

AN INTEGRATION OF TREE-RING AND ALLUVIAL RECORDS OF FIRE HISTORY AT
THE MISSIONARY RIDGE FIRE, DURANGO, COLORADO

by

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INTRODUCTION:

In the ponderosa pine and mixed-conifer forests of the Southwestern United States, recent wildfires with large, high severity burn patches are considered unprecedented by many fire ecologists and forest managers (Covington and Moore, 1994; Allen et al., 2002). Tree-ring records show that prior to the end of the 19th century, fires spread as low intensity surface fires, burning in the understory of open forests (Swetnam and Baisan, 2003; Swetnam and Baisan, 1996). These frequent surface fires had little impact on tree mortality, and are considered low severity in their impact on the soils and vegetation of these ecosystems (DeBano et al., 1998).

In the late 19th century, Euro-American settlement introduced livestock grazing, which removed grasses and fine fuels necessary for fire to spread (Cooper, 1960; Savage and Swetnam, 1990). During the 20th century, fire suppression activity conducted by land management agencies increased in effectiveness, further preventing fires from spreading (Pyne, 1997; Swetnam, 1990). The past century of fire exclusion has resulted in anomalously dense forest conditions in the southwestern ponderosa pine and mixed-conifer forests today (Covington and Moore, 1994). Thickets of small-diameter trees act as 'ladder' fuels, connecting the understory vegetation with the tree canopies (Fule et al., 1997; Fule et al., 2002). The continuous fuel structure now results in extensive high severity fire over large areas. High severity fire in these ecosystems results is defined as fire that results in complete vegetation mortality, along with significant impacts on the surface litter layers and below-ground soil conditions (DeBano et al., 1998).

One significant consequence of extensive high severity fire is the geomorphic response of severely burned watersheds (Wondzell and King, 2003). The consumption of the canopy, litter

and duff reduces obstructions to overland flow. The temperatures reached during high severity fire may create a water-repellant layer in the soil, and soil pores may be blocked with ash (DeBano, 2000; Neary et al., 1999). The combined effects of high severity fire are to reduce infiltration on the hillslopes, and dramatically increase runoff and erosion on the watershed scale (Moody and Martin, 2001; Martin and Moody, 2001). Under these conditions, floods and debris flows can occur in response to short duration, high intensity convective storms, which are an order of magnitude lower than those required for debris flow and flood generation in unburned watersheds (Cannon and Gartner, 2005).

While the timing of wildfires during the 20th century is associated with drought conditions (Swetnam and Betancourt, 1998; Grissino-Mayer and Swetnam, 2000; Westerling and Swetnam, 2003), the large patches of high severity fire are attributed to the dense forest conditions in the ponderosa pine and mixed-conifer forests of the Southwest. Fire-scar records show that surface fires were also extensive during the presettlement period, possibly burning up to thousands of hectares (Swetnam and Baisan, 2003). However, during these widespread fires, high severity fire in pure ponderosa pine was probably limited to localized patches of a few trees (Swetnam and Baisan, 1996). Estimates of high severity patch size in upper-elevation mixed-conifer stands with longer fire return intervals ranged from a few hectares up to approximately 100 hectares (Wu, 1999; Abolt, 1997; Fule et al., 2003, Huckaby et al., 2001; Margolis, 2003, Alington, 1998). Although the timing and extensiveness of recent wildfires is expected due to drought conditions, the high severity fire behavior seems to be outside of the range of historical variability.

Review of fire history methods:

Multiple methods of studying fire history provide a context for understanding recent wildfire behavior as well as the geomorphic response associated with burned watersheds. Tree rings, alluvial fan stratigraphy and charcoal records from lake sediment cores provide information about the variability in fire size, severity and timing over a range of time scales (Whitlock and Anderson, 2003; Swetnam and Baisan, 2003; Meyer et al., 1995; Pierce et al., 2004). This study focuses on tree-ring and alluvial fan methods, which document the timing, severity and extent of fires on different temporal scales.

Tree-ring methods:

Tree-ring methods reconstruct the timing and severity of fires with annual precision, yet are typically limited to approximately the past 400 years of record within the Southwestern U.S. (Swetnam and Baisan, 1996). These methods include both fire-scarred trees and age-structure data. Fire-scarred trees are an annual record of fires, which are typically composited to identify the spatial and temporal patterns of surface fires for a site (Swetnam and Baisan, 1996). Conifer age-structure data show decadal patterns of forest regeneration, which may provide evidence of high severity fire when associated with the surface fire history (Huckaby et al., 2001). For example, the lack of individuals dating prior to a fire event identified by fire scars may be used to infer high severity fire.

Aspen age-structure data may also provide evidence of high severity fire patches. Aspens sprout vegetatively when disturbed by fire, and can quickly colonize canopy openings created by fire in the spruce-fir ecosystems of the Southwest (Margolis, 2003). Hence, aspen regeneration

dates with an even-aged distribution may indicate high severity fire, especially if supported by other types of evidence. This usually includes death dates of conifer trees within the stand, as well as the association with fire-scar dates.

Alluvial fan methods:

Alluvial fan stratigraphy can provide information about the timing and relative severity of fires over millennial time scales. Fire-related sedimentation events identified on alluvial fan surfaces are dated by applying radiocarbon ^{14}C analyses to charcoal within the deposits (Meyer et al., 1995; Pierce, 2004). Alluvial fan stratigraphy has been used to interpret both low and high severity fire regimes from ponderosa pine to lodgepole pine forests (Meyer et al., 1995; Pierce, 2004). This method relies on observations from recently burned watersheds, where the extent of high severity fire is one of the main variables influencing the type of geomorphic response from small tributary basins (Meyer and Wells, 1997; Cannon and Gartner, 2005; Pierce, 2004). Debris flow deposits with abundant charcoal are used to infer extensive high severity fire events, while charcoal-rich sheetflood deposits have been used to interpret low severity fire regimes in the contributing watersheds (Meyer et al., 1995; Pierce et al., 2004).

The most frequently observed process for debris flow initiation is runoff-dominated erosion by surface overland flow (Cannon and Gartner, 2005). This occurs when surface runoff concentrates into rills and gullies on the hillslope, entraining sediment as the flow travels down the slope. The runoff converges and erodes channel sediments, progressively increasing the ratio of sediment to water in the flow. The sediment-charged channel flow may transition to continuous debris flow conditions downstream (Cannon et al., 2003; Meyer and Wells, 1997).

These processes primarily result from small, high relief tributary basins underlain by sedimentary and metamorphic bedrock types (Cannon and Gartner, 2005). Given similar basin conditions in a region, a threshold in high severity burned area is required to generate debris flows (Cannon et al., 2003).

Low severity fires generally do not produce sufficient runoff to initiate debris flows (Cannon and Gartner., 2005). Low-severity fires burn vegetation and char litter on the forest floor, without greatly altering the depth and spatial cover of the litter and duff layers (Wells et al., 1979, DeBano et al, 1998; Robichaud, 2000). The intact litter and duff layer promotes relatively higher infiltration rates, while protecting the mineral soil from rainsplash erosion (Martin and Moody, 2001; Robichaud, 2000; Wells et al., 1979). Based on plot-scale studies, the percentage of bare mineral soil exposed on severely burned plots evidently is an important variable in runoff and erosion rates (Benavides-Solorio, 2000; Robichaud, 2000; Robichaud and Waldrop, 1994). Although basins burned at low severity contain small patches of exposed soil, there is little increase in runoff at the watershed outlet, because overland flow generated in bare patches often re-infiltrates in areas with sufficient litter and duff (Wells, 1987; Lavee et al., 1995; Reid et al., 1999). Occasionally, flooding at the watershed scale may result from basins burned primarily at low severity, though usually in response to relatively higher magnitude storm events (Inbar et al., 1998). When identified within alluvial fan deposits, sheetflood deposits have been inferred to represent a subset of low severity fire events in the contributing watershed (Pierce, 2004).

Sedimentation on alluvial fans is often patchy and localized, leaving a discontinuous record of deposition for a single fan (Blair and McPherson, 1994). Therefore, depositional

events observed on multiple fans throughout a region are combined to identify regionally synchronous fire-related geomorphic responses, which are most likely to be associated with climate variations at this scale (Meyer et al., 1995, Pierce et al., 2004). This technique is similar to the combination of multiple fire-scar samples throughout a region, used to identify regional fire years (Swetnam and Betancourt, 1998). Aggregated records of fire-related depositional events are then compared graphically and statistically with records of climate variability to evaluate the nature of climate-fire associations (Meyer et al., 1995; Pierce et al., 2004).

Objectives:

The goal of this research is to combine alluvial fan and tree-ring records at the scale of a single low-order drainage basin. The scale of the study limits the interpretation of fire and climate relationships from the alluvial fan deposits, yet the data will be compared with other tree-ring and lake sediment fire history studies from the region to provide a context for the results. Alluvial fan stratigraphy has been applied at a few locations in the Southwest, but this approach has never been directly compared with tree-ring records at the drainage basin-scale at any location (Gonzales et al., 2004; Meyer et al., 1995; Pierce, 2004).

