PAIRED CHARCOAL AND TREE-RING RECORDS OF HIGH-FREQUENCY HOLOCENE FIRE FROM TWO NEW MEXICO BOG SITES

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Abstract

Two primary methods for reconstructing paleofire occurrence include the dendrochronological dating of fire scars and stand ages from live or dead trees (extending back centuries in the past) and sedimentary records of charcoal particles from lakes and bogs, providing perspectives on fire history which can extend back for many thousands of years. Studies using both proxies have become more common in regions where lakes are present and fire event frequencies are low, but are rare where high-frequency surface fires dominate, and sedimentary deposits are primarily bogs and wetlands. Here we investigate sedimentary and fire-scar records of fire in two small watersheds in northern New Mexico, presently characterized by high-frequency fire, where bogs and wetlands (Chihuahueños Bog and Alamo Bog) are more common than lakes. Our research demonstrates that (1) the sedimentary charcoal record can be reproduced between multiple cores within a deposit; (2) comparison of tree-ring fire scar and charcoal proxies both document the anomalous (compared to the remainder of the Holocene) lack of fire during the 20th century; (3) sedimentary charcoal records probably underestimate the frequency of fire in high-frequency, mixed conifer stands; and (4) the sedimentary record is complicated by factors such as burning and oxidation of these organic deposits, diversity of vegetation patterns within watersheds, and bioturbation by ungulates. Thus we consider a suite of particular challenges in developing and interpreting fire histories from bog and wetland settings in the Southwest. The identification of these issues and constraints with interpretation of sedimentary charcoal fire records does not diminish their essential utility in assessing millennial scale patterns of fire activity in this arid part of North America.

Introduction

Fire is widely recognized as a keystone disturbance process in forested landscapes of the southwestern United States (Swetnam and Baisan 1996), driving myriad ecological patterns and other processes (Bogan et al. 1998). Fire activity is sensitive to climatic conditions, such that fire regimes change through time in response to climatic variability (Swetnam and Betancourt 1998, Grissino-Mayer and Swetnam 2000, Swetnam and Baisan 2003, Westerling et al. 2006, Kitzberger et al. 2007). Since climate reconstructions for the Southwest indicate substantial variability at all time scales (Grissino-Mayer 1996), fire activity almost certainly has also varied markedly through time. However, quantitative documentary records of fire activity in the Southwest only extend back about a century (Westerling et al. 2006). Thus reconstruction of prehistoric fire regimes requires use of paleoenvironmental methods, each with particular strengths, weaknesses, and uncertainties (Swetnam et al. 1999).

Two primary methods for reconstructing paleofire occurrence are: a) dendrochronological dating of fire scars and stand ages from live or dead trees (Swetnam and Baisan 1996, Margolis et al., in press), which in the Southwest can typically push back regional fire histories up to 500 years before present (BP); and b) the development of sedimentary records of charcoal particles from lakes and bogs (Patterson et al. 1987, Whitlock and Anderson 2003), providing perspectives on fire history which can extend back for many thousands of years. Each of these techniques has unique strengths as well as weaknesses. Used in conjunction, the two proxies can provide complementary information on past fire activity (Whitlock et al. 2004). To deduce long-term patterns of forest fire, dendrochronological approaches can be used to calibrate sedimentary reconstructions, such as has been done in fire history studies from Alberta (MacDonald et al. 1991, Laird and Campbell 2000), the Klamath/Siskiyou region (Mohr et al. 2000, Briles et al. 2005), northern Rockies (Brunelle and Whitlock 2003, Brunelle et al. 2005), western Washington (Higuera et al. 2005), and Finland (Pitkänen et al. 1999). Similarly, studies comparing forest stand ages (to estimate long-interval stand-replacing fire histories) with sedimentary charcoal fire dates come from British Columbia (Hallett and Walker 2000, Gavin et al. 2003, Hallett et al. 2003, Gavin et al. 2006, Hallett and Hills 2006), Yellowstone (Millspaugh and Whitlock 1995), and Alaska (Anderson et al 2006). Research that combines both charcoal and tree-ring fire history methods has been particularly rare in settings where high-frequency surface fires were dominant, and from bogs and wetlands, as most charcoal records from western North American forests have been developed from sites characterized by long-interval, stand-replacing fire regimes and from lake sediments. This is largely because water-saturated lake and bog environments most conducive to accumulating charcoal-bearing sediments are most commonly found in cold, mesic, high-elevation settings in western North America where fires are less frequent, whereas the relatively few perennially-wet sedimentary basins at drier, lower-elevation sites tend to have been altered by people to better impound water for livestock or human use. However, charcoal records can be developed from those suitable bogs and meadows that are found within drier lower-elevation forest types (Anderson and Smith 1997; Whitlock and Anderson 2003), although the processes of charcoal creation and deposition in these settings are less certain than lakes, introducing additional interpretation challenges.

One major question surrounding the use of sedimentary charcoal to reconstruct fire histories concerns the reproducibility of these records. Because the development of high-resolution sedimentary charcoal chronologies is expensive and labor-intensive, such chronologies rarely are replicated to determine the consistency of charcoal patterns between different sediment samples collected within a single site. Indeed, we are unaware of any such examples of within-site replication of charcoal chronologies in the published literature.

In this paper we contribute information relevant to sedimentary charcoal analysis of non-lake sites. Our goals here are to investigate long-term records of high-frequency fire activity from paired and replicated charcoal and tree-ring proxies of fire at two moderate-elevation bog sites in the Jemez Mountains, northern New Mexico. We use these records to:

1. Demonstrate the replication of the sedimentary charcoal record from multiple cores within a deposit;
2. Reconstruct variation in fire regimes and fire/climate relationships over millennial time scales at two sites with moderate-to-high fire event frequencies;
3. Compare fire history methods and interpretations between tree-ring and charcoal proxies of fire occurrence at the individual sites; and
4. Consider the particular challenges of developing and interpreting fire histories from bog and wetland settings in the Southwest.

Fire history of the Southwestern US and the Jemez Mountains

It is well-recognized that fire has been a keystone ecological process for at least several centuries in forested landscapes of the southwestern United States (Swetnam and Baisan 1996, 2003), including the Jemez Mountains of northern New Mexico (Touchan et al.1996, Allen 2002). An extensive network of dendrochronological fire history research sites has been developed in the Southwest (Swetnam et al. 1999), with multiple study sites in many mountain ranges across the region (Fulé et al. 2003, Swetnam and Baisan 2003, Brown and Wu 2005). Tree-ring fire scar records document high-frequency surface fire regimes prior to ca. AD 1900 in most southwestern ponderosa pine forests, and in many mixed conifer forests (Swetnam and Baisan 1996). Livestock overgrazing and active fire suppression caused sharp declines in regional fire activity from the late 1800s through the late 1900s (Swetnam and Baisan 2003). These patterns are mirrored at fire scar sites in the Jemez Mountains (Touchan et al. 1996, Allen 2002).

In contrast, comparable high-resolution sedimentary charcoal fire history sites are rare in the mountains of the Southwest. Several low-resolution (i.e., centennial-scale) records occur for the Kaibab Plateau of Arizona (Weng and Jackson 1999) and for the southern Rockies (Peterson 1981, 1985; Fall 1997). Recently, however, a number of high-resolution records of fire have been produced (i.e., Bair 2004; Toney and Anderson 2006; Anderson et al., 2007a [submitted] Anderson et al., 2007b [submitted]), which have the potential for reconstruction of fire event frequencies at decadal-scales. These Holocene-length records show periods of synchroneity in burning across broad spatial scales, suggesting the importance of climate in determining long-term changes in fire frequency here.

Study Area

Chihuahueños and Alamo bogs are located in the Jemez Mountains of northern New Mexico (Figure1). The heart of this volcanic range is physiographically dominated by the Valles Caldera, formed by collapse after huge pyroclastic eruptions ~1.1 million years BP, and the central resurgent dome, Redondo Peak (Wolff and Gardner, 1995). These relatively low mountains reach maximum elevations of ~3500m. Chihuahueños Bog is located just outside the caldera rim on the north side of the Jemez Mountains at an elevation of 2925 m, within the Santa Fe National Forest (Figure 1; Brunner-Jass 1999). The 2.3 ha bog is at the mouth of a small watershed near the lip of Chihuahueños Canyon (Figure 2), situated on a low-relief upland (~45 m total relief in this watershed). Unpublished geological mapping indicates that Chihuahueños Bog occurs at the geological contact between Bandelier Tuff to the south and an irregular Tschicoma dacite hill to the north, and perhaps the bog occupies a paleotopographic feature (Steve Reneau, personal communication). While the bog is apparently kept wet throughout most years by subsurface water flows, after dry winters during extended drought episodes the surface of large portions of the bog can dry out (CDA, personal observation in 2000 and 2006).

The surface cover of Chihuahueños Bog is currently dominated by large sedges and some grasses (Figure 2), including *Deschampsia cespitosa*. The bog occurs amidst mixed conifer forest, typical of that found elsewhere in the Jemez Mountains and the southern Rocky Mountains (Allen 1989), with nearly every conifer species extant in the Jemez Mountains growing in this small watershed. The upland forests are dominated by Douglas-fir (*Pseudotsuga menziesii*), with co-dominant species including white fir (*Abies concolor*), Engelmann spruce (*Picea engelmannii*), quaking aspen (*Populus tremuloides),* Colorado blue spruce (*Picea pungens*), corkbark fir (*Abies lasiocarpa* var. *arizonica*), and southwestern white pine *(Pinus strobiformis*). Ponderosa pine (*P. ponderosa*) dominates the exposed southeast aspect canyon slopes below the bog level, with a few individuals found on the uplands too. Other woody species growing around the bog include common juniper (*Juniperus communis*), Gambel oak (*Quercus gambelli*), shrubby cinquefoil (*Potentilla fruticosa*), and kinnickinnick (*Arctostaphylos uva-ursi*). A variety of herbs and grasses grow in a relatively sparse understory in the upland forest, including bluegrass (*Poa* sp.), bluebells (*Campanula parryi*), wild strawberry (*Fragaria* sp.), paintbrush (*Castilleja* sp.), pussytoes (*Antennaria* sp.), sage (*Artemisia* sp.), and yarrow (*Achillea lanulosa*). The upland forests throughout the small bog watershed have been heavily logged in recent decades, reducing the material available for dendrochronological sampling of fire scars; however, the adjoining upper slopes of Chihuahueños Canyon remain uncut, with many fire-scarred ponderosa pines present.

Alamo Bog is located within the Valles Caldera National Preserve on the northwest flank of the resurgent dome of Redondo Peak, at 2630m elevation (Figure 1; Brunner-Jass 1999). Alamo Bog extends as a linear wet meadow for >1 km along the drainage axis of Alamo Canyon (Figure 3; Brunner-Jass 1999). This unusual fenlike feature is maintained by groundwater flows along the valley bottom, with pockets of upwelling water and hydrothermal gas venting, and portions have the “bouncy” feel of a quaking bog. The Alamo Bog watershed exhibits substantial topographic relief, with steep forested slopes extending 400 m above the bog. North-facing slopes are currently blanketed in dense mixed-conifer forest, dominated by Douglas-fir and aspen, but characteristically including ponderosa pine on the lower slopes, white fir and southwestern white pine in mid-slope stands, and grading into dominance by Engelmann spruce and corkbark fir at the highest slope positions. Understory species in these mesic forests are similar to those at Chihuahueños Bog. In contrast, the south-facing slopes exhibit open stands of ponderosa pine and Gambel oak (and a few small groups of mixed-conifer species) interspersed among grasslands and dry meadows. Selective logging has removed large trees from most of the south aspect hillslopes and all lower slopes near the bog, while the highest north aspect slopes were clearcut in the early 1970s (Figure 3). Like Chihuahueños Bog, the current surface cover of Alamo Bog is dominated by large sedges and grasses, prominently including the large wetland bunchgrass *Deschampsia cespitosa*.

Two climate stations occur close to Chihuahueños Bog and Alamo Bog. Annual average maximum and minimum temperature and precipitation for the Pajarito Mountain station (3158 m [10,360 ft], ca. 20 km SE of Chihuahueños Bog, and 17 km east of Alamo Bog) are 10.0 °C, 0.6 °C and 53.6 cm (Anderson et al., 2007b [submitted]; http://weather.lanl.gov). For the Los Alamos station (2256 m [7400 ft]), ca. 24 km SE of Chihuahueños Bog, and 7 km east of Alamo Bog, similar parameters are 15.5°C, 2.5°C, and 45.9 cm (Anderson et al., 2007b [submitted]; http://www.wrcc.dri.edu/summary/climsmnm.html). Maximum precipitation occurs during the July-August summer monsoon, recording nearly ½ the annual precipitation total. Winter (Dec, Jan or Feb) is usually the driest season, but spring (Apr, May, Jun) is also quite dry. The snow-free season is usually May through October, but snow can fall at any month at the Pararito Mountain site (Anderson et al. 2007b [submitted]).

