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Temporal and spatial climatic controls on Holocene fire-related erosion and sedimentation, Jemez Mountains, New Mexico

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ABSTRACT

In the Jemez Mountains, tree-ring data indicate that low-severity fires characterized the 400 yr before Euro-American settlement, and that subsequent fire suppression promoted denser forests, recent severe fires, and erosion. Over longer timescales, climate change may alter fire regimes; thus, we used fire-related alluvial deposits to assess the timing of moderate- to high-severity fires, their geomorphic impact, and relation to climate over the last 4000 yr. Fire-related sedimentation does not clearly follow millennial-scale climatic changes, but probability peaks commonly correspond with severe drought, e.g., within the interval 1700–1400 cal yr BP, and ca. 650 and ca. 410 cal yr BP. The latter episodes were preceded by prolonged wet intervals that could promote dense stands. Estimated recurrence intervals for fire-related sedimentation are 250–400 yr. Climatic differences with aspect influenced Holocene post-fire response: fire-related deposits constitute 77% of fan sediments from north-facing basins but only 39% of deposits from drier southerly aspects. With sparser vegetation and exposed bedrock, south aspects can generate runoff and sediment when unburned, whereas soil-mantled north aspects produce minor sediment unless severely burned. Recent channel incision appears unprecedented over the last 2300 yr, suggesting that fuel loading and extreme drought produced an anomalously severe burn in 2002.

Introduction

The Jemez Mountains host a diverse ecosystem, highly valued natural resources, and important cultural, recreational, and scientific sites. All have been directly impacted by severe fires within recent decades, and the associated erosion and sedimentation generate additional concerns (Orem and Pelletier, 2015). These severe and extensive fires have been attributed to human activities following Euro-American settlement that increased forest densities, including livestock grazing, logging, and fire suppression (e.g., Allen et al., 2002). In the interior western USA, however, warming climate and earlier spring snowmelt have also contributed to increased burn area and fire severity, and are the dominant factors in high-elevation and northern Rocky Mountain forests (e.g., Meyer et al., 1992; Pierce et al., 2004; Westerling et al., 2006; Bigio et al., 2010).

Documentation of fire and erosion over long timescales can provide insights into the influence of past climates on these phenomena, under limited human impacts. Tree-ring fire-scar chronologies have provided high-resolution records of low-severity fire in the Jemez Mountains over the past ca. 400 yr (Touchan et al., 1996; Allen, 2001; Allen et al., 2008), and charcoal content in bog sediments has shown broad relative changes in fire activity over the past 8000 yr (Allen et al., 2008; Anderson et al., 2008). However, further Holocene-scale records are needed to understand long-term climatic influences on fire, in particular high-severity fires (i.e., those with high soil burn severity; Parsons et al., 2010). Such fires often result in major hillslope and channel erosion, and debris-flow and flash-flood sedimentation on alluvial fans (Meyer and Wells, 1997; Cannon, 2001). Therefore, we developed a chronology of fire-related alluvial fan sedimentation over the last 4000 yr to test whether climate variations promoted the occurrence of severe fire and enhanced erosion and sedimentation (e.g., Meyer et al., 1995), and whether recent fires are anomalous in their severity and geomorphic effects.

An important consideration in understanding relations among Holocene fire, climate, and erosion in the study area is whether contrasts in microclimate with aspect could result in significant differences in fire and erosional response. Drier south-facing (equatorward) slopes are dominated by open ponderosa pine stands, with generally thin soils and substantial areas of exposed bedrock. In contrast, north-facing (poleward) slopes feature denser mixed-conifer forests that are more susceptible to infrequent high-severity fires (Allen et al., 1995), but also have a thicker, largely continuous mantle of soil and colluvium that can absorb runoff when unburned. Given these contrasts, the nature of Holocene fire-related sedimentation and its relation to climate may differ substantially with aspect. We address these questions by comparing the depositional processes and timing of fire-related

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sedimentation in north-facing and south-facing basins, as well as the relative proportion of fire-related deposits identified in alluvial fans from both aspects.

Study area

The Jemez Mountains in north-central New Mexico stand as a broad range surrounding a central caldera complex, which formed over two major periods of volcanic activity in the last two million years (Doell et al., 1968; Izett et al., 1981). Mesas capped by 1.15 Ma welded Bandelier Tuff slope gently away from the Valles Caldera rim and are incised by narrow canyons (Fig. 1). This variably welded, rhyolitic ash-flow tuff underlies slopes in the study area (Kelley et al., 2004) and tends to weather to predominantly silt to pebble-sized sediment, along with larger clasts up to boulder size. The study area covers about 4.5 km^2 (450 ha) between about 2370 and 2670 m elevation, and is centered on an unnamed drainage west of the Valles Caldera, between Barley Canyon and Lake Fork Canyon. This 5-km-long canyon contains New Mexico Highway 126, and is herein termed "NM 126 Canyon". The study area lies within the perimeter of the August 2002 Lakes Fire, which burned at moderate to high severity and was spurred by exceptionally severe summer drought conditions in northern New Mexico (http://droughtmonitor.unl.edu/mapsanddata/maparchive.aspx, accessed 30 August 2015).

NM 126 Canyon trends east–west, with largely north- and south-facing sideslopes, and contrasts in slope characteristics with aspect are striking. On average, south-facing slopes are about 5° steeper than north-facing slopes in this and adjacent valleys (Paulo de Sa' Rego, written communication, 2012) an asymmetry apparent in the map of Poulos et al. (2012) and noted elsewhere in the region where soil moisture plays a strong role in bedrock weathering (Burnett et al., 2008). Steep exposed bedrock is more common on rugged south-facing slopes, which typically display a thin and discontinuous colluvial cover. Storm runoff from bedrock surfaces can entrain abundant sediment from colluvium at cliff bases, a process termed the "firehose effect" (e.g., Melis et al., 1994). A thicker, more continuous soil and colluvial mantle characterizes north-facing slopes, which have a generally smooth, curvilinear form. Ephemeral tributaries draining both canyon sides have built small alluvial fans on the main valley floor, and most fan feeder channels also contain alluvial fill. These alluvial sediments include fire-related deposits that are the primary focus of this study. After the 2002 Lakes Fire (Fig. 1), hillslopes locally displayed rills, and some alluvial fans and channels underwent major post-fire deposition and (or) incision that exposed stratigraphy. The incised channel in lower NM 126 Canyon reveals an alluvial fill at least 3 m thick.

Forest cover in the Jemez Mountains ranges from pure ponderosa pine (*Pinus ponderosa*) to mixed-conifer stands that include mainly Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), and Engelmann spruce (*Picea engelmannii*), with local aspen groves (*Populus tremuloides*) (Allen et al., 1995; Touchan et al., 1996). In the study area, ponderosa pine dominates south aspects, and mixed-conifer and aspen stands cover north aspects, as is widely observed in the Jemez Mountains (Allen et al., 2008). The study area has likely seen a broadly similar distribution of tree species over the late Holocene (Anderson et al., 2008). A rapid upward shift of the ponderosa pine to piñon-juniper ecotone in the Jemez Mountains during the severe