Alluvial fan stratigraphy is helpful for understanding the variability in fire regimes throughout the mid to late Holocene. These relatively longer records complement tree-ring fire history records in that they are relatively spatially precise, and provide specific fire-severity information. However, for the time period of the past 500 years, radiocarbon dating has low precision due to uncertainties in the calibration with calendar years (Stuiver and Reimer, 1993). The use of high temporal resolution tree-ring records may help constrain the timing of recent

alluvial deposits, while the combination of methods will extend the fire history record for the study site.

Specific questions to be addressed by this research are:

1. Does the type of recent sediment deposition represent the fire history reconstructed from tree-ring records?
2. What does the combined fire history suggest about the timing, extent and severity of past fires in the study basin?
3. Is there evidence of stand-replacing fire over centennial and longer time scales, which may provide a context for assessing the impact of recent wildfires in the study region?

METHODS:

Study Setting:

In the summer of 2002, the Missionary Ridge Fire burned through more than 72,000 acres (30,000 ha) of the San Juan National Forest in southwestern Colorado (Figure 1). The burned area exhibited a mosaic of unburned, low, moderate, and high severity burn classes, with approximately 50% of the area burned at moderate and high severities (Burned Area Emergency Response (BAER) Team, 2002). The relative burn severity, as mapped by the BAER team in 2002, reflects the effect of the fire on the soil conditions. This was mapped during field surveys, which assessed the relative amount of water repellency, ash depth, and remaining ground cover.

Following the fire, debris flows and sediment-laden floods were generated from several low-order tributary basins, incising older alluvial deposits throughout the burned area. As is

common with fire-related debris flow activity, these events were initiated in response to short duration, high-intensity convective storms, frequently occurring during the summer months in the Southwest (Cannon et al., 2003).

This study focuses on a 1 km² drainage basin, with approximately 80% of the area burned by moderate- and high-severity fire. It is an east-facing tributary basin of the Los Pinos River Valley, located on the northwest side of the Vallecito Reservoir (Figure 1). The elevation of the drainage basin ranges from 2,350 m (7,700 ft) at the drainage outlet to 3,000 m (9,800 ft) at the upper ridge. Post-fire debris flow and flood events exposed a record of fire-related sediments, which had been aggrading in the valley bottom over the late Holocene. Although the age of the sediments have been documented in a previous study, deeper exposures with buried wood became exposed in the two years since the initial study (Gonzales et al., 2004). The detail of the stratigraphy presented an ideal opportunity to compare the alluvial fan and tree-ring records of fire history at the same study site.

The study basin is underlain by Permian age bedrock, primarily the Hermosa Limestone, with a small proportion of Cutler Sandstone on the southern ridge. The main valley was glaciated during the last full-glacial period, and the hillslope colluvium is composed of reworked till deposits up to approximately 2,700 m in elevation (Gonzales et al., 2004). The soils are both cryalfs and udalfs, which are well-draining soils distinguished by a horizon of clay accumulation (Jeff Redders, pers. comm.). The forest type is mixed-conifer with a species composition of Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), ponderosa pine (*Pinus ponderosa*), aspen (*Populus tremuloides*) and Engelman (*Picea engelmannii*) and blue spruce (*Picea pungens*). The basin contains cool-wet mixed-conifer stands on the northeast facing

slopes, which have mixtures of Douglas fir, white fir, spruce and aspen with few ponderosa pine. Warm-dry mixed conifer stands have a greater proportion of ponderosa pine with little spruce and aspen, and are present on the southeast facing slopes. The rainfall measured at the dam over the past 60 years shows average precipitation of 56 cm/year, with 25% occurring in the winter as snowfall.

Tree-Ring Methods:

Field methods:

We collected 14 fire-scarred ponderosa pine trees located throughout the study basin (Figure 1). The location, live or dead status, slope and aspect of the fire-scarred trees was recorded. The majority of sampled trees had been killed by the recent fire, and therefore, it was possible to collect complete cross-sections containing the fire scars (Arno and Sneek, 1977). Although the sampling was ‘targeted’ at trees with the greatest number of scars, the distribution of samples and the number of samples collected has generally been found to be adequate for identifying widespread fires in an area this size (Swetnam and Baisan, 2003).

For the age-structure data, we selected four 0.1 – 0.4 ha plots (Figure 1). The plot locations were chosen to be among living trees, near fire-scar sampling locations, and to include a range of tree sizes. Three of the four plots were located within patches of unburned, low and moderately burned forest. A fourth site was selected because of its proximity to fire-scar samples, and the range of tree sizes present within the plot, although the site had been severely burned by the recent fire.

The plots were rectangular (100 m x 40 m) in shape, and are a modified version of a linear transect used in previous southwestern age-structure studies (Abolt, 1997; Baisan and Swetnam, unpublished data). We recorded the diameter breast height (DBH), location (x and y coordinates), species and living status of all trees in the plot. Trees less than 10 cm DBH were tallied within a five meter range of coordinates, though not given a specific location. We cored all trees larger than 25 cm DBH at an average height of 30 cm. The aim of the sampling was to obtain the pith, and several attempts were made on each tree.

Age-structure data was also collected from one aspen stand (~ 10 ha), located on a north-facing slope in the center of the basin (Figure 1). The boundary of the aspen stand was defined in aerial photos and from a ridge on the opposite side of the basin. A linear transect perpendicular to the fall line of the slope was sampled to determine the age structure of the stand. Two trees were cored at 20 meter intervals along the transect for a length of 100 m. The trees were cored until the pith was obtained at a coring height of approximately 30 cm. A second transect from the same aspen stand was cored parallel to the original transect, located approximately 30 m down the slope.

Laboratory Methods:

All fire-scar samples and conifer age-structure cores were mounted and sanded using progressively finer grades of sandpaper down to 400 grit. The aspen cores were cut with a razor and finished with 500 grit sandpaper by hand. The samples were crossdated (assigned annual dates to individual tree rings) according to standard dendrochronological methods using a master chronology developed from the age-structure cores (Stokes and Smiley, 1968). Species

identification of the age-structure cores was corrected in the lab according to specific wood features, since species identification in the field had been difficult for the burned trees. If the age-structure cores did not include the pith, the number of missing rings and the growth rate was estimated with concentric circles (Applequist, 1958).

To estimate the number of years to coring height, we used the relationship of age at coring height reported in other studies from Colorado and the Southwest (Kaufmann et al., 2000; Heinlein et al., 2005). Kaufmann and others (2000) reported a range of growth rates for ponderosa pine and Douglas-fir seedlings at the Cheesman Lake study area in central Colorado. The rates for low and medium growth for each species corresponded with that of our sample. We also checked our estimates with age ranges reported in Heinlein and others (2005) and results from southern Arizona (Jose Iniguez, unpublished data). Given the uncertainty of estimating the age to coring height, the recruitment ages were divided into 10 year bins for analysis.

Analysis:

We plotted all crossdated fire-scar samples in a master fire chronology using a spreadsheet program, and observed the temporal and spatial patterns in the surface fire history (Dieterich, 1980). The initial year of the period of analysis was defined by the first year to scar at least three recording trees. This criterion was used in a study with a similar fire-scar sample size, study area size, and forest type in the Southwest (Heinlein et al., 2005). A recording tree is one that has been scarred by a fire, and is more susceptible to subsequent scarring, making it a reliable indicator of surface fires in the study area (Romme, 1980).

The Mean Fire Interval (MFI) was calculated for the entire period of analysis from 1679 – 1879 AD, as well as the sub-periods of 1679 – 1778 AD and 1778 – 1879 AD. The sub-periods were defined by the fire year, 1778 AD, and were used to compare the surface fire patterns between the 18th and 19th centuries. The year 1778 was chosen because it divides the period of analysis into two separate 100-year periods. The period of analysis ends in 1879 AD, which was the past widespread fire year for the site. This year also coincides approximately with the time when Euro-American settlement began to impact the forests of the region (Grissino-Mayer et al., 2004).

The percentage of recording trees scarred in each fire year was used to determine widespread fire years (Swetnam and Baisan, 1996; Swetnam and Baisan, 2003). Due to the small sample size, widespread fire years were defined as years, when greater than 50% of the recording trees were scarred. A separate analysis of the spatial pattern of fires was performed by mapping the locations of scarred trees during the widespread fire years (Brown et al., 1999). This analysis determined the relative extent and pattern of the widespread fires. The age-structure data was plotted by species, and analysed for recruitment patterns between from 1600 – 1900 AD associated with widespread fire years.

Sediment Sampling Methods:

The sediment sampling locations were chosen within a 75 m reach of the exposed channel just above the point where the channel feeds into the alluvial fan. Three stratigraphic sections were chosen for their height of natural exposure and clarity of concentrated charcoal

layers delineating sedimentary units (Figure 2). Several buried logs were trapped in the alluvial deposits within stratigraphic sections B and C, and these were sampled with a hand saw.

