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# Late Holocene geomorphic record of fire in ponderosa pine and mixed-conifer forests, Kendrick Mountain, northern Arizona, USA

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**Abstract.** Long-term fire history reconstructions enhance our understanding of fire behaviour and associated geomorphic hazards in forested ecosystems. We used $^{14}C$ ages on charcoal from fire-induced debris-flow deposits to date prehistoric fires on Kendrick Mountain, northern Arizona, USA. Fire-related debris-flow sedimentation dominates Holocene fan deposition in the study area. Radiocarbon ages indicate that stand-replacing fire has been an important phenomenon in late Holocene ponderosa pine (*Pinus ponderosa*) and ponderosa pine–mixed conifer forests on steep slopes. Fires have occurred on centennial scales during this period, although temporal hiatuses between recorded fires vary widely and appear to have decreased during the past 2000 years. Steep slopes and complex terrain may be responsible for localised crown fire behaviour through preheating by vertical fuel arrangement and accumulation of excessive fuels. Holocene wildfire-induced debris flow events occurred without a clear relationship to regional climatic shifts (decadal to millennial), suggesting that interannual moisture variability may determine fire year. Fire-debris flow sequences are recorded when (1) sufficient time has passed (centuries) to accumulate fuels; and (2) stored sediment is available to support debris flows. The frequency of reconstructed debris flows should be considered a minimum for severe events in the study area, as fuel production may outpace sediment storage.

**Additional keywords:** charcoal, crown fire, debris flows, fire history, terrain.

## Introduction

Echoing a pattern repeated throughout the western USA (Westerling *et al.* 2006), the ponderosa pine (*Pinus ponderosa*) and mixed conifer forests of the Colorado Plateau experienced an escalation in fire size, severity and homogeneity during the latter half of the 20th century. Dendrochronological studies encompassing the most recent 400–500 years have attributed this fire behaviour to departures in forest composition and structure from presettlement conditions (e.g. Covington and Moore 1994; Covington *et al.* 1997; Fulé *et al.* 1997; Heinlein *et al.* 2005). However, a longer context for late Holocene fire occurrence might elucidate the role of climate variability in fire frequency and severity in this region – a role that has been demonstrated well in studies from other mountainous regions. Ponderosa pine (PIPO) forests of the southern Colorado Plateau (Fig. 1) have been the subject of extensive dendrochronological research into natural variability in regional fire systems. This research has characterised a 'presettlement' surface fire regime with annual to decadal fire recurrence intervals (i.e. 2–20-year interval of Swetnam and Baisan 1996 (1700–1900 AD); 3.7 years for all fires and 6.5 years for widespread fires, Fulé *et al.* (1997) (1637–1833 AD)) – averaging slightly longer for ponderosa pine–mixed conifer (PIPO-MC) forest types (e.g. Fulé *et al.* 2003 (1702–1879 AD); Heinlein *et al.* (2005) (1690–1892 AD)) where interval length may vary with species composition. Ubiquitous surface fire is a governing ecological control in these ecosystems, maintaining diverse understorey and canopy communities, forest structure and nutrient cycling, and regulating species composition in favour of shade-intolerant and fire-tolerant tree types (Cooper 1960; Covington and Moore 1994; Fulé *et al.* 1997).

Through additional dendrochronologic, sedimentologic and geomorphic proxies (e.g. stand generation reconstructions, sedimentary charcoal in lake beds, soils, small hollows and alluvial deposits), fire histories in many regions of North America have been extended through much of the Holocene. This longer temporal context allows a better characterisation of the full range of natural variability. External drivers (i.e. climate variability, anthropogenic factors) and internal thresholds

