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Extended drought in the Great Basin of western North America in the last two millennia reconstructed from pollen records

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Abstract

There is growing evidence that within the last 2000 years western North America has had several droughts lasting >100 years. In this paper we review the pollen evidence from four sites that record evidence of drought within the Great Basin. We use pollen ratios between taxonomic indicators of wet and dry climate to interpret droughts and compare these records with submerged stumps, tree-ring chronologies, packrat middens, and δ^{18}O data from sediments. Pollen records provide evidence for long term changes that affect vegetation over a broad region. Studies in the Great Basin have identified four periods of low lake levels that have been interpreted as century long droughts, with drought termination dates at approximately 1800, 1200, 800, and 550 cal yr BP. Our pollen records indicate that the period between 2000 and 1800 cal yr BP was dry, with the driest sites being in the western Great Basin. The century ending at 1200 cal yr BP may have been dry, but the pollen record does not support severe drought. Both of our high-resolution pollen records, Pyramid Lake and Mission Cross Bog, clearly identify a drought ending ~800 cal yr BP., whereas only the Pyramid Lake record indicates a drought ending at 550 cal yr BP. Evidence for wet climate at this time in northeastern Nevada constrains the regional extent of this drought.

1. Introduction

The Great Basin contains many geological and biological archives that have been used to reconstruct Holocene climate change, including lake level changes in closed-basin lakes (Stine, 1990; Benson, 1993), analysis of δ^{18}O (Benson et al., 1997, 2002; Yuan et al., 2004) and pollen (Wigand and Rhode, 2002; Mensing et al., 2004) from lake sediments, tree-ring studies from long-lived conifers (LaMarche, 1973), macrofossil plant analysis preserved in woodrat middens (Wells and Berger, 1967; Spaulding, 1985), and dating of submerged stumps (Harding, 1935, 1965; Lindström, 1990; Stine, 1990, 1994). Climate reconstructions from these records have been correlated with hemispheric (Benson et al., 1997) and regional (Cook et al., 2004) climate change. The wide range of proxy climate records found within the Great Basin provide an important resource for reconstructing changes in past precipitation regimes which are critical for developing a better understanding of the potential for extended droughts in a region with growing water demands.

A number of studies have identified extended droughts in the Great Basin of western North America over the last 2000 years (Stine, 1990, 1994; Benson et al., 2002; Mensing et al., 2004). Recently, Cook et al. (2004) argued for an elevated period of drought in western North America between 1050 and 650 cal yr BP (900 AD and 1300 AD) with specific decadal droughts centered in 1015, 915, 800 and 695 cal yr BP (936, 1034, 1150, and 1253 AD). In this paper, all dates have been converted to calendar years before present (cal yr BP) using Calib 5.0 (Stuiver et al., 1998, 2005). Although each climate proxy has limitations in terms of chronological precision and interpretation, multiproxy efforts to reconstruct climate histories for broad geographic regions are an important contribution to climate research and can contain meaningful climatic signals (National Research Council, 2006).

Submerged stumps found in lakes and stream beds provided early evidence that dry periods of potentially one century or longer have periodically occurred within the Great Basin (Harding, 1935, 1965; Lindström, 1990; Stine,

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1990). Although droughts of long duration are given terms such as epic or mega-droughts, identification of climate and vegetation change on this time scale is challenging with pollen analysis. One problem in identifying change over a century or less using pollen analysis is that many species within the Great Basin are drought tolerant, and can survive long dry periods without significant changes in population. Typically, only the most severe or prolonged droughts can be identified with pollen analysis.

A second problem is one of sampling at high enough resolution to characterize short term change. Although there have been numerous pollen studies in the northern Great Basin, the majority of studies are analyzed at low resolution with samples about every 200–300 years (Mehringer, 1985; Thompson, 1992). High-resolution analysis requires sites where sediments accumulate at a rapid rate and such sites are uncommon in the Great Basin. Sites with high sedimentation rates allow us to identify climate change at decadal to century scale for comparison with tree-ring records and other proxy datasets. Sites with slow sedimentation rates, while still useful for expanding the geographical extent of climate change studies, typically cannot identify events lasting for only one century.

In this paper, we present data from four sites across northern Nevada including Pyramid Lake in western Nevada, Newark Valley Pond in eastern Nevada, and new data from Kingston Meadow in central Nevada, and a high-resolution record from Mission Cross Bog in northern Nevada (Fig. 1) and compare these records for evidence of droughts. Sediments in lakes, springs, meadows and fens collect pollen from local, extra-local and regional sources, depending on basin size, so that fossil pollen assemblages provide a record of regional vegetation that can be used to interpret regional climate change, particularly droughts (Jacobson and Bradshaw, 1981). Drought as used in this paper is defined as any extended period of time that affects plant growth sufficiently to be evident in the pollen record. We are not able to quantify the magnitude of the change in precipitation but are limited to identifying shifts towards wetter or drier climate. The relative magnitude of any one drought is characterized by the extent and duration of change. The purpose of this paper is to compare our pollen records with other proxy records of drought in the northern Great Basin of western North America over the last 2000 years in order to better understand their regional extent.

2. Great Basin pollen records

2.1. Pyramid lake

Pyramid Lake (1160 m surface elev., 119.5°W 40°N) is a closed-basin lake located in the rainshadow of the Sierra Nevada (Fig. 1). The primary tributary is the Truckee River, which has its headwaters on the eastern slope of the Sierra Nevada. One-third of the Truckee River's flow originates from Lake Tahoe. Most precipitation in the Sierra Nevada falls during the winter months (Houghton et al., 1975). Pyramid Lake lies along the ecotone between the saltbush (*Atriplex*) and sagebrush (*Artemisia*) vegetation zones (Billings, 1949). Saltbush (including a number of species in the Chenopodiaceae family, also referred to as shadscale) typically dominates where annual precipitation is <150 mm, whereas sagebrush dominates where precipi-