The alluvial deposits were distinguished by changes in sorting, sedimentary structures, texture, color and sometimes by the presence of concentrated charcoal layers. Clasts were defined as sediment particles greater than 2 mm in size, and were removed before describing the matrix material (all sediment particles less than 2 mm). The composition of the matrix was determined using a field method for distinguishing the relative proportion of sand-, silt- and clay-sized sediments (Thien, 1978). The deposit characteristics were used to infer depositional processes. Poorly-sorted deposits with randomly oriented clasts, supported by a fine-grained matrix were inferred to be debris flow deposits (Costa, 1988). Moderately to well-sorted deposits with possible weak stratification and imbrication of clasts were inferred to be fluvial and hyperconcentrated flow deposits (Costa, 1988).

The type and abundance of charcoal in the deposits was used to infer a relationship to fire-related disturbance in the contributing basin. Given abundant angular charcoal, the deposit type was used to interpret the severity and relative extent of past fire events (Meyer et al., 1995; Pierce, 2004). Debris-flow deposits were inferred to represent a significant portion of the basin burned by moderate and high severity fire (Meyer et al., 1995; Pierce, 2004). Alternatively, well-sorted and fine-grained fluvial deposits with abundant charcoal indicated a subset of low- or moderate-severity fire events in the contributing basin (Pierce, 2004). We used the watershed response following the Missionary Ridge Fire to help interpret the extent of high severity fire from debris flow deposits identified in the alluvial stratigraphy. For the Missionary Ridge Fire

area, Cannon and others (2003) found that all debris-flow producing basins contained a combination of at least 50% moderate- and high-severity fire.

The chronology of fires was based on radiocarbon dating of charcoal pieces within the deposits (Meyer et al., 1995; Pierce, 2004). Charcoal was separated from bulk sediment samples by submerging the sediment in a bucket of water. The charcoal was then surveyed for annually produced plant material, such as twigs and needles. These materials may more closely represent the age of the fire, which may have promoted sediment transport and deposition. In contrast, angular pieces of charcoal are likely from the some unknown part of remnant logs, potentially yielding an age older than the fire event, because the burned wood could be from the inner rings of trees up to several centuries old. Rounded charcoal pieces were avoided, since they were likely reworked charcoal from older deposits. The relative size the charcoal from the deposits was also surveyed, in order to choose the largest angular pieces. Larger pieces may more closely represent the age of the deposit, compared with relatively small charcoal pieces, which may be reworked from older deposits (Blong and Gillespie, 1978).

Once samples were selected and cleaned, they were submitted for radiocarbon dating at the NSF- Arizona Accelerator Mass Spectrometry (AMS) Laboratory. Radiocarbon ages were converted to calendar ages using the CALIB 5.0 program with the INTCAL04 calibration curve (Stuiver and Reimer, 1993; Reimer et al., 2004). The calendar ages of events were expressed with their 2 sigma age range.

We used radiocarbon dating and evidence of surface soil development to determine whether multiple sediment layers resulted from the same fire event, or from separate fire events. Multiple sediment-laden flood and debris flow events may derive from multiple storm events

following a single high severity fire event, as was observed during the summer following the Missionary Ridge Fire (Cannon et al., 2003). Similarly, a single debris flow or flood event may contain multiple phases of sedimentation producing multiple sediment layers (Meyer and Wells, 1997; Meyer et al., 2001; Pierce, 2004). Multiple sediment layers may also represent separate fire events, and the timing of these events may be distinguished with radiocarbon dating, if they occurred longer than approximately 200 years apart.

RESULTS:

Tree-Ring Results:

We successfully crossdated 13 of 14 fire-scarred trees sampled. One sample had complacent tree-ring growth, and could not be matched with the master chronology. From visual inspection of the master fire chronology (Figure 3), the fire events appeared to be frequent and patchy during the late 17th and 18th centuries, followed by a shift to more synchronous and widespread fire events in the 19th century. The MFI for all fires during the period of analysis was 14.3 years, while the MFI for fires scarring at least two recording trees was 18.2 years (Table 1). A comparison of the MFI (min. 2 trees scarred) for the subperiods from 1679 – 1778 AD (MFI = 16.5) and 1778 – 1879 AD (MFI = 20.2) shows that fires were slightly more frequent in the earlier part of the record than the latter.

A different comparison of the surface fire regime between the 18th and 19th centuries is illustrated with a plot of the number of recording trees and the percentage of scarred trees in each

fire year (Figure 4). There are many fires, scarring between 10 – 40% of the recording trees (2 and 4 trees), which occur frequently in the 17th and 18th century, while the occurrence of these ‘small’ fires ceases in the 19th century. Also evident is the cessation of surface fires during the 20th century, even though there are several recording trees living through this period.

Common to both centuries were the widespread fire years: 1724, 1748, 1773, 1806, 1818, 1851 and 1879. These fires scarred at least 50% of the recording trees (≥ 6 trees), and were mapped to assess the spatial pattern of the fires during these years (Brown et al., 1999). The fire-scarred trees were located in three clusters within the basin. The maps show that the years 1724, 1818 and 1851 (Figure 4a) were the most extensive surface fire years, because fires burned all three clusters of fire-scarred trees, including the site on the southern ridge (Figure 1).

An important analysis of the surface fire history is the length and timing of fire-free intervals. Intervals or gaps may relate to the age-structure recruitment, and help with the interpretation of high severity fires (Brown and Wu, 2005). The longest fire-free interval at this site for widespread fires was from 1818 – 1851, a period of 33 years. This site also exhibited other fire-free intervals: 1851 – 1879 (28 years), 1724 – 1748 (24 years), 1679 - 1707 (28 years).

Ponderosa pine, Douglas-fir and white fir recruitment occurred on all plots, although there was considerable variability in the overall patterns of recruitment (Figure 5). Ponderosa pine recruitment was fairly continuous through time, with no distinct peaks. The Douglas-fir and white fir recruitment was more variable through time and had broader and larger surges of recruitment on some of the plots. Aspen regeneration was present on one of the plots. The sampling was not intended to test for a shift in species and tree density associated with fire

exclusion. The lack of 20th century recruitment of all species in our data was a result of sampling entirely large and mature trees, and will not be discussed with respect to the fire history.

Plot A was located on an east-facing ridge, adjacent to the aspen stand (Figure 1). The plot had almost no ponderosa pine recruitment, and the tree density was much higher than the other plots (Table 4). This plot is located up the slope from fire-scar sample # 3, which recorded surface fires in both 1851 and 1879. It had the highest frequency of Douglas-fir and white fir recruitment, lasting from 1850 – 1890, with a strong peak in 1870. This peak appeared to have survived any impacts of the surface fire in 1879, which may have caused the regeneration of the adjacent aspen stand. Since the oldest tree on the plot dates to the 1850 decade, the recruitment could represent post-fire stand regeneration following a response to high severity fire on the plot during the 1851 fire year, which was also an extensive regional fire year (Huckaby et al, 2001).

Plot C was located on the southern ridge, where fire-scar samples 8 and 9 were collected. The ponderosa pine recruitment within the plot was consistent through time, with a small peak in 1670. The Douglas-fir and white fir recruitment began in 1790, and it had a small peak in the decades 1820 and 1830, followed by a sharp rise in recruitment beginning in the 1860's. During the 19th century, the only surface fires recorded on this plot were in 1818 and 1851. The first peak may relate to a fire-free interval between 1818 and 1851. Some trees recruitment that established during this period may have been killed by the 1851 surface fire, but a second peak apparently began in 1860. The lack of fire in 1879 on this plot would have allowed this peak to persist through to the 20th century. The evidence does not suggest extensive high severity fire behavior during any of the fire years on this plot, since that would have removed the older ponderosa pine, Douglas-fir and white firs.

Plot D was located on a south-facing slope, between two openings in the forest. This plot had the oldest ponderosa pine trees sampled within a plot. The ponderosa pine recruitment was fairly continuous through the record, although there were two noticeable gaps. The first gap was in the first half of the 18th century, and the second shorter gap was in the early 19th century. It was not possible to relate the earlier gap to the surface fire history, since the fire-scarred samples from this plot were not recording fires at this time. The second gap may relate to both the 1806 and 1818 fires preventing the establishment on the plot. The Douglas-fir and white fir recruitment does not have noticeable recruitment peaks, and may reflect the fact that this plot recorded all of the surface fires during the 19th century.

Plot E was a relatively mesic plot located on a flat bench in the central portion of the basin. This plot showed two peaks in the ponderosa pine recruitment in the decades 1750 and 1780. The ponderosa pine recruitment did not continue into the 19th century, when recruitment shifted to being dominated by Douglas-fir and white fir. The Douglas-fir and white fir recruitment occurred throughout the late 18th and 19th centuries, with distinct peaks in 1790, 1830 and 1860. These peaks appear to reflect the fire-free intervals in the surface fire history. The fire-scarred trees near this plot (trees # 12 and 13) recorded the 1818, 1851 and 1879 fires. The spiky and variable shape to the age distribution, which included a sharp decrease in recruitment followed each of the peaks (1800 – 1820, 1840 – 1850 and 1870 – 1890), may indicate mortality of seedlings from surface fire.

