 2003: Figure 5).

It is in this area that cattle tanks were excavated along the gently sloping valley slope of Boone Creek at what are presumed to have been the springs with higher discharge. Excavation of the cattle tanks destroyed the sediment records associated with these features. However, springs in the more lightly grazed area in the northwest corner of the Depot are apparently unmodified and contain intact sediment records.

*Groundwater and Fens*

Wetlands with intact sediments should contain records of the precipitation history of the area. In arid environments with sandy surface sediments, precipitation has been demonstrated to be the single most important contributor to the recharge of shallow aquifers and thus spring discharge (Yang 2006). Contrary to assumptions that evapotranspiration and capillary action would allow little precipitation to reach an aquifer overlain with six m or more of sand, precipitation (especially high magnitude events) is a demonstrated significant contributor to shallow aquifers (Verhagen et al. 1974). The response time of shallow aquifers to changes in precipitation is relatively rapid, and spring discharge from shallow to even moderately deep aquifers has been shown to reflect local precipitation trends with lag times of a few years to as short a period as a few months (Downing and Perterka 1978; Gentry and Burbey 2004). Groundwater has also been demonstrated to be the major contributor to fens compared to direct precipitation or surface flow. Geochemical modeling in fens in Minnesota indicated that rainwater contributed only 6-13% of water, and fluctuations in groundwater contribution to water in fens could be directly correlated to annual precipitation (Almendinger and Leete 1998). Considering the small size of the surface basins occupied by the pocket fens, this must also be true for the fens at PCD.

The northwest corner of the Depot on the eastern side of the valley of Chico Creek has a high density of fens. It is in this area, where the valley slopes of Chico Creek are steeper than elsewhere at the Depot, that saturation of the unconsolidated Pleistocene alluvium and colluvial deposits by spring discharge has apparently caused several small slope failures. The sediments in PCD-3, PCD-5, and PCD-6 have accumulated in small basins formed on what are thought to be the surfaces of slump blocks associated with small landslides (Figure 4a). These slumps are roughly contemporaneous and date to a hypothesized period of higher effective moisture that resulted in increased spring discharge sufficient to cause multiple slope failures. The sediments deposited on the basal gravels (derived from Pleistocene alluvium) in PCD-3, PCD-5, and PCD-6 are fine textured lake sediments that were deposited during a period of high effective moisture when small ponds formed in the relatively deep basins bounded by the fresh scarp face. Because the scarp and sides of these basins were initially steep and unvegetated, sediment was readily available for transport. Consequently, initial sediment accumulation rates in these pools would be high. Over time, decreasing slope angle due to erosion and re-vegetation of the scarp face would result in decreased sedimentation rates. As sediments began to fill these basins and the
water became shallow, lake sediments would transition to peat in the stratigraphic sequence and sedimentation rates would again increase (Figure 4b). Barring a return to conditions moist enough to reinvigorate movement of the slumps, the most recent sediments in these basins should be shallow water deposits such as peat.

Regional Climate

Climate records for the Depot itself are available but are somewhat incomplete. The instrument records that are available only cover the period from 1957 to 1977 and do not contain annual or seasonal values for average, minimum, and maximum temperature (posted at www.wrcc.dri.edu). However, when coupled with the records from surrounding weather stations, a relatively complete picture can be obtained. The Pueblo Chemical Depot and the Chico Basin Ranch core locations are situated in a zone of lower annual precipitation that falls between the base of the foothills (where snowfall begins to contribute a greater percent of annual precipitation) and an area of increased precipitation to the east (Figure 5). Precipitation at the Depot is a summer dominant pattern with an annual average of 10.42 inches (in.) most of which (2.07 in.) falls in July. The average annual precipitation increases along a west-east transect from 11.82 in. at the Pueblo airport located 6 mi. west of the Depot, to 12.54 in. at Ordway located 35 mi. east of the Depot, to 17.18 in. at Holly where the Arkansas River enters Kansas 118 miles east of PCD. The month of maximum precipitation shifts from August in Pueblo, to July at Ordway, to June in Holly. This indicates a decreasing influence of the North American Monsoon (NAM) on summer precipitation as you travel east of the project area.

The project area is at the extreme northern extent of the area influenced by the NAM (Adams 1997; Higgins et al. 1997). The area around the Depot receives 45% of its average annual precipitation between July and September, which suggests at least an attenuated influence of the NAM on precipitation (Figure 6). The NAM is a convection driven precipitation phenomenon that usually begins in the Sierra Madre Occidental of northwestern Mexico in June and extends

Figure 6. Map of the extent of the effect of the North American Monsoon on summer precipitation in the American Southwest. Portions of southeastern Colorado, including PCD, receive 45% of annual precipitation during the summer months of July, August and September (JAS), and are on the very northern edge of the area affected by the NAM. Map adapted from Higgins et al. (1997: Figure 7).
northward over the course of several months usually penetrating into northern New Mexico and southeastern Colorado by mid-July to early August (Higgins et al. 1997, 1999). Particularly wet summers in the American Southwest are usually the result of the northerly displacement of the subtropical ridge while a southerly shift are associated with dry Arizona summers. The northward displacement of the subtropical ridge (590 isobar) brings more tropical influence to Arizona and hence greater summer rains. From Adams (1997: Figure 4). Note that during the northward displacement of the subtropical ridge southeastern Colorado is under the ridge and subject to greater precipitation.

Vegetation at the Depot is dominated by three communities: shortgrass prairie, sandsage shrubland and greasewood shrubland. Minor areas of riparian habitat occur in the channel of Chico Creek and in the fen basins. The following descriptions of the vegetation communities at the Depot are taken from Rondeau (2003). The shortgrass prairie occupies nearly 11,500 acres at the Depot and is dominated by blue grama (*Chondrosum gracile*). A few areas are dominated by either alkali sacaton grass (*Sporobolus airoides*) or galleta grass (*Hilaria jamesii*), depending on soil type. Grass cover generally averages between 35-50% and bare ground generally averages between 20-55%, depending on past grazing regime. However, live (green) grass canopy cover dropped to less than 5% in 2002 in response to extended drought conditions (Rondeau 2003:4).
The sandsage-dominated prairie occupies approximately 4,000 acres at the Depot and is best characterized as a very sandy substrate dominated by sandsage with an average of 15% canopy cover. The ground cover is often sparse with a mix of grasses and forbs, although grasses are normally more dominant than forbs (at least during August and September). Blue grama, needle-and-thread, and sand dropseed (*Sporobolus cryptandrus*) are the most common grasses, but they seldom exceed 10% cover. Plains buckwheat (*Eriogonum effusum*), zinnia (*Zinnia grandiflora*), and sunflowers (*Helianthus* spp.) are common forbs, and bush morning glory (*Ipomoea leptophylla*) and yucca (*Yucca glauca*) are common shrub-like plants (Rondeau 2003:4).

Greasewood shrubland occupies approximately 2,400 acres on the Depot with the largest occurrence along Boone Creek. This community is recognized by the presence of greasewood (*Sarcobatus vermiculatus*) with an average of 3% canopy cover; rabbitbrush (*Chrysothamnus nauseosus*) may co-dominate and cholla (*Cylindropuntia imbricata*) may be present. The grass cover averages 50% and is often dominated by alkali sacaton, blue grama, or galleta grass (Rondeau 2003:4).

The area where the PCD fens are located is mapped as the boundary between the sandsage and shortgrass communities, but it is actually in an area where the three communities mix. On the terrace tread above the fens, cholla is the dominant shrub with lesser amounts of greasewood and sagebrush. The presence of greasewood indicates the presence of a high water table (Rondeau 2003:3) which would be expected directly above the fens.