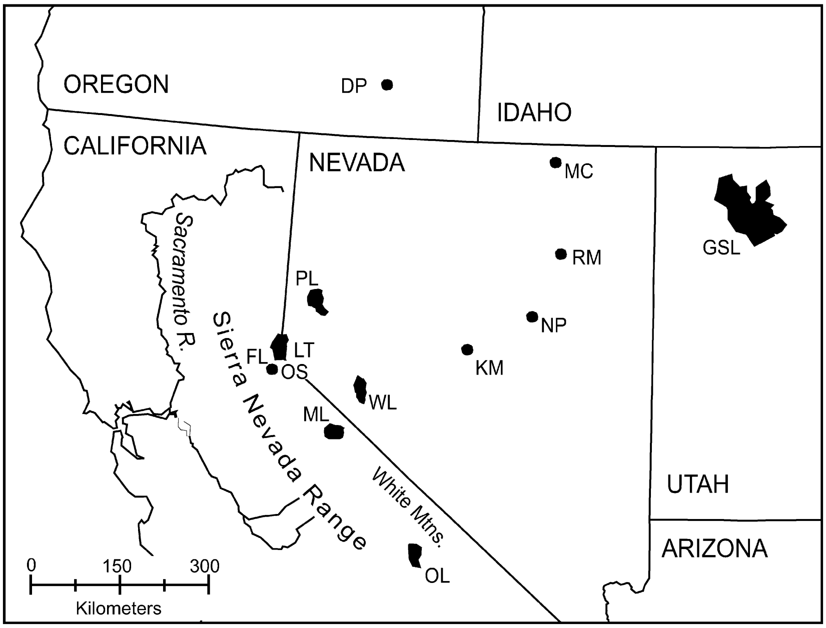


Fig. 1. Location map of sites mentioned in the text: DP, Diamond Pond; FL, Fallen Leaf Lake; GSL, Great Salt Lake; KM, Kingston Meadow; LT, Lake Tahoe; MC, Mission Cross Bog; ML, Mono Lake; NP, Newark Valley Pond; OL, Owens Lake; OS, Osgood Swamp; PL, Pyramid Lake; RM, Ruby Marshes; WL, Walker Lake.

tation is >180 mm. Vegetation on the western, wetter side of Pyramid Lake is dominated by big sagebrush (*Artemisia tridentata*). Previous studies have interpreted the sagebrush/saltbush ratio as a relative measure of available moisture (Byrne et al., 1979; Wigand, 1987; Mensing, 2001; Mensing et al., 2004).

Mensing et al. (2004) reconstructed a 7000 year record of drought at Pyramid Lake using the sagebrush/saltbush ratio as a proxy for lake-level change. Seventy 1-cm thick samples were analyzed for the core section spanning the last 2700 years with an average time between samples of 40 years (range 5–97 yr, s.d. = 19.4 yr). They demonstrated that Chenopodiaceae pollen was highest when lake level was low and a large playa surface became exposed, allowing saltbush to disperse into this habitat. Conversely, periods of wetter climate favored expansion of sagebrush and rising lake levels eliminated playa habitat. The signal was lagged 40–50 years due to the time required for plant succession onto the playa and expansion of the saltbush population. Since change in the sagebrush/saltbush ratio at Pyramid Lake was associated with periods when lake level dropped enough to allow saltbush to colonize the exposed shoreline, they inferred that minima in this ratio represented the most severe drought episodes.

Mensing et al. (2004) reported four periods of extended drought during the last 2500 years, from 2500 to 2000, 1500 to 1250, 800 to 725, and 600 to 450 cal yr BP (Fig. 2). Between 2500 and 2000 cal yr BP, the sagebrush/saltbush ratio repeatedly achieved minima comparable to those recorded during the middle Holocene (the driest period of the record) and equal to those in the historic period when Pyramid Lake fell 20 m because of water diversions. The three subsequent droughts were not as pronounced in intensity, but persisted for between 75 and 250 years.

2.2. Kingston meadow

Kingston Meadow (2400 m elev., 117.1°W 39.2°N) is a wet meadow dominated by sedge (*Carex rostrata* and *C. nebrascensis*), along a riparian system in the Toiyabe Range of central Nevada (Fig. 1). Surface water covers most of the meadow to a depth of approximately 10 cm. Castelli et al. (2000) identified four meadow types in the riparian zones of central Nevada. The meadow types are based on

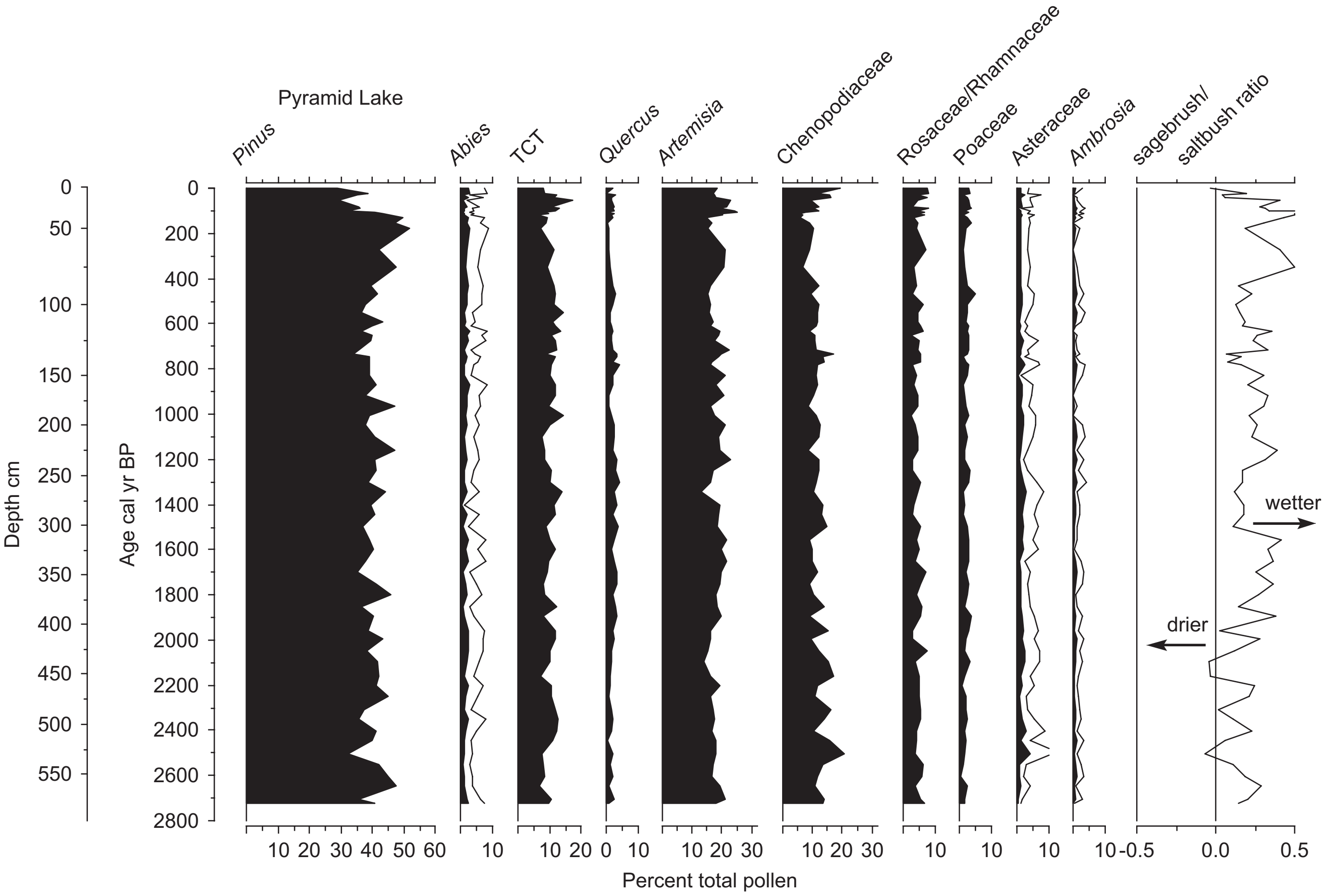


Fig. 2. Pollen diagram of selected terrestrial pollen types from Pyramid Lake (Mensing et al., 2004). The sagebrush/saltbush (*Aretmisia*/Chenopodiaceae) ratio is calculated as $(a-c)/(a+c)$, where '*a*' represents percent *Artemisia* pollen and '*c*' represents percent Chenopodiaceae pollen. Values range from +1 (*Artemisia* present and Chenopodiaceae absent) to −1 (Chenopodiaceae present and *Artemisia* absent), with 0 representing equal percentages of each pollen type. Positive values represent increased *Artemisia* (wetter climate) and negative values represent increased Chenopodiaceae (drier climate). Exaggeration line represents 3× exaggeration.