At Plot E, there was abundant aspen growing among the fire-scarred ponderosa pines, Douglas-fir and white fir. The aspen recruitment had two distinct dates based on the pith age of the cores. The peaks have ages of 1851 and 1879, which suggests regeneration associated with

the surface fire history. However, the aspen trees with pith ages of 1851 and 1879 were located adjacent to one another scattered throughout the plot and among older ponderosa pine and Douglas-fir predating 1851, which makes the interpretation of high severity fire unlikely.

The separate pure aspen stand located on a north-facing slope in the center of the basin had an area of approximately 10 ha. This stand is indicated by the shaded area in Figure 1. A set of cores from the linear transect had a distribution in pith ages from 1879 – 1881. This stand likely regenerated in association with the 1879 widespread fire. There were no old, burned snags observed within the stand, which suggests that the slope may have been populated by aspen (rather than conifer) prior to the 1879 fire. The fire may have been high severity for the aspen, causing tree mortality and canopy opening within the stand, however, there may not have been a shift in species from conifer to aspen stand as a result of the fire.

Alluvial stratigraphy:

Range of deposit characteristics:

The majority of the alluvial sediments exposed in this reach of the channel were fine-grained and well-sorted. The fine-grained deposits had a matrix primarily composed of silt- and sand-sized sediments, with little evidence of a significant clay proportion. The matrix supported gravel-sized clasts, which varied in size from 0.5 – 2.0 cm in diameter. Within the thicker deposits of fine-grained sediment, the gravel clasts were concentrated in 10 cm thick lenses, indicating weak stratification of the deposits. However, at the locations where sampled, there was little evidence of orientation or imbrication of the clasts within the lenses. These deposits were likely deposited by streamflow and hyperconcentrated flow processes.

The key feature of the fine-grained deposits was the light yellow color reflecting a tufa source for both the matrix and the clasts. Tufa spring deposits were located in the central portion of the basin, where 1 m thick in situ deposits were exposed in the channel. Deposits were both root casts and thin sheets of calcium carbonate accumulation draping over sediment deposits. The bedrock in the upper third of the basin was the Pennsylvanian age Hermosa Group limestone (Gonzales et al, 2004), which supplies carbonate-rich groundwater at other locations in the region (Mary Gillam, pers. comm.). The location of the thickest tufa deposits observed in October 2005 is marked on Figure 1. Tufa was the primary component of the fine-grained deposits, suggesting that the deposits were primarily composed of reworked channel material, with likely little input of hillslope material.

There were also fine-grained deposits with a gray-colored matrix, supporting pebbles and cobbles between 2 – 20 cm in diameter (long axis). These deposits were classified as intermediate between the tufa-rich deposits and debris flow deposits, and possibly represent hyperconcentrated flow deposition. The darker color of the matrix contrasts the light color of the tufa-rich deposits, and suggests a proportion of hillslope sediments mixed with reworked channel sediments. The darker color likely represents a greater proportion of organic material incorporated from hillslope soils.

Toward the top of each section, a greater percentage of gravel-sized clasts (3 – 5 cm in diameter) was evident in the deposits (Figure 2). These gravel-rich deposits had no cohesion, and the imbrication of clasts indicated deposition by fluvial processes (Costa, 1988). These gravel-rich deposits varied locally, yet were present along the length of the exposure.

There were two poorly-sorted debris flow deposits exposed in this channel reach (Figure 2). One of the deposits was a thin localized deposit in stratigraphic section C, with a cohesive fine-grained matrix, supporting cobbles up to 15 cm in diameter (long axis). The second debris flow deposit was located between 20 – 40 m along the length of the exposure. The matrix had a dark brown color, and supported a range of cobbles to boulders up to 1 m in diameter. The cobbles and boulders of both deposits were a mix of lithologies including the local bedrock and granitic boulders derived from the glacial till and hillslope colluvium in the basin. The relatively dark matrix of the debris flow deposits indicates a partial hillslope sediment source.

Some of the stratigraphic units were bounded by concentrated charcoal lenses. These layers of charcoal and ash were deposited by fluvial processes, rather than in situ burned soil horizons. They sometimes had weak stratification, and were composed of primarily silt- and sand-sized charcoal fragments. They sometimes contained larger angular charcoal pieces between 2 – 5 mm, but there were no distinguishable needles or other organic material, indicative of a burned soil surface (Meyer et al., 1995; Pierce, 2004). These units usually bounded breaks in texture and color of the fine-grained deposits. Occasionally, these charcoal layers were very prominent, and were traced for several meters along the length of the exposure. The most prominent layer was a 10 cm thick deposit at the top of stratigraphic section B, which had burned wood chunks (20 - 30 cm in length) and smaller angular charcoal pieces supported by a dark gray, silty matrix (Figure 2).

Relation of deposit type to fire-related disturbance:

There was abundant charcoal within all of the sediment deposits, although the association with fire-related disturbance varied by deposit type. Although the tufa-rich, fine-grained deposits had abundant charcoal, we are fairly confident that the transport and deposition of sediment was probably unrelated to specific fire-related disturbance events. The tufa-rich composition suggests that there was little hillslope material incorporated within the deposits. This indicates that there were generally stable hillslope disturbance conditions during the period of tufa-rich, fine-grained deposition.

Given the abundance of charcoal in the tufa-rich, fine-grained sediments, we infer that these deposits may reflect a low severity fire regime in the contributing basin. Under this scenario, frequent surface fires produced charcoal on the hillslopes, which was transported to the channel by overland flow or wind (Whitlock et al., 2003). Separately, low frequency, high magnitude discharge events transported and deposited charcoal and sediment together in the valley bottom. Some of the tufa-rich fine-grained deposits appear to be deposited by hyperconcentrated flow processes, possibly part of a discontinuous ephemeral gully system.

The majority of the tufa-rich fine-grained deposits indicate low energy deposition behind obstructions in the channel. In the case of stratigraphic section A, the colluvial slump possibly provided an obstruction for sediment accumulation in this section of the channel. In addition, buried wood and glacially-derived boulders likely provided obstructions in the form of step-pools as a mechanism of sediment storage in the valley bottom (Chin, 1989; Chin, 2003). Hence, separate fine-grained deposits bounded by charcoal-rich layers probably do not represent fire events, but may represent discharge events, which scoured and deposited sediment with charcoal.

We interpret that fine-grained deposits with a darker matrix supporting gravel- to cobble-sized clasts possibly represent specific fire-related disturbance events. The darker color of the matrix suggests a source of hillslope sediment. Over the length of the tree-ring record, patches of high severity fire occurred during some of the widespread surface fire years as inferred from the age-structure data (e.g. 1851, 1879). Some of these high severity fire patches may have generated sufficient runoff to mobilize and transport channel sediment, while also incorporating hillslope sediment from the disturbed area of the basin. The increased runoff possibly mobilized clast material from the valley bottom, which is reflected in the cobble-sized material in the deposits.

In the case of the debris flow deposit, the link to extensive high-severity fire is more clearly and confidently interpreted. Debris flow initiation requires significant runoff to entrain enough hillslope and channel sediment. Extensive high-severity fire on the slopes can supply sufficient runoff for debris flow generation under normal rainfall conditions. The dark matrix of the debris flow deposit indicates that hillslope sediments were entrained in the deposit. In addition, the fine-grained deposits exposed below the debris flow deposit suggest that there was enough channel sediment available for debris flow initiation at the time of fire event (Cannon, 2001; Wells, 1987).

Chronology of deposition:

The oldest alluvial deposit had an age of 2,895 calibrated calendar years before present (cal yr BP), and is tufa-rich fine-grained deposit at the bottom stratigraphic section A. Subsequent to this, the two debris flow deposits have similar radiocarbon ages, occurring around

~ 2,600 cal yr BP and likely representing the same depositional event (Table 3). The colluvial slump deposit within stratigraphic section A with an age of ~ 3,200 cal yr BP, possibly reflecting charcoal incorporated in the hillslope sediments at an earlier time. The slump likely occurred following the debris flow event at ~ 2,600 cal yr BP, and is evidence of possibly deep channel scour at this location as a result of the debris flow.

Following the debris flow event, there was continuous fine-grained deposition in the valley bottom over the past 2000 cal yr BP (Figure 6). The fine-grained deposition was primarily composed of the tufa-rich deposits, although two intermediate fine-grained deposits were included within the stratigraphy. Locally within each stratigraphic section, the deposition was episodic, with periods of rapid deposition followed by hiatuses. There were apparent age reversals in the upper portion of each stratigraphic section, where the deposit type transitioned to gravel-rich fluvial deposition. The age reversals suggest reworking of charcoal from deposits higher up in the basin or imprecision in the dates. Given the carbonate-rich environment, contamination of charcoal is possible. However, the pre-treatment procedures of the AMS radiocarbon methods should have sufficiently removed the contamination by carbonate in the deposits. The more likely explanation for age-reversals is the choice of charcoal pieces. The largest angular pieces are preferred, and if smaller fragments were chosen, they may be reworked from older deposits (Blong and Gillespie, 1978). At the top of both stratigraphic sections, several recent alluvial deposits from the past 500 cal yr BP had broad age ranges due to the conversion between radiocarbon years and calendar years. For example, the thick charcoal layer in stratigraphic section B described above had an age range from 1600 – 1950 AD.