Field Methods

On May 12, 2005, Kevin Gilmore and Don Sullivan of the University of Denver (DU) Department of Geography examined several small springs located in the northwest corner of the Depot. The springs were numbered consecutively from north to south beginning at the perimeter road that extends around the Depot. The depth of the sediments associated with these springs was determined using a 2 m-long probe. Locations within the basins of three springs designated PCD-3, PCD-5 and PCD-6 were determined to contain more than 2 m of sediment. Sediment cores were collected from these springs using a plywood platform placed directly on the surface of the peat. Cores were obtained using a hand-operated square rod piston corer, which consists of a 1 m-long, 8 centimeter (cm) diameter metal tube that is pushed into the sediment to obtain undisturbed samples of sediment. Sediment is retained in this tube by the force of the vacuum that is maintained by a piston that fits inside the tube and held at the top end of the sample pipe by tension on a cable attached to the top of the piston. Samples were extruded from the sample tube and then wrapped in plastic wrap and foil for transport. A total of 220 cm of sediment was recovered from both PCD-3 and PCD-5 and a total of 233 cm of sediment was recovered from PCD-6. The cores were transported back to the soils laboratory at the DU Department of Geography for analysis. PCD-5 core 05-1 (the first core collected in 2005 from this fen) and core PCD-6 05-1 were selected for laboratory analysis.

Laboratory Methods

Sediment cores were sampled at 1 cm intervals for all analyses. Organic carbon and bulk density were determined using loss on ignition techniques developed by Dean (1974). For each sample,
3 cubic cm of sample were placed in a numbered, pre-weighed crucible. Samples were heated in an oven for 2-3 hours at 100°C Centigrade (C) to drive off all water—this minus the weight of the crucible was the dry sample weight. After cooling and weighing, samples were then heated in a furnace for two hours at 550°C to burn off the organic carbon—this minus the weight of the crucible was the weight of the inorganic fraction of the sediment sample. The percentage of organic carbon in each sample was determined by subtracting the weight of the inorganic fraction from the dry sample weight then dividing the difference by the dry weight. Bulk density was determined by dividing the dry sample weight by the sample volume.

**Loss on ignition and bulk density**

The different characteristics of sediments reflect different aspects of the environment under which they were deposited. For example, the proportion of organic carbon in sediment serves as a proxy for lake productivity, which in turn is a reflection of temperature; changes in the percentage of organic carbon in lacustrine sediments represent changes in the productivity of biomass in the lake, which is in turn related to changes in temperature. Increasing organic carbon in lake sediments reflects increases in temperature (Yang 1989), with decreases in organic carbon representing decrease in temperature and lake production or greater inorganic sediment influx (Mayle et al. 1997). Although it has been argued that most of the organic matter in lake sediments originates in soils within the drainage basin and therefore is not representative of lake production (Mackereth 1966), recent research suggests that the majority of organic matter in temperate lakes is autochthonous (generated within the lake) and does in fact represent lake production (Gorham et al. 1974; Dean and Gorham 1998). Although no data are available for the application of this model to the higher organic content sediments that have accumulated in fens, the accumulation of organic material in these sediments is also thought to reflect productivity and by extension temperature. However, this relationship may be more tentative for peat as there is little data on how much the variation in organic matter production in these features is actually related to variations in the composition of plant communities during the different stages of seral succession, fluctuation in water table, or other factors independent of temperature.

Changes in the bulk density of lake sediments can represent either changes in the rate of inorganic sediment influx, a decrease in the production of organic carbon, or both. As a general rule, bulk density is often inversely proportional to organic carbon in sediments and increases as sedimentation rate increases. Sediments can enter fen basins in several ways: by transport in surface streams, by overland flow, by mass wasting events affecting hillslopes surrounding the basin, or as fine textured sediments transported by eolian action.

An increase in sedimentation rate and consequent increase in bulk density in lacustrine sediments is a function of sediment availability for both fluvial and eolian transport, both of which should be related to vegetation cover. Eolian activity is associated with both cold-arid and warm-arid conditions (Forman and Maat 1990). At high elevations and latitudes, increased eolian transport should correlate with episodes of increased aridity and cold temperatures. At low elevations, it should be associated with episodes of increased aridity and possibly higher temperatures. Similarly, increased fluvial transport of sediments should be a function of vegetation cover on hillslopes of the drainage basin and concomitant sediment availability. At any elevation, an increase in the bulk density of lacustrine sediments should be associated with periods of
increased aridity regardless of whether the source of the sediment is from fluvial or eolian processes. Determining the source of sediments depends on the physical characteristics of particles, the particle size distribution, and how well sorted the sediment is.

Colorimetric peat humification analyses

Peat humification analysis is a relatively new approach to studying paleoenvironmental change for researchers in North America with most of the work having been done on peat from ombrotrophic bogs (precipitation sustained wetlands) in Europe (Blackford and Chambers 1991, 1993; Langdon and Barber 2004, 2005; Roos-Baraclough et al. 2004) and high elevation fens in western Colorado (Sullivan and Gilmore 2005, 2006; Sullivan, et al. 2004; Taylor 2003, Williams 2005). The relative rates and extent of peat decomposition (humification) in wetlands is primarily dependent on the depth of the water table. As peat forms in the portion of the sediment column above the water table (acrotelm), it is exposed to oxygen which allows for much more rapid decomposition than after it passes into the continually saturated and anaerobic area below the water table (catotelm). The acrotelm/catotelm boundary is defined as the point where the water table reaches its lowest depth in the summer (Anderson 1998:208). Decomposition rates are up to 100 times greater in the acrotelm than in the catotelm (Malmer 1992a, 1992b).

During extended periods of dry conditions, the water table drops exposing a greater amount of peat in the acrotelm. Humic acid is a product of decomposition and the longer the residence time in the acrotelm the greater is the amount of humic acid that accumulates at this level in the sediments. Humification analysis uses simple techniques to determine the relative humification of peat samples through a core, providing a qualitative measure of peat decomposition and indirectly water table fluctuation. Preliminary results of pollen analysis at Church Camp Fen on Grand Mesa support the interpretations of humification analysis. Arboreal pollen increases during periods of decreased temperature and increased moisture characterized by decreased percent organic content and decreased humification, and shrub and grass pollen increase during periods of higher temperature and decreased moisture characterized by greater percent organic content and increased humification (Sullivan and Gilmore 2005). The rate of decomposition, or humification, of peat in a fen is related to effective moisture. As precipitation decreases, the water table is depressed, more peat is exposed to oxygen and decomposition in the exposed portion of the sediment column is accelerated which results in increased levels of humic acid (Anderson 1998; Blackford and Chambers 1993). Fluctuations in the proportions of humic acid in sediment cores serve as a proxy for fluctuations in effective moisture. The usefulness of this method has been demonstrated for fens in the mountains of Colorado by Taylor (2003) and Williams (2005).

Humification of peat was determined using the procedures outlined in Aaby (1976), Blackford and Chambers (1993) and Anderson (1998) and summarized in Taylor (2003). At 1 cm intervals, 3 cubic cm samples were taken and dried in a 100°C oven. Then, 0.2 grams (g) of each sample was homogenized by grinding with a mortar and pestle. Each sample was then placed in a numbered beaker, and each beaker was filled with 100 milliliters (ml) of a 0.5% solution of NaOH. The samples were first brought to a boil, and then the heat was reduced, allowing the samples to simmer for one hour. After boiling, each beaker was filled with 200 ml of deionized water. Each sample was then filtered into another beaker through Watman #1 Qualitative Filter
A 10 ml portion of the filtrate of each sample was then diluted with 10 ml deionized water and tested for percent transmittance using a Hach DR/2010 Portable Data Logging Spectrophotometer. Following Blackford and Chambers (1993), the spectrophotometer was set to read at 547\(\mu\)m because wavelengths between 540 and 550\(\mu\)m have been found to be most sensitive to changing humic acid content. At this stage in the analysis care was taken to process each sample in exactly the same way and in the same amount of time, as Blackford (1990) found that samples faded if they were exposed to NaOH longer than four hours. Each sample was tested for percent transmissivity (%T) three times, and then a second 10 ml portion of the sample was decanted and diluted and again transmittance was measured three times. The spectrophotometer was zeroed with a control vial of deionized water before each sample was tested. These six measurements were then averaged to obtain an averaged %T value for each sample.