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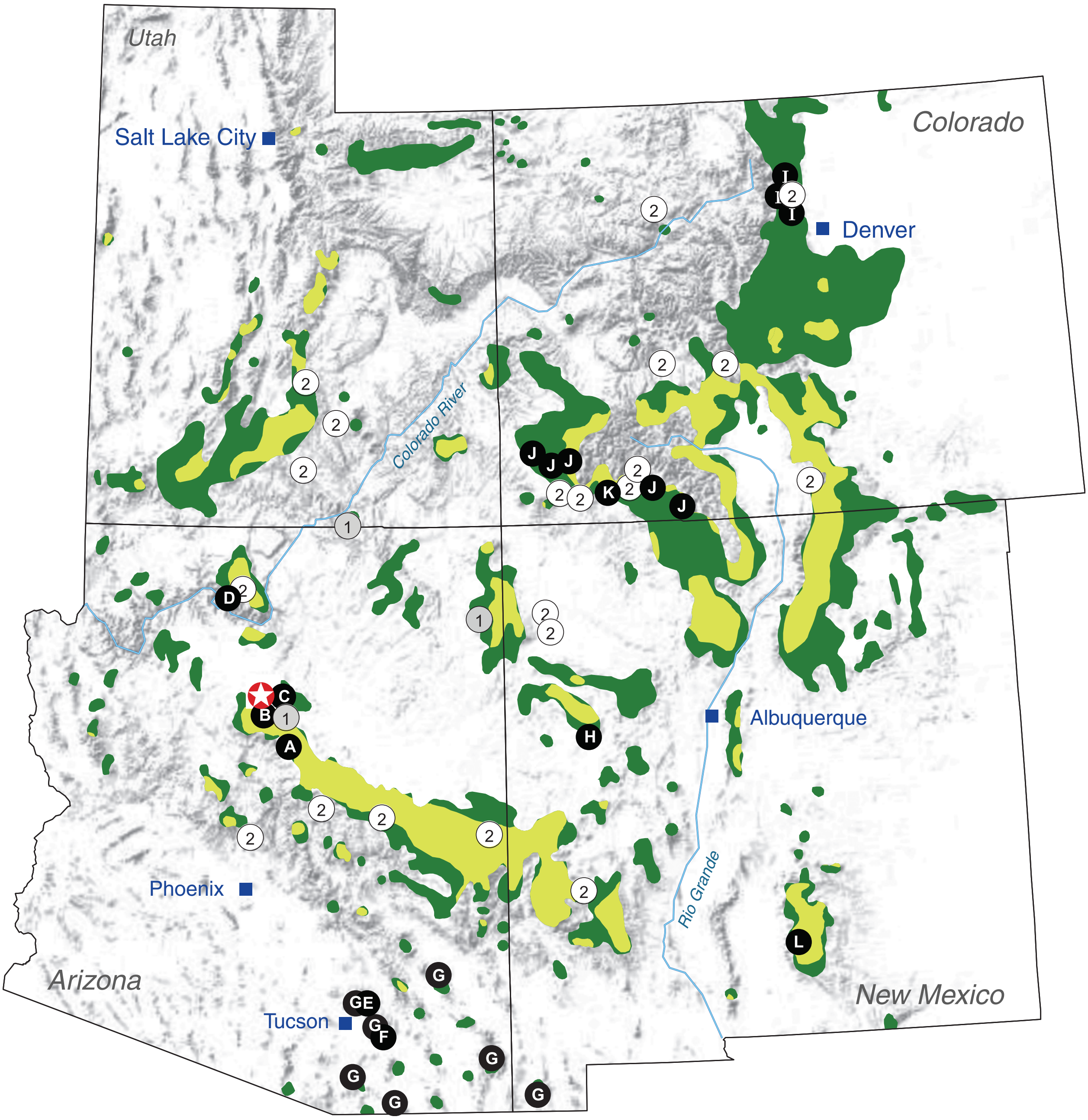