DISCUSSION:

Comparison of tree-ring and alluvial fire history records:

Both records indicate a predominantly low severity surface fire regime in the study basin. The fire regime for the past several hundred years is better defined through the tree-ring record, as having frequent low-severity surface fires during the late 17th – 19th centuries. Frequent surface fires with similar MFI values were observed in other tree-ring fire history studies in the mixed-conifer ecosystem of the San Juan Mountains (Grissino-Mayer et al., 2004; Wu, 1999).

The fine-grained deposition in the valley bottom is consistent with a surface fire regime. The fine-grained deposits had abundant charcoal reflecting the occurrence of fire, yet the tufa-rich composition originating in the center of the basin does not indicate disturbance to the forest and hillslopes. In the absence of disturbance, sediment was likely transported and stored behind obstructions in the channel. Buried logs along with cobbles and boulders are the main mechanism for sediment storage in the valley bottom (May and Gresswell, 2003; Chin, 1989). Buried logs within the alluvial deposits have ages consistent with the surrounding sediment (Table 3).

The tree-ring and sediment records are best compared by the largest and most recent high severity fire event occurring prior to the Missionary Ridge Fire. The synchronous and widespread fire behavior during the 19th century observed in the tree-ring record suggests that the fuel accumulation during fire-free intervals could have promoted patches of high severity fire. The combined tree-ring data (fire scars and age structure) shows evidence of a small patch of high severity fire occurring in the year 1851 AD at age-structure plot A. The association of conifer recruitment with the surface fire history suggests that a high severity fire patch occurred

in the year 1851 AD. This was one of the most widespread surface fire years at this site as well as elsewhere in the Southwest, and the Colorado Front Range (Veblen et al., 2000; Brown et al., 1999; Swetnam and Baisan, 1996; Swetnam and Betancourt, 1998). It was also a year with evidence of high severity burn patches in the ponderosa pine ecosystems of the Colorado Front Range (Brown et al., 1999; Huckaby et al., 2001).

The pure aspen stand on the north-facing slope also represents a larger patch of high severity fire in the year 1879 AD, which was approximately 10 ha in size. 1879 AD was also the year of the Lime Creek Burn, a historically documented stand-replacing fire, which burned extensively in the upper elevation mixed conifer and spruce-fir ecosystem near Silverton, Colorado. The estimated size of these high severity patches are both much smaller than the extent of high severity fire, which occurred during the Missionary Ridge Fire.

The identification of these two high severity fire events in the tree-ring record helps define the age of recent alluvial deposits relating to hillslope disturbance. The most recent deposit (prior to the post-Missionary Ridge Fire debris flows) reflecting disturbance in the basin is an intermediate fine-grained deposit with a darker matrix, supporting cobbles up to 15 cm in diameter in the upper portion of stratigraphic section B (Figure 2). This deposit is topped by the extensive and thick charcoal-rich layer described in the results. The stratigraphy of the deposits suggests that they were deposited together as one event. The calibrated calendar age range of three radiocarbon ages from the set of deposits is approximately 1500 – 1950 AD (Figure 7). The set of deposits could have been generated in response to the high-severity fire, indicated by the regeneration of the aspen stand in 1879 AD. A 10 ha patch of high severity fire at this location would have likely generated sufficient runoff to transport and deposit sediment with

burned material in a broad section of the valley bottom (Figure 1). The gravel-rich deposition above the charcoal layer also has a recent calendar age range (Figure 7), and may represent reworked channel sediments through fluvial processes in the absence of fire activity.

Combined fire history record:

If the relationships of deposit type to fire-related disturbance presented in this paper are approximately correct, then the alluvial record can be used to interpret the longer record of fire history for the site. The continuous fine-grained deposition over the past 2,000 cal yr BP indicates that a low severity fire regime has dominated during this period. There were no clear erosional surfaces, and little evidence of paleo-channels that might relate to previous disturbances. Given the abundance of available sediment in the channel, if an extensive high severity fire of comparable magnitude to the Missionary Ridge Fire had occurred over the past 2,000 cal yr BP years, it likely would have initiated a debris flow and scoured the available channel material. The geomorphic response following the Missionary Ridge Fire in this watershed incised alluvial sediments in the valley bottom, and debris flow deposition occurred within the tributary channel and on alluvial fan. Hence, I conclude that the Missionary Ridge Fire within the studied watershed appears to be an unusually large fire when compared to the combined fire history record of the past 2,000 cal yr BP.

Within the record of fine-grained deposition from the past 2,000 years, there were two intermediate deposits, which probably relate to small patches of high severity fire in the basin. These were the fine-grained deposits with a darker matrix, supporting gravel- and cobble-sized clasts. The first was located in stratigraphic section A, and had an age of 544 cal yr BP (442 –

646 AD). The second was located below the buried logs in stratigraphic section B (Figure 2), and had an age of 714 cal year BP (635 – 771 AD). These deposits are illustrated with thicker lines in Figure 6. These deposits probably represent increased runoff from small patches of high severity fire, which likely burned during widespread surface fire years. These events in the alluvial record possibly represent an analogous period to the 19th century, when reduced fire frequency promoted fuel accumulation during fire-free intervals.

Evidence of stand-replacing fire over centennial and longer time scales:

In addition to the small patches of high severity fire, there was evidence of one relatively extensive high severity fire, that resulted in the generation of a substantial debris flow (~ 2,600 cal yr BP). This debris flow scoured the channel, and possibly promoted the colluvial slump to occur. We infer this event to be analogous in magnitude with the debris flow response following the Missionary Ridge Fire. Given that the basin was burned by approximately 80% moderate and high severity fire combined during the recent event, and the threshold for debris flow generation from the entire Missionary Ridge Fire was 50% moderate and high severity fire, the prior debris flow event (~2,600 cal yr BP) likely initiated from an similarly extensive high severity fire in the contributing basin.

Although data from one watershed does not necessarily indicate a regional shift in fire regime at this time, the prior debris flow event possibly relates to broader-scale climate and vegetation changes. The event coincides with the end of the neoglacial period, characterized by wetter and possibly cooler climate during the late Holocene (Enzel et al., 1992; Koehler et al., 2005, Armour et al., 2002). A charcoal record from a high-elevation lake shows that this period

had less frequent but more intense fires in the spruce-fir forests near Silverton, CO (Toney and Anderson, in press). Pollen from two lake sediment records suggest that the forests were more dense during this period, with minor shifts in vegetation composition (Toney and Anderson, in press; Fall, 1997).

CONCLUSIONS:

The fire behavior interpreted from the combined tree-ring and alluvial record indicates that the Missionary Ridge Fire appears to have resulted in more extensive high severity fire and a more extensive geomorphic response than fires that have occurred during the past 2000 years. While the interpretation of low severity fire regimes from alluvial stratigraphy is less clear for this study site, the tree-ring record provided a high resolution record of fire severity for the past 400 years, which helped interpret the alluvial deposits. Future work documenting the watershed response of low and moderately burned watersheds may improve the interpretation of low severity fires regimes from this study site. In addition, further work documenting the alluvial stratigraphy from other tributary basins in the region would help provide a context for the recent Missionary Ridge fire, along with the timing of prior debris flow events.