**Accelerator mass spectrometry (AMS) \(^{14}\)C sample preparation**

Ten bulk sediment samples for AMS dating were selected from the cores, four from PCD-5 and six from PCD-6. These samples were submitted to Beta Analytic where they were subject to standard sample preparation for peat and organic sediment. For peat, preparation was alternating acid-alkali-acid washes to remove both carbonate and humic acids, and for organic sediments the pretreatment was a series of acid washes to remove carbonate.

**Results**

Given the limited funding for this project and the similarity between the records recovered from PCD-3 and PCD-5, the core from PCD-3 was dropped from analysis in order to concentrate the available resources on the cores from PCD-5 and PCD-6. The core from PCD-6 provided a peat record amenable to humification analysis, and the core from PCD-5 provided what was thought to be a comparable record of lake sediments representing the same period of time.

**AMS dating, age-depth models and lithology**

AMS dates were calibrated using the INTCAL98 calibration database (Stuiver et al. 1998). These dates are presented in Tables 1 and 2. Sediment accumulation rates were calculated using both a simple linear interpolation model between the \(^{14}\)C dates (Figures 8 and 9) and a polynomial age-depth model was also calculated in Excel (Figure 10). Sediments in the fens are actively aggrading at present and so the data for the upper part of the cores was interpolated to reflect a “present” of AD 2005, (the year the cores were collected) rather than the conventional “present” of AD 1950. This was accomplished by adding 55 years to the linear interpolation model for the portion of each core between the upper most date and the surface of the sediments.

All of the AMS dates are in stratigraphic order with the exception of the date from 168-169 cm in PCD-6. Not only is this date out of stratigraphic order, it is almost twice as old as the basal date from the same core. This suggests that this date represents contamination of this level of the core by old carbon that was stored on the landscape and subsequently transported into the fen and incorporated into the sediments. Because this date represents an event that predates the initiation of the deposition of organic sediments in the fen, it was rejected. There is also some
Paleoclimatic Investigations at the Pueblo Chemical Depot,
Pueblo County, Colorado

Table 1.
PCD-5 AMS Dates

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Sample Depth (cm)</th>
<th>Material Dated</th>
<th>Uncorrected $^{14}$C age</th>
<th>Two Sigma Calibrated Date Range</th>
<th>Intercept used for interpolation model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beta 214556</td>
<td>26-27</td>
<td>peat</td>
<td>100±0.4 $^1$</td>
<td>Modern carbon</td>
<td>AD 1850 (100 BP)</td>
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<tr>
<td>Beta 214558</td>
<td>79-80</td>
<td>lake sediments</td>
<td>230±40</td>
<td>AD 1950-1550 (0-420 BP)-</td>
<td>AD 1660 (290 BP)</td>
</tr>
<tr>
<td>Beta 214560</td>
<td>161-162</td>
<td>lake sediments</td>
<td>1840±40</td>
<td>AD 250-80 (1700-1870 BP)</td>
<td>AD 150 (1800 BP)</td>
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<tr>
<td>Beta 214819</td>
<td>208-209</td>
<td>lake sediments</td>
<td>7960±50*</td>
<td>6670-7060 BC (8620-9010 BP)</td>
<td>*</td>
</tr>
</tbody>
</table>

$^1$Percent Modern Carbon

*Rejected-too old

Table 2.
PCD-6 AMS Dates

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Sample Depth (cm)</th>
<th>Material Dated</th>
<th>Uncorrected $^{14}$C age</th>
<th>Two Sigma Calibrated Date Range</th>
<th>Intercept used for interpolation model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beta 214557</td>
<td>50-51</td>
<td>peat</td>
<td>160±40</td>
<td>AD 1950-1660 (0-290 BP)</td>
<td>AD 1800 (150 BP)</td>
</tr>
<tr>
<td>Beta 214820</td>
<td>85-86</td>
<td>peat</td>
<td>450±40</td>
<td>AD 1620-1420 (330-530)</td>
<td>AD 1450 (500)</td>
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<tr>
<td>Beta 214559</td>
<td>131-132</td>
<td>peat</td>
<td>1360±40</td>
<td>AD 710-630 (1240-1320 BP)</td>
<td>AD 660 (1280 BP)</td>
</tr>
<tr>
<td>Beta 214561</td>
<td>168-169</td>
<td>peat</td>
<td>4120±40*</td>
<td>2570-2870 BC (4520-4820 BP)*</td>
<td>*</td>
</tr>
<tr>
<td>Beta 214821</td>
<td>209-210</td>
<td>peat</td>
<td>1950±40</td>
<td>AD 130-40 BC (1820-1990 BP)</td>
<td>AD 60 (1890 BP)</td>
</tr>
<tr>
<td>Beta 212752</td>
<td>227-228</td>
<td>peat</td>
<td>2100±40</td>
<td>30-200 BC (1980-2150 BP)</td>
<td>110 BC (2060 BP)</td>
</tr>
</tbody>
</table>

*Rejected-out of sequence

question as to the accuracy of the basal date for PCD-5. This date is much older than expected given the sedimentation rates observed in other fens and in the same fen in the portions of the core above this section. This date represents a sedimentation rate of 150 years per cm, which is close to an order of magnitude slower than any other section of any other pocket fen in eastern Colorado. This could represent another old carbon problem such as that described above for PCD-6, it could indicate a hitherto undetected unconformity in the sediments, or it could be an accurate reflection of sedimentation rates toward the bottom of the core. At this point in the analysis and in the absence of additional AMS dates, the actual mechanism creating this problem in chronology is unidentified. Additional dates on the PCD-5 core may clarify the validity of this date at some point, but due to the problems described above; this date was discarded for the current analysis.

Another potential source of problems in chronology in pocket fens is the trampling of sediments by large mammals such as bison and later cattle. At the time it was sampled, the surface of Burnt Creek Fen on Chico Basin Ranch exhibited obvious signs of recent trampling. However, the expectation is that disturbance from trampling would more likely manifest itself in dates that were out of sequence because they were too young for the strata they were thought to date, not too old. This would be due to younger material from the surface being displaced into the deeper strata. Older material would be displaced upward, but one might predict that it would be less volume and it would be displaced a shorter distance upward in the profile. However, the mixing of strata due to trampling does not begin to explain AMS dates in the middle reaches of a core.
Figure 8. Linear interpolation age-depth model, stratigraphic description and bulk density for PCD-5.

Figure 9. Linear interpolation age-depth model, stratigraphic description and bulk density for PCD-6.
that predate the apparent initiation of sediment deposition in the fen, unless older material is being transported into the fens on the feet of large animals.

Although the general lithology of the cores from PCD-5 and PCD-6 are generally similar and reflect the environment in which they both formed, the stratigraphy between these fens varies quite a bit. The classification of the sediments found in the pocket fens of eastern Colorado are guided by the characteristics outlined for field identification of hydric soils (Hurt and Vasilas 2006). The sediments are classified as one of three classes of hydric soils based on the organic material content (LOI): peat and muck (here designated peat), mucky mineral soils (here designated mucky sediments), and mineral soils (here designated lake sediments). In the sandy soils (<20% clay, estimated) found in the PCD fens, peat and muck contain a minimum of 12-14% organic material (0-20% clay), mucky mineral sediment (mucky sediments) range from 5-12% organic material with 0% clay to 7-14% organic material with 20% clay, and soils with less than 5% organic carbon content are classified as mineral soils (Hurt and Vasilas 2006). For the purposes of the present study, the lower limit of organic content for peat was designated as 12%, and the upper limit for organic matter content for lake sediments was designated as 5% with the organic matter content for transitional sediments designated as 5-12% organic sediments. The upper 25-30 cm in all three fens is relatively undecomposed sedge peat. The surface section of peat in PCD-5 has a maximum value of 65% organic material and the upper section of peat in PCD-6 has a maximum value of 48% organic matter.