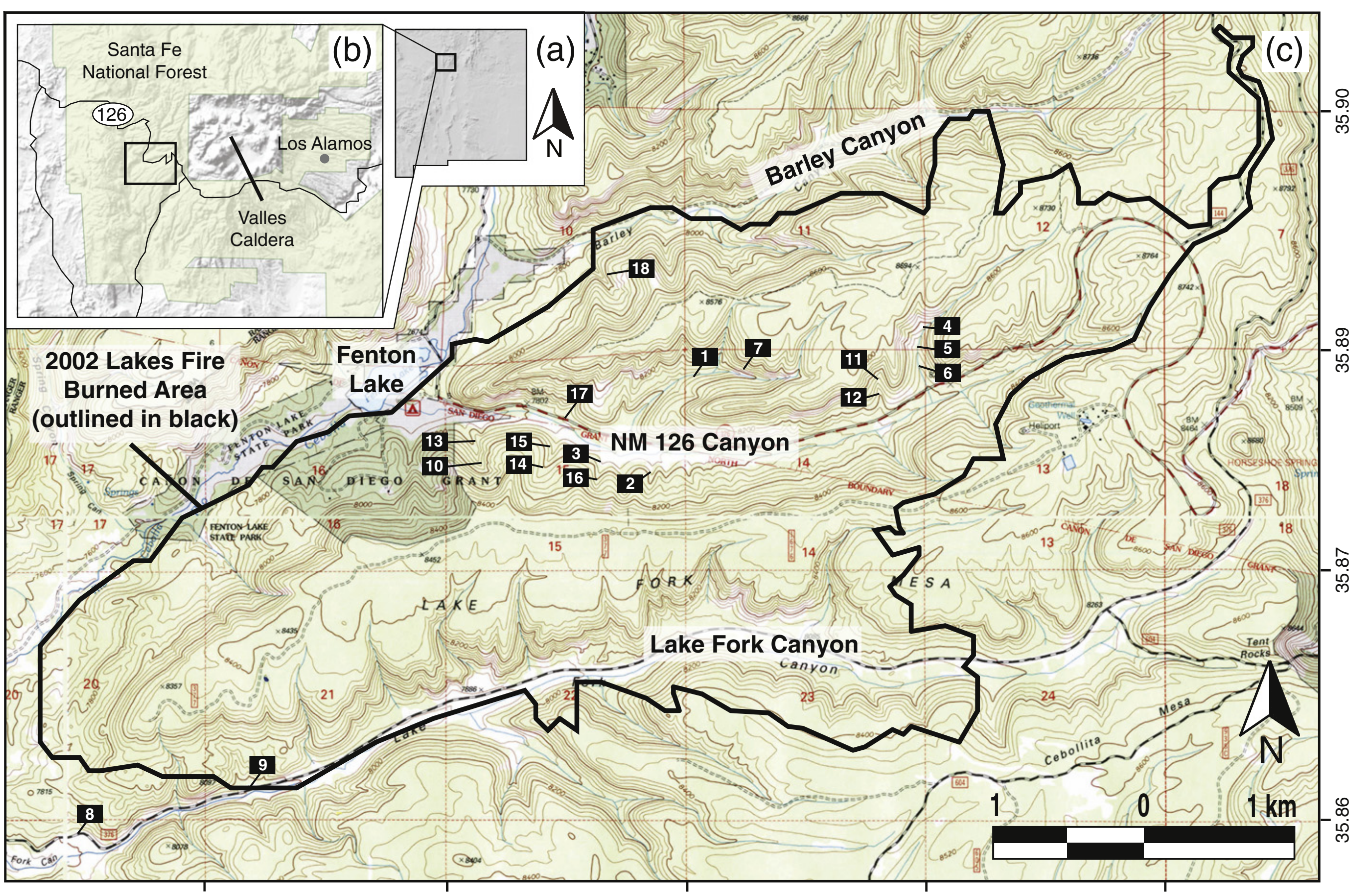

Figure 1. Study area maps showing (a) location of map in b within New Mexico, USA, (b) location of the study area within the Santa Fe National Forest west of the Valles Caldera, and (c) topographic map of the study area from USGS Seven Springs and Jemez Springs 7.5 minute quadrangles; contour interval 40 ft (12.2 m). Station locations are indicated by numbered black boxes.

1950s drought (Allen and Breshears, 1998) implies a significant potential for climate-induced forest composition changes, however, and Holocene climatic changes may have produced significant alterations in forest composition and (or) density.

Mean annual precipitation in the Jemez Mountains ranges from about 300 mm at 2000 m elevation to 900 mm at 2500 m elevation (Touchan et al., 1996). Annual precipitation is bimodal; the winter (December–January) maximum occurs mainly as snowfall, and the summer (July–August) maximum involves convective storms associated with the North American monsoon, which account for 40% of total annual precipitation (Touchan et al., 1996). The typical modern fire season extends from April to September, with June being the peak month, prior to the onset of moderate- to high-intensity monsoon rains that are also responsible for most post-fire sedimentation events (e.g., Cannon et al., 2001).

Fire-climate relationships

As climate influences fire activity over a wide range of timescales, through changes in forest type, structure and fuel moisture, we consider mechanisms by which climate may have controlled the occurrence of moderate- to high-severity fires in the Holocene, and thus fire-related sedimentation. Short-term climate change can result in fine fuel accumulation and fuel moisture changes, which strongly affect fire ignition and behavior (e.g., Swetnam and Betancourt, 1998; Littell et al., 2009; Abatzoglou and Kolden, 2013; Williams et al., 2014). Longer-term climatic changes can change forest structure and species composition, shift ecotones, and greatly influence fire regimes, including fire frequency, severity, and extent (e.g., Meyer and Pierce, 2003; Anderson et al., 2008; Marlon et al., 2012).

Prior to large-scale management and land-use impacts with Euro-American settlement, Southwestern ponderosa pine stands generally featured an open structure maintained by low-severity fires; an open canopy also promotes surface fires by stimulating the growth of grasses and other fine surface fuels (e.g., Covington and Moore, 1994). In the Jemez Mountains, tree-ring fire-scar records indicate that frequent, low-severity surface fires were dominant from ca. 400–50 cal yr BP, with mean fire intervals of 5–25 yr (Touchan et al., 1996; Allen, 2001). The potential also exists for significant enhancement of low-severity fire activity in this period by Native Americans (e.g., Roos et al., 2010), given large populations in the southern Jemez Mountains (Kulisheck, 2005, 2010). Ponderosa-pine stands, which dominate south-facing slopes in the study area, show a strong relationship between fire occurrence and greater precipitation in the preceding few years, emphasizing the importance of surface fuel accumulation (Swetnam, 1990; Touchan et al., 1996). However, multidecadal wet intervals can support the growth of ladder fuels, which, if followed by prolonged severe drought, may result in large canopy fires (e.g., Swetnam and Baisan, 2003; Morgan et al., 2008; Pierce and Meyer, 2008; Frechette and Meyer, 2009). In mixed-conifer stands in the Jemez Mountains (as on north aspects in the study area), fire shows a weak relationship with antecedent precipitation (Touchan et al., 1996), and decreased canopy moisture is important in fire activity in these denser forests (e.g., Swetnam and Baisan, 2003; Margolis and Swetnam, 2013).

Stand-replacing fires become a characteristic part of fire regimes in mixed-conifer forests of northern New Mexico starting at elevations a few hundred meters above the study area, in particular on moister aspects, and are strongly associated with severe drought (Margolis et al., 2007; Margolis and Balmat, 2009). Fire may also propagate into mixed-conifer stands from adjacent ponderosa-pine stands, so that they are affected by fire and climatic controls associated with the drier ponderosa forest (Margolis and Balmat, 2009). In either forest type, severe fires become more likely if fire suppression—either by human activities or an unusually wet climate—extends over a period of several decades or more and allows development of denser stands, especially if these largely fire-free periods are followed by severe drought (Roos and Swetnam, 2011). In general, a lack of winter precipitation promotes an earlier fire season start, and late onset and limited rainfall in the summer monsoon allow for an extended fire season. In either case, extremely low values of canopy fuel moisture and severe fires are promoted by anomalously high temperatures (Williams et al., 2013).

Tree-ring fire histories in the Southwest show that the most important climatic control on fire at the annual to interdecadal scale is the El Niño Southern Oscillation or ENSO (Swetnam, 1990; Swetnam and Betancourt, 1998). Surface fire activity is reduced due to a few years of increased precipitation under El Niño conditions, which promote grass and fine fuel accumulation; when dry La Niña years follow, widespread surface fires occur. Given uncertainties associated with radiocarbon dating, fire-related sedimentation records cannot resolve such multiannual cycles, but longer-term variations in the amplitude, frequency, or dominant phase of such oscillations may partly explain changes in Holocene fire-related sedimentation (Frechette and Meyer, 2009).

In this study, we apply the relationships above to interpret how moderate- to high-severity fires and related post-fire erosion were influenced by changing climate and vegetation over the late Holocene. We consider how the geomorphic effects of fire may vary with spatial differences in climate, given large contrasts in landscape with aspect in the study area. In addition, to provide perspective on potentially anomalous modern fires, we compare Holocene post-fire erosion and sedimentation with that following the severe drought and Lakes Fire of 2002 in the study area.