Methods

Both Chihuahueños and Alamo bogs were cored in August 1996, after steel probing rods were used to find the deepest sediment deposits. A Livingstone corer was used to collect multiple cores at both sites. Cores were brought to the Laboratory of Paleoecology at Northern Arizona University for storage and analysis (Brunner-Jass 1999). Chihuahueños Bog sediment cores CHB1 and CHB2 were taken ca. 2 m apart in the middle of the bog where the sediments were the thickest with a Livingstone corer. CHB1, the longer of the two cores, measured 465 cm. At Alamo Bog sediment cores AB3 and AB4 were collected from ca. 2 m apart, with the deeper core 4 extending 496 cm. The longest core at each site was initially selected for detailed laboratory analyses, including detailed stratigraphy, magnetic susceptibility, pollen, plant macrofossils, radiometric dating, and charcoal – see Brunner-Jass (1999) and Anderson et al. (2007a [submitted]) for details on the standard methodologies used. Subsequently we sampled the upper portions of each replicate core for charcoal content. Multiple radiometric methods were utilized to date these cores. Radiocarbon dates were obtained from dating charcoal fragments or bulk sediments. Radiocarbon ages were calibrated to calendar ages using CALIB version 5.0 (Stuiver et al. 1998). Gamma spectrometry was used to develop ^{210}Pb and ^{137}Cs ages of whole sediments samples from the upper portions of each core (R. Ku, pers. comm., 2004).

High-resolution charcoal records were developed from all four cores by sampling every cm downcore for charcoal (Brunner-Jass 1999, Anderson et al. 2007a [submitted]). Charcoal extraction and analyses followed the methods developed by Whitlock and Millspaugh (1996), with samples sieved through 125-μm and 250-μm screens. The two primary (long) cores were sampled at cm-resolution for the entire length of AB-3 and the upper 399 cm of CHB-1. Charcoal concentrations were also sampled for the upper portions only from the two replicate cores (CHB-2 and AB-4), to allow comparison of reconstructed charcoal patterns between cores within a site. The top 99 cm of CHB-2 were sampled at cm-scale resolution, and the upper 68 cm of AB-4 were sampled at 0.5 cm-scale resolution. We used CHAPS (Charcoal Analysis Programs; see Whitlock and Anderson, 2003) to reconstruct long-term Fire Event Frequencies (FEF) for the charcoal records at these two bog sites. Fire "events" were determined for peak charcoal influx values that exceeded a threshold of 1.0 times the background charcoal influx rate, averaged across a 300-year moving window.

Fire-scarred conifer trees were located and sampled in the forests adjoining both Chihuahueños Bog and Alamo Bog (Figures 2, 3). Where possible, samples were selected to emphasize (a) clusters of fire-scarred trees, (b) fire-scarred trees close to and upslope of each bog, and (c) representative coverage of the area and the forest types near each bog. At Chihuahueños Bog logging in recent decades has removed most of the older trees from the gentle terrain surrounding the bog, leaving very little upland fire-scarred wood available to sample. Thus the nearest fire-scarred samples were almost entirely found 100-300 m from the bog on the more exposed slopes of Chihuahueños Canyon, which drops off steeply just east the bog (Figure 2). Chainsaws were used to collect whole or partial cross-sections from both live and dead trees using standard methods (Arno & Sneck 1977). Full cross-sections were taken from dead trees and partial sections from live trees. Sampled species were primarily ponderosa pine, southwestern white pine, and Douglas-fir. All conifer samples were transported to the Laboratory of Tree-Ring Research at the University of Arizona, where they were prepared and crossdated according to standard dendrochronological procedures (Stokes & Smiley 1968). Seasonal position of fire scars was assigned based upon the relative position of individual scars within the annual growth rings. Dormant season fires, indicated by fire scars, were assigned to the subsequent year, based on the dominant occurrence of spring and early summer fires in the region (Barrows 1978, Dieterich and Swetnam 1984, Grissino-Mayer et al. 2004). Bog fire scars were successfully crossdated from 3 live and 10 dead trees, and at Alamo Bog from 9 live and 43 dead trees (Morino et al. 1998, and unpublished data). In addition, the origin date of one aspen stand in the Alamo Bog watershed (Figure 3) was estimated by crossdating near-basal increment cores collected from near the base of 13 overstory aspen trees within the stand (Morino et al. 1998, Margolis et al., in press).

Fire scar data were graphed and analyzed with the FHX2 software (Grissino-Mayer 2001). A superposed epoch analysis (Swetnam and Baisan 2003) module in FHX2 was used to determine lagged inter-year relationships between the Palmer Drought Severity Index (PDSI), a measure of climatic moisture conditions, and fire activity as reconstructed from fire scars. For each bog site we compared annual PDSI values from the Cook et al. (2004) dendroclimatic reconstruction for the nearest grid point (#118, 107.5 ° W, 37.5 ° N) to years with spreading fire activity (i.e., years with at least 10% of previously scarred sample trees recording a fire scar, and at least two trees scarred).

Results and Discussion

<u>Chihuahueños Bog</u>

Cross-dated fire scars from 13 sampled trees in the forests adjoining Chihuahueños Bog record fires back to AD 1454 (Figure 4). Ten spreading fires (at least 2 trees scarred) are recorded between AD 1617 and 1902. Fires typically scarred most of the sampled trees, indicating a spreading surface fire regime. For this period the mean interval between spreading fires was ~36 years, a long inter-fire interval compared to other mixed conifer forests in the Jemez Mountains (Touchan et al. 1996). The most recent fires date to 1857 and 1902, with no subsequent fire activity recorded, which is consistent with regional and local landscape patterns of historic fire suppression (Swetnam and Baisan 1996, Allen 2002). Fire seasonality could be determined for 29 of 64 scars, distributed as 5 dormant, 15 early earlywood, 5 mid-earlywood, and 6 latewood. As observed elsewhere in the Southwest (Swetnam and Baisan 2003), after AD 1800 the fire seasonality is strongly shifted toward early season fires (1 D, 10 EE, 1 L)

Superposed epoch analysis for widespread fires at Chihuahueños Bog between AD 1618 and 1906 (Figure 5) shows a PDSI departure exceeding -2 during fire years (year = 0), indicating very dry conditions with a statistical significance level > 99.9%. This pattern of extreme dryness in fire years is typical of mesic, high-productivity, upper elevation forest types in the Southwest with abundant fuels, where fire occurrence is largely controlled by the episodic occurrence of dry climate conditions rather than fuel availability (Swetnam and Baisan 1996, Allen 2002).

Considering the ~16,000 cal year Chihuahueños Bog sediment record, charcoal concentrations vary markedly through time (Figures 6a, 7), reflecting changes in climate, vegetation, and fire regimes. Initial charcoal concentrations are low (mostly ones or tens of particles/cc) from the basal 50 cm of sand and gravel deposits in this core, reflecting tundra or steppe vegetation surrounding a small pond (Anderson et al. 2007b [submitted]). Development of spruce-*Artemisa* woodland around 14,000 cal BP at Chihuahueños Bog is followed by transitions to mixed conifer forest by ca. 11,500 cal BP, which, with modifications, continues to today (Brunner-Jass 1999, Anderson et al. 2007b [submitted]). The Chihuahueños Bog charcoal record exhibits modest increases in charcoal deposition typical of spruce woodland or spruce forest (Anderson et al. 2007b [submitted]) by ca. 14,000 cal BP, but with little indication of increased fire activity through the change to mixed-conifer forests in the earliest Holocene. Major increases in Chihuahueños Bog charcoal concentrations occur around 9000 cal BP (Figure 6a]), associated with intensified warming and strengthening of the summer monsoon (Friedman et al. 1988), probably with elevated lightning ignition rates (Anderson et al. 2007a [submitted]). However, interpretation of this big increase in background charcoal concentrations at 9000 cal BP is confounded by the apparent concurrent drying of the Chihuahueños Bog basin (Figure 7a), inferred from the accompanying macrofossils, lack of pollen preservation, and low sedimentation rate (~2500 years represented by only ~25 cm of sediment) (Brunner-Jass 1999, Anderson et al. 2007b [submitted]). Plotting charcoal as a flux of particles/cc/year (Figure 7a) confirms the generally high background rates of charcoal deposition since 9000 cal BP, but removes the 6000-8000 cal BP "bulge" seen in raw background concentrations (Figure 6a). Also, the lower temporal resolution of each sample centimeter from this short dry-environment portion of the core essentially smoothes any higher-resolution fluctuations in charcoal concentration, which likely explains the relative lack of variability (peaks and dips) in charcoal concentrations during this period. Overall the high charcoal concentrations and flux rates observed in the Chihuahueños Bog sediments since 9000 cal BP are much greater than the peak deposition rates found in sediments from higher elevation lakes in this region (Anderson et al. 2007a [submitted]).

A different pattern emerges after ca. AD 1900 (Figures 6a, 8a), when concentrations decline to essentially zero in the top 16 cm of CHB-1 (mean = 1.5 particles/cc, range = 0-6). Although little charcoal was also recovered from 29-40 cm depth in this core (Figures 8a), relatively substantial charcoal concentrations actually occur in this zone (mean = 25.4 particles/cc, range = 6-58).

The patterns of charcoal deposition observed in core CHB-1 are replicated impressively well in the top meter of core CHB-2 (Figure 8b), including the near-absence of any charcoal in the uppermost layers. This almost complete lack of charcoal in the uppermost horizons of both cores, which by ^{210}Pb dating of CHB-1 corresponds to fire cessation in the late 1800s, is consistent with the fire-scar evidence that the last spreading local fires occurred in 1857 and 1902 (Figure 4). The striking deficit of charcoal deposition since ca. AD 1900, clearly replicated by two cores, appears to be an anomaly over the last ~9,000 years at Chihuahueños Bog (Figure 6a).

At Chihuahueños Bog the CHAPS runs yield an estimated FEF ranging around ~5 fire events/1000 years over the course of the past 16,000 years (Figure 7b), or a mean interval of 200 years between fires. Highest FEF values of 7-8 events/1000 years are estimated for the late Pleistocene and early Holocene (prior to 9500 cal BP) when charcoal influx was low. In contrast, FEF estimates drop to 2-3 fire events/1000 years for the mid-Holocene (ca. 5500 – 8500 cal BP), when background charcoal influx is high but few peaks are evident in the record. For the post-AD 1600 period of overlap between the charcoal and well-replicated fire scar records, only two charcoal fire “events” are recognized, versus ten spreading fire-scar events. The overall FEF of 4-5 events/1000 years for this time window yields a mean interval of ~222 years between fires, six times lower than the fire-scar-estimated mean interval of 36 years for the period AD 1617-1902.

Alamo Bog

Cross-dated fire scars from 52 sampled trees in the forests adjoining and upslope of Alamo Bog record fires back to AD 1422 (Figure 9). The last widely spreading fire occurred in 1879, with a few scars showing up on a tree or two into the early 1900s. Pre-1900 fire frequencies in this watershed varied by forest type and landscape position. A history of high-frequency synchronously spreading fires is recorded in the more xeric portions of this watershed where ponderosa pine is dominant (n = 24 samples), with return intervals between fires ranging from 4-27 years, and a mean fire return interval of ~12 years from AD 1644-1879. High frequency surface fire regimes of this sort were typical of pre-1900 ponderosa pine forests in the Jemez Mountains (Touchan et al. 1996). In contrast, the mesic mixed conifer stands on the north aspects above Alamo Bog (n = 28 samples) show a longer mean fire return interval of ~20 years, with intervals ranging from 9-45 years. Despite lower frequencies, fire date synchrony among widely dispersed mesic subsite samples, and between xeric and subsite samples in many years (Figures 3, 4), indicates that pre-1900 surface fires spread widely across this watershed. Considering all sampled trees in this watershed yields a mean fire interval of ~12 years for the period AD 1644 – 1879 (counting only the 23 years in which fires scarred at least 10% of previously scarred trees, with a minimum of two scarred trees), as the higher frequency xeric subsite samples drive the joint fire interval statistics.

In addition, tree-ring establishment dates were estimated to be 1880 (+/- 2 years) for ten of thirteen sampled aspen trees from an aspen stand ~300m upslope of Alamo Bog (Figure 3). This corresponds well with the 1879 date of the last widespread surface fire in that area (Figure 4), suggesting that this particular aspen stand regenerated from a high-severity burn patch within the mixed-conifer forest matrix on that north-facing slope. The observed combination of old-growth conifer forest with basal fire scars present and interspersed even-aged aspen stands indicates that a mixed-severity fire regime (with both widespread surface fires and interspersed crown fire patches) historically characterized this mesic portion of the Alamo Bog watershed.

Superposed epoch analysis for widespread fires at Alamo Bog between AD 1510 and 1883 (Figure 5) shows a PDSI departure exceeding -2 during fire years, indicating very dry conditions with a statistical significance level > 99.9%. In addition, superposed epoch analysis shows a significant (>99%) tendency toward wet conditions two years prior to fire years, which is typical of high-frequency fire regimes in fuel-limited southwestern ponderosa pine ecosystems (Swetnam and Baisan 1996), including sites in the Jemez Mountains (Touchan et al. 1996). This two-year lag is thought to reflect the buildup of fine fuels (grasses, pine needles) from the wet years, enhancing the fuel connectivity that enabled widespread surface fire activity in subsequent dry years.