two basic criteria; indicator species and measured depth to water table. Although both sedge and grass can occur in all four meadow types, standing water supports abundant sedge and as depth to the water table increases grasses become more abundant (Castelli et al., 2000).

Depth to water table can be controlled by faulting or geomorphic features, such as alluvial fans (Chambers et al., 1998). Once these geomorphic features are in place climate becomes the key factor in determining a meadow's depth to water table. We calculated the grass (Poaceae) to sedge (Cyperaceae) pollen ratio as a measure of drought, with increased grass pollen indicating dry periods, and increased sedge pollen representing wet periods.

Radiocarbon dates for the Kingston Meadow core revealed a complex stratigraphy characterized by periods of nearly instantaneous accumulation of up to a meter of sediment and organic material (dating to 480 cal yr BP), followed by periods of very slow deposition (Smith, 2003). We speculate that periods of very rapid sedimentation are associated with debris flows during flood events, since these sediments contained woody fragments. For this study, we discuss twelve samples from the core section dating from 2600 to 480 cal yr BP (150–220 cm depth). The core was sampled at low resolution (10 cm intervals, 260 yr between samples), with higher resolution sampling between 190 and 210 cm (1–5 cm intervals, range 26–130 yr,) where sedimentation type changed rapidly. The breaks in sedimentation did not allow a continuous high resolution analysis, but the results identified one distinct drought centered about 2020 cal yr BP indicated by a sharp increase in grass pollen, a decrease in sedge pollen, and a change from peat to clay in the meadow (Fig. 3). Age-constrained alluvial chronologies from geomorphic studies of the watersheds in the region suggest that from approximately 2500–1900 cal yr BP dry conditions led to hillslope erosion, fan building and valley aggradation (Miller et al., 2004). These authors did not find evidence for downcutting or tectonic activity in the meadows at this time.

2.3. Newark valley pond

Newark Valley Pond (1750 m elev. 115.7°W 39.7°N) is one of many springs in Newark Valley located in central Nevada (Fig. 1) near the edge of a large playa and at the base of the eastern slope of the Diamond Range (3216 m elev.). The spring discharges into a ~7 m diameter pool and flows through a wet meadow into another pool approximately 20 m in diameter with a maximum water depth of 50 cm. The area is grazed and there is some evidence to suggest that the second pool is periodically maintained to provide water for livestock. The unique snail fauna found in many Nevada springs (Taylor, 1985) suggests that these springs have persisted continuously since the last glacial maximum, and in fact we obtained a

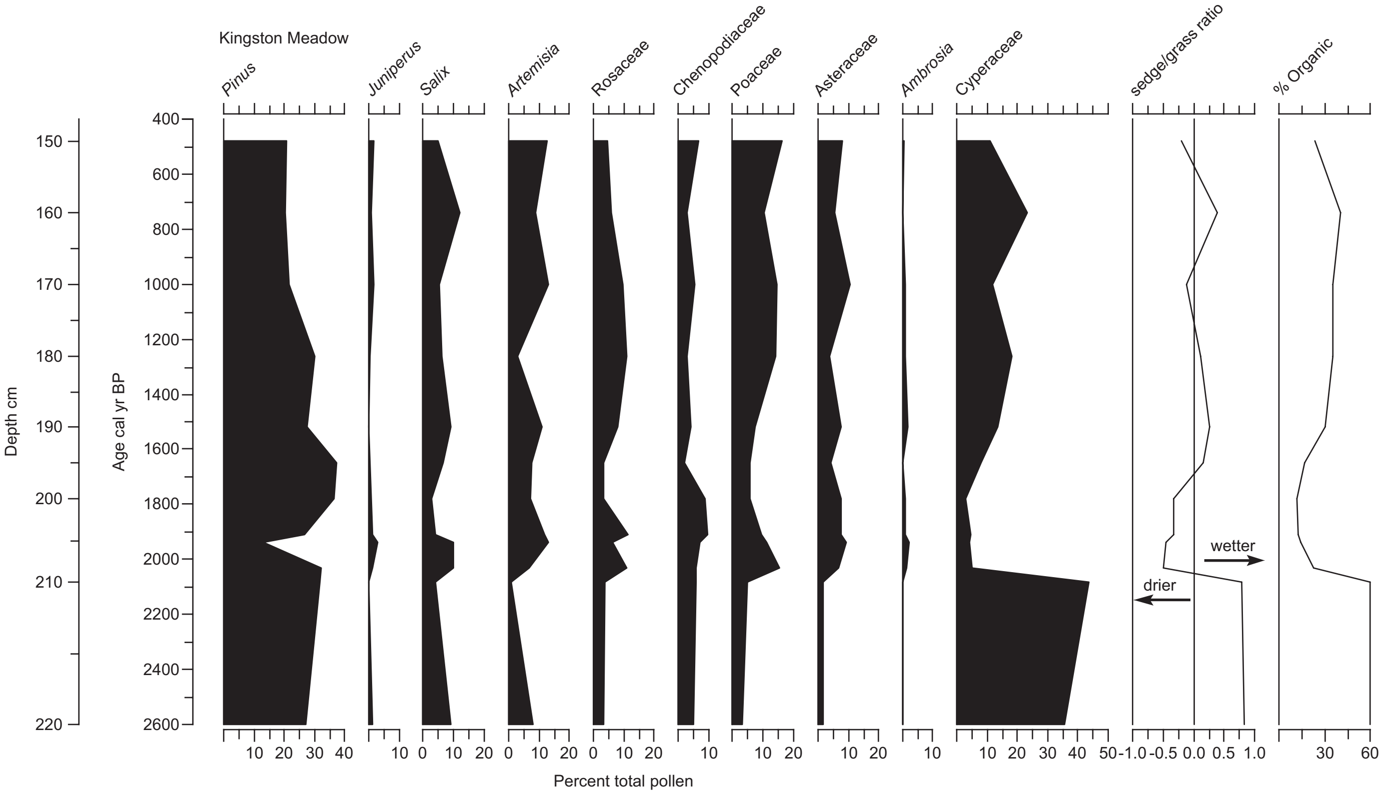


Fig. 3. Pollen diagram of selected terrestrial pollen types from Kingston Meadow (Smith, 2003). The sedge/grass ratio (Cyperaceae/Poaceae) is calculated as $(s-g)/(s+g)$ where s represents sedge pollen (Cyperaceae) and g represents grass pollen (Poaceae). Positive values represent increased Cyperaceae (higher water table and wetter climate) and negative values represent increased Poaceae (lower water table and drier climate).

radiocarbon age of 22,120 ± 90 ^{14}C (Beta 185018) at the base of a 340 cm long core (Mensing et al., 2006). The sedimentation rate for the upper 5,000 years was very slow (47–127 yr^{-1} cm^{-1}) resulting in a low-resolution record. In this study we present results from the analysis of 14 samples spanning the period from 3200 cal yr BP to the present. The typical sample interval was 3–5 cm, with an average time of 244 years between samples (range, 35–381 yr).