Methods

Identification and dating of fire-related deposits

In the Jemez Mountains and similar terrain, small tributary alluvial fans are built mainly by infrequent flows of high sediment concentration. High-severity fires often promote such events, mostly by greatly increasing runoff generation in intense rainstorms (Meyer and Wells, 1997; Cannon, 2001). Low-severity fires typically leave patches of intact vegetation and litter on soil surfaces, which restrict runoff generation and erosion (e.g., Larsen et al., 2009); these rough patches also slow runoff, allowing reinfiltration. Thus, post-fire sedimentation after low-severity fires is usually quite limited (e.g., Lavee et al., 1995; Rubio et al., 1997; Pelletier and Orem, 2014). In contrast, severe fires produce extensive bare, smooth slopes, with low infiltration rates from surface sealing and sometimes water-repellent soils (Shakesby and Doerr, 2006; Larsen et al., 2009). With high-intensity precipitation, these conditions result in extreme runoff generation and sediment entrainment from both slopes and channels, producing large post-fire debris flows and sediment-charged floods, often with multiple flow processes and depositional units during the same event (Meyer and Wells, 1997; Cannon et al., 2001). Thus, fire-related deposits in alluvial fans are inferred to reflect mostly moderate- to high-severity fire (Parsons et al., 2010) over much of the fan's drainage basin.

Fire-related debris-flow deposits often contain abundant macroscopic angular charcoal, as it is transported in concert with the matrix fluid of fine sediment and water. Post-fire hyperconcentrated-flow and flood-streamflow deposits less commonly contain visible charcoal (Meyer et al., 1995). Observations of modern events show that in these more dilute flows, coarse, charcoal-poor deposits are often left on fans, whereas much of the low-density charcoal is transported with fine sediment to lower-energy depositional sites (Meyer and Wells, 1997; Cannon, 2001; Frechette and Meyer, 2009). Where charcoal within the deposit is relatively abundant, angular, and coarse, however, all of these deposit types represent evidence of fire in the associated drainage basin. Evidence for fire also exists where thin layers of charred needles, twigs, cones, and other materials are preserved within fan deposits, representing a charred forest litter layer at a former soil surface. These readily bioturbated layers can be preserved when rapidly buried by sedimentation following the same fire event. Charcoal fragments from fire-related deposits and charred litter layers can be radiocarbon dated, yielding a proxy record of fire-related sedimentation representing moderate- to high-severity fire within the alluvial fan watershed (e.g. Meyer et al., 1995; New, 2007; Frechette and Meyer, 2009). In the Jemez study area, a composite record of fire-related sedimentation was developed based on 11 total stratigraphic sections (stations), 10 of which are in alluvial fans representing small tributary basins ranging between approximately 5 and 75 ha in area (Figs. 1 and 2). One station was located within the main NM 126 Canyon arroyo, and stratigraphy was documented at additional stations where dates were not obtained (Fitch, 2013) (Fig. 1).

Alluvial fan deposits (n = 106) were classified by depositional process as debris flow, hyperconcentrated flow, or flood streamflow facies, using field observations and laboratory grain-size analyses of 117 samples (Fitch, 2013) and the flow classification of Pierson and Costa (1987). Interpretation of a fire-related origin was based on charcoal characteristics (i.e., abundance, size, and angularity), depositional process as above, and comparison to modern fire-related alluvial deposits documented by Meyer and Wells (1997), Cannon (2001), and Cannon et al. (2001). Deposits stemming from the 2002 Lakes Fire were also used as modern analogs to better identify Holocene fire-related deposits in the study area (Fitch, 2013).

A total of 54 charcoal samples were chosen for ^{14}C dating. Needles, seeds and cones and other relatively short-lived materials were dated whenever possible (n = 14) in order to minimize "inbuilt" error in materials with substantial ^{14}C age at the time of fire (Gavin, 2001), such as inner rings from an old tree, or dead wood in snags or logs. Samples were pretreated as per standard methods (Dickin, 2005) and ^{14}C-dated using accelerator mass spectrometry (AMS). Radiocarbon ages are reported as in Stuiver and Polach (1977) and converted to calibrated calendar years using the CALIB 6.0 software program (Stuiver and Reimer, 1993). The INTCAL04 calibration curve (Reimer et al., 2004) was employed, as in similar studies in the region (Frechette and Meyer, 2009; Jenkins et al., 2011); differences with the more recent IntCAL13 curve over the study period are small (a few tens of years or less).

Using ^{14}C ages, recurrence intervals for fire-related sedimentation events were calculated using two methods that yielded (1) mean at-a-station and (2) mean within-basin recurrence intervals. For mean at-a-station recurrence intervals, the total age range of deposits at each station was divided by the maximum number of fire-related events interpreted there, resulting in a minimum recurrence interval; a maximum recurrence interval was calculated using the minimum number of possible events. The resulting estimates for each station were then averaged to yield representative minimum and maximum recurrence intervals for the study area. At-a-station recurrence intervals for fire-related deposition were also averaged separately for north-facing and south-facing basins. For mean within-basin recurrence intervals, stations from the same drainage were evaluated, and dates that are statistically the same at the 95% level were considered a single fire event. For example, at stations 1 and 7, samples 7-7 and 1-11 (weighted mean ages of 400 and 460 cal yr BP, respectively) were considered one fire event. As with the at-a-station method, these within-basin recurrence intervals for fire-related deposition were averaged for the full study area, and separately for north-facing and south-facing basins.

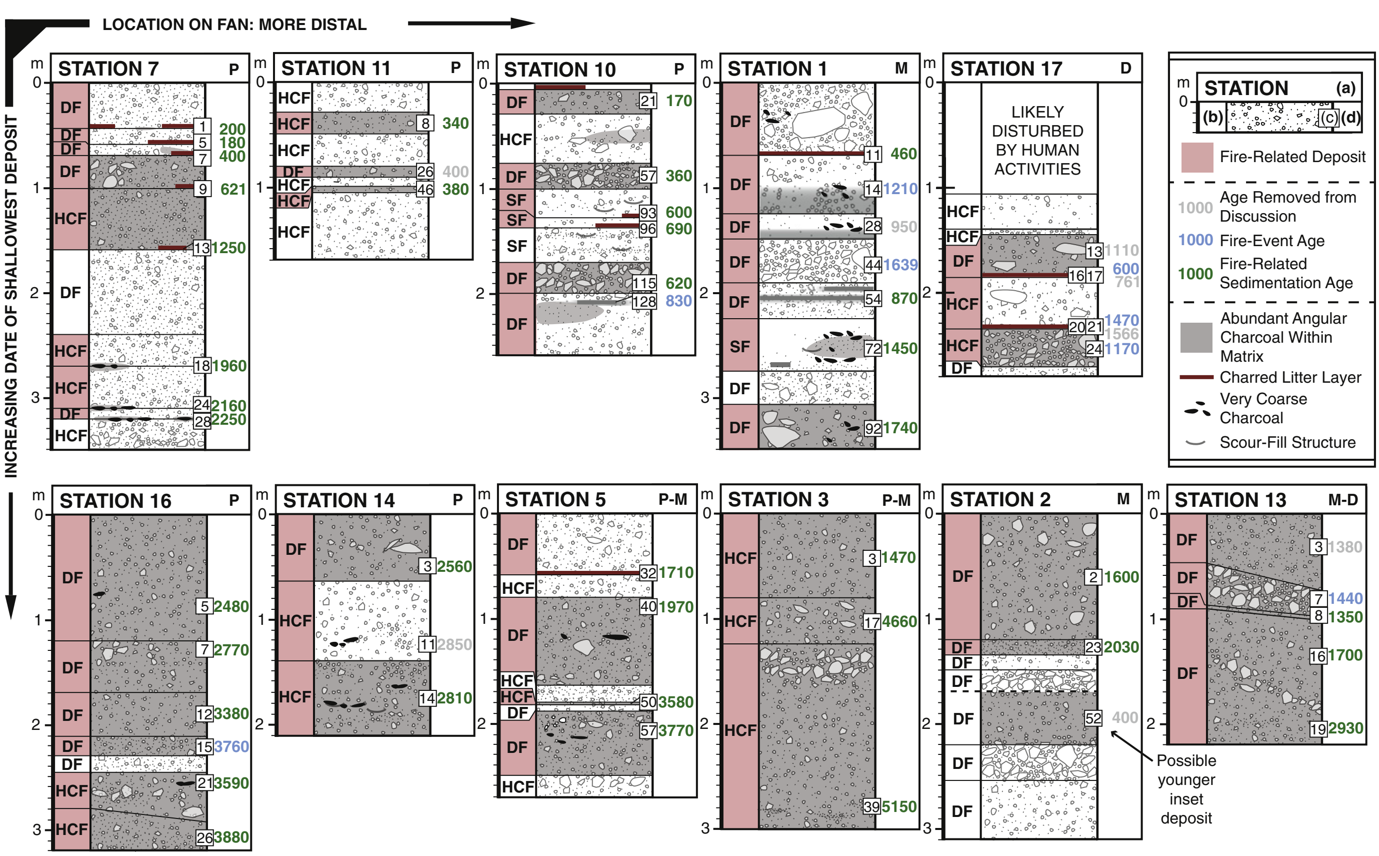

Figure 2. Stratigraphic sections at numbered stations, arranged by relative fan location and showing ^{14}C ages. Information located according to letters at top of key includes: (a) fan location, where P is proximal, M is medial and D is distal; (b) deposit classification, where DF is debris flow, HCF is hyperconcentrated flow and SF is streamflow; (c) sample number for the associated ^{14}C age, where e.g. sample 1 in Station 7 is sample 7-1; and (d) weighted mean of the calibrated ^{14}C age in cal yr BP, rounded to the nearest 10 yr. Full uncertainty ranges and probability distributions for ^{14}C ages are shown in Figs. 3 and 4 and Supplementary Table 1.