**Fig. 1.** Regional overview showing studies cited in this text. Kendrick Mountain study area, northern Arizona, is denoted with a star. Forests of interest to the present study include predominantly ponderosa pine (dark green areas) and ponderosa pine–mixed conifer (light green areas), constructed with the composite ranges of *Pinus ponderosa*, Douglas-fir (*Pseudotsuga menziesii*) and white fir (*P. concolor*) (Thompson *et al.* 1999), three significant components of regional ponderosa pine–mixed conifer (PIPO-MC) forests. Mixed conifer forests without a significant *P. ponderosa* component are not depicted, as these are thought to have a distinctly different natural fire regime. Climatological reconstructions discussed in this study include: (1) annual temperature and precipitation (Salzer and Kipfmueller 2005), and (2) composite palynological temperature proxy (Viau *et al.* 2006) derived from North American pollen database of Grimm (2000). Regional fire-scar fire history reconstructions for similar forest types include (*a*) Covington and Moore (1994); (*b*) Fulé *et al.* (1997); (*c*) Heinlein *et al.* (2005); (*d*) Fulé *et al.* (2003); (*e*) Iniguez *et al.* (2008); (*f*) Iniguez *et al.* (2009); (*g*) Swetnam *et al.* (2001); (*h*) Grissino-Mayer and Swetnam (2000); (*i*) Veblen *et al.* (2000); and (*j*) Grissino-Mayer *et al.* (2004). Geomorphic fire history records include (*k*) Bigio (2006) and (*l*) Frechette and Meyer (2009), New (2007).

(i.e. fuel and ignition dynamics, forest composition) may control the occurrence of high-severity fires on a temporal scale that is not recorded by fire-scar methods, although regional collections of fire histories can reveal these influences for the latest Holocene (e.g. Fulé *et al.* 2003; Swetnam and Baisan 2003). Reconstruction of Holocene fire history, particularly through periods of severe regional drought, is of special interest given recent climate change projections.

This study focusses on the geomorphic record of wildfire to infer Holocene stand-replacing fire events on Kendrick Mountain, northern Arizona. Much of Kendrick Mountain was subject to stand-replacing fire in the summer of 2000; numerous charcoal-laden debris flows occurred following the fire during the North American monsoon season, in the late summer and early fall (autumn). Analogous fire-related debris-flow sequences of this type have been well studied throughout mountainous terrain of the western United States in the past 20 years. Current initiation models propose that burned, steep terrain subject to moderate- or high-severity wildfire can issue forth debris flows in response to high-frequency rainfall events (Cannon *et al.* 2008), provided there is sufficient sediment to support a debris flow, and that significant time for vegetation regrowth has not passed. Sedimentologic fire reconstructions rely on dates obtained from burned materials in fire-related deposits. Following the methods of Meyer *et al.* (1995), we extracted and dated charcoal produced by wildfires and entrained in fire-related debris flows. Assuming a causative link between stand-replacing fire and debris flows, fire-related debris-flow deposits provide a chronicle of prehistoric stand-replacing fire events (e.g. Cannon and Reneau 2000; Cannon *et al.* 2003). We emphasise that the charcoal ages are maximum-limiting ages on the fires, although debris flows have been widely observed to closely follow wildfires.

This project is significant for several reasons. The broad temporal range of the method enhances our understanding of long-term severe fire occurrence in PIPO and PIPO-MC forests before widespread historical, post-settlement modification of the regional fire environment. Furthermore, the complexity of the terrain in the study area may be an important variable; recent regional fire history reconstructions in PIPO forests have been conducted on relatively gentle terrain. Recent studies in southern Arizona and the Black Hills of South Dakota (Swetnam *et al.* 2001; Lentile *et al.* 2006; Iniguez *et al.* 2008) have brought attention to the role that steep topography can play in altering fire behaviour in xeric PIPO ecosystems, either through an increase in fuels loading as a result of physical boundaries to previous fire spread, or through vertical fuel arrangement that functions to magnify fire intensity.

Although it is highly unlikely that every high-severity fire event will be captured in the sedimentary record, it is essential to a more comprehensive understanding of the long-term range of variability in the fire regime of the study area, and throughout the southern extent of PIPO and PIPO-MC forests in general. At present, fire regime descriptions for the most recent 400 years in purely PIPO forests generally exclude stand-replacing fire (but see Brown *et al.* 1999, 2008; Sherriff and Veblen 2006), and few studies have adequately quantified the recurrence interval and scale of severe-fire episodes in high-elevation PIPO-MC forest types based on fire-scar data or other indicators such as tree establishment dates (e.g. Veblen *et al.* 2000; Fulé *et al.* 2003; Grissino-Mayer *et al.* 2004; Heinlein *et al.* 2005). An understanding of the relative spatial and temporal scales of crown to surface burning is critical from both an ecological and management standpoint.