These three sediment types correspond to the visual breaks in the graphed organic matter data between different sections of the core fairly closely. Sediments from PCD-5 below the upper most peat stratum are relatively low in organic material (<10%) and have bulk densities above 1.0 g/cm³ which indicates that for the majority of the time since initial formation it could be characterized as a small pond, an environment in which mineral sediments accumulated with little organic matter. PCD-5 also contains a stratum of fine well-sorted sand with low organic content that may be eolian in origin. In contrast, the sediments contained in PCD-6 are best
characterized as mucky peat (lower bulk density, higher organic content) that grades into mucky sediments and then into lake sediments (higher bulk density, lower organic matter) in the intermediate depths of the core. These lake sediments grade back into transitional sediments toward the bottom of the core.

Sediment accumulation rates vary between different parts of the cores but in general the sedimentation rates (and therefore temporal resolution) are high, and in the upper parts of the cores are very high (<5 yrs/cm). This is comparable to (if not more rapid than) the most rapid sedimentation rates seen in bogs and fens elsewhere (Gill 2002; Malmer and Wallen 2004; Sullivan and Gilmore 2005; Taylor 2003; Williams 2005). Not only does this level of temporal resolution approach that of tree-ring records but the temporal depth exceeds previously reported tree-ring records on the plains and plains margins by a factor of two or three (Cook et al. 2004; Cook et al. 1999; H. Weakly 1962; W. Weakly 1971; Woodhouse et al. 2002).

**Peat humification, organic matter and bulk density**

The results of humification, organic material, and bulk density determinations of the sediments from PCD-5 and PCD-6 are presented graphically in Figures 11 and 12. In ombrotrophic (precipitation fed) bogs, there is a trend toward greater decomposition of peat with depth which requires that the data be de-trended prior to interpretation (Ellis and Tallis 2000; Langdon et al. 2003; Mauquoy et al. 2002). However, this does not seem to be the case in the peat records contained in the pocket fens and therefore there is no need to de-trend the data prior to interpretation. Several episodes of higher percent transmittance and lower organic matter interpreted as cool/wet periods and episodes of lower corrected percent transmittance and higher organic matter that are interpreted as warm/dry periods are represented in the data. These episodes are also recognized in cores from Chico Basin Ranch approximately 10 mi. (16 kilometers [km]) northwest of the Depot (Gilmore 2006; Gilmore and Sullivan 2006; Sullivan and Gilmore 2006) and in high elevation peat records from Grand Mesa on the Western Slope of the Colorado Rockies (Sullivan and Gilmore 2006). The differences between the sediments of the two fens are readily apparent. The sediments in PCD-5 reflect the wetter and less organically productive depositional environment of a small pond with the amount of organic material (both percent and total grams) being much less than that in the peaty sediments of PCD-6. Bulk density also reflects the consistently higher mineral sediment content throughout the profile of PCD-5. Humification analysis was not performed on the sediments from PCD-5 due to the low organic content.
Figure 11. Percent organic matter, grams organic matter, and bulk density for PCD-5.

Figure 12. Percent transmittance (organic material corrected), percent organic material, grams organic material, and bulk density for PCD-6.
Because the measure of humic acid in a sample is in part controlled by the proportion of the sample that is organic material, a correction factor must be applied to the percent transmissivity data to control for the effects of changing amounts of organics. This is accomplished by dividing the %T by the percent organic material (%OM) of the sample (Blackford and Chambers 1993). This technique seems to work well for the high organic content peat from ombrotrophic bogs that European workers are examining, and it also works in larger high elevation minerotrophic fens on Grand Mesa (Taylor 2003; Sullivan and Gilmore 2005, 2006). When the organic content of sediments exceeds approximately 70%, most of the physical characteristics of the sediment (such as bulk density) are equally dependent on the amount of organic material and mineral content in the sediments (Figure 13). Thus, dividing %T by %OM is an appropriate method of correction. However, the organic content of the peat and mucky peat contained in the eastern Colorado pocket fens rarely exceeds 60%, and most of the peat recovered from pocket fens have mean organic percentages of between 20% and 40% organic content. Therefore, the characteristics of these sediments (including percent organic content) are much more dependent on mineral sediment content (Figure 14). Because the percent organic content in these sediments is in essence controlled by the mineral content, dividing %T by %OM does not provide a suitable correction. However, the actual amount of organic material in each sample (g OM) is more independent of the mineral content of the sediment (Figure 15). This correction has been used elsewhere with good results (Roos-Barracough et al. 2004), and is the correction used in this report. This correction is expressed as percent transmittance corrected by grams organic material or %T/OM.

Different climatic episodes are manifested differently in the characteristics of the different sediment classes in the PCD cores. Particle size and percent mineral sediments represented by bulk density and sedimentation rates are affected by climate (Figures 8 and 9). In keeping with the model outlined by Forman and Maat (1990) discussed above, higher rates of sedimentation in PCD-5 and PCD-6 are generally associated with warm, dry conditions although sediment input into fens seems to come mostly through slopewash and not eolian deposition. In sections of peat

![Figure 13. Relationship between bulk density and mineral content in grams (left) and organic content in grams (right) of peat at Church Camp Fen, Grand Mesa, western Colorado. In fen sediments that contain over 70% organic material, the relationship between mineral ($R^2=0.6694$) and organic ($R^2=0.4853$) sediments to bulk density are relatively equal, and higher than approximately 90% organic content percent mineral content becomes dependent on organic material content.](image-url)
and mucky sediments, warm, dry episodes are characterized by higher values of percent organic matter and low bulk density which is interpreted as greater organic production within the fen and faster accumulation of organic material as peat. Warm, dry episodes are characterized in lake sediments by relatively high bulk densities, low sedimentation rates, and coarser mineral sediments. The coarser mineral sediments are interpreted as representing greater sediment availability due to decreased vegetation cover within the drainage basin the fen occupies. Decreased vegetation cover allowed for the mobilization and transport of coarser sediments by slopewash driven by more intense precipitation from the stronger convection storms associated with warmer summer temperatures. Slower sedimentation rates and higher bulk density is due to both the reduced organic production in ponds compared to fens, and overall decreased precipitation and greater runoff due to shorter, more intense episodes of precipitation.
Cool, wet episodes also manifest themselves differently in different portions of the core. These episodes are characterized in sections of peat by lower sedimentation rates and higher bulk densities, which are interpreted as representing generally lower organic productivity in fens and low sediment availability due to increased vegetation cover within the drainage basin outside of the fen. Cool, wet episodes in lake sediments are also characterized by low sedimentation rates and high bulk density with mineral sediments dominated by fine sand. As with cool and wet episodes in peat, these characteristics are interpreted as representing both the lower productivity of ponds and the relative lack of sediment availability due to greater vegetation cover in the drainage basin.

Data Processing and Display

In order to derive more meaningful and nuanced interpretations of the records provided by pocket fens, the heterogeneity of the sediments needs to be addressed. Compared to larger fens and bogs whose sections of organic sediments are relatively homogenous, pocket fens represent smaller, more dynamic systems whose hydrological and sedimentological characteristics vary more widely through time than larger peatlands. Although the physical characteristics of peat (bulk density, percent organic matter, fiber content and level of decomposition, and particle size distribution among others) vary along a continuum, relatively steady states in the history of the fen are apparent in the data and can be characterized by certain definable ranges of sediment characteristics. In both of the analyzed cores from the PCD fens, sediment characteristics vary diachronically in the same fen and synchronically among different fens between peat, mucky sediments, and lake sediments. These differences among fens are most likely tied to non-climatic factors.