The ~ 9000 cal year Alamo Bog record displays extremely high concentrations of charcoal throughout most of the AB-3 core length (Figure 6b), with particularly high influx values between ca. 300-4700 cal BP (Figure 10a). As at Chihuahueños Bog, the observed charcoal concentrations at Alamo Bog are often thousands of particles/cc, up to 40X greater than the peak deposition rates found in higher elevation lakes in this region (Anderson et al. 2007a [submitted]). As at Chihuahueños Bog, charcoal is essentially absent only from the topmost portions of the long Alamo Bog sediment core. Charcoal concentrations in the top 70 cm of replicate core AB-4 show the same basic patterning as upper core AB-3 (Figure 11), although we lack sufficient dating precision to be able to securely match concentration peaks and valleys. There is a near complete absence of charcoal in the uppermost horizons of both cores, which by ^{210}Pb dating of AB-3 corresponds to fire cessation in the late 1800s, consistent with the fire-scar evidence that the last widespread local fire occurred in 1879.

At Alamo Bog the CHAPS analysis reconstructed an estimated FEF ranging around ~9 fire events/1000 years over the course of the past 8000+ years (Figure 10b), or a mean fire interval of 111 years between fires. Highest FEF values of 12-13 events/1000 years are estimated for ca. 1500-3500 cal BP, a late Holocene maximum in FEF seen at several other sites in the southern Rocky Mountains (Anderson et al. 2007a [submitted]). The lowest FEF estimates of 6-7 fire events/1000 years occurs in the mid-Holocene (ca. 4500 – 6500 cal BP), when both background and peak charcoal fluxes decline in the Alamo Bog record. Over the past 500 years the FEF of ~9 events/1000 years yields an MFI of 111 years between fires, nine times lower than the fire scar estimated MFI of 12 years for the period AD 1644-1879.

Particularities of fire history interpretations from bog sedimentary charcoal records:

1) Uncertainty of transport processes relating paleofire activity, upland charcoal production, and charcoal deposition in sampled bog sediments.

Interpretation of sedimentary charcoal records from bogs and wetlands is challenged by uncertainties in paleocharcoal production and deposition processes (Whitlock and Anderson 2003). Charcoal recovered from lake sediments must originate in flammable terrestrial ecosystems in the surrounding landscape, and be transported into the lake via aeolian processes (e.g., lofted by convection from high-intensity crown fires and transported downwind) or by surface runoff. Where steep burnable slopes adjoin a sedimentary basin, accelerated post-fire runoff and erosion (Veenhuis 2002) can transport charcoal directly to a lake margin, where the charcoal can mix and diffuse throughout the lake, eventually to settle and incorporate into deep-water sediments where modern samples are often extracted. As a result, background and peak charcoal concentrations from lake sediments are likely attenuated, and indeed low concentrations are generally observed from lake sediments in the southern Rocky Mountains (Anderson et al. 2007a [submitted]). In contrast, while surface runoff transport of substantial paleofire charcoal to at least the margins of Alamo Bog is plausible due to the steepness of the long adjoining slopes, the small Chihuahueños Bog watershed consists of gentle, low-relief terrain much less conducive to accelerated runoff and erosion processes. In addition, charcoal carried by overland flow to the edge of a bog is likely to be filtered out and deposited near the bog margins due to the low slope gradient and dense and hummocky vegetation cover on the bog surface, and, unlike for lakes, redeposition due to sediment focusing processes are less likely to occur. Thus much or all of such charcoal may not reach the deep sediments of the bog interior where core sampling typically occurs.

2) Uncertainty in the effect of taphonomic processes, such as consumption by fire or decay during dry conditions, and bioturbation.

Notwithstanding the complications listed above, the Chihuahueños Bog and Alamo Bog sediment cores both display extremely high charcoal concentrations throughout most of the Holocene, suggesting dominance of *in situ* charcoal production and deposition processes. In particular, the density of tall perennial bunchgrasses and sedges that dominate the surfaces of both bogs is continuous enough to sustain spreading fire through the dead and dry aerial components of this fine-textured fuel type (Allen, unpublished data), even if the bog surface itself is wet. Further, during severe drought episodes (when tree-rings record high probabilities of fire spreading widely through surrounding forest vegetation) the surface portions of these bogs can dry out (CDA, personal observation), also leaving the exposed organic surface sediments at risk to combustion if exposed to fire, or to oxidation and loss of organic mater. Some combination of frequent *in situ* burning of abundant fine aerial fuels and perhaps even surficial peat sediments could readily generate the high peak charcoal concentrations found in cores from interior portions of both of these bogs. These high peak and background levels of charcoal must be accounted for in the use of bog charcoal records to reconstruct the fire history of adjoining upland forests.

Additionally, the stratigraphic integrity of bog sediments can be physically disrupted by the footprints and wallows of animals (e.g., cattle, elk, and deer). Historically such bioturbation may be greatest during dry years when cattle (or native ungulates in the past) can walk farther into bogs without getting stuck (personal observation – CDA). This factor can be more important when a limited number of radiometric dates are obtained for a core, providing potential for substantial unrecognized temporal transpositions of charcoal-bearing sediments within the bog sediments of any given core sample, introducing unknown artifacts into fire history analyses.

<u>Challenges to fire history interpretation of sedimentary charcoal records from high-frequency fire regime settings:</u>

Fire scars indicate relatively high-frequency fire regimes at Chihuahueños Bog and Alamo Bog, with pre-1900 mean return intervals ranging between 12 and 36 years. Accurate interpretation of such high frequencies from sedimentary charcoal records would require decadal or even subdecadal-scale sampling resolution. Yet typical sedimentation rates are sufficiently low that even high-resolution sediment sampling resolution is too coarse to identify individual fire events at such high-frequency fire sites, as each cm can represent decades to centuries of sediment deposition. In such situations each cm likely includes the charcoal from multiple fire events, resulting in high “background” charcoal concentrations and an inability to distinguish the individual fires. Our comparison of the high-resolution tree-ring data with our coarser-scale sedimentary charcoal records suggests that the commonly used CHAPS analyses may be less appropriate for high-frequency fire regime sites such as these because the CHAPS methodology, which treats charcoal peaks as synonymous with fire events, effectively constrains the number of identifiable event peaks, resulting in an unrealistically low estimate of FEF. In such cases, changes in the background concentrations of charcoal may be a more interpretable index of fire activity through time at the available temporal scales. Overall, at high-frequency fire sites it is not clear how variability in peak charcoal concentrations reflect fire frequency or severity.

The identification of these issues and constraints with interpretation of sedimentary charcoal fire records does not diminish their essential utility in assessing millennial scale patterns of fire activity. We note that there are also challenges associated with the interpretation of dendrochronological fire-scar records (Swetnam and Baisan 1996, Swetnam et al. 1999, Baker and Ehle 2001, Van Horne and Fulé 2006), although these are not the focus of this paper.

Summary and Conclusions

We have developed long-term records of high-frequency fire activity from paired and replicated charcoal and tree-ring proxies of fire at two moderate-elevation bog sites in the Jemez Mountains, northern New Mexico. In this paper we use these records to:

1) Demonstrate the replicability of the sedimentary charcoal record from multiple cores within a deposit;
2) Reconstruct variation in fire regimes and fire:climate relationships over millennial time scales at two historically frequent-fire sites;
3) Compare fire history methods and interpretations between tree-ring and charcoal proxies of fire occurrence at the individual sites; and
4) Consider the particular challenges of developing and interpreting fire histories from bog and wetland settings in the Southwest.

Our research may be the first to confirm the reproducibility of charcoal records from adjacent cores in a deposit. This provides greater confidence in our interpretation of long-term fire histories from sedimentary records (see Anderson et al. 2007a [submitted]).

The paired charcoal/tree-ring methods provide complementary information that aids site-specific interpretations, as shown by many other studies (see introduction). But unlike studies where fire is infrequent, and individual charcoal peaks correspond to distinct fire events, correspondence between documented fires in the tree-ring record and the sedimentary charcoal record is less precise at these frequent-fire sites from New Mexico. For instance, during the time period of overlap of the two methodologies, the sedimentary record considerably underestimates the fire event frequency, when compared to the tree-ring record. This suggests that, over the longer record, fire event frequencies for high-frequency records such as Chihuahuenos and Alamo Bogs may be underestimated by programs such as CHAPS. Thus, although we present analyses here using CHAPS, we place more emphasis on the trends in fire event frequencies, rather than on the absolute value itself, and we also interpret the temporal changes primarily in terms of changes in background concentrations of charcoal.

A number of additional challenges constrain joint interpretation of the long charcoal and shorter tree-ring records from these two particular bogs, and call for caution in directly linking the fire-scar and sedimentary charcoal patterns. Diverse vegetation patterning in the Alamo Bog watershed – high fire frequency ponderosa pine forest on south-facing slopes, and moderate fire frequency mixed conifer forest on north-facing slopes – complicate the interpretation of the sedimentary charcoal record. Charcoal deposition processes in both bogs are less well known than similar processes in lakes (Whitlock and Anderson 2003), and the effect of changes in hydrologic status of the bog, such as the wetting/drying, on charcoal formation and deposition processes is largely unknown. Extremely high charcoal concentrations, abundant fine fuels of the grassy wetland vegetation, and the fire-scar history of relatively frequent surface fires in adjoining forests suggests that pre-1900 surface fires likely spread through aerial herbaceous fuels across both bogs in many years. Thus past surface fires might have produced abundant *in situ* charcoal, as well as charcoal influx from surrounding forested slopes. Burning of the peaty surface bog sediments may have eliminated some of the organic sedimentary deposits during extreme droughts, leaving high charcoal concentrations. The substantial background concentrations of charcoal also likely reflect the high frequency of fire activity affecting these bogs relative to the temporal resolution of 0.5 - 1 cc sampling intervals, further complicating the interpretation of observed charcoal peaks as discrete fire “events” (in contrast to relatively direct calculations of event frequency for long-interval stand-replacing fires from subalpine forest lake basins). The presence of bioturbation, especially during droughts, of the bog sediments by hoof action from ungulates (livestock, elk, deer) could alter the charcoal concentration profiles found within individual sedimentary core samples.

Is the 20th Century fire record anomalous?

The historic cessation of fire since ~AD 1900 seen in the paired and replicated charcoal and tree-ring records at these historically high-frequency fire sites is consistent with many other tree-ring fire histories from the Jemez Mountains and the Southwest as a whole (Swetnam and Baisan 1996), as well as the known regional histories of inadvertent fire suppression since the late 1800s due to livestock overgrazing and active fire suppression by land management agencies since the early 20th century. The unique near-absence of modern charcoal deposition replicated both within and between these two bog sites, combined with high background and peak levels of charcoal throughout most of the rest of the Holocene records from these sites, increases the robustness of the interpretation that this post-1900 lull in fire activity is anomalous at millennial time scales for at least these two localities. Similar gaps in charcoal deposition from uppermost sediment horizons are being found at some other sediment core sites in the Southern Rocky Mountains (Anderson et al. 2007a [submitted]), even though these sites historically had lower frequency fire regimes. Determining the geographic extent of this pattern will require the development of regional networks of additional charcoal sediment records from sites historically subject to high-frequency fire (generally drier, low to mid elevation, unglaciated landscapes), where it is hard to find unmanipulated, persistently wet basins that are needed to foster long-term sediment records.

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References

Allen, C.D. 1989. Changes in the Landscape of the Jemez Muntains, New Mexico. PhD Dissertation, University of California, Berkeley.

Allen, C.D. 2002. Lots of lightning and plenty of people: an ecological history of fire in the upland southwest. In: Fire, Native Peoples, and the Natural Landscape. Washington: Island Press. p. 143-193.

Anderson, R.S., Allen, C.D., Toney, J.L. Jass, R.B., Bair, A.N., 2007a (Submitted), Holocene vegetation and forest fire regimes in subalpine and mixed conifer forest sites, southern Rocky Mountains, USA. For invited special issue on "Fire Climatology" in International Journal of Wildland Fire.

Anderson, R.S., Jass, R.B., Toney, J.L., Allen, C.D., Cisneros-Dozal, M., Hess, M., Heikoop, J., Fessenden, J., 2007b (Submitted), Development of the mixed conifer forest in northern New Mexico, and its relationship to Holocene climate change. Quaternary Research.

Anderson, R.S., Hallett, D.J., Berg, E., Jass, R.B., Toney, J.L., de Fontaine, C.S., DeVolder, A., 2006, Holocene development of boreal forests and fire regimes on the Kenai Lowlands of Alaska. The Holocene 16(6), 791-803.

Anderson, R.S., and Smith, S.J. 1997. The sedimentary record of fire in montane meadows, Sierra Nevada, California, USA: A preliminary assessment. In: Clark, J.S., Cachier, H., Goldammer, J.G., Stocks, B. (Eds.), Sediment Records of Biomass Burning and Global Change. NATO ASI Series 1: Global Environmental Change, vol. 51. Springer, Berlin, pp. 318-328.

Arno, S.F., Sneck, K.M. 1977. A method for determining fire history in coniferous forests of the mountain west. USDA Forest Service General Technical Report INT 42, 1-28.

Baker W.L., Ehle D.L., 2001, Uncertainty in surface fire history: the case of ponderosa pine forests in the western United States. Canadian Journal of Forest Research 31, 1205-1226.

Bair, A.N. 2004. A 15,000 Year Vegetation and Fire History Record from the Southern Sangre de Cristo Mountains of Northern New Mexico. MS Thesis, Northern Arizona University.

Barrows, J.S. 1978. Lightning fires in Southwestern forests. Final Report prepared by Colorado State University for U.S. Department of Agriculture. Intermountain Forest and Range Experiment Station, Ogden, UT. 154 p.