The vegetation around the pond and on the nearby slopes is dominated by sagebrush (*A. tridentata* var. *tridentata, A. tridentata* var. *wyomingensis*). The vegetation on the playa edge is dominated by two members of the Chenopodiaceae family, Bailey's greasewood *(Sarcobatus baileyii*) and shadscale (*Atriplex confertifolia*). We used the sagebrush/saltbush ratio as a measure of drought, similar to the Pyramid Lake study.

The sagebrush/saltbush ratio indicates that the climate shifted to drier conditions between 2500 and 2100 cal yr BP (Fig. 4). The next dry period in the record is centered on 1375 cal yr BP, after which there is evidence for a shift to wetter climate by 800 cal yr BP and remaining wetter through 600 cal yr BP before the record again shifts towards drier conditions. The duration of these dry periods is not well constrained and the magnitude of change is not large, but the timing of these shifts provides a picture of regional climate change in central Nevada.

2.4. Mission cross bog

Mission Cross Bog (2424 m elev. 115.5°W 41.8°N) is located at the junction of the Jarbidge and Copper Mountains within the Humboldt River drainage in northeastern Nevada (Fig. 1). Although named a bog, it is a fen maintained by groundwater flow throughout the year. The bedrock geology is rhyolite overlain by Tertiary age volcanic tuffs (Coates, 1964) that are susceptible to slumping and the Mission Cross Basin appears to have been created from slumping. The earthen dam holding the basin has been breeched in the past and today a beaver dam keeps the water level several meters above the outlet. A spring flows into the north end of the fen, which is nearly circular covering ~8 ha, but there are no inflowing streams.

The fen is located near the upper boundary of the sagebrush zone and the lower elevation of montane forest, dominated by *Pinus flexilis* (limber pine) and scattered *Juniperus scopulorum* (Rocky Mountain juniper). Also present are *Pinus albicaulus* (whitebark pine), and *Abies lasiocarpa* (subalpine fir). These are the lowest elevations in Nevada where subalpine fir and whitebark pine occur (Loope, 1969). The presence of *Abies*

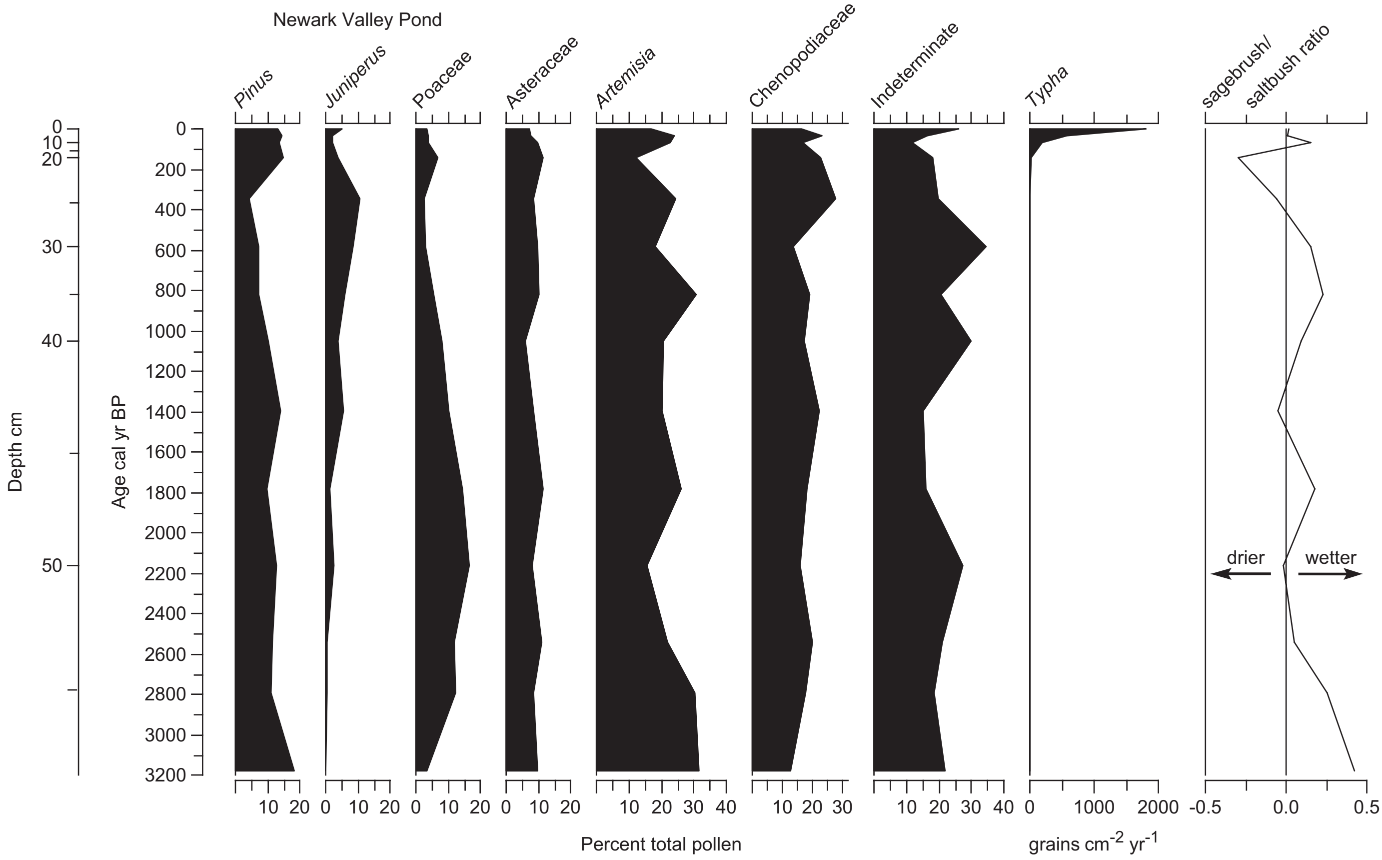


Fig. 4. Pollen diagram of the most common terrestrial pollen types for Newark Valley Pond adapted from Mensing et al. (2006). The sagebrush/saltbush ratio (*Artemisia*/Chenopodiaceae) is calculated as $(a-c)/(a+c)$ where '*a*' represents percent *Artemisia* pollen and '*c*' represents percent Chenopodiaceae pollen. Positive values represent increased *Artemisia* (wetter climate) and negative values represent increased Chenopodiaceae (drier climate).