Our objectives are to: (1) to examine modern fire-induced debris-flow deposits in PIPO and PIPO-MC forests on Kendrick Mountain; (2) reconstruct a record of Holocene stand-replacing fire events; and (3) evaluate possible climatic controls for departures from the historically documented, low-severity, high-frequency fire regime of regional PIPO forests. For the first objective, sedimentological characteristics of debris-flow deposits are related qualitatively to transport and deposition. Age control on charcoal fragments and charcoal identification comprise the data sources for our second objective. Last, we compare various late Holocene climate proxies with the fire record from Kendrick Mountain to evaluate the potential influence of local or regional climate trends on the prevailing fire environment through direct external controls or internal threshold modifications.

## Setting

Kendrick Mountain is the second largest peak in the San Francisco Volcanic Field (~47 km$^2$) and is located ~30 km NNW of Flagstaff, AZ (Fig. 2). The oldest volcanic rocks of the mountain date to 2.70 ± 0.05 million years ago (Ma) (K–Ar date, Wolfe *et al.* 1987). The mountain comprises a range of volcanic rock types, including rhyolite, dacite, andesite, trachyte and basalt (Wolfe *et al.* 1987). Elevations range from 2450 to 3175 m; slopes range from 0 to $>50°$, with the majority of the mountain between 10 and 30°. The lowermost slopes are blanketed with PIPO forest, which transitions into PIPO-MC at higher elevations with the addition of Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) and lesser populations of corkbark fir (*Abies lasiocarpa* ssp. *arizonica*), limber pine (*Pinus flexilis*) and white fir (*Abies concolor* var. *concolor*) (Fig. 1). Isolated spruce-fir stands, dominated by Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*), are present in the uppermost slopes, similar to neighbouring populations on the San Francisco Peaks. Aspen stands (*Populus tremuloides*) are present at high elevations and in narrow, protected drainages. Mapped soil types on Kendrick Mountain are Inceptisols and Entisols (USDA 1991, 1995), suggesting that the periods of Holocene surface stability for soil development have been relatively brief.

Modern climatic data were obtained from the closest climate station with the most complete record at Flagstaff Pulliam Airport, Flagstaff, Arizona, ~34 km from the study area. The average annual precipitation is 58 cm for the 1971–2000 period of record, with a bimodal precipitation pattern in which winter frontal storms from the Pacific and summer monsoonal storms are responsible for most of the precipitation (Staudenmier *et al.* 2005). Annual air temperature averages have varied from 6.6 to 9.7°C (overall 7.9°C average).

The majority of Kendrick Mountain burned during the Pumpkin Fire of 2000. A lightning strike initiated the fire on the south-western side of the mountain on 24 May 2000 (Fig. 2). The fire burned clockwise around the mountain and was fully contained on 7 June, although portions continued to smoulder until extinguished by rainfall in August 2000. A circular area of ~5970 ha burned in a mosaic of burn severities (Fig. 2). Moderate- and high-severity fire accounted for 11% (694 ha) and 32% (2062 ha) of the total burned area respectively; only 7% of the total area inside the fire perimeter remained unburned, aided by the efforts of wildland fire crews attempting to preserve historic structures near the mountain's summit. Within our study