Bogan, M.A., Allen, C.D., Muldavin, E.H., Platania, S.P., Stuart, J.N., Farley, G.H., Melhop, P. and Belnap, J. 1998. Southwest. In: Mac, M.J., Opler, P.A., and Doran, P.D. (Eds.), National Status and Trends Report. U.S. Geological Survey, Washington, D.C. pp 543-592.

Briles, C.E., Whitlock, C., Bartlein, P.J., 2005, Postglacial vegetation, fire, and climate history of the Siskiyou Mountains, Oregon, USA. Quaternary Research 64, 44-56.

Brown, P.M., Wu, R., 2005, Climate and disturbance forcing of episodic tree recruitment in a southwestern ponderosa pine landscape. Ecology 86, 3030-3038.

Brunelle, A., Whitlock, C., 2003, Postglacial fire, vegetation, and climate history in the clearwater range, Northern Idaho, USA. Quaternary Research 60, 307-318.

Brunelle, A., Whitlock, C., Bartlein, P., Kipfmueller, K., 2005, Holocene fire and vegetation along environmental gradients in the Northern Rocky Mountains. Quaternary Science Reviews 24, 2281-2300.

Brunner-Jass, R.M. 1999. ‘Fire Occurrence and Paleoecology at Alamo Bog and Chihuahueños Bog, Jemez Mountains, New Mexico, USA’. MS Thesis, Northern Arizona University.

Cook, E.C., Woodhouse, C., Eakin, C.M., Meko, D.M., Stahle, D.W., 2004, Long-Term Aridity Changes in the Western United States. Science 306, 1015-1018.

Dieterich, J.H., Swetnam, T.W., 1984, Dendrochronology of a fire-scarred ponderosa pine. Forest Science 30(1), 238-247.

Fall, P.L., 1997, Timberline fluctuations and late Quaternary paleoclimates in the Southern Rocky Mountains, Colorado. Geological Society of America Bulletin 109, 1306-1320.

Friedman, I., Carrara, P., Gleason, J., 1988, Isotopic evidence of Holocene climate change in the San Juan Mountains, Colorado. Quaternary Research 30, 350-353.

Fulé, P.C., Heinlein, T.H., Covington, W.W., Moore, M.M., 2003, Assessing fire regimes on Grand Canyon landscapes with fire-scar and fire-record data. 2003. International Journal Wildland Fire 12, 129-145.

Gavin, D.G., Brubaker, L.B., Lertzman, K.P., 2003, An 1800-year record of the spatial and temporal distribution of fire from the west coast of Vancouver Island, Canada. Canadian Journal of Forest Research 33, 573-586.

Gavin, D.G., Hu, F.S., Lertzman, K.P., Corbett, P., 2006, Weak climatic control of forest fire history during the late Holocene. Ecology 87, 1722-1732.

Grissino-Mayer, H.D. 1996. A 2129-year reconstruction of precipitation for northwestern New Mexico, USA. In: Dean, J.S., Meko, D.M., Swetnam, T.W. (Eds.), Tree Rings, Environment, and Humanity. Radiocarbon 1996: 191-204.

Grissino-Mayer, H.D., 2001, FHX – software for analyzing temporal and spatial patterns in fire regimes from tree rings. Tree Ring Research 57, 113-122.

Grissino-Mayer, H.D., Romme, W.H., Floyd-Hanna, M.L., Hanna, D., 2004, Climatic and human influences on fire regimes of the southern San Juan Mountains, Colorado, USA. Ecology 85(6), 1708-1724.

Grissino-Mayer, H.D., Swetnam, T.W., 2000, Century-scale climate forcing of fire regimes in the American Southwest. The Holocene 10, 213-220.

Hallett, D.J., Hills, L.V., 2006, Holocene vegetation dynamics, fire history, lake level and climatic change in the Kootenay Valley, southeastern British Columbia, Canada. Journal of Paleolimnology 35, 351-371.

Hallett, D.J., Mathewes, R.W., Walker, R.C., 2003, A 1000-year record of forest fire, drought and lake-level change in southeastern British Columbia, Canada. The Holocene 13(5), 751-761.

Hallett, D.J., Walker, R.C., 2000, Paleoecology and its application to fire and vegetation management in Kootenay National Park, British Columbia. Journal of Paleolimnology 24, 401-414.

Higuera, P.A., Sprugel, D.G., Brubaker, L.B., 2005, Reconstructing fire regimes with charcoal from small-hollow sediments: a calibration with tree-ring records of fire. The Holocene 15 (2), 238-251.

Kitzberger T., Brown P.M., Heyerdahl E.K., Swetnam T.W., Veblen T.T., 2007, Contingent Pacific-Atlantic Ocean influence on multicentury wildfire synchrony over western North America. Proceedings of the National Academy of Sciences, *U.S.A.* 104, 543-548.

Laird, L.D., Campbell, I.D., 2000, High resolution paleofire signals from Christina Lake, Alberta: a comparison of the charcoal signals extracted from two different methods. Palaeogeography, Palaeoclimatology, Palaeoecology 164, 111-123.

MacDonald, G.M., Larsen, C.P.S., Szeicz, J.M., Moser, K.A., 1991, The reconstruction of boreal forest fire history from lake sediments: a comparison of charcoal, pollen, sedimentological, and geochemical indices. Quaternary Science Reviews 10, 53-71.

Margolis, E.Q., Swetnam, T.W., Allen, C.D. (In press). A stand-replacing fire history in upper montane forests of the Southern Rocky Mountains. Canadian Journal of Forest Research.

Millspaugh, S.H., Whitlock, C., 1995, A 750-year fire history based on lake sediment records in central Yellowstone National Park, USA. The Holocene 5(3), 283-292.

Mohr, J.A., Whitlock, C., Skinner, C.N., 2000, Postglacial vegetation and fire history, eastern Klamath Mountains, California, USA. The Holocene 10(4), 587-601.

Morino, K.A., Baisan, C.H., Swetnam, T.W., 1998, Expanded Fire Regime Studies in the Jemez Mountains, New Mexico. Unpublished final report submitted to USGS Jemez Mts. Field Station, Bandelier National Monument. Laboratory of Tree-Ring Research, University of Arizona.

Patterson, W.A., Edwards, K.J. and Maguire, D.J. 1987. Microscopic charcoal as a fossil indicator of fire. Quaternary Science Reviews 6, 3-23.

Petersen, K.L., 1981, 10,000 years of climate change reconstructed from fossil pollen, La Plata Mountains, southwestern Colorado. PhD Dissertation, Washington State University, Pullman.

Petersen, K.L., 1985, Palynology in Montezuma County, Southwestern Colorado: The local history of Pinyon Pine (*Pinus edulis*). In: Jacobs, B., Davis, O.K., P.L. Fall (Eds.), Late Quaternary Palynology of the American Southwest. American Association of Stratigraphic Palynologists Foundation, Dallas, pp. 47-62.

Pitkänen, A., Lehtonen, H., Huttunen, P., 1999, Comparison of sedimentary microscopic charcoal particle records in a small lake with dendrochronological data: evidence for the local origin of microscopic charcoal produced by forest fires of low intensity in eastern Finland. The Holocene 9, 559-567.

Stokes, M.A., Smiley, T.L., 1968, An Introduction to Tree-Ring Dating. University of Chicago Press, Chicago, IL, 73 pp.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, F.G., v.d. Plickt, J., Spurk, M., 1998, INTCAL98 radiocarbon age calibration 24,000 – 0 cal BP. Radiocarbon 40, 1041-1083.

Swetnam T.W., Allen C.D., Betancourt J.L., 1999, Applied historical ecology: Using the past to manage for the future. Ecological Applications 9, 1189-1206.

Swetnam, T.W., Baisan, C.H., 1996, Historical fire regime patterns in the southwestern United States since AD 1700'. In: Allen, C.D. (Ed.), Fire Effects in Southwestern Forests: Proc. of the 2nd La Mesa Fire Symposium. USDA Forest Service Gen. Tech. Rep. RM-GTR-286. Ft. Collins, CO, pp. 33-46..

Swetnam, T.W., Baisan, C.H., 2003, Tree-ring reconstructions of fire and climate history in the Sierra Nevada and Southwestern United States. In: Veblen, T.T., Baker, W.L., Montenegro, G., Swetnam, T.W. (Eds.), Fire and Climatic Change in Temperate Ecosystems of the Americas. Ecological Studies 160. Springer-Verlag, New York, pp. 158-195.

Swetnam, T.W., Betancourt, J.L., 1998, Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. Journal of Climate 11, 3128-3147.

Toney, J.L., Anderson, R.S., 2006, A postglacial palaeoecological record from the San Juan Mountains of Colorado USA: fire, climate and vegetation history. The Holocene 16, 1-15.

Touchan, R., C.D. Allen,, T.W. Swetnam, 1996, Fire History and Climatic Patterns in Ponderosa Pine and Mixed-Conifer Forests of the Jemez Mountains, Northern New Mexico. In: Allen, C.D.

(Ed.), Fire Effects in Southwestern Forests: Proceedings of the 2nd La Mesa Fire Symposium. USDA Forest Service Gen. Tech. Rep. RM-GTR-286. Fort Collins, CO, pp. 33-46.

Van Horne M.L., Fulé, P.Z., 2006, Comparing methods of reconstructing fire history from fire scars in a southwestern United States ponderosa pine forest. Canadian Journal of Forest Research 36:855-877.

Veenhuis J., 2002, Effects of wildfire on the hydrology of Capulin and Rito de los Frijoles Canyons, Bandelier National Monument, New Mexico. Albuquerque, NM: US Geological Survey, Water Resources Investigations Report 02-4152.

Weng, C., Jackson, S. T., 1999, Late-glacial and Holocene vegetation history and paleoclimate of the Kaibab Plateau, Arizona. Palaeogeography, Palaeoclimatology, Palaeoecology 153, 179-201.

Westerling A.L., Hidalgo H.G., Cayan D.R., Swetnam T.W., 2006, Warming and earlier spring increases western U.S. fire activity. Science 313, 940-943.

Whitlock, C., Anderson, R.S., 2003, Fire history reconstructions based on sediment records from lakes and wetlands'. In: Veblen, T.T., Baker, W.L., Montenegro, G., Swetnam, T.W. (Eds.), Fire and Climatic Change in Temperate Ecosystems of the Americas. Ecological Studies 160. Springer-Verlag, New York. pp. 3-31.

Whitlock, C., Shafer, S.L., Marlon, J., 2004, The role of climate and vegetation change in shaping past and future fire regimes in the northwestern US and the implications for ecosystem management. Forest Ecology and Management 178, 5-21.

Wolff, J.A., Gardner, J.N., 1995, Is the Valles caldera entering a new cycle of activity? Geology 23, 411–414.

Figure Captions:

Figure 1. Locations of Chihuahueños Bog (CHB) and Alamo Bog (AB) in northern New Mexico.

Figure 2. Aerial photograph view of Chihuahueños Bog, with bog outline in blue, sediment core sample area triangle, and fire-scarred tree samples at red dots. Inset photograph showing Chihuahueños bog surrounded by mixed conifer forest.

Figure 3. Aerial photograph view of Alamo Bog, with bog outline in blue, watershed boundary and drainage bottom in yellow, sediment core points at triangle, and fire-scarred tree samples at red (xeric sites) and green (mesic sites) dots. Inset photograph showing Alamo Bog and north aspect mixed conifer forest, arrow indicates dated aspen stand that regenerated in 1879.

Figure 4. Composite fire scar chronology from forests adjoining Chihuahueños Bog. Horizontal lines show the calendar-year life spans of individual trees, and the short vertical lines are fire-scar dates. The longer vertical lines at the bottom of the chronology indicate years with spreading fires, in which fire scarred at least 10% of previously scarred trees and a minimum of two samples. Note the synchronism of fire years across samples, and the cessation of spreading fires after ca. 1902.

Figure 5. Superposed epoch analysis for widespread fires at Chihuahueños Bog (CBT) and Alamo Bog (ABT) between 1600 and 1879 A.D. Dashed lines represent 99% CI and solid lines represent 95% CI.

Figure 6. Total charcoal particles/cc with depth. (a) Chihuahueños Bog core #1. Note major increase in charcoal concentrations with climate transition in early Holocene (at 185 cm). (b) Alamo Bog core # 3. For both (a) and (b), note near complete absence of charcoal since ca. 1900 AD (top ~20 cm).

Figure 7. (a) Charcoal as a flux of particles/cc/year (thin line), smoothed influx rate (thick line), fire “events” indicated by “+”, and reconstructed environment of Chihuahueños Bog core 1 through time. (b) Fire event frequencies (FEF), showing highest fire frequency estimated during late Pleistocene when influx is low and declines during early Holocene despite consistent high influx.

Figure 8. Replicated concentrations of charcoal (particles/cc) in the top meter of Chihuahueños Bog cores 1 and 2, displaying near identical charcoal patterns (arrows link analogous concentrations). Note complete cessation of charcoal in the top horizons, consistent with fire-scar data of last widespread surface fire in 1902.