Slope aspect and geomorphology

As aspect is clearly a strong control on microclimate, forest composition, and slope geomorphology in the study area, we hypothesize that it has also resulted in differences in fire regime and processes of fire-related sedimentation over the late Holocene. Therefore, the stratigraphy in alluvial fans of north- and south-facing basins was compared in terms of depositional process type, proportion of fire-related deposits, and timing of fire-related deposition. Since deposits of individual events do not always have clearly defined contacts, we considered the total thickness of sediment that each process type contributed to fan building, as well as the total thickness of fire-related versus non-fire-related deposits.

Results

Stratigraphy

The 18 stratigraphic sections (stations) described ranged from 1.3 to 3.5 m deep. Charcoal samples were dated at 11 of these stations (Fig. 2). Fifteen of the stations are located in NM 126 Canyon and its tributaries, with 3 in adjacent canyons (Fig. 1); 8 stations were located in fans of north-facing basins, and 9 in fans of south-facing basins, with one station located within the main valley arroyo.

Of the 106 deposits documented, 54 were interpreted as debris-flow, 44 as hyperconcentrated-flow, and 8 as streamflow deposits. Debris-flow deposits appear massive, lacking sedimentary structure or clast orientation, and are the most poorly sorted. By stratigraphic thickness, debris-flow deposits make up 57% of fire-related deposits and 53% of non-fire-related deposits. Hyperconcentrated flow is transitional between debris flow and streamflow; deposits are better sorted than those of debris flow, and may contain grading, weak imbrication or clast orientation parallel to the flow direction, as well as shallow scour-fill structures. Streamflow deposits show the greatest degree of sorting, and commonly exhibit clast imbrication, grading, bedding, and (or) scour-fill structures. The predominance of facies indicating flows of high sediment concentration suggests an overall abundant sediment supply in the study area.

Most deposits inferred to be fire-related were either debris-flow or hyperconcentrated-flow deposits; however, two were streamflow deposits associated with a charred litter layer or abundant, very coarse, angular charcoal fragments. Some sections contained inferred fire-related deposits with a dark matrix due to an abundance of fine charcoal. However, the majority of fire-related deposits either contained coarse, angular charcoal or were associated with a charred litter layer. Charred litter layers were usually well preserved, although some showed evidence of reworking (i.e., Fig. 2, Station 1, 2 m depth) or partial erosion (i.e., Stations 7 and 10, in several places).

Radiocarbon dating

Fire-related deposits were dated at 11 stations over the study area, and the 54 radiocarbon ages obtained (Supplementary Table 1) span a time period extending back to ca. 5300 cal yr BP (Fig. 2). All but 2 ages fall within the last 4000 yr, however, and 33 of the ages (61%) are younger than 2000 cal yr BP, reflecting the greater exposure and preservation of younger deposits for sampling. At Station 7, along a large tributary to NM 126 Canyon that was deeply incised after the Lakes Fire, bedrock is exposed along the opposite channel wall and on the channel floor a short distance upstream. Because the lowest deposit at Station 7 is dated at 2161–2345 cal yr BP (1σ range), the oldest sediment stored along this narrow, tributary valley is likely to be of late Holocene age. The oldest deposit age in the study area, 5051–5287 cal yr BP at 280 cm below the top of Station 3 (Fig. 2), is in a fan that extends unconfined onto the broad NM 126 Canyon floor, where deposits are less likely to be eroded by later flows (Fig. 1).

The stratigraphic context of dated samples is displayed in Fig. 2, with weighted mean calibrated ages shown for simplicity. Complete 1σ and 2σ uncertainty ranges are given in Fig. 3 and Supplementary Table 1, and for interpretation of the timing of events, full probability distributions for each age were employed (Fig. 4). Weighted mean ages were calculated using probability values associated with each year in the calibrated ^{14}C age probability distribution. This provides a relatively robust estimate of the central point age (Telford et al., 2004), but in some cases of multimodal calibrated probability distributions, the weighted mean age itself may have a low probability value.

Given that multiple depositional units can be produced in a single fire-related sedimentation event (Meyer and Wells, 1997), ages from adjacent stratigraphic units that were statistically indistinguishable at the 95% level were considered to date the same event, namely the following pairs of weighted mean ages: Station 11, 80–105 cm, 400 and 380 cal yr BP; Station 13, 0–90 cm, 1440 and 1350 cal yr BP; and Station 14, 65–210 cm, 2850 and 2810 cal yr BP (Fig. 2). Hence, of the 54 samples dated, four samples (11-26, 13-3, 14-11, and 17-21) were removed from analysis to avoid potential duplication of events in the record, with the assumption that the older of the two ages had greater inbuilt error (Fig. 3). Seven samples (1-14, 1-44, 13-7, 16-15, 17-16, 17-20, and 17-24) were associated with age inversion (i.e., the occurrence of an older age at a higher stratigraphic position than a younger age, likely from reworking from an older deposit). However, these ages significantly overlapped the distribution of a more reliable sample from a different station, supporting the interpretation that a fire event occurred at that time (Fig. 3). Sample 10-128 is also added to this subset since the complexity of the enclosing stratigraphy precludes a reliable deposit association, but the age distribution is statistically indistinguishable from that of a more reliable sample from another station. These eight sample ages are considered “fire-event ages”, as they provide valuable evidence of fire activity, but cannot be considered to date a fire-related sedimentation event. Three samples (1-28, 17-13 and 17-17) were considered unusable for analysis due to age inversion and a lack of significant overlap with the probability distribution of a more reliable sample. Sample 2-52 was also removed due to age inversion and uncertainty in its stratigraphic association; re-examination of this section indicated that it may have been from a younger inset deposit or colluvial material (Fig. 3). Removal of the four inverted and four duplicate ages leaves 38 ages that are confidently associated with fire-related sedimentation events, most likely representing moderate- to high-severity fire within the associated small basin, along with eight fire event ages.

The individual probability distributions for each sample were summed to produce curves representing the relative probability over time of fire-related sedimentation, and fire-related sedimentation plus fire events (e.g., Meyer et al., 1992, 1995), hereafter referred to as “fire-sedimentation probability” and “fire-event probability”, respectively (Figs. 3 and 4). Based on the summed probability curves and number of samples supporting fire activity (Fig. 3), peaks in fire-sedimentation probability occurred around 2850–2750 cal yr BP and 2050–1950 cal yr BP, with broad maxima around 1700 cal yr BP and 1450 cal yr BP, and multiple peaks between 700 and 150 cal yr BP. As some sharp peaks can be produced as artifacts of calibration and summation, we compared them to a synthetic probability curve constructed by summing calibrated probability distributions for each year from 0 to 4000 ^{14}C yr BP (Persico and Meyer, 2013), and found that none of the peaks used in interpretation were created or significantly enhanced by calibration effects.