Non-climatic factors that could influence the depositional regime in fens could include (but are not limited to) characteristics of the aquifer affecting individual spring discharge such as the orientation and composition of paleochannels within the aquifer or the topography of the aquitard surface favoring greater discharge in some fens over others. Other factors include differences between fens in the rate of development and the length of time spent in different developmental stages (seral succession) related to initial basin morphology at fen inception or geomorphic agents such as reactivation of landslides causing deepening of the fen basin or size and morphology of the surface drainage basin the fen occupies. All of these factors could individually or in conjunction effect the nature of the sediment record in a particular fen and consequently obscure the recognition of the climate signal and complicating the interpretation of the record.

In order to compensate for these individual variations in fen environment and response, the sediments in segments of the core were characterized as peat, mucky sediments or lake sediments according to the criteria outlined above, and then means and standard deviations for percent organic matter (%OM) and percent corrected transmittance (%T/OM) were calculated for these different sections of core. This was done in an attempt to filter out most of the larger idiosyncratic variations in the data exclusive to the fen being studied which then allows for the climate signal to be isolated from the data noise that obscures it. These statistics were then used to determine deviations above and below the mean for each section of the core. These results were used to construct diagrams that display color coded divergences of the data above and
below the mean, as well as darker colors that signify significant deviations (greater than one standard deviation above and below the mean). This graphic display of the data makes the length and relative intensity of past climatic deviations explicit.

Care should be exercised in making interpretations based on the significant deviations that occur at transition points between one sediment type and another. Unless the transition between sediment types is abrupt (which does occur at some transitions), extreme deviations from the mean on both sides of the transition (both above and below the mean) are inevitable. Therefore, the strength of the data immediately adjacent to transitions, and consequently the interpretations of climate based on these zones, is by nature not as powerful as the data and interpretations from the parts of the core representing more stable depositional regime.

Endeavoring to control for the effects of local conditions on fens and the unique sedimentary records that result from these local conditions, it is obvious that the sediments from PCD-5 and PCD-6 provide a record of warm/cool temperature episodes in the organic material records and wet/dry periods in the humification record of PCD-6. These reflect the dynamic nature of the climate of the past 3000 years on the High Plains of eastern Colorado (Figures 16 and 17).

Figure 16. Organic material curve for PCD-5, corrected for sediment characteristics and utilizing the linear interpolation age-depth model. Mucky and lake sediments are displayed at an expanded scale to show greater detail of events documented in these parts of the core. Lighter red shows higher than mean values and dark red shows values greater than one standard deviation above the mean, interpreted as warm temperature events. Light blue and dark blue show values below the mean and one standard deviation below the mean and are interpreted as episodes of lower temperature.
Although the correlation associated with the second order polynomial age-depth models for both cores is significant, the lack of intercept with the two-sigma ranges of three of the five calibrated dates on the PCD-6 core suggests that there may be problems with this model. The first possibility is that there are insufficient dates on the core to provide enough data points for the model. This could be remedied with additional AMS dates. Another problem may be that due to the heterogeneity of the sediments in pocket fens, they are not as amenable to models generated for the relatively homogenous sediments found in larger and more stable depositional features such as the ombrotrophic bogs used previously in analysis of paleoclimate. A single model may not be adequate to describe the depositional complexity of sediments reflecting the relatively rapid shifts back and forth between different hydrologic regimes and associated depositional environments observed in pocket fens. Due to these difficulties, the linear interpolation age-depth model was used to generate the graphs used for the paleoclimatic interpretations herein. Even though the linear interpolation model assumes a constant rate of deposition between dates, (which is obviously a gross oversimplification), it presents the best option on which to base interpretations of the sediments at this point. Hopefully additional dates will be obtained that will help to refine the chronology of the paleoclimatic records contained within these cores.
Discussion

The corrected transmittance, organic content, and changes in lithology coupled with the AMS dated stratigraphy from PCD-5 and PCD-6 provide a continuous, high resolution record of paleoenvironment for the last 2800 years that is unlike any other currently available for the western High Plains. The High Plains is a region for which few paleoenvironmental records exist, and the late Holocene is a time period for which little high resolution sedimentary data is available. Cores from other fens in the Chico Creek basin north of the Depot at Chico Basin Ranch also provide comparable records. Cores from both of these localities offer a record of major climate shifts of the past 3000 years that would have had a significant effect on the lives of the prehistoric occupants of the region, and they also document recent changes in climate that are affecting the current human inhabitants of this region. The PCD cores provide a record of climatic episodes that have been recognized elsewhere but never before in the same record or in this region. These climatic episodes are discussed below, and the graphic representation of these interpretations is found in Figure 18.

Periods of Warmer (ca. 850-700 BC, 2800-2650 BP), and Cooler (ca. 425-650 BC, 2375-2600 BP) Temperatures

These periods of hypothesized warmer and cooler temperatures occur at the bottom of the PCD-5 core, before organic sediments began accumulating in PCD-6. The episode of warmer temperatures is thought to correlate to a period recognized elsewhere that was characterized by persistent warm, dry conditions on the plains that lasted from approximately 1000 BC to AD 350-450. There is wide spread evidence for this episode on the plains and elsewhere. A period of dune reactivation and eolian deposition is documented in northeastern Colorado 3000-1500 BP (1050 BC-AD 450) (Madole 1995, Muhs 1985). Discontinuous eolian deposits on the Kuner and Kersey terraces in the Kersey area on the Colorado Piedmont are dated 3230-2290 BP (1280-340 BC) (Jepson et al. 1994: Table II; McFaul et al. 1995). At Bayou Gulch south of Denver, eolian deposition was initiated prior to 3400 BP and had ended prior to 1660 BP (cal. 1700 BC-AD 400) (Gilmore 1991). To the north, an episode of dune reactivation is documented 3000-1500 BP (1050 BC-AD 450) in the east-central part of the Nebraska Sand Hills (Ahlbrandt et al. 1983). Forman et al. (1992, 2001: Figure 13) summarize widespread episodes of dune reactivation and eolian deposition on the Great Plains beginning 2000 years ago. However, in eastern Colorado, Nebraska, and western Kansas these episodes were initiated 500-1000 years earlier, ca. 3000-2500 BP (1050-550 BC) which indicates that this recognized period of aridity involving the entire Great Plains may have begun 500-1000 years earlier in the Central and High Plains.

Locally, this episode in the PCD-5 core correlates with a similar double-peak signal in the record from Burnt Creek Fen at Chico Basin Ranch dated 1000-650 BC (2950-2500 BP). The timing of this event is problematic in both cores; the chronology of this part of the PCD-5 core is extrapolated from a date 56 cm above the end of the event, and the correlative event in the Burnt Creek Fen sediments is in a part of the core where the chronology is interpolated between a date of AD 1826 and 2880 BC at 238 cm. Also complicating the chronology, there is a 500-year difference between the linear and second order polynomial age-depth models for the extrapolated basal date for the PCD-5 sediments, which makes extrapolations to the base of this record
problematic. Given the dates presently available for the core, it is difficult to correlate these episodes with any regional chronology.

As with the episode of hypothesized warmer temperatures that precedes it, the dating of an episode of cooler conditions documented in the PCD-5 data is also somewhat problematic. This episode predates the beginning of the PCD-6 record, and a correlative episode does not occur in the record from Burnt Creek Fen or any other regional record. This suggests that these data may represent a depositional environment specific to PCD-5 rather than a regional deviation of climate.