Figure 9. Composite fire scar chronology from the Alamo Bog watershed. Horizontal lines show the calendar-year life spans of individual trees, and the short vertical lines are fire scar dates. The longer vertical lines at the bottom of the chronology indicate years with spreading fires, in which fire scarred at least 10% of previously scarred trees and a minimum of two samples. Xeric and mesic site trees are plotted in separate groups, with sampled trees are arrayed within each site group from lowest elevation (bottom) to highest. Note the high frequency of fire activity prior to 1880, the synchronism of fire years across samples, and the cessation of spreading fires after ca. 1879.

Figure 10. (a) Charcoal as a flux of particles/cc/year (thin line), smoothed influx rate (thick line), fire “events” indicated by “+”, and reconstructed environment of Alamo Bog core 3 through time. (b) Fire event frequencies (FEF), showing higher-frequency bulge during mid-late Holocene.

Figure 11. Concentrations of charcoal (particles/cc) in the upper portions of Alamo Bog cores 3 and 4. Note the same basic charcoal patterns in the top 70 cm of the replicate cores, including complete cessation of charcoal in the top horizons, consistent with fire-scar data of last widespread fire in 1879.

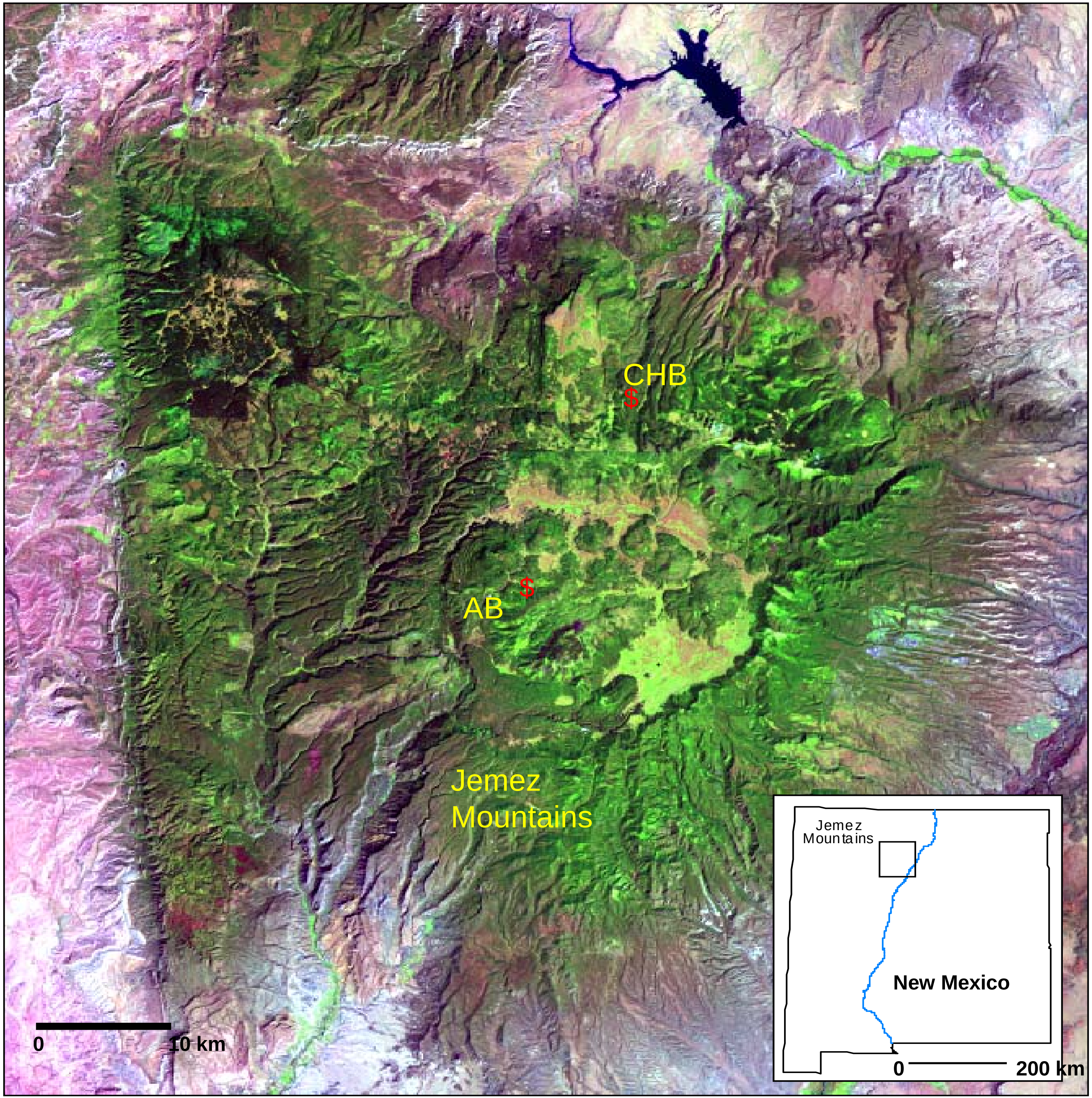
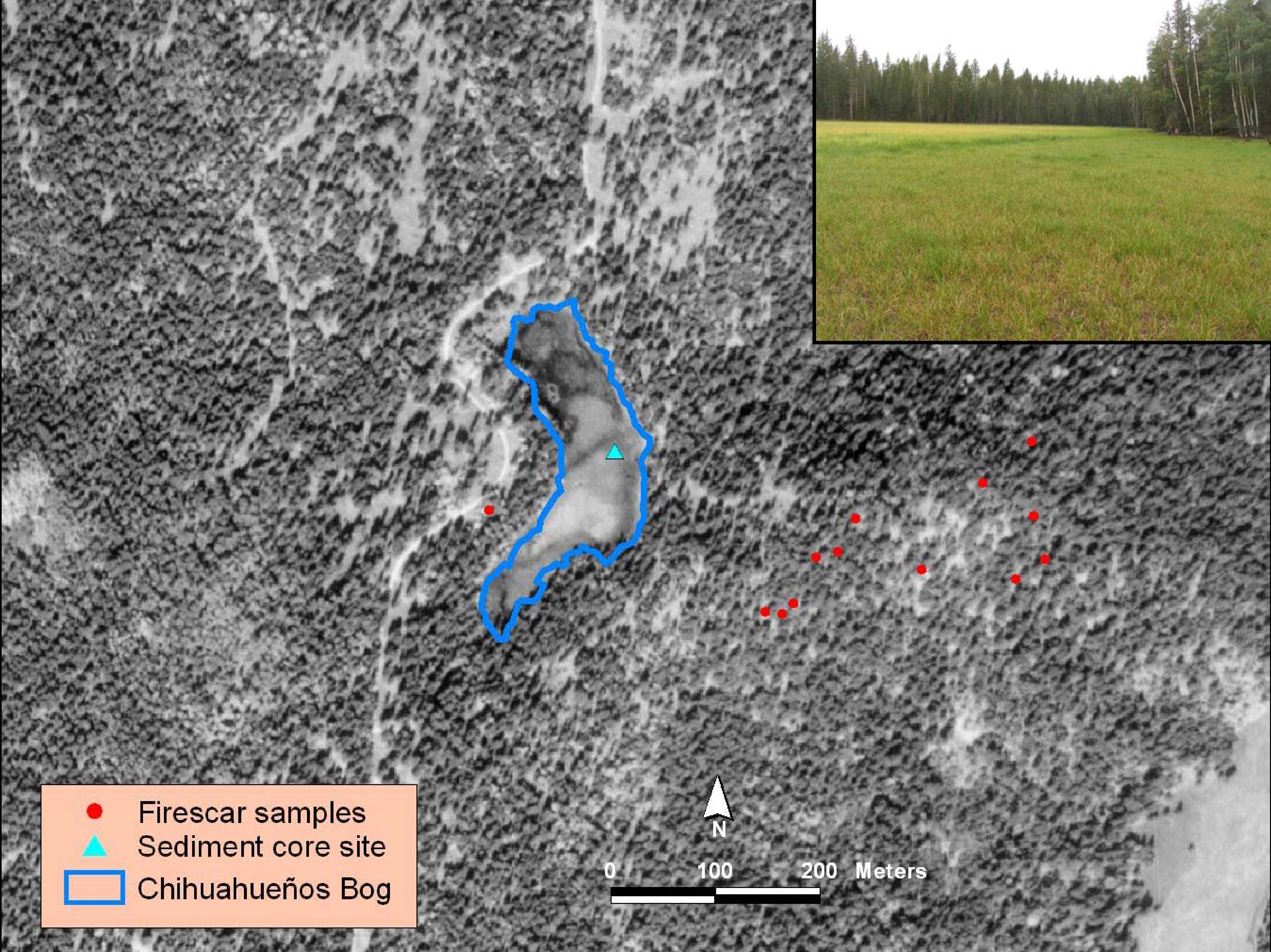

CHB
$
$
AB
Jemez
Mountains
0
10 km
Jemez
Mountains
New Mexico
0
200 km

Fig. 1


Firescar samples
Sediment core site
Chihuahueños Bog
N
0
100
200
Meters

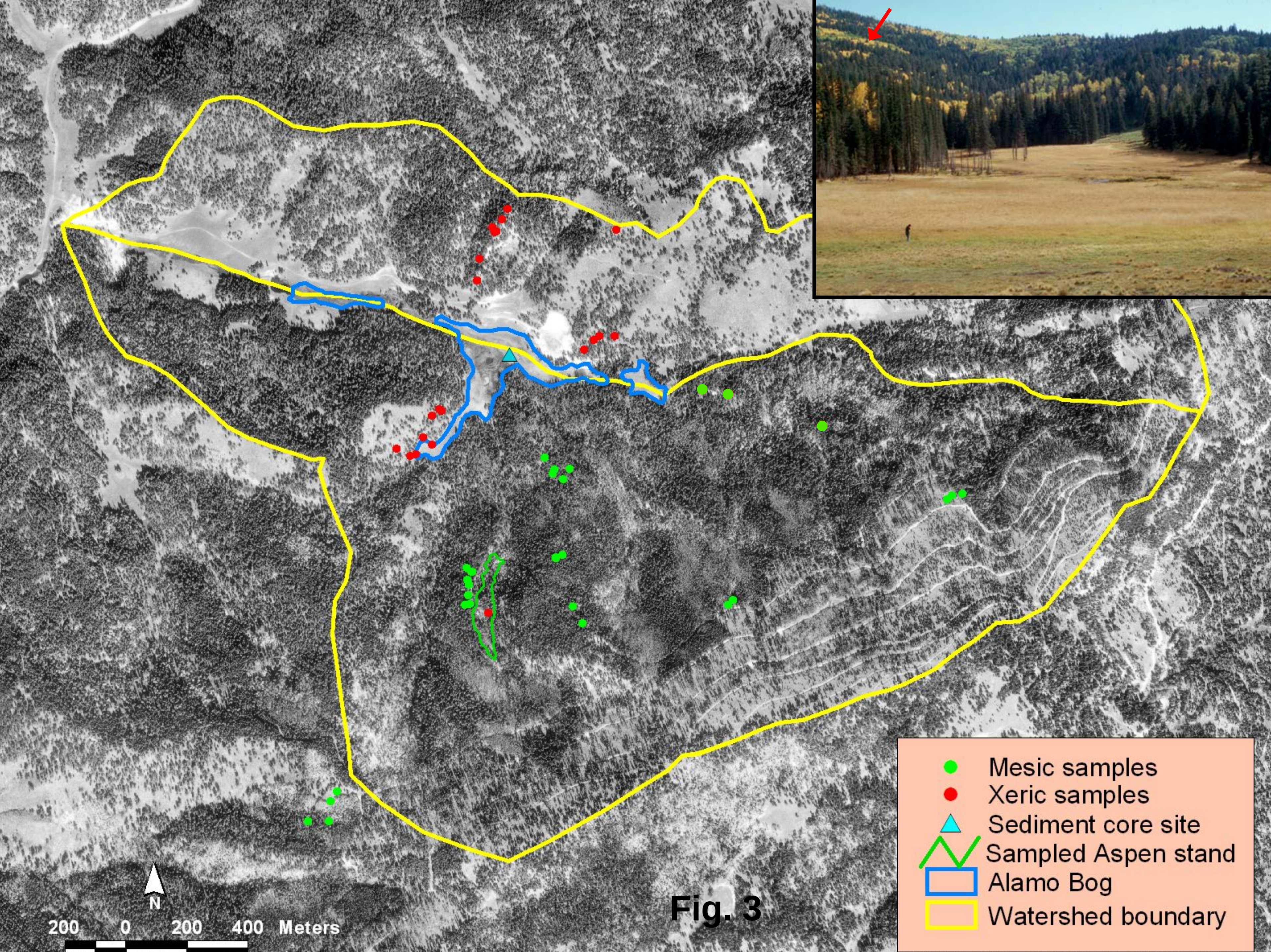
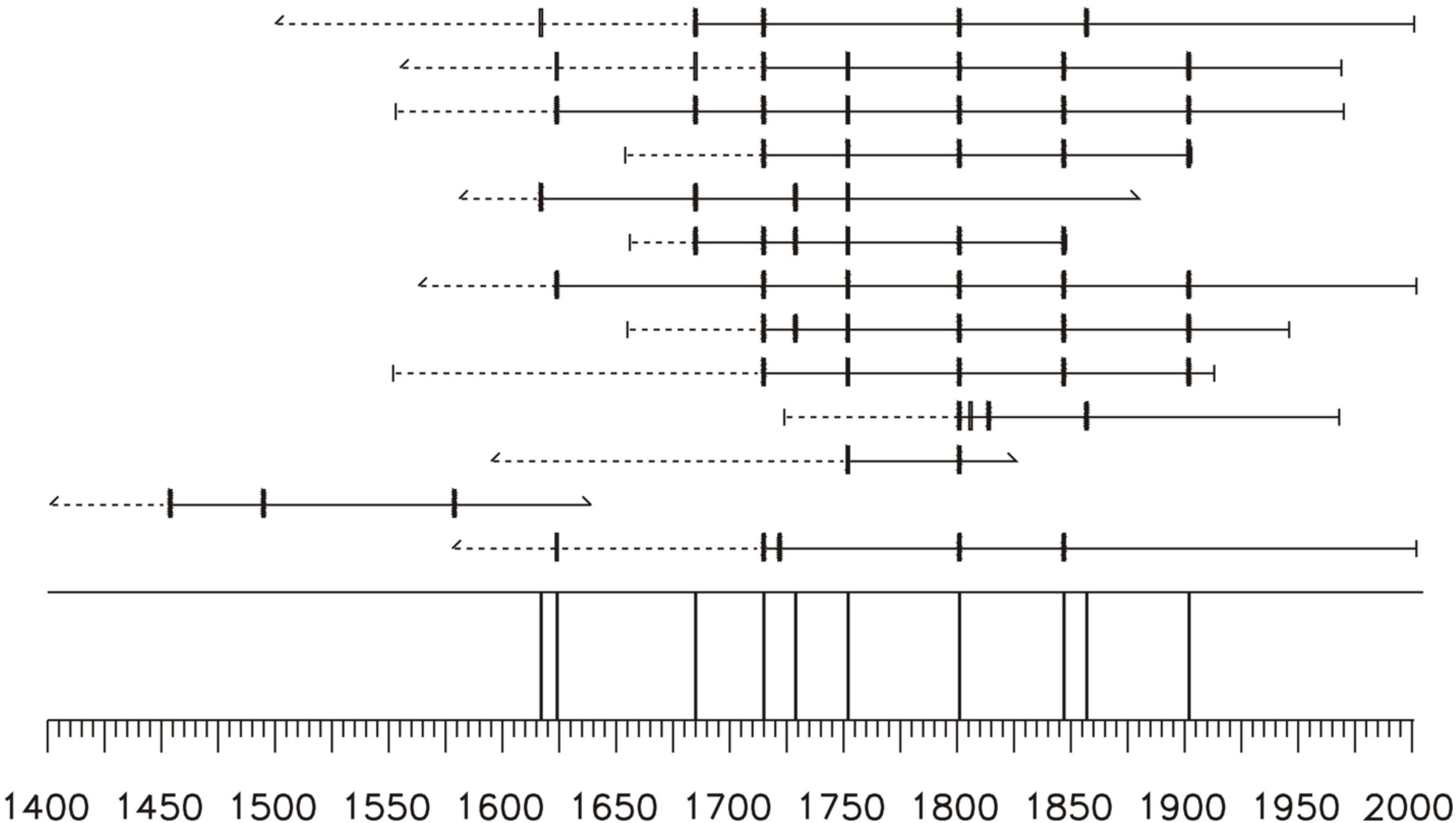