Aspect, fan deposition, and event frequency

At the 17 stations representing north- and south-facing tributary basins, fire-related deposits make up 57% of the total stratigraphic thickness of alluvial deposits. Alluvial fans of north-facing basins are

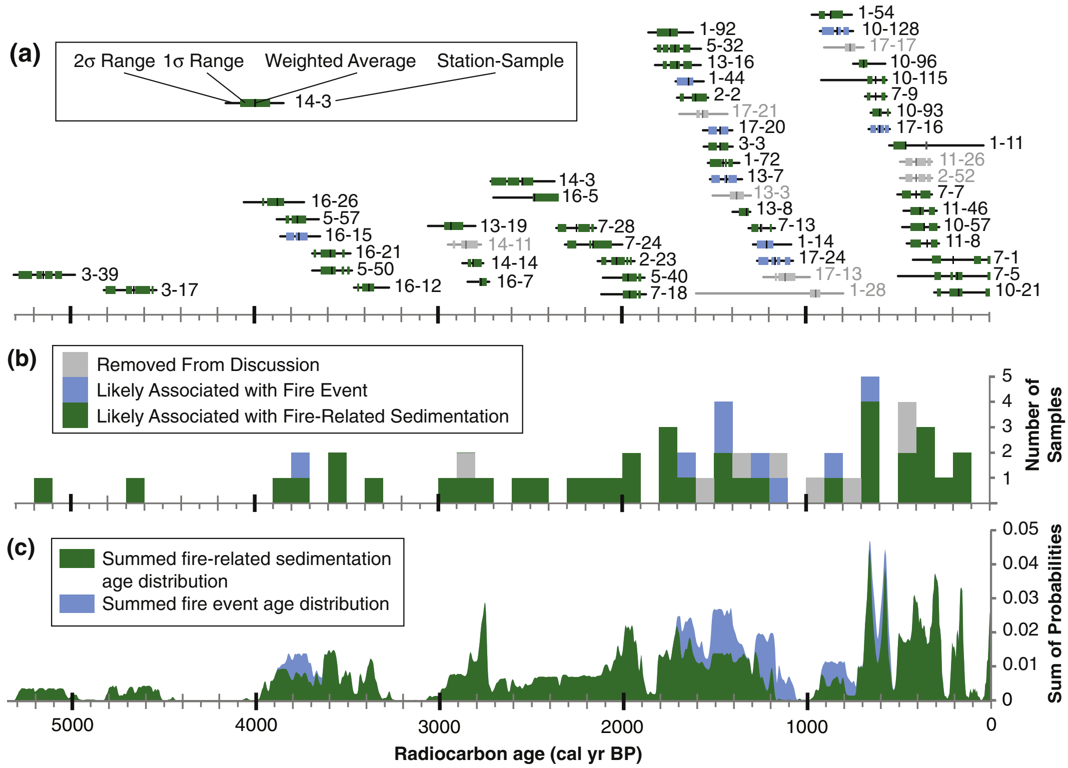

Figure 3. (a) Plot of all calibrated ^{14}C ages. 1σ ranges are rounded to nearest 10 cal yr BP, with only ranges greater than 10 yr displayed; calibrated 2σ ranges are rounded to nearest 10 cal yr BP, and only gaps and bars greater than 100 yr are shown. (b) Histogram of weighted mean calibrated ages in 100-year class intervals, where dates on the interval boundary are rounded up into the next higher class. Bar colors in (a) and (b) correspond to ages of types shown in the key and explained in the text. (c) Summed probability distributions for calibrated ^{14}C ages representing fire-related sedimentation and fire events.

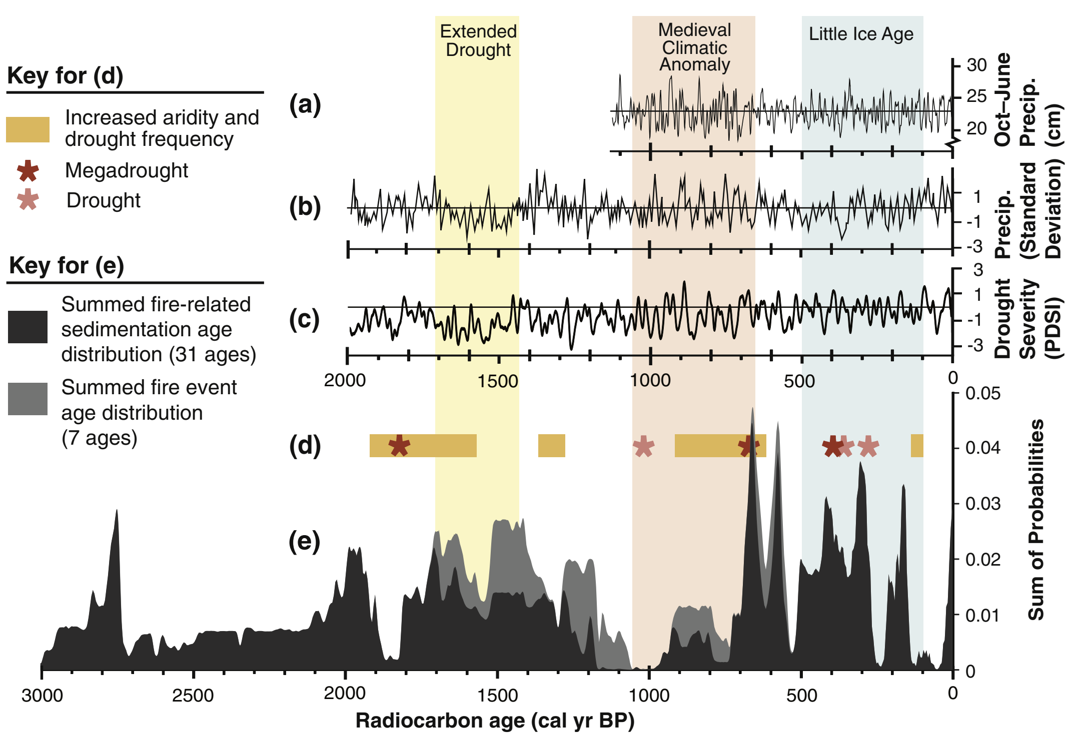

Figure 4. Summed probability distributions for calibrated ^{14}C ages representing fire-related sedimentation and fire events compared to paleoclimate information: (a) Tree-ring reconstruction of October–June precipitation for the Jemez Mountains smoothed using a Gaussian function (Touchan et al., 2011), plotted around the mean value for CE 1896–2007. (b) 10-year smoothing spline fit through tree-ring reconstruction of precipitation for El Malpais, northwestern New Mexico (Grissino-Mayer, 1996); (c) 20-year low-pass filtered mean Palmer Drought Severity Index (PDSI) tree-ring reconstruction for the four grid points surrounding the Jemez Mountains (Cook et al., 2004a). Negative PDSI values indicate dry conditions, while positive values indicate wet conditions. Paleoclimatic conditions in (d) are generalized from Stahle et al. (2000, 2009), Cook et al. (2004a, 2004b, 2007), Jimenez-Moreno et al. (2008), and Routson et al. (2011). Summed probability distributions at (e) show relative fire-sedimentation and fire-event probability, where fire event ages represent charcoal samples that could not be directly associated with sedimentation, but nonetheless represent fires; probability values for fire events are summed on top of fire-related sedimentation probabilities.

Table 1
Percent of total thickness of fan deposits of north and south-facing basins.

	Cobble lobe (debris flow)	Debris flow	Cobble lobe (hyper-concentrated flow)	Hyper-concentrated flow	Streamflow
Fire-related deposits					
North-facing basins	2	54	0	42	3
South-facing basins	0	63	0	32	5
All deposits					
North-facing basins	4	51	1	41	3
South-facing basin	0	58	0	38	4

dominated by fire-related deposits, which total 77% of the total measured stratigraphic thickness. Fire-related deposits are much less important in alluvial fans of south-facing basins, where they account for 39% of the total deposit thickness. Fan deposits from north and south aspects show that neither aspect is dominant in a particular depositional process type by more than 10% thickness (Table 1).

Minimum–maximum at-a-station recurrence interval estimates for fire-related sedimentation events suggest that they occur on average every 330–350 yr within the study area. Mean at-a-station recurrence intervals are 380–400 yr in north-facing basins and 250–290 yr in south-facing basins, indicating somewhat more frequent events on drier south aspects. Combining stations from the same tributary drainage for within-basin estimates yields shorter mean recurrence intervals of 270 yr within the study area: 290 yr in north-facing basins, and 240 yr in south-facing basins. Combining stations may yield a more complete record for the basin but results in a greater potential for the same fire event to be counted more than once, as some ages may stem from the same fire event but have different levels of inbuilt error that result in statistically different ages.