lasiocarpa, and *Juniperus scopulorum* (species typical of the Rocky Mountains) and the absence of *Juniperus occidentalis* and *Juniperus osteosperma* (Great Basin species) identify this location to be transitional with vegetation from the north and west but not the south, and mark it as lying between the floristic Great Basin and the Rocky Mountains (Little, 1971). Species growing on the fen include sedges (Cyperaceae), *Menyanthes trifoliata* (bog-bean), *Pedicularis groenlandica* (elephant-head), *Thalictrum* spp. (meadow-rue), and *Salix* spp. (willow).

Thompson (1984) previously cored this site for comparison with a low-elevation pollen record from the Ruby Marshes, but restricted his analysis to a low-resolution study with samples on average every 250 years. His work yielded a record that appeared to be sensitive to climate change and he encouraged our reanalysis of the site at higher resolution. In 1997 we recovered a new 13.5 m core and analyzed the upper 520 cm (Allan, 2003). In 2004 we again cored the site, recovering a core of 17.8 m (Norman, 2007). Five radiocarbon dates obtained on the 2004 core allowed us to match the record with the 1997 core. Peat growth in the fen is very rapid ranging from 0.48 $\mathrm{cm^{-1}\,yr^{-1}}$ near the surface to 0.16 $\mathrm{cm^{-1}\,yr^{-1}}$ at the 520 cm depth, dating to 1910 cal yr BP (Allan 2003). Here we present results from 51 1-cm thick samples from the upper 710 cm spanning the period 2800 cal yr BP to the present. Samples were taken at intervals of 4–33 cm and average 55 yr between samples (range 13–207 yr, sd = 35 yr).

We used the ratio of conifer (*Pinus* and *Abies*) to sagebrush (*Artemisia*) as a measure of drought, with an increase in sagebrush indicating an upslope expanse of drought tolerant shrubs in association with a drier climate and an increase in conifers indicating an expansion of forests down slope during wetter periods (Fig. 5).

Periods when the conifer/sagebrush record show a dominance of sagebrush for at least 100 years occur at 2500, 2200, 1900, 1400, 1000, 800, and 450–250 cal yr BP (Fig. 5). Despite several potential droughts, the period prior to 2000 cal yr BP appears to have been wetter overall than the last 2000 years, with the most extended dry periods occurring during the most recent centuries. This contrasts with the Pyramid Lake record which is driest between 2500 and 2000 cal yr BP, with the more recent droughts appearing less severe. Mission Cross Bog has vegetation similar to the Pacific Northwest and Rocky Mountains and this shift may reflect changes in source areas for storms across this time period.

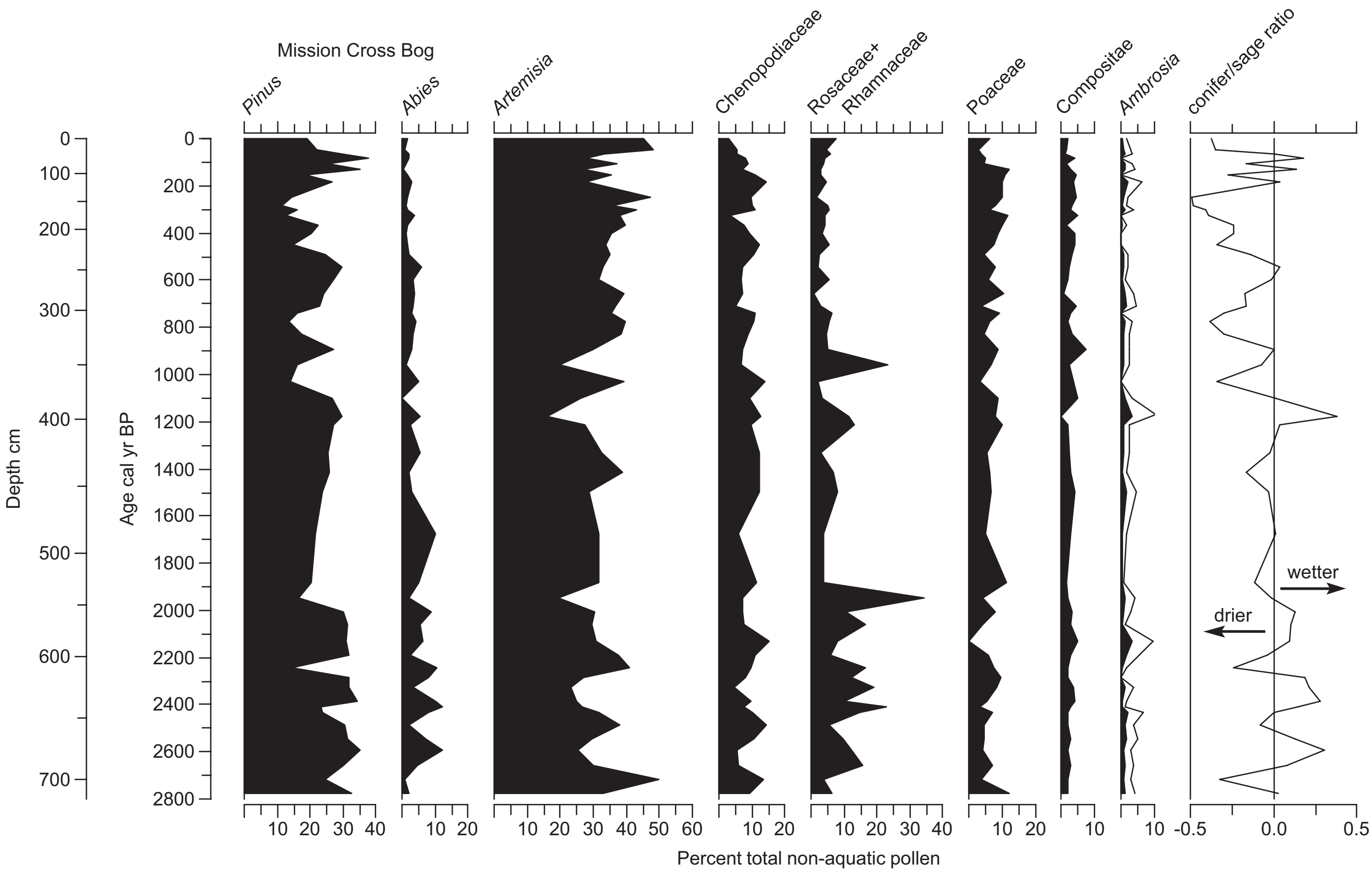


Fig. 5. Pollen diagram of the most common terrestrial pollen types at Mission Cross Bog, adapted from Allan (2003) and Norman (2007). The conifer/sagebrush ratio is calculated as $(c-s)/(c+s)$ where 'c' represents percent *Pinus* + *Abies* pollen and 's' represents percent *Artemisia* pollen. Positive values represent increased conifers (wetter climate) and negative values represent increased *Artemisia* (drier climate). Exaggeration line represents 3 × exaggeration.