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FIGURES:

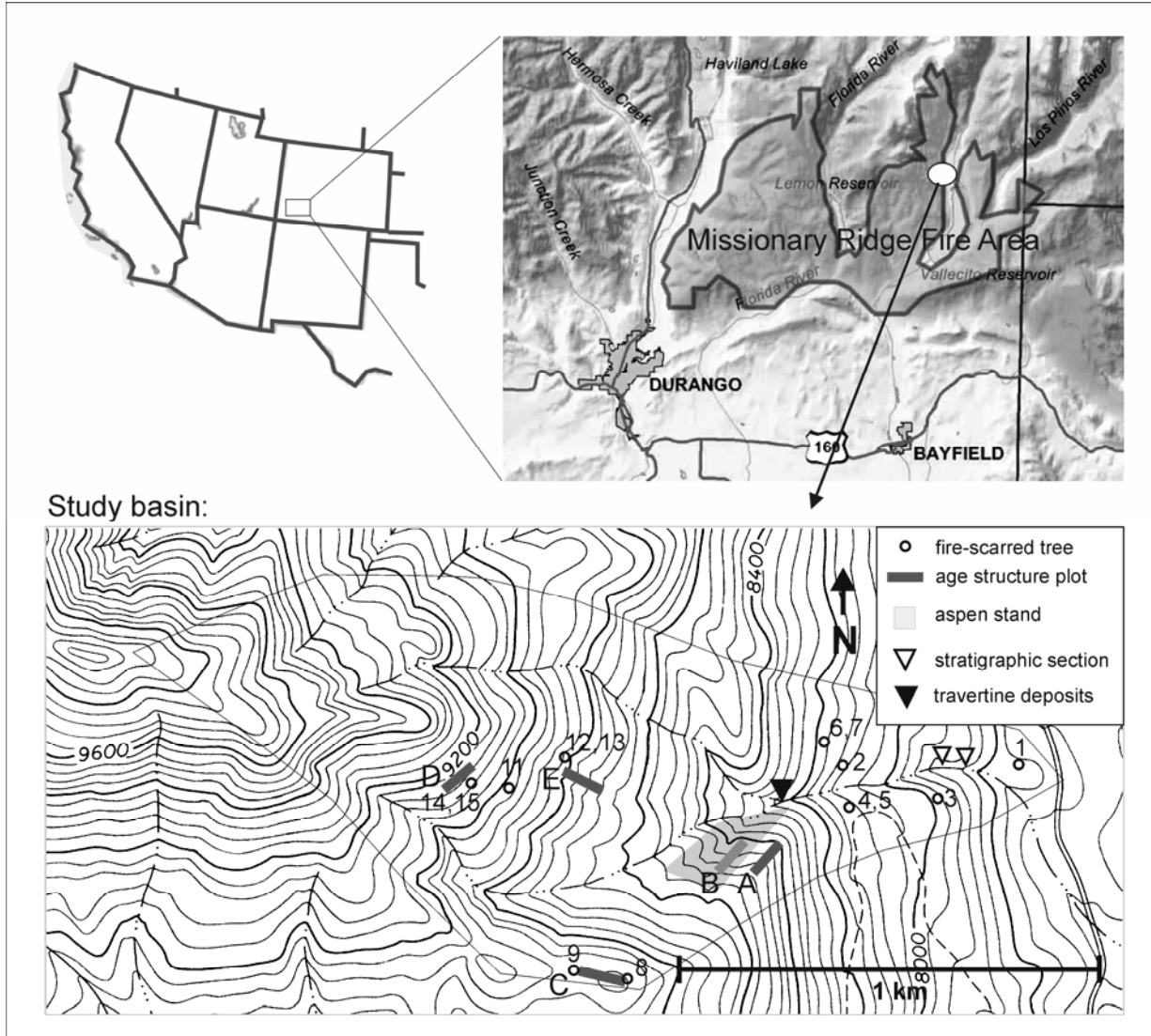


Figure 1: Geographic location of the Missionary Ridge Fire and the study basin. The basin was burned at 80% moderate and high severity by the Missionary Ridge Fire of June, 2002. The thin black outline represents the watershed boundary.

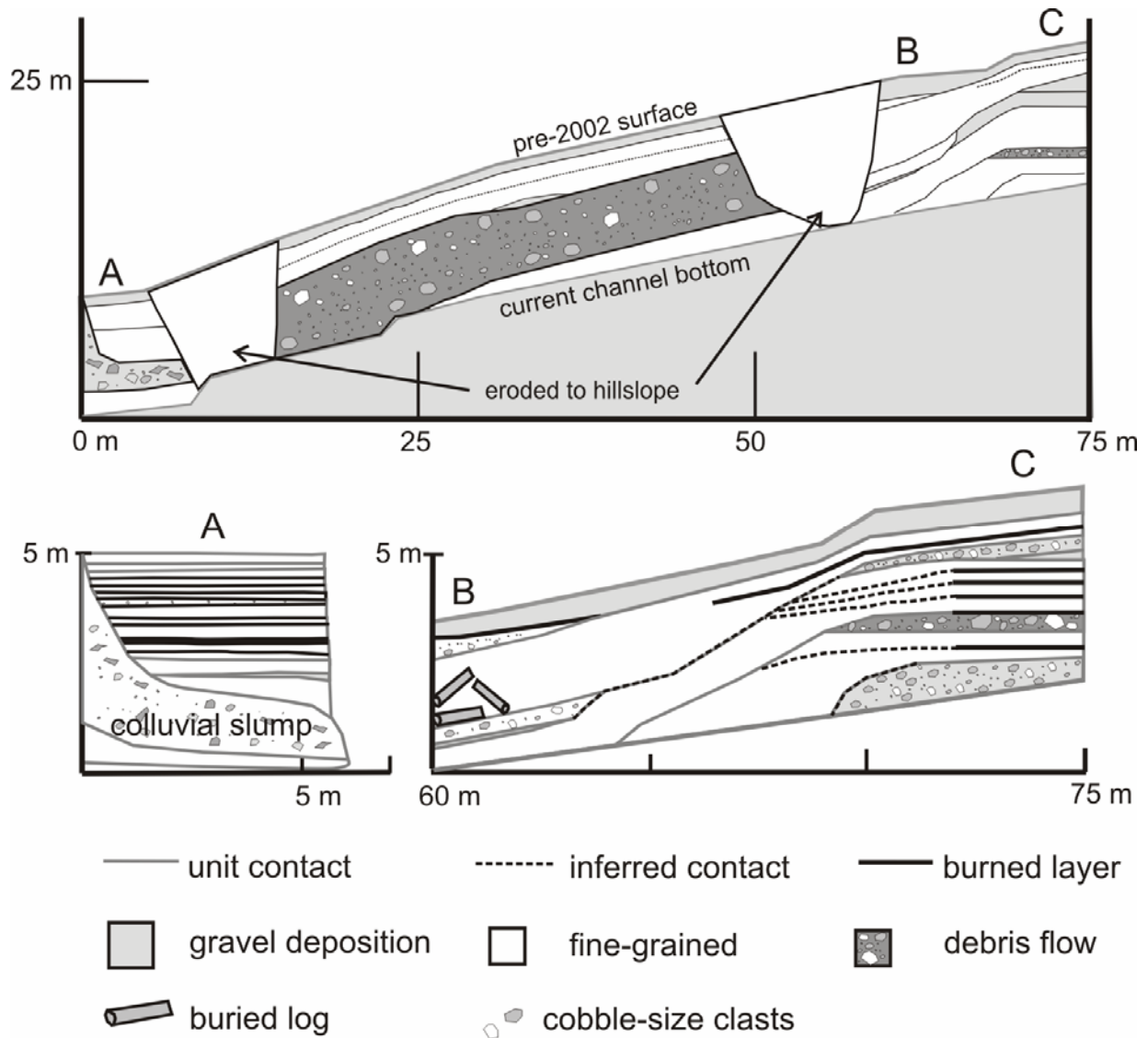


Figure 2: Cross-section view of the exposed channel reach with the labeled stratigraphic sections. The figure is drawn to scale, except for the vertical axis in the upper figure is doubled. The deposit types range from fine-grained, fine-grained with cobble-sized clasts, gravel-rich, and debris flow.

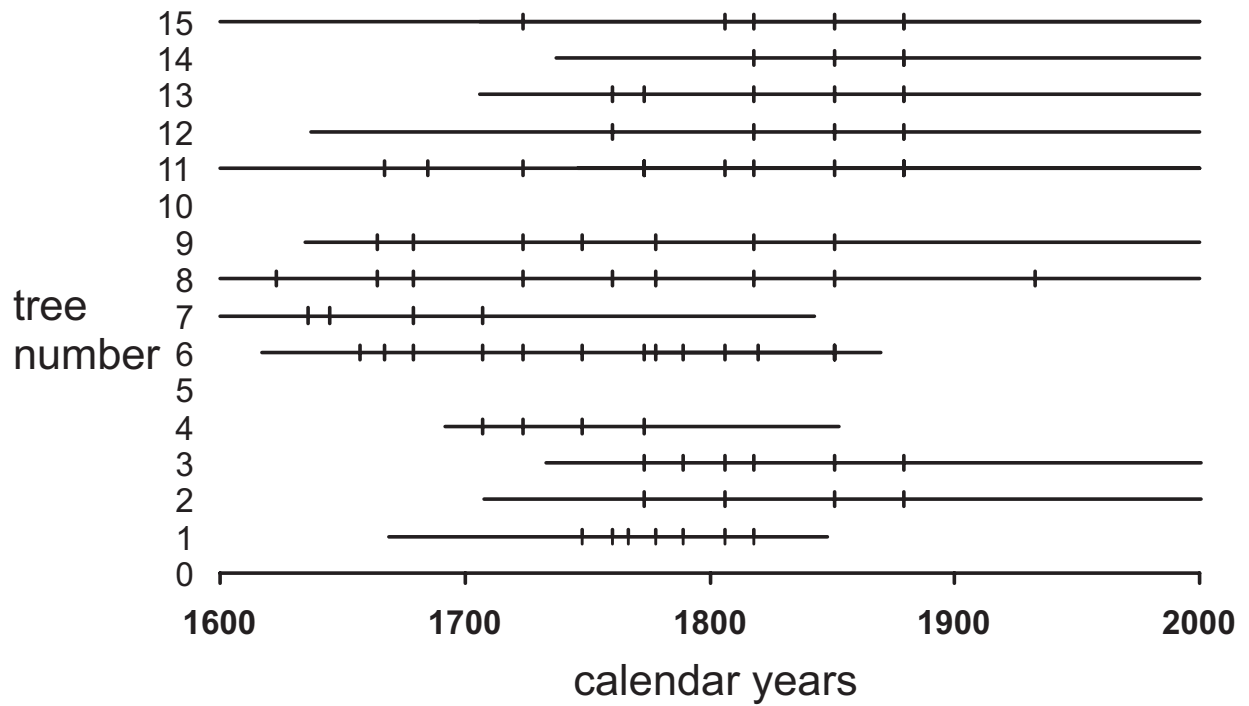


Figure 3: Master fire chronology. Each line represents one tree, which are arranged in order of elevation in the basin. Each tick mark represents one fire scar. The period of analysis is from 1679 – 1879.