Discussion

Fire-related sedimentation history and climatic associations

The fire-related sedimentation and fire-event ages provide information on changes in fire activity and its geomorphic effects over the last ca. 5300 yr in the study area. Based on minima in probability 1900–1800 and 1100–1000 cal yr BP, the fire-sedimentation chronology can be partitioned into three periods: 5300–1900 cal yr BP, 1900–1000 cal yr BP and 1000 cal yr BP to present (Figs. 3 and 4). Tree-ring paleoclimate records are also available for comparison for the latter two intervals (Grissino-Mayer, 1996; Cook et al., 2004a; Stahle et al., 2009; Roos and Swetnam, 2011; Touchan et al., 2011). We emphasize that associations of peaks in fire-related sedimentation with climatic intervals as short-lived as multidecadal in scale are made tentatively, given analytical and calibration-related uncertainties in ^{14}C ages, along with the likelihood of inbuilt age errors that often make ages years to a few decades too old.

Fire-alluvial history: 5300–1900 cal yr BP

The record of fire-related sedimentation from 5300 to 3000 cal yr BP is not as well supported as the younger part of the chronology; as with other fire-related sedimentation records, decreasing exposure and preservation result in fewer ages with time before present (e.g., Meyer et al., 1995; Frechette and Meyer, 2009), especially before 4000 cal yr BP (Fig. 3). Following this time, however, four ages contribute to a peak in fire-sedimentation probability between 2850 and 2750 cal yr BP (Fig. 3). Speleothem oxygen-isotope ratios in southern New Mexico suggest relatively dry conditions in this interval, with a rapid shift to wetter climate by 2700 cal yr BP, but whether increased moisture is associated with summer or winter precipitation (or both) in this record is unknown (Asmerom et al., 2007). Between 2000 and 1950 cal yr BP, a cluster of three ages produce a prominent peak in fire-sedimentation probability. Carbon isotopes in soils suggest a transition from wet to dry conditions at roughly 2200 cal yr BP near the southern New Mexico border (Buck and Monger, 1999). A high-resolution tree-ring precipitation reconstruction is available for lower elevations approximately 150 km southwest of the study area, in the lava fields of El Malpais, New Mexico (Grissino-Mayer, 1996). This long record shows a shift from wet conditions ca. 2000–1970 cal yr BP to moderate drought persisting from ca. 1960–1900 cal yr BP (Fig. 4). Tree-ring records in the upper Rio Grande basin in Colorado also show the onset of an extended interval dominated by drought at ca. 1950 cal yr BP (Routson et al., 2011). These relations suggest the possibility that a generally wetter climate may have limited surface fires and produced denser forest stands in the study area, providing conditions for severe fires and post-fire sedimentation on the transition to drier conditions ca. 2000–1950 cal yr BP.

Fire-alluvial history: 1900–1000 cal yr BP

Interpretation of fire activity from 1900 to 1000 cal yr BP is based on a total of 13 ages (Fig. 3). The minimum in fire-sedimentation probability 1900–1800 cal yr BP overlaps a period of above-normal precipitation from 1869–1693 cal yr BP in the El Malpais reconstruction (Grissino-Mayer, 1996), suggesting suppression of fire by a wetter climate, although fire-related sedimentation returns to relatively high probability again by 1800 cal yr BP (Fig. 4). Prominent broad peaks in fire-sedimentation and fire-event probability lie at 1700–1600, 1520–1400, and 1280–1180 cal yr BP. Southwestern USA paleoclimate records show frequent droughts and often general aridity from 1900–1000 cal yr BP; for example, Palmer Drought Severity Index (PDSI) reconstructions (Cook et al., 2004a) indicate that in the study region, over 90% of this period was marked by drought (Fig. 4). The El Malpais reconstruction indicates extended drought from 1700–1450 cal yr BP, but it also reflects above-normal precipitation 1430–1290 cal yr BP (Grissino-Mayer, 1996) (Fig. 4). Frequent droughts and general aridity are inferred in southern Colorado 1950–1550 cal yr BP and 1350–1250 cal yr BP (Routson et al., 2011), broadly consistent with the period of increased fire-related sedimentation in the Jemez Mountains study area. A megadrought 1828–1778 cal yr BP (Routson et al., 2011) generally corresponds with the rise in probability of fire-related sedimentation events after the 1900–1800 cal yr BP minimum. Further evidence for general aridity between ca. 1600–1400 cal yr BP comes from paleolake records compiled by Castiglia and Fawcett (2006) for the southwestern USA.

Despite evidence for aridity, maximum Holocene ENSO frequency and variance from 2000–1500 cal yr BP is corroborated by six independent reconstructions, with stronger and more prolonged El Niño events (Conroy et al., 2008) that typically yield higher winter–spring precipitation in the southwestern USA; in some ENSO reconstructions, this period extends to 1200 cal yr BP (Moy et al., 2002; Rein et al., 2005). If relatively strong El Niño conditions prevailed over periods of decades, surface fire activity would be suppressed, allowing stands to become denser and more susceptible to severe fire in a subsequent La Niña phase and associated drought. Speleothems in southern New Mexico also show high variability in precipitation from 1900–1250 cal yr BP, with major droughts around 1900, 1650, and 1550 cal yr BP, followed by dampened variability lasting until 800 cal yr BP (Rasmussen et al., 2006). The minimum in fire-related sedimentation ca. 1050–950 cal yr BP is not notable for either uniformly wet climate or drought, but wetter-than-average conditions prevail from 1000–950 cal yr BP in both cool- and warm-season precipitation reconstructions (Stahle et al., 2009), and a long period of minimal predicted fire extends from

1100–1000 cal yr BP in the Roos and Swetnam (2011) reconstruction for ponderosa pine forests of the southern Colorado Plateau.

Periods of increased fire-related sedimentation similar to the Jemez record have been observed ca. 1700–1300 cal yr BP in ponderosa pine-mixed conifer forests of the Sacramento Mountains of southern New Mexico (Frechette and Meyer, 2009), and ca. 1850–1550 cal yr BP on Kendrick Mountain in northern Arizona (Jenkins et al., 2011). In contrast, in colder, high-elevation Yellowstone National Park, Wyoming, a distinct minimum in fire-related sedimentation occurred between 1650 and 1250 cal yr BP (Meyer et al., 1995). In this environment dominated by infrequent high-severity fire in lodgepole pine (*Pinus contorta*), the lull in activity was inferred to stem from cool and wet climate, concurrent with glacial advances in the Pacific Northwest (Reyes et al., 2006). It is also part of a strong millennial-scale pattern of temperature changes characterized by colder periods of minimal fire, and warmer, drought-prone periods with major fire-related sedimentation; broad peaks in fire-sedimentation probability occurred ca. 1900–1700 and 1200–1000 cal yr BP in Yellowstone. No clear relations to millennial-scale climate variations are seen in the Jemez, northern Arizona, or southern New Mexico fire-related sedimentation records, however (Frechette and Meyer, 2009; Jenkins et al., 2011). In the interior Southwest, late spring–summer weather conducive to fire was probable even in colder periods of the late Holocene; also, fire is often limited by early onset and abundant rainfall of the summer monsoon, whereas summer rainfall is much less consistent in Yellowstone.

Overall, whereas paleoclimate data for the Jemez Mountains and surrounding region suggest that the 1900–1000 cal yr BP period is generally characterized by drought, it is also marked by significant climatic variability and frequent shifts, with both anomalously wet and dry periods. During wetter decades with limited surface fire activity, stands may have become denser, with ladder fuels that promoted severe fires during subsequent droughts (e.g., Pierce and Meyer, 2008; Roos and Swetnam, 2011). Even within an overall drought period, fire-related sedimentation can be spurred by rare but high-intensity precipitation during the summer monsoon, when convective storms are most likely to generate debris flows on recently burned slopes. Based on charcoal concentrations in two Jemez Mountains bogs, Anderson et al. (2008) estimated that the highest late Holocene fire-event frequencies occurred from 2000–1000 cal yr BP, and similarly inferred that high precipitation variability joined with extended periods of drought to produce abundant forest biomass and frequent burning in this period.