Figure 18. Percent transmittance (corrected) and percent organic material data from PCD cores, with interpretation of paleoclimatic episodes.
Terminal Archaic Drought (ca. 50 BC-AD 375, 2000-1575 BP)

The data from both PCD-5 and PCD-6 suggest a period of severe drought previously unrecognized in records from eastern Colorado. This episode is here designated the Terminal Archaic Drought (TAD) because it corresponds to the transition in eastern Colorado from the Archaic period to the Late Prehistoric period. The Archaic was characterized by low population, high mobility, and technological stability, whereas the Late Prehistoric period was characterized by increased population, decreased mobility, the appearance of new technologies in the archaeological record (such as the addition of the bow and ceramics), and changes in economy, social structure and ideology (Gilmore 1999, 2007; Zier and Kalasz 1999). Although the signal in both cores is significant, the length of the TAD varies considerably between the two cores. This may be an artifact of data processing associated with the division between lake sediments and mucky sediments in the PCD-5 core, or it could simply be an error in the chronology that could be corrected by obtaining AMS dates in both cores that bracket this episode. Contrary to the evidence presented by the data from PCD, evidence from both geomorphic and archaeological sources in the Arkansas Basin suggest it was a period in which no dramatic environmental change was evident (Painter et al. 1999).

The TAD falls close to the end of the 1500 year period of arid conditions characterized by dune reactivation and eolian deposition documented for eastern Colorado, Nebraska and western Kansas discussed above. However, this episode as expressed in the data from PCD (as well as Burnt Creek Fen) can be characterized as the longest and most severe drought documented for the 2800 years represented by the PCD cores, and in fact is the most severe drought documented during the 7800-year record from Burnt Creek Fen (Gilmore and Sullivan 2006). In the PCD-6 data, this episode exhibits two peaks in the percent corrected transmittance and percent organic material curves separated by an intermediate return to more mesic conditions. Although not previously documented in eastern Colorado, the TAD is recognized (not by this name) as a regional phenomenon (Woodhouse and Overpeck 1998), and has been documented in records of lake salinity on the Northern Plains (Laird et al. 1996, Laird et al.1998; Fritz et al. 1993, Fritz et al. 2000) and tree ring records in northwestern New Mexico (Grissino-Mayer 1996). One of the problems that limit regional correlation is the paucity of continuous climate proxies that extend earlier than approximately AD 1000.

Culturally, the TAD covers one of the most dynamic periods in the prehistory of eastern Colorado. During this period, human population (as inferred by proxy) is beginning to increase at a rate much faster than anytime during the past 10,000 years. The frequency of radiocarbon dates through time has been used as a proxy for prehistoric population trends (Gilmore et. al. 1999, Reed and Metcalf 1999, Zier and Kalasz 1999). Calibration of radiocarbon ages using the shareware program CALIB version 5.0 (Stuiver and Reimer 1993; Stuiver et al. 1998) allows for the generation of summed probability curves that more accurately reflect the distribution of radiocarbon ages in time than the frequency of radiocarbon ages by century. Summed probability curves generated from calibrated radiocarbon dates have been used to document more subtle trends in population (Benedict 1999; Cobb and Butler 2002; Gilmore 2005, 2007). A comparison of the proxy population curve (summed probability distribution of radiocarbon ages) for the portion of the Arkansas Basin east of the mountains and the hypothesized climate record from the PCD cores is presented in Figure 19.
Figure 19. The summed probability distribution curve (proxy population) for the plains portion of the Arkansas River Basin, eastern Colorado with cultural chronology for the area (Zier and Kalasz 1999), compared to paleoclimate episodes. The boundary between the Late Archaic period (blue), and the Developmental period (light yellow) defines the Archaic-Late Prehistoric transition.
Examination of the data set for the portion of the Arkansas River Basin on the plains suggests that the rate of natural population increase was low from the end of the Pleistocene to just before the end of the Late Archaic period (ca. 200 BC) when the number of radiocarbon ages and sites began to increase dramatically. It is this hypothesized increase in population that is thought to have been a major causal factor of the culture change observed in the archaeological record. This increase in population may be the result of a long-term exponential trend in population that commenced when humans first entered the New World at the end of the Pleistocene and was manifest as an exponential progression only when population reached critical size which in eastern Colorado was just prior to the end of the Late Archaic Period.

Coincident with population growth during the TAD, there is also an apparent intensification of the use of wild resources that begins during the early Developmental period and progresses toward the end of this period (ca. AD 800-900) when corn appears in the archaeological record. Many theories seeking to explain what drives the change from a hunting-gathering subsistence system to food production are variations on a theme, explaining the origins of food production and subsequent intensification as a response (at least in part) to population pressure (Binford 1968; Boserup 1965; Cohen 1977), or population “packing” within environmentally or socially circumscribed areas (Binford 1983). Although determining cause and effect relationships between culture, technological and economic innovation, and population is problematic, it is obvious that there is often a correlation between population and the adoption or invention of technologies and other cultural changes observed in the archaeological record. Within a model of population growth as the forcing mechanism, innovations are assumed to have been adopted because they impart increased efficiency in the procurement and processing of resources (such as the introduction of the bow and ceramics) or because of the need to supplement existing resources (such as the adoption of limited corn horticulture).

An extended period of severe drought coincident with exponential increase in population would have provided an additional forcing mechanism that would make imperative cultural innovation and/or group fission and migration. As regional population increased and filled available territories, out migration would become less of an option, and the fissioning of groups would result in an increased number of social groups with smaller territories and less access to critical resources, eventually forcing the adoption of technological innovations. Many of the technological innovations that define the Late Prehistoric period are related to increased efficiency in resource procurement (the bow) or increased efficiency in the processing of less calorically dense resources (ceramics). Ceramics allow more efficient processing of less nutritionally valuable resources such as small seeds, and efficient boiling allows for greater nutrient availability in some foods. Drought caused resource shortages would only serve to accelerate the acquisition of technological innovations.

**Audubon Advance? (ca. AD 525-660, 1425-1290 BP)**

This episode of significantly increased effective moisture and decreased temperature is correlated to similar but lower magnitude wet events documented on the Northern Plains of North Dakota at AD 575-625 (Laird et al. 1996) and at AD 575-650 in the tree ring record from northwest New Mexico (Grissino-Mayer 1996). In Colorado, this episode is correlated to the Audubon advances of the Holocene cirque glaciation chronology of Benedict (1973, 1981, 1985). Moraines of Audubon age are uncommon and where they have been found they are...
small. This episode is characterized as a period when summers were cool and winters were snowy, resulting in an expansion of areas of persistent snow cover without the wind drift concentration of snow in cirques that resulted in the expansion of cirque glaciers (Benedict 1981:118).

The PCD-6 record indicates that conditions were significantly cooler and wetter during this episode. However, the record from PCD-5 indicates that this episode was somewhat cooler than average but actually warmer than the previous and subsequent two centuries. This suggests that these data may represent a rare period of local environmental conditions that favored the hydrologic regime of PCD-6 and not PCD-5. However, regardless of whether conditions were significantly cooler and wetter or warmer and wetter at this time, it comes in the middle of an extended period of slightly above average effective moisture on the plains that lasted over 300 years from the end of the Terminal Archaic Drought (ca. AD 660) until the beginning of more arid conditions that commenced at ca. AD 975 with the beginning of the Medieval Warm Period.

During this period (AD 660-975), population in the Arkansas basin was growing rapidly which would be expected during an episode of increased effective moisture. Increased effective moisture should result in more abundant resources and thus increased carrying capacity. Increased carrying capacity coupled with the relatively recent development of more efficient technological and social adaptations to resource scarcity during the Terminal Archaic Drought would have allowed for relatively rapid population growth unchecked by environmental constraints.