3. Discussion

Lake-level studies in the western Great Basin have identified four periods of low lake levels that have been interpreted as century long droughts (Stine, 1990, 1994; Benson et al., 2002), with drought termination dates at approximately 1800, 1200, 800, and 550 cal yr BP (Fig. 6). Evidence that these lowstands persisted for >100 years comes primarily from submerged stumps with >100 annual growth rings. Droughts of this duration should be visible in high-resolution pollen records. We focus on the stump record rather than tree-ring reconstructions of drought because tree-rings are annually resolved and typically identify droughts at a decadal scale, which is below the resolution which can usually be confidently identified in landscape vegetation change.

3.1. *Drought period terminating ~1800 cal yr BP*

There are a number of lines of evidence to suggest that for the period ending ~1800 cal yr BP a number of sites across the Great Basin experienced extended drought in the Great Basin (Fig. 7). Sedimentary evidence of subaerially desiccated clays and stream gravels have been interpreted as a Mono Lake low stand with an interpolated termination date of ~1800 cal yr BP, constrained between dates of 1942 and 1535 cal yr BP (Stine, 1990). Sediments from Mono Lake contain sand layers and increased *Artemisia* pollen at 2400 cal yr BP, indicating lowered lake levels and a dry climate (Davis, 1999). LaMarche (1973) speculated that the lowering of treeline by about 30 m on Campito Mountain in the White mountains between 2500 and 2400 cal yr BP was in response to drier conditions. Woodrat

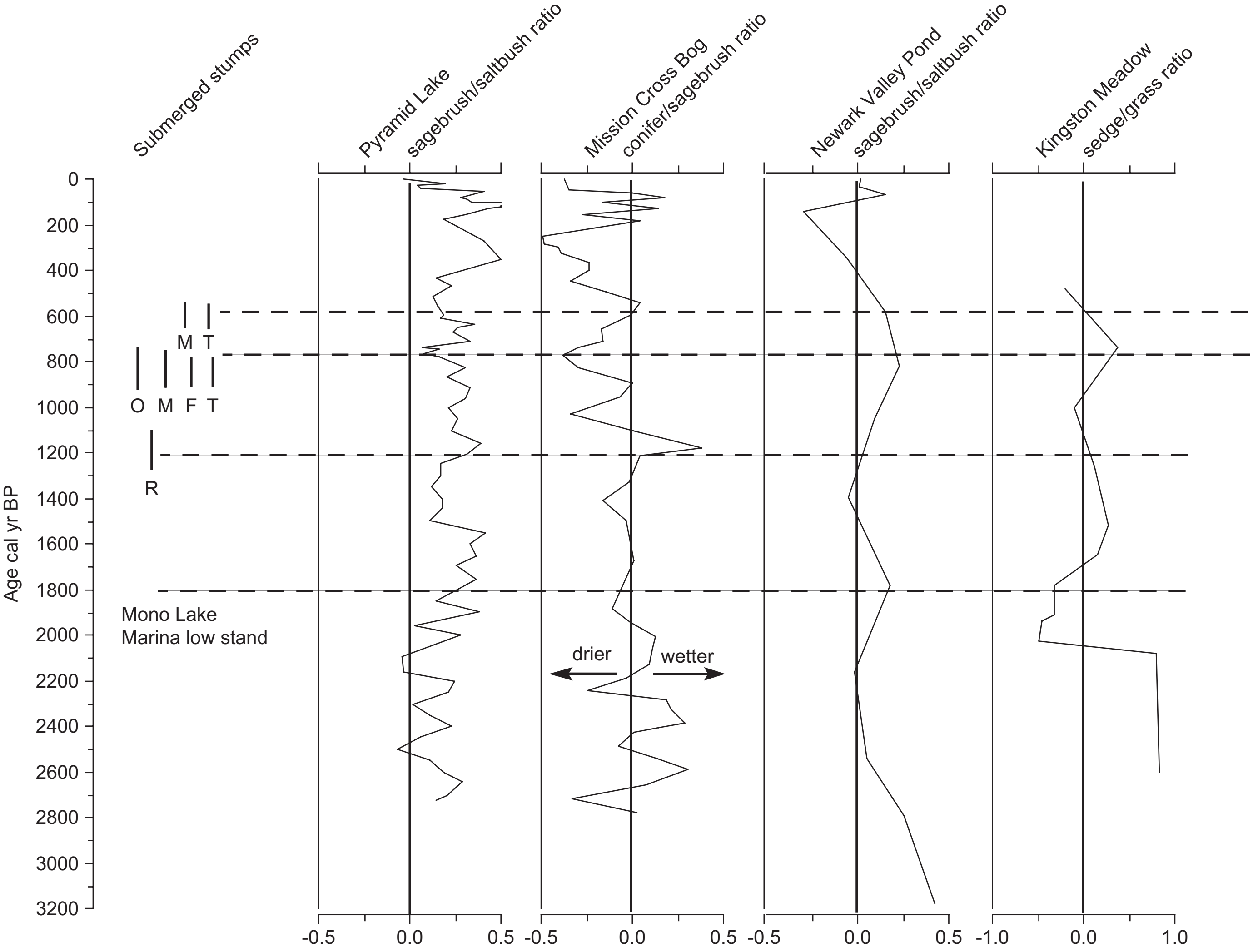
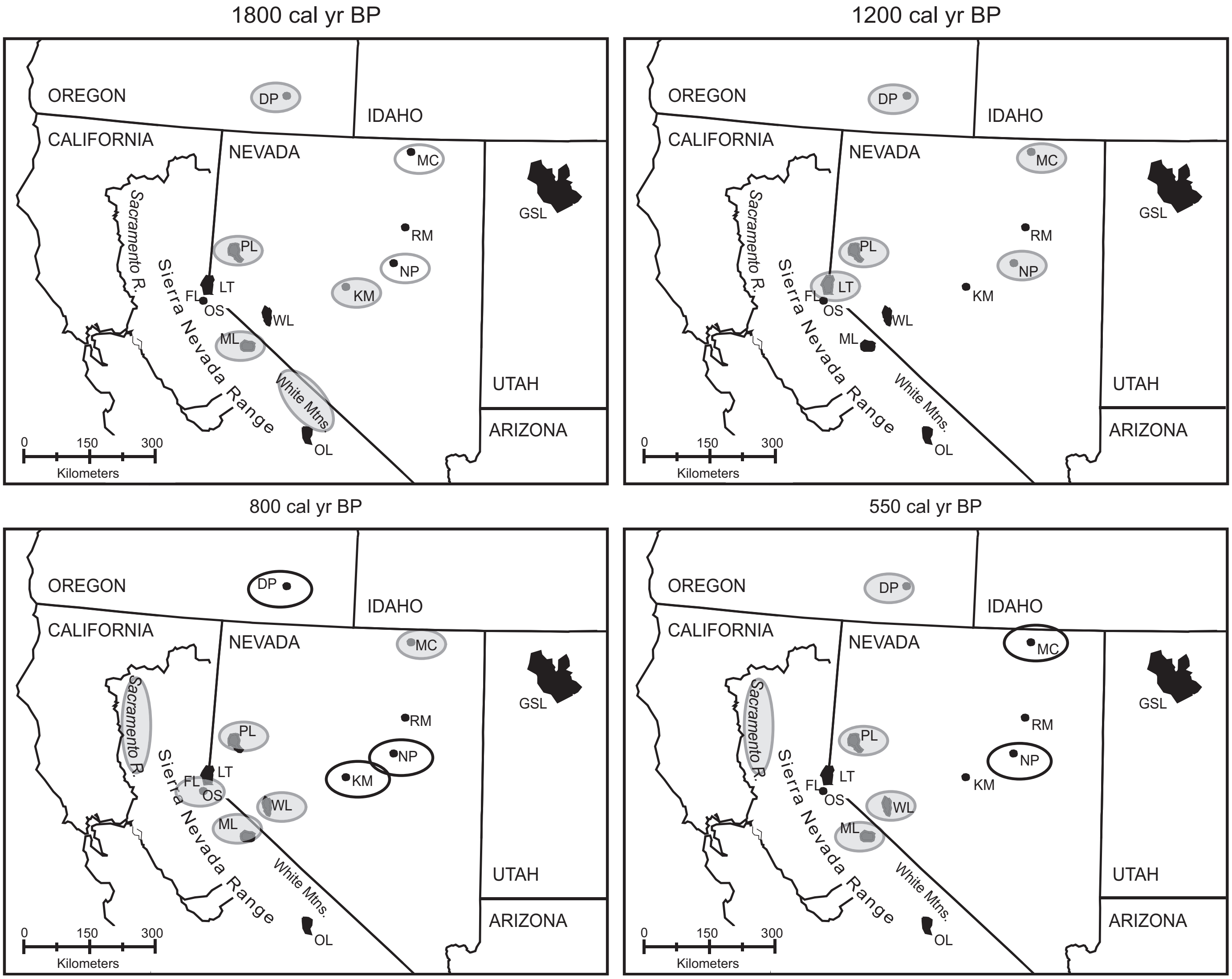