Fire-alluvial history: 1000 cal yr BP to present

The record of fire-related sedimentation from 1000 cal yr BP to present is supported by a total of 15 ages (Fig. 3). Peaks in fire-sedimentation probability occur between 700–575 cal yr BP (5 ages), 500–275 cal yr BP (6 ages), and 225–150 cal yr BP (3 ages). From ca. 400 cal yr BP to present, however, uncertainty exists in the association of individual probability peaks with actual fire and sedimentation events, because of the broad, multimodal calibrated probability distributions resulting from large atmospheric ^{14}C variations during this period, where only one of 3–4 peaks can represent the actual age (Reimer et al., 2004). An additional consideration is that from 800–300 cal yr BP, the southern Jemez Mountains became home to Puebloan populations of roughly 5000–8000 people, primarily in lower elevations 7 km or more to the south of the study area (e.g., Kulisheck, 2005, 2010). These people may have used local low-severity burning in order to enhance edible plant production (Roos et al., 2010) and for other management purposes, along with increasing ignitions in general (Bowman et al., 2011). Fire regime alteration on a large scale by Pueblo people was considered unlikely by Allen (2002), however. The nearest identified archeological site is a small pueblo approximately 2 km to the south in middle Lake Fork Canyon (Fig. 1), occupied ca. 550–300 cal yr BP (Kulisheck, 2005), suggesting the possibility of valley-floor agricultural use and other anthropogenic impacts on vegetation and fire spread within the study area. Human activities are less likely to directly affect the record of fire-related sedimentation, given its association with moderate- to high-severity fires on steep slopes and the abundance of lightning strikes in the Jemez Mountains for natural ignitions; however, the nature and magnitude of anthropogenic effects remain to be addressed more directly (e.g., Bowman et al., 2011).

The period from ca. 1000–500 cal yr BP is one in which paleoclimate records indicate episodes of widespread and severe aridity in the southwestern USA, combined with relatively large decadal to centennial changes in precipitation (Cook et al., 2004b; Rasmussen et al., 2006; Jimenez-Moreno et al., 2008; Routson et al., 2011). A “megadrought epoch” prevailed in the Four Corners area and much of the western USA from 1050–650 cal yr BP, a period termed the Medieval Climatic Anomaly (MCA; Stine, 1998; Cook et al., 2007). The MCA featured large oscillations in multidecadal PDSI (Cook et al., 2004b), and high decadal-scale variability in the El Malpais and Jemez Mountains precipitation records (Grissino-Mayer, 1996; Stahle et al., 2009; Touchan et al., 2011). A major peak in fire-related debris-flow activity occurred in the northern USA Rocky Mountains (Meyer et al., 1995; Pierce et al., 2004; Riley et al., 2015), and lake-sediment charcoal records show elevated fire activity in the western USA overall (Marlon et al., 2012). Fire-related sedimentation in the Jemez study area and Sacramento Mountains of southern New Mexico is not exceptional throughout most of the MCA (New, 2007; Frechette and Meyer, 2009); nonetheless, sharp peaks in probability are seen in both records at ca. 650 cal yr BP, near the nominal end of the MCA (Fig. 4), and fire-sedimentation probability in northern Arizona shows a prominent peak ca. 700 cal yr BP (Jenkins et al., 2011). Fire activity around this climatic transition may have been spurred by the multidecadal “Great Drought” of 674–653 cal yr BP in the Four Corners area (Cook et al., 2007; Frechette and Meyer, 2009); or, given the significant potential for inbuilt age error that would make ^{14}C ages a few decades too old, by a later drought from ca. 625–580 cal yr BP recorded at El Malpais, New Mexico (Stahle et al., 2009). However, fire-related sedimentation in the Jemez study area also shows a sharp peak in probability ca. 575 cal yr BP, near the end of the later drought at El Malpais, but close to the onset of prolonged moderate drought conditions in the smoothed regional PDSI record (Fig. 4; Cook et al., 2004a). Both droughts contained intervals of reduced precipitation in both cool and warm seasons at El Malpais, and fall within a time of high vulnerability to severe crown fires as predicted from tree-ring paleoclimate data by Roos and Swetnam (2011). They were also preceded by over two decades of pluvial conditions that commonly affected both seasons, in particular before the 674–653 cal yr BP drought, which may have been sufficient for forest stands to develop ladder fuels.

The latter part of the last millennium encompasses the Little Ice Age, a period with little general agreement on bracketing dates, but apparent as a colder interval in Northern Hemisphere temperature reconstruction of Mann et al. (2008) from 500–50 cal yr BP, and evident in various paleoclimatic proxy records in western North America (Carrara, 1989; Davis and Shafer, 1992; Luckman, 2000; Jimenez-Moreno et al., 2008). Episodes of widespread and severe drought across the western USA were less common than in the MCA (Cook et al., 2004a, b) (Fig. 4). Tree-ring reconstruction of October–June precipitation in the Jemez Mountains (Touchan et al., 2011) indicates mostly lower variability than in the 1000–500 cal yr BP period, and the El Malpais record shows generally higher precipitation after 500 cal yr BP (Grissino-Mayer and Swetnam, 2000). A predominantly low-severity fire regime from 400–50 cal yr BP is indicated by tree-ring fire-scar data in the Jemez Mountains (Swetnam and Baisan, 1996; Touchan et al., 1996; Allen, 2001), and may stem in part from overall lower Little Ice Age temperatures, and thus an effectively wetter climate. These conditions may have helped to maintain canopy moisture and inhibit severe fire (Williams et al., 2013), while promoting the growth of grasses and other fine surface fuels for low-severity fires initiated during frequent moderate droughts (e.g., Swetnam and Betancourt, 1998). Fire-related sedimentation in the Jemez study area is not clearly different from earlier parts of the last millennium, consistent with the findings of Roos and Swetnam (2011). The predominance of relatively thin deposits from this interval, however, suggests lower-severity fire activity (Fitch, 2013; Fig. 4), consistent with tree-ring records and similar fire-related sedimentation in southern New Mexico 500–100 cal yr BP and southern Colorado 300–150 cal yr BP (Frechette and Meyer, 2009; Bigio et al., 2010).

While overall somewhat cooler, wetter, and less variable than the preceding centuries, the last 500 yr nonetheless feature some notable droughts. Distinct peaks in Jemez fire-sedimentation probability are apparent at ca. 410, 300, and 170 cal yr BP, and the prominent peak in fire-sedimentation probability at ca. 410 cal yr BP falls shortly before the onset of a severe multidecadal drought across the southwestern USA ca. 400 cal yr BP (AD 1550), which persisted with limited rainfall in all seasons for nearly 50 yr, and was preceded by nearly 50 yr of predominantly wetter-than-normal conditions (Stahle et al., 2000; Stahle et al., 2009) (Fig. 4). One to a few decades of inbuilt age error, as can be expected, would place the time of peak fire-sedimentation probability within this megadrought, and high fire-sedimentation probability exists within the drought regardless. The probability peak at 300 cal yr BP has similar timing and climatic associations to that at 410 cal yr BP, shortly preceding drought that followed several wetter decades, though neither interval was as prolonged or persistent (Grissino-Mayer, 1996; Stahle et al., 2009; Touchan et al., 2011). A very large shift from wet to dry conditions in the Southwest also occurred 203–202 cal yr BP (Swetnam and Betancourt, 1998), producing the driest year until 1996 in the Jemez Mountains precipitation reconstruction (Touchan et al., 2011), and sparking the most extensive wildfires in ca. 400 years of tree-ring records across the Southwest (Swetnam et al., 1999). A minor peak in fire-sedimentation probability at ca. 200 cal yr BP possibly reflects this climatic shift and fire episode. The subsequent higher peak at 170 cal yr BP is not associated with clearly anomalous precipitation values in the Jemez Mountains and El Malpais reconstructions (Grissino-Mayer, 1996; Stahle et al., 2009; Touchan et al., 2011). There is also no clear association of anomalous climate with the minimum in fire-sedimentation probability centered near 225 cal yr BP. The minimum from 140–30 cal yr BP likely stems from our avoidance of bioturbated sediments near the modern soil surface for dating, but may also reflect Euro-American fire suppression (e.g., Allen et al., 2002).

Overall, at least some Jemez fire-related sedimentation events from 500–50 cal yr BP appear to have been spurred by major droughts within this overall cooler period, preceded by above-normal precipitation that limited surface fires for some decades. We present these interpretations with caution, however, given the multimodal calibrated probability distributions in this period, and potential differences between charcoal ^{14}C dates with inbuilt age and actual fire dates. There is also limited correspondence of probability peaks within this period between the Jemez fire-related sedimentation record and those from Kendrick Mountain, northern Arizona (Jenkins et al., 2011) and the Sacramento Mountains, southern New Mexico (Frechette and Meyer, 2009). Ultimately, only 4 of the 11 dated Jemez stratigraphic sections contain deposits from this period, suggesting that unlike the 2002 Lakes Fire, the associated fires did not burn at high severity over large parts of the study area.