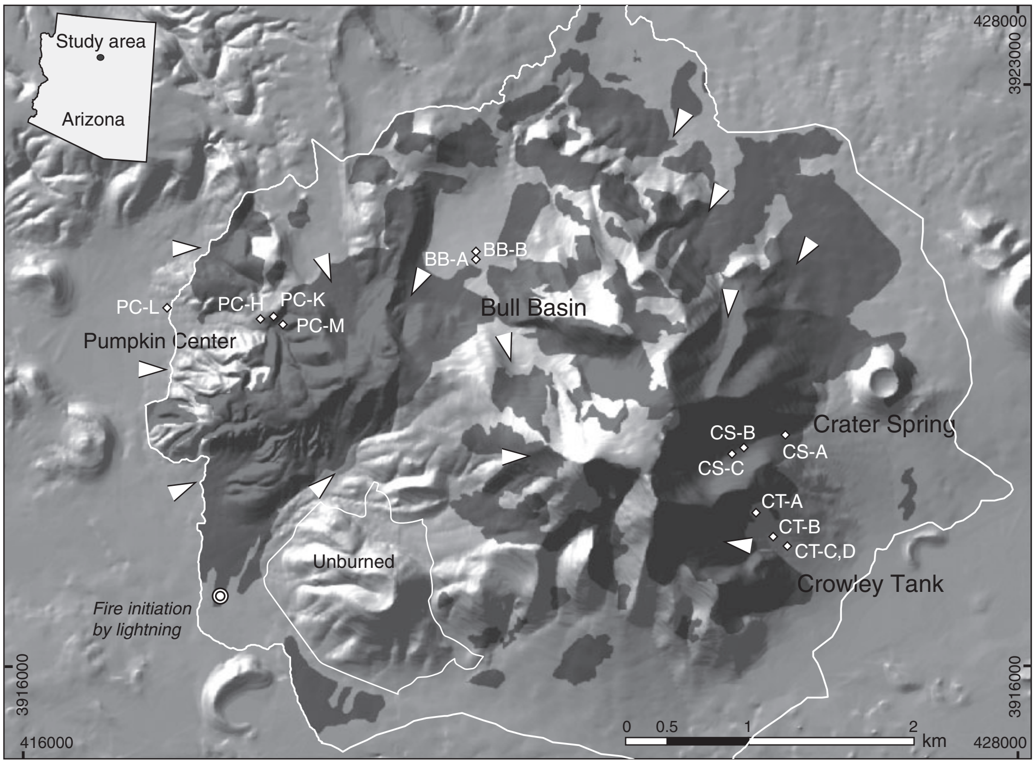

**Fig. 2.** Kendrick Mountain study area, showing study sites and the complex burn mosaic of the 2000 Pumpkin Fire. Dark shaded areas indicate moderate- to high-severity burn; white perimeter covers an area of ~6000 ha. All parts of the mountain burned to some degree, save for the hill to the south-west of the mountain and a small area near the peak where fire crews made efforts to protect historical structures. Study exposures for stratigraphic fire history information delineated with white dots (e.g. PC-L, CS-A). Triangles point upstream into basins where additional post-2000 debris flows were identified, but not included for paleofire studies.

basins, moderate- and high-severity fire burned between 52 and 91% of total basin area; laterally continuous moderate- and high-severity burn patches in these basins ranged in size from 15 to 159 ha. Rainfall during the subsequent late summer monsoon seasons generated debris flows, hyperconcentrated flows and sediment-laden water floods from the moderately to severely burned portions of the mountain, up to as many as 5 years after the fire in some basins (Fig. 3).

Debris flows from rainfall-induced sediment erosion and progressive channel bulking are common phenomena following moderate- to high-severity fires, and can be produced by relatively small rainfall events (e.g. ≤2-year recurrence intervals; Cannon *et al.* 2008). These are common during the first several years following a fire and before vegetation recovers. Removal by fire of the vegetative cover that normally attenuates raindrop impact and secures unconsolidated sediments, coupled with decreased water infiltration due to surface sealing by fine sediments and ash, cumulatively promote overland flow to channels. Runoff from hillslopes erodes sediment temporarily stored in channels to produce debris flows, which propagate through progressive bulking from continued channel erosion (e.g. Cannon *et al.* 2001*a*, 2001*b*; Santi *et al.* 2008; Moody and Martin 2009). Deep channel scour (1–5 m) was observed in many of the drainages in the study area; hillslope rilling was recorded to a lesser degree, and no large soil-slip scars were observed.