Fig. 6. Comparison of the ratios calculated for all four pollen sites, Pyramid Lake, Mission Cross Bog, Newark Valley Pond, and Kingston Meadow. Vertical black lines represent the 2-sigma ranges for radiocarbon ages on submerged stumps, or age range determined from dendrochronological analysis for Fallen Leaf Lake. F—Fallen Leaf Lake (Biondi et al., 2006a); M—Mono Lake (Stine, 1990, 1994); O—Osgood Swamp (Stine, 1994); R—Rubicon Point, Lake Tahoe (Benson et al., 2002); T—Lake Tenaya (Stine, 1994). Horizontal dashed lines indicate best estimates of drought terminations based on tree-stump dates and lake transgressions.


1800 cal yr BP

1200 cal yr BP

800 cal yr BP

550 cal yr BP

Fig. 7. Regional maps for droughts terminating at: (A) 1800; (B) 1200; (C) 800; and (D) 550 cal yr BP showing sites interpreted as having evidence for dry (gray filled ellipses) or wet (unfilled ellipses) climate. DP, Diamond Pond; FL, Fallen Leaf Lake; GSL, Great Salt Lake; KM, Kingston Meadow; LT, Lake Tahoe; MC, Mission Cross Bog; ML, Mono Lake; NP, Newark Valley Pond; OL, Owens Lake; OS, Osgood Swamp; PL, Pyramid Lake; RM, Ruby Marshes; WL, Walker Lake.

middens near streams in the Toiyabe Range in central Nevada have their lowest diversity at 2000 cal yr BP, suggesting extirpation of riparian species during severe drought (Miller et al., 2001). Geomorphic evidence from the same region interprets active deposition on alluvial fans associated with loss of hillslope vegetation during a period of low rainfall (Miller et al., 2004). Pyramid Lake δ^{18}O data indicate a drought of 100 years from ~2000–1900 cal yr BP (Benson et al., 2002). Tree-ring reconstructions of PDSI (Cook et al., 2004, supplemental data) indicate that the central Great Basin was in drought conditions through much of the period from 2000–1800 cal yr BP. Pollen evidence for drought from Diamond Pond in southeastern Oregon indicate a sharp decline in aquatic plant macrofossils and decreasing juniper pollen after about 2050 cal yr BP (Wigand, 1987).

The pollen record varies across sites during this period. The Pyramid Lake pollen record suggests low lake levels between ~2500 and 1900 cal yr BP and Kingston Meadow dried to become a grassy meadow between 2000 and 1800 cal yr BP. Newark Valley Pond was drier between 2500 and 2200 cal yr BP, but between 2000 and 1800 cal yr BP wet conditions returned. Mission Cross Bog in northeastern Nevada is variable through this period. The climate appears to have been generally wetter, but between 2000 and 1900 cal yr BP it was drier (Fig. 5).

Records across the Great Basin support the argument that in general this was a dry period, with possibly the driest period being between 2000 and 1800 cal yr BP. The record is clearest in the western Great Basin. The eastern Great Basin receives more spring and summer precipitation associated with low pressure systems originating in eastern

Nevada and convective storms. If temperatures were warmer during this period, it may have increased the amount of precipitation associated with these systems, bringing increased precipitation to the eastern part of the state. Further research is needed to determine whether temperatures were warmer or cooler during this period (Tausch et al., 2004).

3.2. *Drought terminating ~1200 cal yr BP*

A submerged tree stump from Rubicon Point, Lake Tahoe was radiocarbon dated to 1240 ± 40 ^{14}C yr B.P. (~1200 cal yr BP), suggesting the termination of an extended drought about this time (Benson et al., 2002). The tree-ring reconstruction from the northern Sierra Nevada identified the termination of a drought ~1120 cal yr BP (Meko et al., 1999). The δ^{18}O from Pyramid Lake records two periods of lowered lake levels between 1400 and 1250 cal yr BP (Benson et al., 2002). Diamond Pond also shows evidence of a drier climate (Wigand, 1987). This extended dry period is not identified in the tree-ring reconstructions of western North America (Cook et al., 2004); however, there are very few chronologies extending back this far.