**Medieval Warm Period (ca. AD 975-1250, 1025-700 BP)**

The records from PCD-5 and PCD-6 both contain strong signals for an episode of significantly decreased effective moisture and increased temperature that correlates to the Medieval Warm Period (MWP), an episode that is recognized in paleoclimate records throughout North America and Europe (Bradley 2000; Broecker 2001; Cook et al. 2004; Cook et al. 1999; Daniels and Knox 2005; Laird et al. 1996; Mann and Jones 2003; Meeker and Mayewski 2002; Pederson et al. 2005; Woodhouse and Overpeck 1998; Woodhouse et al. 2002). There is question whether the MWP was global in scale, and whether it was characterized by uniformly warm temperatures (Bradley 2000; Broecker 2001).

The signals correlated to the MWP in the PCD cores show strong and significant deviations above the mean in temperature throughout the period. This significant warmth is accompanied by a period of significantly below average effective moisture that is shorter than the episode of increased temperature that lasted from AD 975-1075. From AD 1075-1175, effective moisture is close to the mean or even slightly above it. From AD 1175-1225, effective moisture is below average, but not significantly so, while temperatures are still significantly high. The association of high temperatures with average to above average effective moisture may indicate a period of time when higher temperatures did result in significant strengthening of the effects of the NAM to the point where monsoon driven summer precipitation was sufficient to overcome the increased evapotranspiration rates brought about by increased temperatures.

During the MWP, human population on the plains of the Arkansas Basin continued to increase. Although drought during the first century of the MWP was significant, it was insufficient to
cause a drop in population due to out migration. It is during the initial century of the MWP when drought conditions were the most severe that relatively mobile people of the Developmental Period begin to aggregate into small villages that were occupied at least part of the year. Aggregation, increased sedentism, and the occupation of small villages of masonry houses all characterize the Apishapa Phase of the Diversification Period (Zier and Kalasz 1999). It is also during the Diversification Period that corn becomes much more common and is found in greater quantities than during the previous Developmental Period. This increase in corn corresponds to the period AD 1075-1175 when temperatures were high but effective moisture was also above average, a combination of conditions that would have been ideal for corn horticulture. Either aggregation or dispersion of population can be adaptations to decreased carrying capacity and resource stress. Populations may aggregate in times of stress and the aggregation of population observed in the larger Apishapa phase sites has been attributed to increased competition for fewer resources brought about by drought (Zier and Kalasz 1999:207). Aggregation of population and increased reliance on cultigens are characteristics of the Apishapa phase that may represent a cultural response to increasing resource stress and social circumscription related to deteriorating climate and decreasing carrying capacity associated with the first century of the MWP.

Short episodes of increased temperature and decreased effective moisture that occurred during an otherwise cool/wet period documented in the PCD cores may correlate to the tenth century and late thirteenth century droughts recognized in the Four Corners area that affected population movements and ultimately contributed to abandonment of the region by the Ancestral Puebloans (Adams and Petersen 1999). However, the present chronological control on these portions of the PCD cores is insufficient to discern these short-term episodes. In the core from Blue Tub Fen at Chico Basin Ranch, a spike of lower than average effective moisture between two episodes of increased effective moisture and lower temperature is dated to AD 1290 which agrees with the timing of the late 13th Century drought that contributed to the abandonment of the Four Corners by the Ancestral Puebloans. A refined chronology provided by additional AMS dates on the lake sediments section of the PCD-6 core could clarify these associations.

*Little Ice Age (ca. AD 1250-1860, 700-90 BP)*

Immediately following the MWP, there is an extended episode in the records of both PCD cores of significant increased effective moisture and decreased temperature that is correlated with the Little Ice Age (LIA). Like the MWP, the LIA is recognized throughout North America and Europe (deMenocal et al. 2000; Mann and Jones 2003; Mauquoy et al. 2002; Meeker and Mayewski 2002; Pederson et al. 2005). This episode is recognized both by the expansion of alpine glaciers and by more general climatic changes. These changes are known to have had greater spatial and temporal heterogeneity than previously recognized (Fritz et al. 2000; Matthews and Briffa 2005) and there is evidence that suggests that global scale forcing mechanisms initiated and maintained this episode (O’Brien et al. 1995).

There is a considerable difference between the PCD cores in amplitude of the signal interpreted as the LIA. This difference is probably due to data processing. The general shape of both curves during this period is the same, but the mucky sediments in PCD-5 contain much less organic material than the mucky sediments in the PCD-6 core, resulting in the mean for organic material being much lower in the PCD-5 data than in the PCD-6 data. The net result is that a small
increase in the organic material in the PCD-5 core relative to the PCD-6 core results in data that suggest warmer conditions than during the same period in PCD-6.

The humification record for PCD-6 indicates several peaks of significant increase in effective moisture separated by periods of much dryer, but still relatively mesic, conditions. One or both of these decreases may correlate to the late fifteenth century “megadrought” documented in tree ring records for the Great Plains and Western United States (Woodhouse and Overpeck 1998). Although these episodes of greatly decreased effective moisture never drop below the mean for effective moisture, the drop relative to the data before and after is significant, and a decrease in effective moisture from very high levels to almost the mean suggests that these were significant drying events, the significance of which may be obscured by the mode of data processing and display.

Within a few decades of the initiation of the LIA, the population in the Arkansas Basin begins an apparent precipitous drop, and except for a short period of apparent stability or even slight increase from AD 1325-1400, continued to decrease until AD 1700 when the curve levels off until the end of the record. It is during this time of rapid population decline (ca. AD 1350-1450) that the Athapaskan speaking ancestors of the modern Navajo and Apache of the Southwest and southern Plains occupied the mountains and plains of Colorado east of the Continental Divide, eventually abandoning Colorado and joining populations in established territories to the south and southwest. It was both the depopulation of eastern Colorado and the cooling climate favoring people with a culture adapted to high latitudes that allowed small bands of Athapaskans to colonize Colorado at that time. These people were adapted to the high elevation environments that were similar to the high latitude environments of their homeland in northern Canada and interior Alaska. This allowed them to utilize portions of the High Country down to the foot of the Front Range that were only used intermittently by the dwindling resident Diversification Period populations of eastern Colorado. The slight increase in population ca. AD 1350-1400 may represent the entry of this population into the Arkansas Basin.

This last portion of the proxy population record is probably the least reliable section as the number of radiocarbon ages for the period after 250 BP are few in number and are approaching the useful upper limit of the method. Historic records and estimates of population suggest that the Native American population decrease did level out in the late nineteenth and early twentieth centuries. After 1900, census figures and other estimates of population suggest that Native American population began to increase after a sustained 400 year decline that in some regions of North America had bottomed out at 5% or less of precontact population (Ubelaker 1992).

**Recent Climate Change (ca. AD 1860-present)**

Comparison of multiple proxy records of paleoclimate and the instrument records of the past 120 years suggest that global temperature is increasing at a rate unprecedented during the Holocene (Mann et al. 1999; Mann and Jones 2003). This rise in global temperature has been attributed to increased atmospheric CO\(_2\) that is a byproduct of the increased use of fossil fuels associated with industrialization and the ubiquitous internal combustion engine. This global trend is reflected in both the instrument records from Pueblo and the PCD cores, and it is only here that the resolution of the core data begins to suffer by comparison to the sub-annual resolution of the instrument record. The instrument records from Pueblo (AD 1888-2005) show a definite upward
trend in summer temperature, and a slightly less obvious upward trend in summer precipitation (Figure 20). This increase in summer precipitation may reflect the strengthened effects of the NAM due to increased temperature.