Mesic samples
Xeric samples
Sediment core site
Sampled Aspen stand
Alamo Bog
Watershed boundary
N
200 0 200 400 Meters

Fig. 3



1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000

Fig. 4

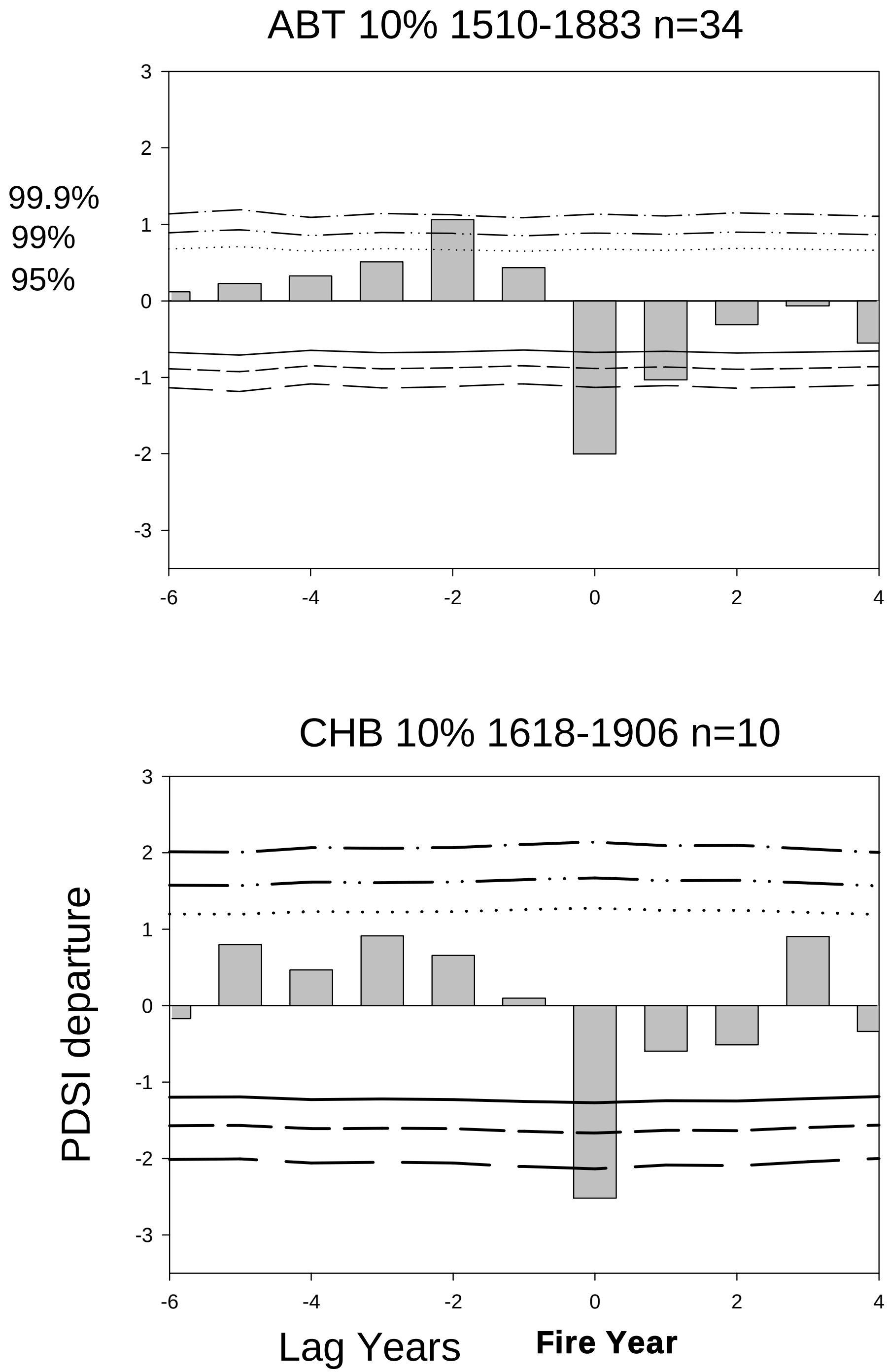
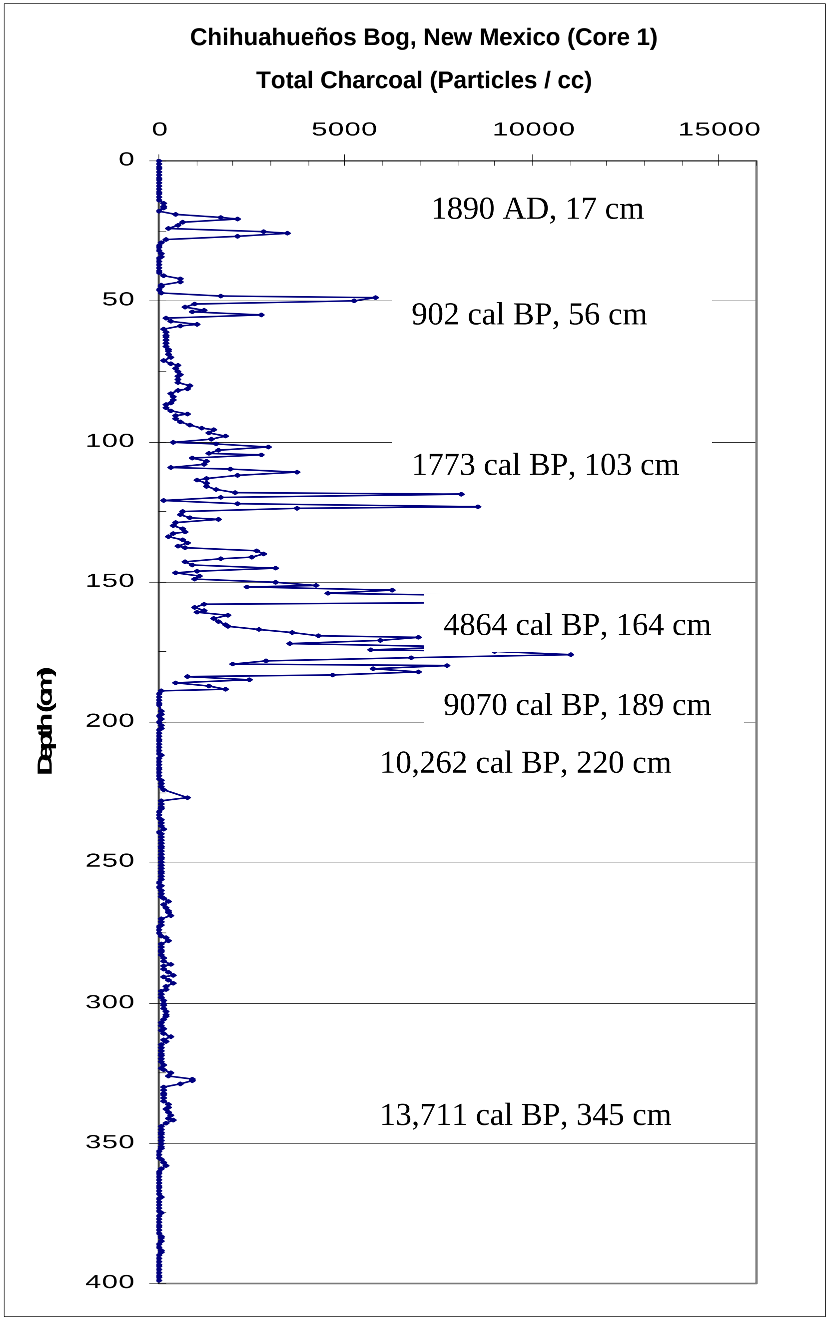
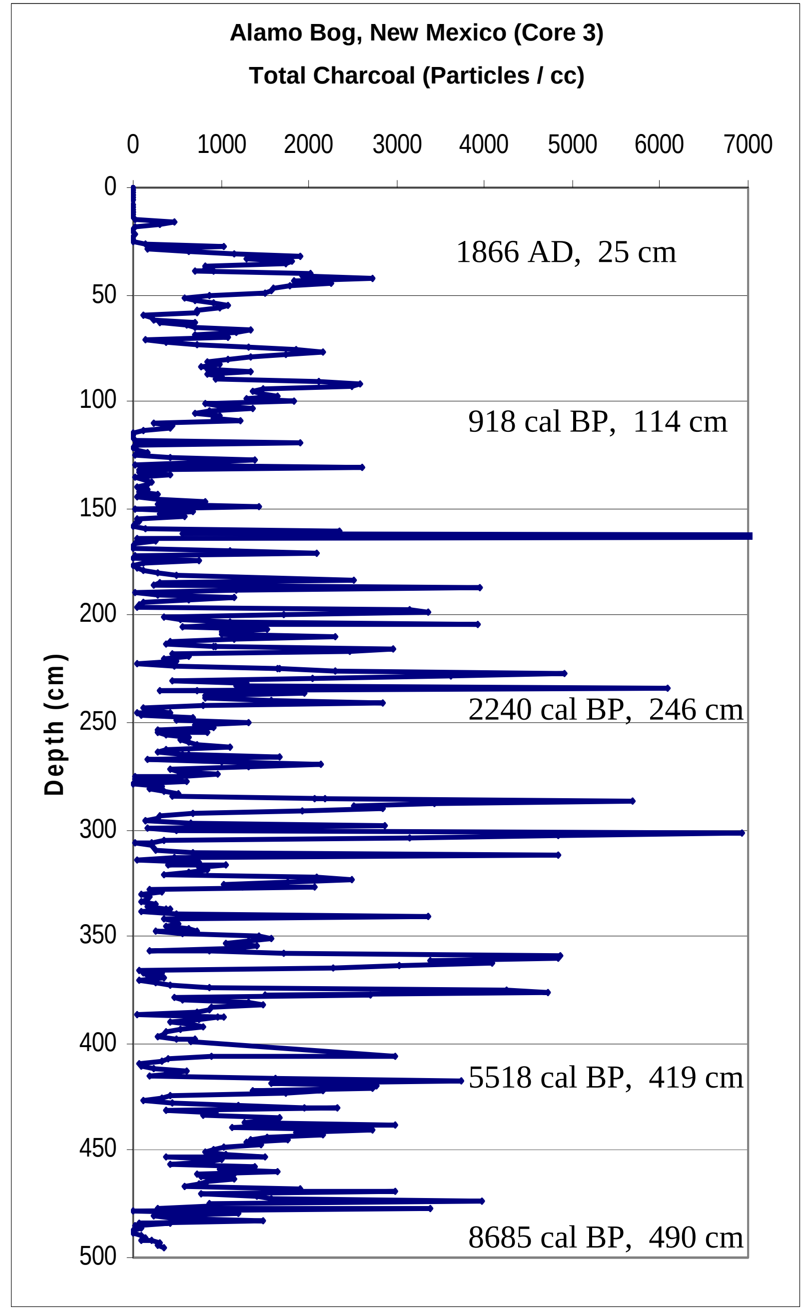