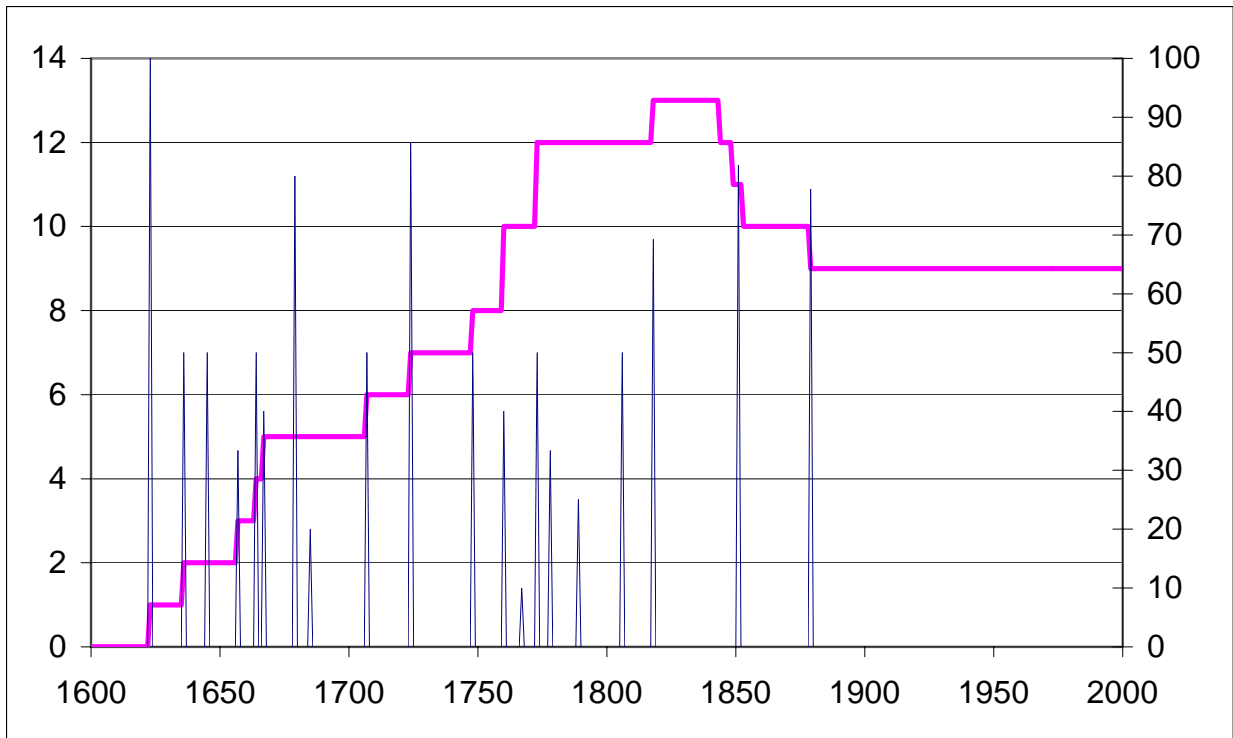


Figure 4: The number of recording trees (continuous line) with the percentage of scarred trees (vertical lines).

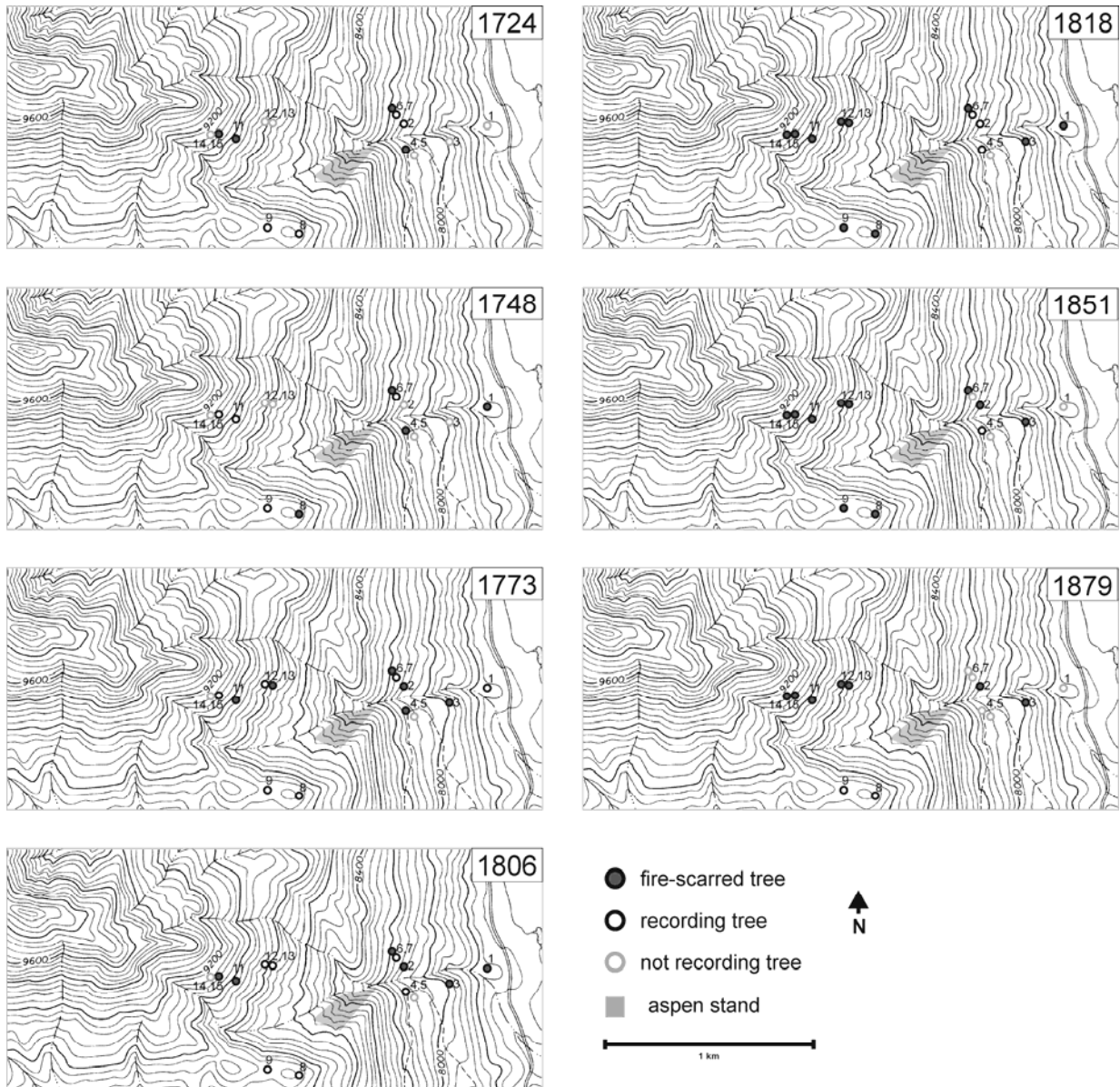


Figure 4a: Map of fire-scarred trees during the widespread fire years.