Longer-term changes in vegetation, fire regime, and erosion

Pollen data from the Jemez Mountains indicate that no major variations in forest species composition have occurred in the last 6000 years (Anderson et al., 2008). Nonetheless, fire regimes in the late Holocene may have been influenced by relationships and feedbacks among climate, forest structure, and fire severity. A low-severity surface fire regime may prevail until unusually wet conditions allow ladder fuels to grow to the point where a dense stand structure is at risk for severe fire. Once initiated, a high-severity regime may persist until seed sources for ponderosa pine and recovery species associated with a mixed-conifer forest assemblage are largely depleted (Savage and Mast, 2005). The sparse forest condition that results from these severe burns could in part explain the minimum in fire-related sedimentation from about 1100–900 cal yr BP, during the earlier part of the drought-ridden MCA, when high interannual wet-to-dry variability may also have favored fine fuel growth and low-severity surface fires (Roos and Swetnam, 2011), with an eventual recovery of open stands. Fire-related sedimentation overall is most likely related to moderate to high-severity fires, and the recurrence interval estimates of 250–400 yr are broadly consistent with return intervals for high-severity, stand-replacing fires at upper elevations in the surrounding region (Margolis et al., 2007, 2011). Changes in fire severity, however, are difficult to assess in the Jemez stratigraphic record. Severity can be reasonably inferred from deposits where clear differences in unit thickness and depositional process are apparent (e.g., Pierce et al., 2004), but the Jemez deposits are overall more uniform in character.

Without preservation or exposure of deposits older than 5300 cal yr BP, no direct inferences on earlier Holocene fire activity can be made. However, at Station 7, where the alluvium was incised to bedrock after the 2002 Lakes Fire, the absence of deposits older than ca. 2300 cal yr BP suggests that large debris flows and floods in the middle Holocene scoured most alluvium from the channel, flushing sediment into NM 126 Canyon. As after the Lakes Fire, such major erosive events are consistent with the occurrence of high-severity fire over much of this larger tributary basin, although extreme floods in the absence of fire could also be responsible (Harden et al., 2010). The lack of older alluvium above bedrock also suggests that erosional response after the Lakes Fire was at least locally greater than at any time in the last 2300 yr. To resolve this question with more confidence, however, further comparison of modern post-fire erosion and deposition with Holocene activity is needed, through expansion of the study area and possibly trenching to access older deposits.

Slope aspect and the relative importance of fire in sedimentation

Fire-related deposits make up an estimated 57% of the total thickness of all alluvial fan deposits analyzed. A potential bias toward sampling of exposures with clear evidence for fire-related sedimentation must be considered, as that would inflate the estimate. As a contrary effect, some fire-related deposits contain little charcoal, in particular those of flood-streamflow facies, and a lack of recognition of their post-fire origin would reduce the estimated proportion of fire-related sediment. Regardless, the overall abundance of fire-related deposits shows that fire is an important influence on hillslope erosion and fan sedimentation in the Jemez Mountains.

Alluvial fans of north-facing basins are dominated by fire-related deposits, which make up 77% of the total measured stratigraphic thickness. North-facing slopes have a relatively thick and continuous cover of permeable soil and colluvium, which along with denser vegetation enhance infiltration and limits runoff and erosion in the unburned state. When impacted by severe fire, the potential for surface runoff generation and fan sedimentation is greatly increased over the unburned state. Using the at-a-station and within-basin methods, a somewhat greater mean recurrence interval for fire-related sedimentation in the more mesic north-facing basins relative to south aspects is also consistent with a greater susceptibility to severe fire. In contrast, fire-related deposits make up only 39% of the total deposit thickness in fans from south-facing basins. With sparser vegetation cover, thinner soils, and large areas of exposed bedrock, south-facing slopes can produce substantial runoff and sediment during intense storms, even in the unburned state (Wilcox et al., 1997; Wilcox et al., 2003). It is possible that a significant percentage of deposits from south-facing basins that were not identified as fire-related were emplaced after low-severity surface fires, which contributed limited charcoal to deposits; however, the same bias would exist in north-facing basins, with perhaps a slightly lesser effect because of somewhat less frequent surface fires. Also, while some post-fire hyperconcentrated-flow and streamflow deposits lack visible charcoal, making them difficult to identify as fire-related (Meyer and Wells, 1997), the greater relative amount of fire-related deposits from north-facing basins cannot be attributed to differences in depositional processes among aspects, as percentages of deposit types from north- and south-facing basins are similar.

Given the large differences in the proportion of identified fire-related deposits, we infer that fire has had a substantially greater influence on erosion on north-facing slopes than on south-facing slopes over the late Holocene. These findings indicate that investigations of fire as a catalyst for erosion should consider potentially large differences with aspect, and that through post-fire erosion, a warmer, more drought-prone climate may have greater geomorphic impacts on moister aspects. The timing of late Holocene fire-related sedimentation is not clearly different among aspects, however (Fitch, 2013), suggesting that moderate- to high-severity burns promoting post-fire erosion are not restricted to highly unusual climatic conditions on either north or south aspects, at least over the small spatial scale of the study basins.

Conclusions

This study examines Holocene fire–climate-erosional linkages in the Jemez Mountains, over both time and space, and the relative importance of post-fire activity in erosion and sedimentation. The radiocarbon chronology indicates that changes in post-fire sedimentation are not as clearly related to millennial-scale Holocene climatic changes as in higher elevations of the northern Rocky Mountains, where fire occurs dominantly by stand-replacing burns during warm, drought-prone centuries (Meyer et al., 1995; Pierce et al., 2004). Nonetheless, climate is still an important control in the Jemez study area, as with some caution given the resolution of ^{14}C dating, we infer that peaks in fire-sedimentation probability around 1800, 650, 410, and 300 cal yr BP are associated with severe, typically multidecadal regional droughts. These droughts are also commonly preceded by decades of wetter climate that could produce largely fire-free periods and promote denser stands. Perhaps in opposition to these relations, fire-related sedimentation was relatively minor from 1050–700 cal yr BP over most of the Medieval Climatic Anomaly, with its severe multidecadal droughts over much of the western USA (Cook et al., 2004b, 2007). However, the earlier MCA droughts were not anomalously severe and prolonged in the Jemez Mountains (Stahle et al., 2009; Touchan et al., 2011), and development of a pervasive open forest structure due to persistent drought and severe fire in the previous 700 yr (Cook et al., 2004b; Routson et al., 2011) could have reduced the potential for severe fire.

The high percentage of fire-related alluvial deposits clearly shows that fire is an important geomorphic agent in the study area. North- and south-facing basins do not differ significantly in fan depositional processes or timing of fire-related sedimentation (Fitch, 2013); however, with sparser vegetation, thinner soils and greater exposed bedrock, drier south-facing slopes can more readily generate fan sedimentation without burning. With a thicker soil mantle and higher infiltration rates, more densely vegetated north-facing slopes also have lower potential for runoff and sediment generation in the unburned state, such that a greater relative amount of sedimentation occurs when infiltration is reduced by severe fires. Since forest type, fire regimes, and recurrence intervals can differ substantially with aspect, studies of Holocene fire-climate relations and geomorphic effects should consider the consequent range of variability that may exist even on small spatial scales.

Despite the deeply incised tributary channels in the study area, no deposits older than 5300 cal yr BP were identified, implying major channel erosion and sediment evacuation during the middle Holocene, possibly stemming from extensive high-severity burns and (or) increased storm intensity and flood magnitudes. In contrast, channels and fans have been in a dominantly aggradational mode over the late Holocene. Major debris flows and floods after the 2002 Lakes Fire appear to have been more erosive than any in the last few millennia, producing incision of channels where no clear evidence exists for similar downcutting in the late Holocene. These observations suggest that Euro-American fire suppression and stand densification combined with exceptional drought in 2002 to produce an unusually severe fire and large magnitude of post-fire response. In light of connections between drought and fire-related sedimentation in the late Holocene, and subsequent, more extensive severe burns in the Jemez Mountains like the 63,000 ha Las Conchas Fire of 2011, it appears likely that ongoing warming will further exacerbate post-fire erosion and sedimentation.

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