ABT 10% 1510-1883 n=34
99.9%
99%
95%
3
2
1
0
-1
-2
-3
-6
-4
-2
0
2
4
CHB 10% 1618-1906 n=10
PDSI departure
Lag Years
Fire Year

Fig. 5

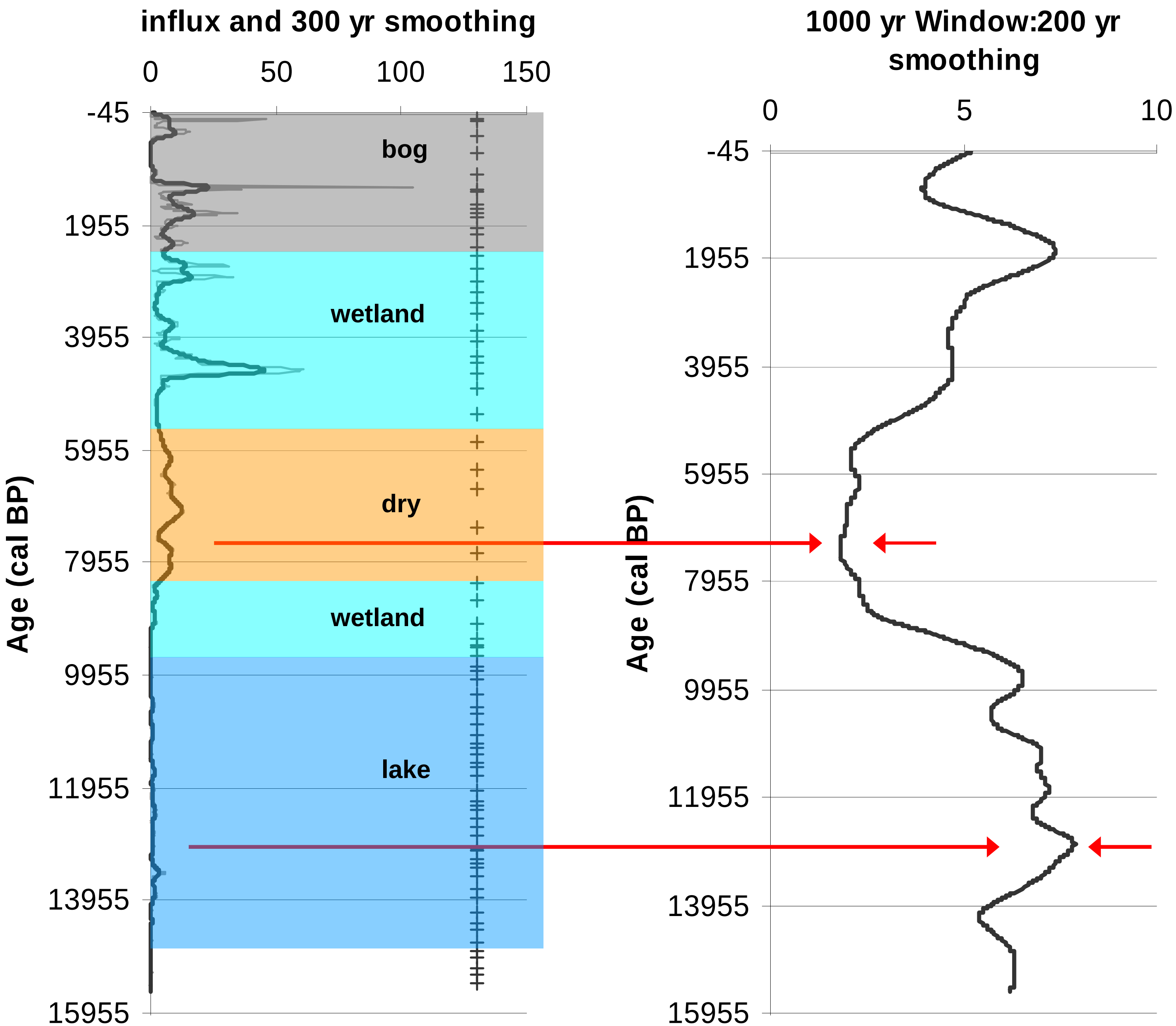


Chihuahueños Bog, New Mexico (Core 1)
Total Charcoal (Particles / cc)
0
5000
10000
15000
0
50
100
150
200
250
300
350
400
Depth (cm)
1890 AD, 17 cm
902 cal BP, 56 cm
1773 cal BP, 103 cm
4864 cal BP, 164 cm
9070 cal BP, 189 cm
10,262 cal BP, 220 cm
13,711 cal BP, 345 cm



Alamo Bog, New Mexico (Core 3)
Total Charcoal (Particles / cc)
0
1000
2000
3000
4000
5000
6000
7000
0
50
100
150
200
250
300
350
400
450
500
Depth (cm)
1866 AD, 25 cm
918 cal BP, 114 cm
2240 cal BP, 246 cm
5518 cal BP, 419 cm
8685 cal BP, 490 cm

Fig 6a & b



influx and 300 yr smoothing
0
50
100
150
-45
1955
3955
5955
7955
9955
11955
13955
15955
Age (cal BP)
bog
wetland
dry
wetland
lake
1000 yr Window:200 yr smoothing
0
5
10
-45
1955
3955
5955
7955
9955
11955
13955
15955
Age (cal BP)

Fig 7a & b

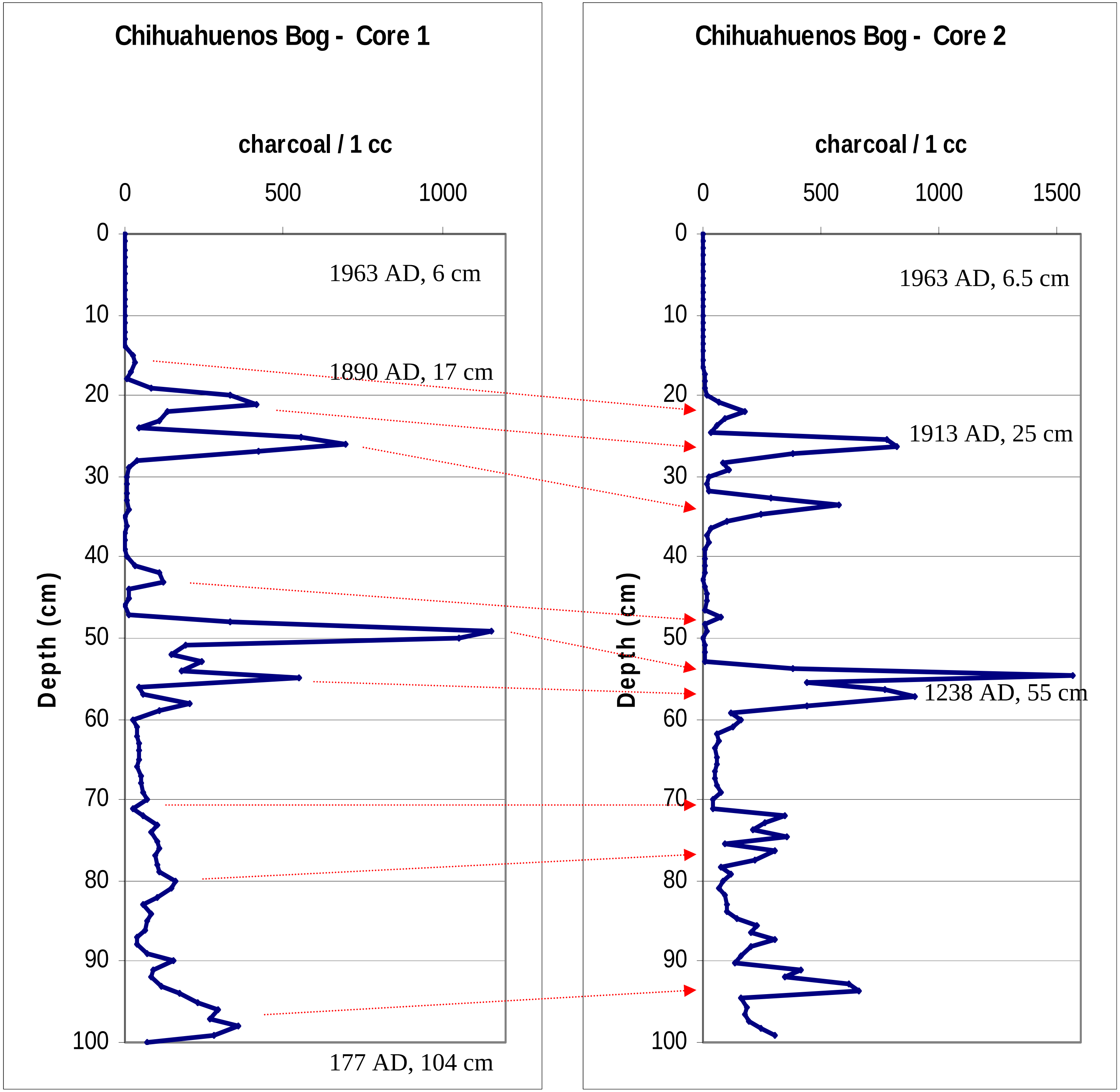
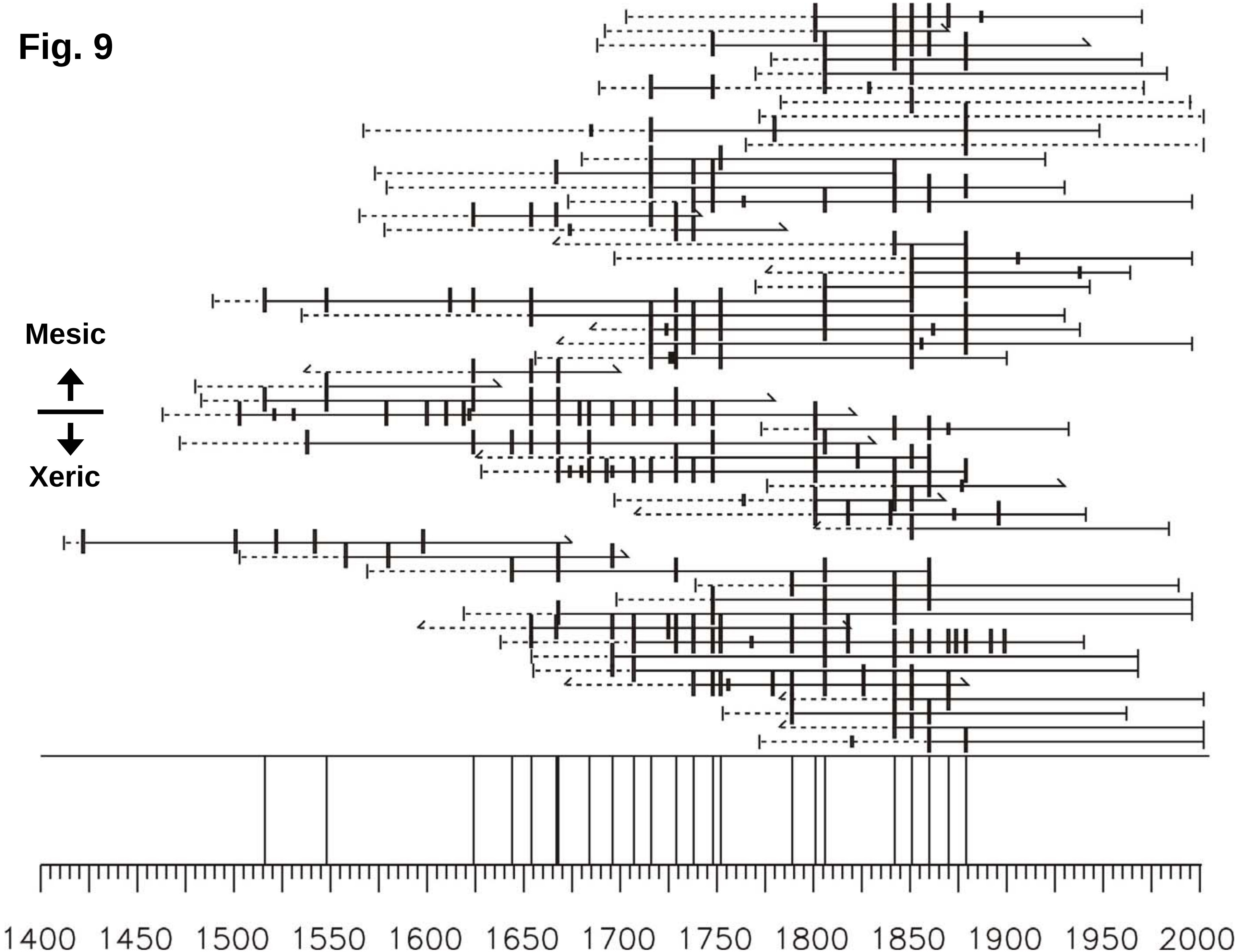
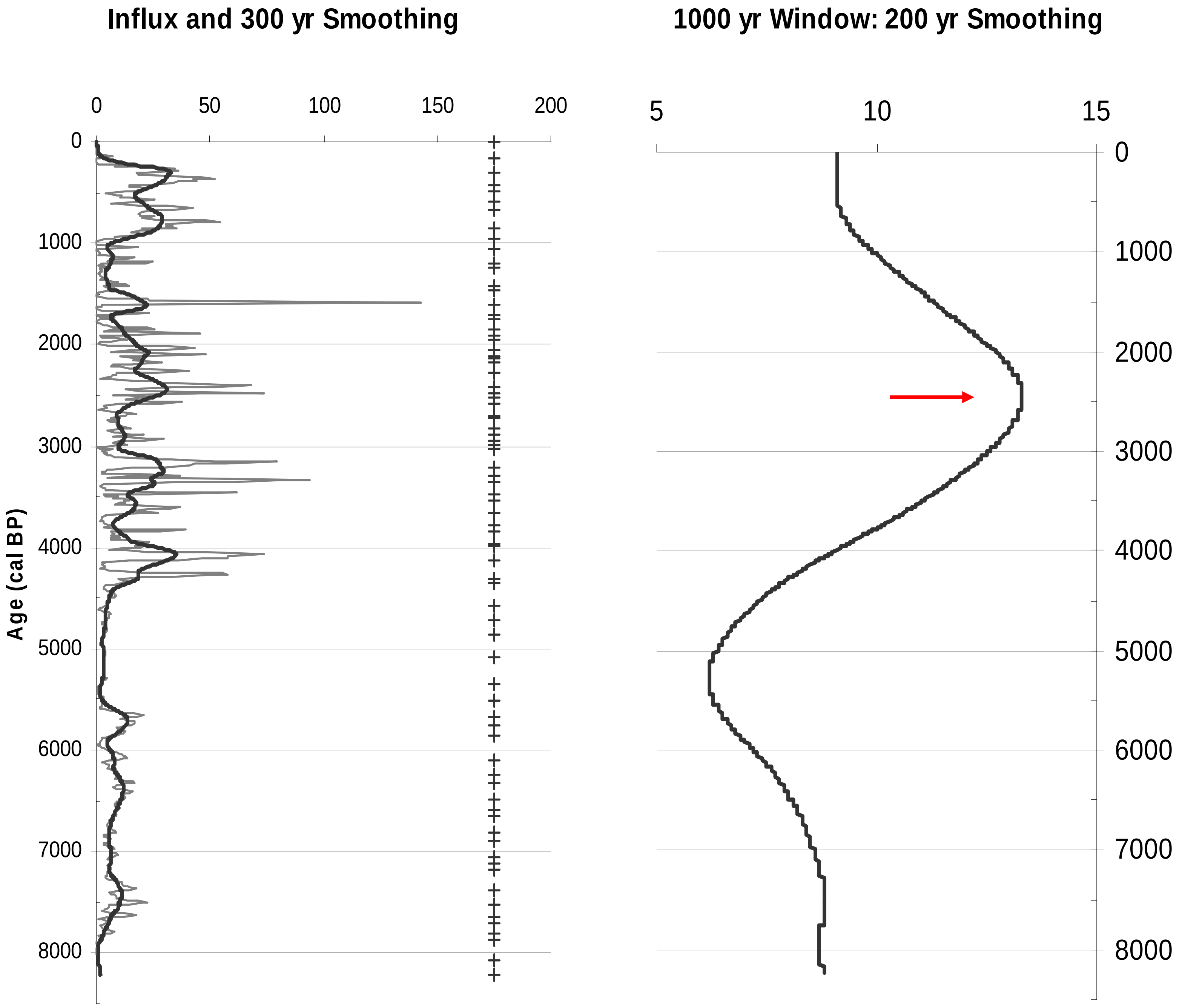