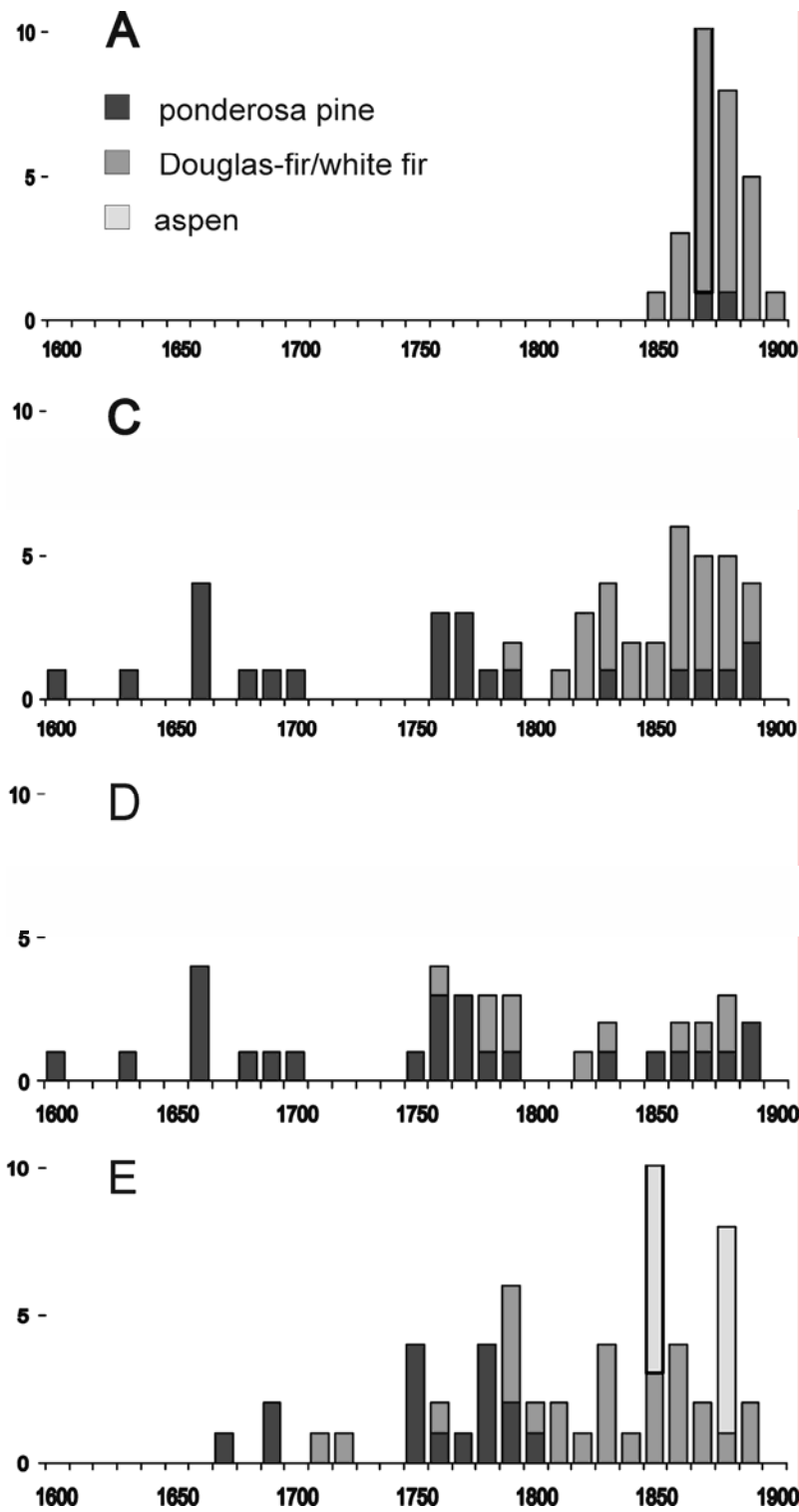


Figure 5: Age-structure data arranged by plot and species.

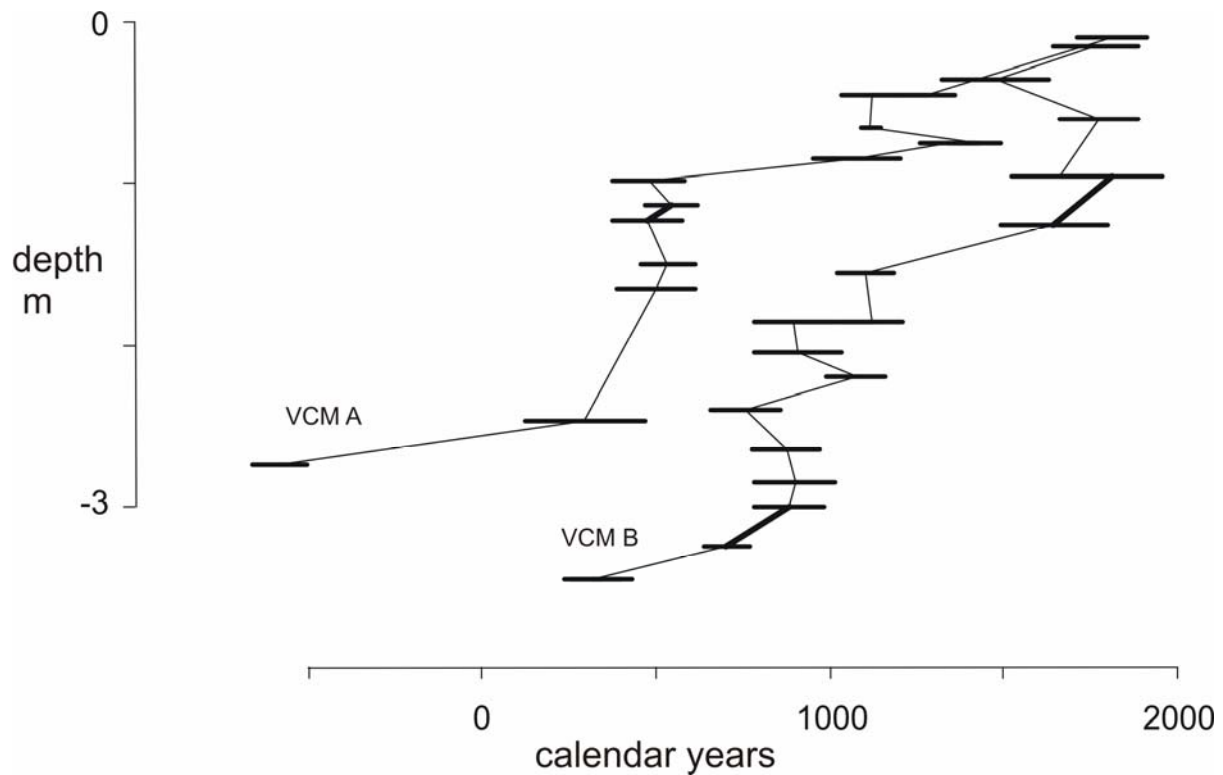
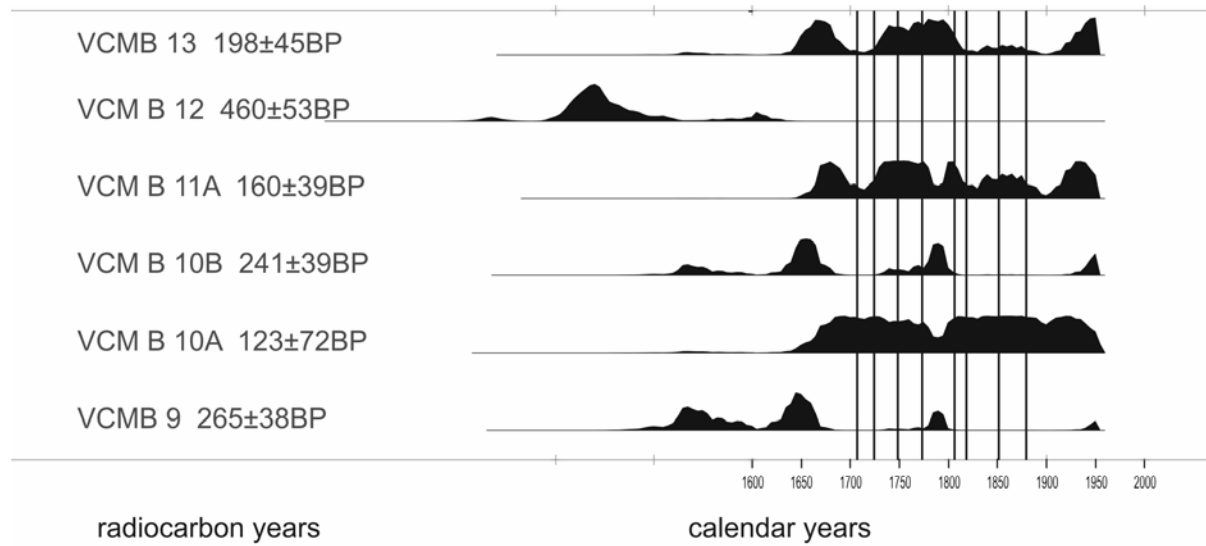


Figure 6: Each series represents charcoal samples from the median depth of each sediment layer in the stratigraphic sections A and B. VCM indicates the site name used for sample identification. The horizontal lines represent the 2 sigma age range of calendar years. Darker lines represent intermediate fine-grained deposits with a darker matrix, supporting cobble-sized clasts.



Atmospheric data from Reimer et al (2004);OxCal v3.10 Bronk Ramsey (2005); cub r:5 sd:12 prob usp[chron]

Figure 7: The calibrated age range of the six youngest sediment deposits in stratigraphic section B. The vertical lines represent widespread surface fire years.