At Pyramid Lake, the data suggest that lake levels remained low between ~1500 and 1200 cal yr BP (Fig. 6). Although it is a low-resolution record, the Newark Valley Pond pollen data also indicate drier climate centered on 1400 cal yr BP. In northern Nevada, the Mission Cross Bog pollen record indicates drier climate, but not extended drought. Taken as a whole, the pollen record shows dry climate through this period; however, the severity of drought does not appear to be of the magnitude seen at other times.

There is a consistent record of dry climate across the northern Great Basin during this time period, although beyond the pollen record and one submerged stump at Lake Tahoe, this drought is not well documented. We suggest that while there may have been dry periods at this time, it was not severe.

3.3. *Drought terminating ~800 cal yr BP*

Droughts during the period referred to as the Medieval Climate Anomaly have been well documented and are often referred to as mega-droughts (Cook et al., 2004). Tree-ring reconstructions of drought across the Western United States identified two periods of increased aridity between ~930–900 and 825–780 cal yr BP (AD 1021–1051 and 1130–1170, Cook, 2006). The tree-ring reconstruction of the Sacramento River stream flow indicated that the most intense 20-year drought of the last ~1000 years was between AD 1140 and 1160 (810–790 cal yr BP) (Meko et al., 2001).

At Fallen Leaf Lake, located near the southern end of Lake Tahoe, trees up to 25 m in height have been found rooted upright 36 m below the current lake surface. A limb from one of these trees has recently been cross dated with a tree-ring chronology developed from western juniper (*Juniperus occidentalis*) within the Fallen Leaf Lake watershed. The limb dated to the period 865–795 cal yr BP (1085–1153 AD, Biondi et al., 2006a). The outer rings were missing, so this date provides the minimum death date. Logs raised from the lake have between 130 and 200 rings, indicating that if the trees grew in place during an extended drought, the lake would have been low for possibly two centuries (~990–790 cal yr BP). Although numerous records support the mega-drought hypothesis, the possibility that geomorphic processes were responsible for drowning trees should be thoroughly tested to confirm the hypothesis (Biondi et al., 2006b).

Stine (1994) reviewed radiocarbon dates on submerged stumps in Mono Lake, Lake Tenaya, Osgood Swamp and the West Walker River and concluded that dry climate persisted in the eastern Sierra Nevada from ~1038 to 838 cal yr BP. The δ^{18}O record from Pyramid Lake identifies a drought from 900 to 800 cal yr BP (Benson et al., 2002). Analysis of δ^{18}O data in sediments from Walker Lake also identified the termination of a century long drought at 750 cal yr BP (Yuan et al., 2004).

Both of our high-resolution pollen records, Pyramid Lake and Mission Cross Bog, clearly identify this drought (Fig. 6); however, the two low-resolution records both indicate a wetter climate at this time. The resolution of these two records does not allow for identification of events on the scale of one century, so it is possible that central Nevada may have been dry, but we need higher-resolution records to confirm this difference. The high resolution record at Diamond Pond in the northern Great Basin (Fig. 7) shows a pronounced wet episode from 900–800 cal yr BP, suggesting the regional limits of this drought (Wigand, 1987).

Elsewhere throughout the west there appears to be overwhelming evidence for drought at this time (Cook et al., 2004). That study suggested that anomalously warm temperatures during the Medieval Warm Period may have led to increased occurrence of droughts. Models suggest that warm temperatures over the tropical Pacific may lead to extended La Nina-like conditions, and persistent drought in the western United States (Cook et al., 2004). But the mechanisms that might have forced this climate shift are unclear since the amount of radiative solar forcing during this period is still speculative (Cook, 2006).

3.4. *Drought terminating ~550 cal yr BP*

Radiocarbon dating of relict stumps rooted in lakes and streams in the western Great Basin and eastern Sierra Nevada found death dates of ~600–550 cal yr BP (Stine, 1990, 1994). Tree-ring counts on these stumps indicated ages of up to 140 years bracketing the drought period between ~740 and 550 cal yr BP. A stream flow reconstruction for the Sacramento River developed from tree-rings, found that the driest 50-yr period on record in the last 1100 years was between ~600 to 550 cal yr BP (1350 and 1400 AD) (Meko et al., 2001). A compilation of tree-ring reconstructions from throughout the western United States identified the period from 710–690 cal yr BP (1240–1265 AD) as one of the longest persistent droughts within the last 2000 years (Cook, 2006). Pyramid Lake δ^{18}O data show low lake levels at ~700–640 and 600–540 cal yr BP (Benson et al., 2002). At Walker Lake, a large closed basin lake in the western Great Basin, the δ^{18}O data indicate a century-scale drought event terminating at 590 cal yr BP (Yuan et al., 2004). At Diamond Pond, Oregon at least two major droughts occurred during this time period, ~650 and 525 cal yr BP indicated by an increase in greasewood (*Sarcobatus*) pollen (Wigand, 1987).

The pollen record at Pyramid Lake is consistent with other records of drought at this time (Fig. 6) with evidence for lower lake levels between 650 and 500 cal yr BP. In contrast, the record at Mission Cross Bog in northeastern Nevada indicates a wetter climate centered on 600 cal yr BP (Fig. 6). Across the Great Basin, it appears that while drought persisted in the west, the east had returned to a wetter climate by this time. Cook et al.'s (2004) reconstruction of aridity identifies a wet period centered on AD 1321 (~630 cal yr BP), indicating that by this date the extended period of drought had ended across some regions in the west. The pattern of drought in the Great Basin is similar to that seen ~1800 cal yr BP (Fig. 7), suggesting that possibly similar mechanisms may be responsible for the climate during theses two time periods. Eastern Nevada has more intense summer monsoon activity than the western part of the state, and warmer summer temperatures may have increased summer precipitation during these time periods. If this were the case, it is unclear that this would have contributed significantly to annual rainfall totals since evidence from the American Southwest (Stahle et al., 2000) indicates extended drought across this region that is generally associated with the abandonment of Chaco Canyon in New Mexico (Benson et al., 2002).

4. Conclusion

Pollen records provide evidence for regional scale extended droughts across the western and central Great Basin within the last 2000 years. The exact timing of these droughts is difficult to determine from the sedimentary record due to errors associated with radiocarbon dating and lags from plant succession, but at several sites, our interpretation of drier climate indicated by the pollen record coincides with death dates on submerged stumps which have been interpreted to represent drought terminations. Our pollen records indicate that the period between 2000 and 1800 cal yr BP was dry, with the driest sites being in the western Great Basin. The century ending at 1200 cal yr BP may have been dry, but the pollen record does not support severe drought. Both of our high-resolution pollen records, Pyramid Lake and Mission Cross Bog, clearly identify a drought ending ~800 cal yr BP., whereas only the Pyramid Lake record indicates a drought ending at 550 cal yr BP. Extended dry periods identified in the pollen record should not be interpreted to mean periods of continuously dry years, but they are good indicators of long term trends in aridity and suggest that the Great Basin is subject to sustained dry conditions that could impact western water resources.

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