Chihuahuenos Bog - Core 1
charcoal / 1 cc
0
500
1000
0
10
20
30
40
50
60
70
80
90
100
Depth (cm)
1963 AD, 6 cm
1890 AD, 17 cm
177 AD, 104 cm
Chihuahuenos Bog - Core 2
charcoal / 1 cc
0
500
1000
1500
0
10
20
30
40
50
60
70
80
90
100
Depth (cm)
1963 AD, 6.5 cm
1913 AD, 25 cm
1238 AD, 55 cm

Fig. 8a & b

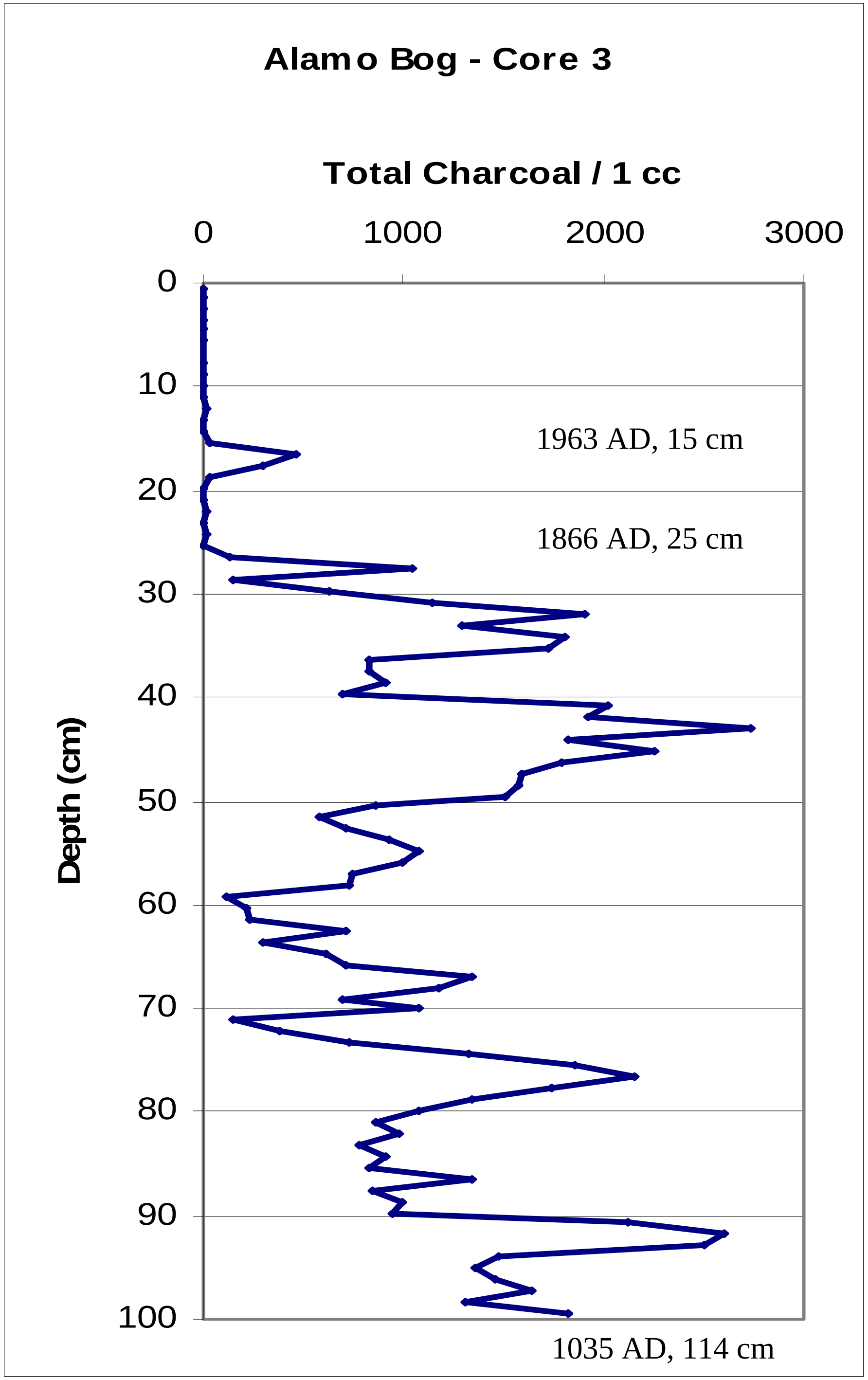
Fig. 9


Mesic
Xeric
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000

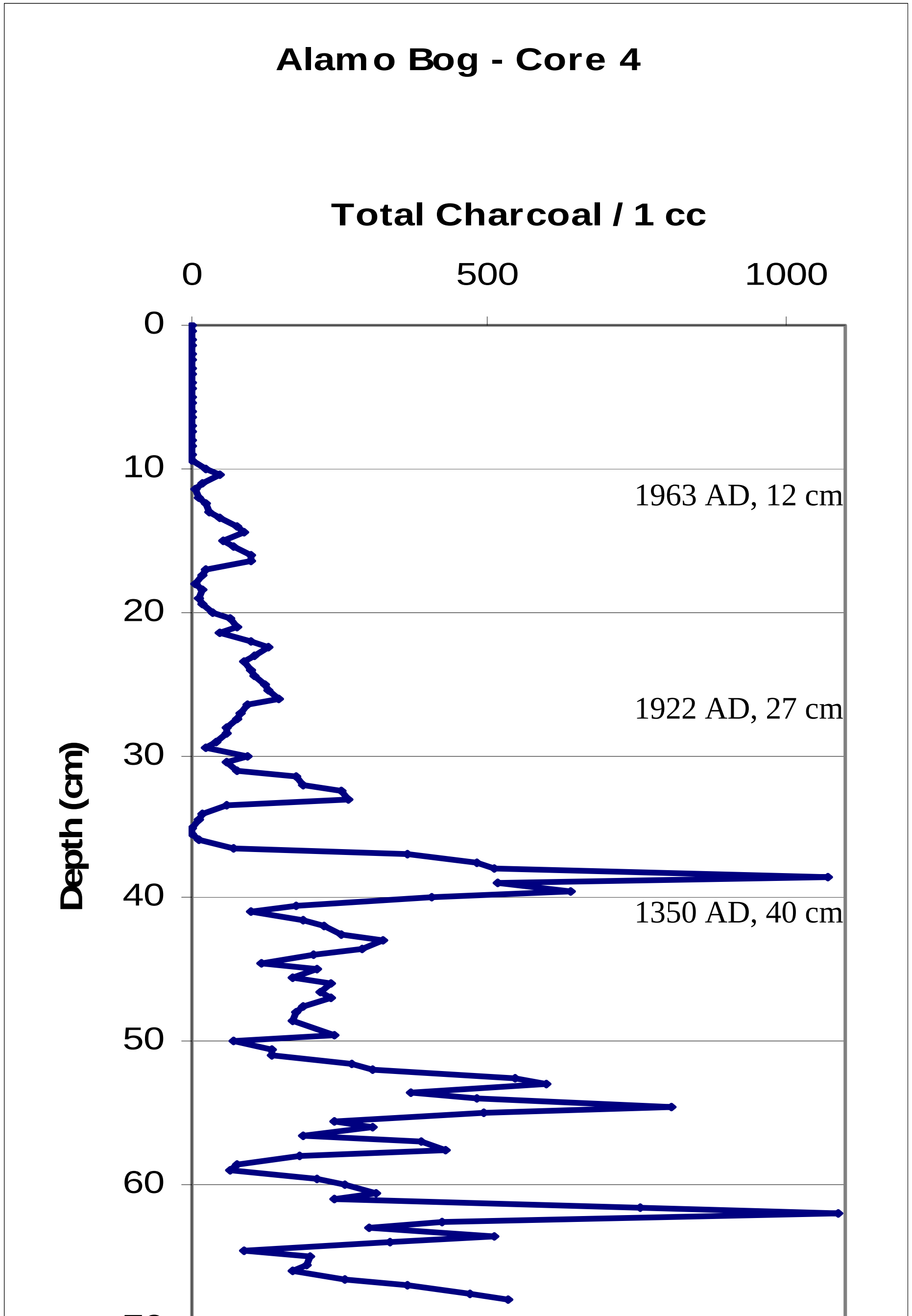


Influx and 300 yr Smoothing
1000 yr Window: 200 yr Smoothing
0
50
100
150
200
0
1000
2000
3000
4000
5000
6000
7000
8000
Age (cal BP)
5
10
15
0
1000
2000
3000
4000
5000
6000
7000
8000

Fig. 10a & b



Alamo Bog - Core 3
Total Charcoal / 1 cc
0
1000
2000
3000
Depth (cm)
0
10
20
30
40
50
60
70
80
90
100
1963 AD, 15 cm
1866 AD, 25 cm
1035 AD, 114 cm



Alamo Bog - Core 4
Total Charcoal / 1 cc
0
500
1000
Depth (cm)
0
10
20
30
40
50
60
70
1963 AD, 12 cm
1922 AD, 27 cm
1350 AD, 40 cm

Fig. 11a & b