The instrument record for Pueblo offers an illuminating example of the interaction and expression of regional climate versus local environment, how regional events may not be expressed locally, and how local events can be significant in their impact but not expressed on a regional scale (Figure 21). For instance, the Dust Bowl drought of the 1930s is the most significant drought in both magnitude and length documented in the instrument record for Pueblo. This episode consists of both a significant decrease in summer precipitation and a significant increase in summer temperature. However, other major regional droughts of the 1950s, 1970s and 1980s vary in their local expression and are not as significant as local events such as the drought documented for 1969-1971 in the Pueblo instrument record.

The instrument records of summer temperature and precipitation are not directly comparable to the records of percent organic matter and percent corrected transmittance data from the PCD cores. The instrument data is collected at an annual level of resolution whereas the data from the upper parts of the PCD cores are collected at a lower level of resolution; 5.78 year (yr)/cm at PCD-5 and 4.04 yr/cm at PCD-6. This reflects a relatively high sedimentation rate in both cores but even at a sampling interval of one cm the %T/OM and %OM values derived from sediment analysis are in essence running averages of annual data compiled for 4-6 year intervals. In order to compare the instrument data with the core data, running averages based on a 5-year interval (a compromise between 4.04 and 5.78 yr/cm) were calculated for the instrument data record for Pueblo (Figure 22). There are some similarities between the instrument and sediment records but there are also significant differences.

The records were graphed at approximately the same vertical scale so that deviations above and below the mean would be somewhat comparable. What is immediately noticeable is the deviations in the sediment record are much greater in magnitude than those documented in the instrument record. However when the annual instrument data in Figure 21 are consulted, it becomes obvious that this decrease in the magnitude of deviations from the mean in the five year running average is an artifact of the averaging function and not a reflection of the actual data. Another difference is that the sediment record shows much warmer and dryer conditions at the very top of the core versus the past 25 years of the instrument record, which documents an increase in temperature but also documents an increase in precipitation. This is probably due to the difference in what is actually being measured, not a basic disagreement between the two records.
Figure 20. Summer (June, July and August) precipitation (top) and temperature (bottom) for Pueblo, Colorado for the years 1888-2005. Trendlines for the data show a weak upward trend for summer precipitation and a much stronger upward trend in summer temperature. Data available at the National Oceanic and Atmospheric Administration (NOAA) website at www.crh.noaa.gov.
Figure 21. Instrument records for summer precipitation and temperature with above the mean and below the mean events for Pueblo, Colorado. Above the mean and below the mean events are indicated by lighter colors, and significant events (one standard deviation above or below the mean) are indicated by darker colors. Major twentieth century droughts, both regional and local in their extent, are also indicated.
Figure 22. Five-year running averages for summer precipitation and temperature for Pueblo, 1888-2005 compared with the upper 120 years (extrapolated) of the PCD-5 and PCD-6 cores. This period is represented in these cores by the upper 21 cm (PCD-5) and 30 cm (PCD-6).
Precipitation and effective moisture are two related but still different variables. Additionally, the proxy measure of effective moisture (as provided by humification analysis) is a relative rather than absolute measure of this variable. Despite these differences, the overall shape of the curves are remarkably similar, considering that the dates in the upper part of both cores are extrapolated from below and that even slight variations in sedimentation rate or small sampling errors over a short section of core could result in large differences between it and the instrument record. The signals documenting the major events in the instrument record, including the early twentieth century wet period and the Dust Bowl drought of the 1930s, are evident in the PCD core records even if the timing is not exact. A suite of lead (Pb) isotope dates on the upper part of the cores would greatly enhance the chronological control of the cores during the period for which historical climate records are available, and would possibly allow the core data to be calibrated using the instrument records.

Effective moisture is a function of both precipitation and evapotranspiration, the latter of which is dependent on temperature. The seeming contradiction between a simultaneous increase in precipitation with a significant decrease in effective moisture can be explained by the difference in the variables being measured. As shown above in Figure 20, the instrument data indicate that summer precipitation and temperature are both increasing, but temperature seems to be increasing at a much more rapid rate than precipitation. In this situation, rapid increase in temperature should result in increased evapotranspiration, and this increase could in turn completely negate the effects of increased precipitation, resulting in a net decrease in effective moisture as seen in the upper part of the PCD cores as well as the humification record on Grand Mesa (Taylor 2003). Though direct comparisons between the core data and the instrument data are perhaps not appropriate because of different variables being measured and the inherent difficulties in comparing relative and absolute values, the instrument data can be used to inform interpretations of the core data. One relationship the instrument data can help clarify is the one between temperature and effective moisture.

Changes through time in effective moisture can be seen in the relationship between temperature and precipitation. Despite the fact that the trend over the past 117 years in the instrument data for Pueblo is an increase in both summer temperature and precipitation, there is also a weak inverse relationship between summer temperature and precipitation with low summer precipitation correlating to high temperature (Figure 23). Although this relationship is not particularly strong ($R^2=0.1697$), it does validate the evidence from the %T/OM and %OM analyses that indicate most episodes of high humification (low effective moisture) are also episodes characterized by high percent organic material (high temperature). However, the relationship between %T/OM and %OM for PCD-6 is much more dependent ($R^2=0.8811$) than the one between summer temperature and precipitation (Figure 24), or the one between %T/OM and %OM in the high organic content peat from fens on Grand Mesa (Taylor 2003) where the inverse correlation between %T/OM and %OM is intermediate between the correlation between precipitation and temperature instrument data and the %T/OM and %OM data for PCD-6 ($R^2=0.0823$) (Figure 25).
Paleoclimatic Investigations at the Pueblo Chemical Depot, Pueblo County, Colorado

Figure 23. Inverse polynomial relationship between summer temperature and precipitation for instrument data from Pueblo, Colorado.

Figure 24. Inverse power relationship between humification and percent organic material in the sediments from PCD-6.
The relatively strong and dependent relationship between %T/OM and %OM on PCD-6 suggests that the proxy measurements of effective moisture and temperature in high mineral content peat from pocket fens may be as much a reflection of the mineral content of the sediment as a reflection of paleoclimate. This is especially apparent on the left side of the graph in Figure 24 where the lake sediments are plotted. The relationship between %T/OM and %OM is much stronger in lake sediments (<%5 OM) than it is in peat (>%12 OM). This suggests that the relative accuracy of the climate records from pocket fens increases proportionally to the organic content of the sediments. The conclusion is that peat records are going to more accurately preserve the signals that reflect the length and amplitude of climatic events, and the record of paleoclimatic signals within mucky or lake sediments should be considered less reliable. With this in mind, the greater percent organic matter and humification values observed in the upper sediments of both cores is unexpected as intuitively one would expect that the most recent peat would show the least amount of decomposition because it would have had the least amount of time to show signs of decomposition. This is not the case, and the significant signals for increased temperature and lower effective moisture in the uppermost portion of the core representing the past few decades suggests that anthropogenic climate change is significant and producing a strong signal in the PCD pocket fens.

Figure 25. Inverse polynomial relationship between humification (effective moisture) and percent organic material (temperature) data from Church Camp Fen, Grand Mesa (Taylor 2003).
Conclusions

This study has demonstrated the value of pocket fens to provide records of past climate dynamics that extends beyond the temporal and response ranges of other proxies available for the Great Plains. The records of paleoclimate presented here contain evidence of hemispheric and continental scale episodes of climate (i.e., the MWP and the LIA) as well as apparently smaller regional and local scale deviations (i.e., the TAD). New methods of data processing were developed that permitted the amplification of faint climate signals and at the same time allowed excision of data noise contained within the complex sediments deposited in these features. The recognition of new and relatively common sources for paleoenvironmental data opens up the possibility of investigating the way in which paleoclimate is expressed in diverse environments. The quantity and distribution of pocket fens in the Arkansas Basin and elsewhere in eastern Colorado and the quality of the records contained in them increases the potential of paleoclimatic research in semi-arid environments.
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