## Methods

### Site selection

Channel deposits underlying preserved fill–cut terraces along channel reaches within four drainage basins were selected for this study. They include a range of drainage sizes, aspects and elevations, in an attempt to capture the full range of fire-related debris-flow sedimentation across the mountain (Fig. 2). In each basin, debris-flow incision and deposition subsequent to the 2000 Pumpkin Fire provided an analogue for the interpretation of paleofire events from preserved deposits (Fig. 3*c*). High spatial variability in geomorphic response to fire is evident in both the modern and prehistoric fluvial systems, with deposition over some channel reaches and deep incision, in some cases to bedrock, in adjoining segments. The terrain and channel sediment characteristics responsible for this variability were not evaluated in this study.

Exposures of alluvial deposits were chosen primarily for their thick sections exposed in channel walls, and for site accessibility. Within each basin, we described two to five channel-wall segments, incised by recent debris flows into fill–cut deposits, for a total of 13 individual study sites (Fig. 2). One site, PC-L, was located along an incised channel reach in a proximal alluvial fan setting. Incision into fan surfaces was uncommon in the study area; distal fan deposits following the fire were mainly fluvial, suggesting a transition from debris

**Fig. 3.** (*a*) Channel scouring from modern debris flows and subsequent fluvial processes exceeded 5 m in some areas. Photograph is from the central portion of the Pumpkin Center drainage. (*b*) A boulder in the modern (post-Pumpkin Fire) debris flow deposit from an unnamed basin adjacent to Pumpkin Center suggests the recent deposits are good analogues for the preserved deposits, an example of which is shown from a channel cut in the upper portion of Crater Spring drainage basin (*c*). Both of these deposits overlie preserved burned soil, litter layers or both, shown as the lenses of dark material denoted by arrows.

flows into dilute flows and flooding over proximal and medial fan reaches.

Spatial data were recorded in the field with a GeoExplorer® 3 (Trimble Navigation Limited, Sunnyvale, CA, USA) GPS unit. All locations were measured in Universal Transverse Mercater (UTM) coordinates, NAD27 datum, zone 12N, units of metres. Spatial data were plotted using *ArcMap* (Environmental Systems Research Institute, Inc. (ESRI) 1995–2006, Redlands, CA, USA).

### Sedimentology and stratigraphy

At each exposure, descriptions of stratigraphic units included primary sedimentary structure, contacts, matrix and clast sorting, imbrication, colour and presence of charcoal layers. We collected ∼4 L of sediment from each unit for laboratory analyses, which included the quantification of particle size (major classes), and charcoal concentration (milligrams of charcoal per litre of sediment).

We classified particle size using a 2-mm sieve and standard size measurements. Particles were quantified by volume into three general classes: sand and finer particles (<2 mm), granules and pebbles (2–64 mm) and cobbles (64–250 mm) to approximately quantify deposit sorting. Boulders ( $>$250 mm) were noted in the field only. Charcoal was isolated from the coarse ( $>$2 mm) fraction using flotation methods; only coarse charcoal concentration was quantified because large, angular charcoal fragments are unlikely to survive episodes of reworking and are therefore suggestive of a single episode of rapid entrainment and burial following fire.

Debris-flow units were identified as having massive structure and a lack of clast sorting or orientation that would suggest fluvial deposition. We assigned a fire-related origin to deposits with high concentrations (relative to post-2000 deposits) of large, angular charcoal (Meyer *et al.* 1995). As intense rainfall is known to produce debris flows independently of fire, we also relied on stratigraphic relations to a preserved burned litter surface or charcoal layer to indicate rapid debris transport and deposition following fire. Transient sedimentary changes, such as thin, discontinuous lenses of well-sorted materials within a debris-flow horizon, were included with larger sediment packages. We attribute these minor features to post-fire runoff that produced multiple small debris-flow pulses or rheological shifts that produced transitions between debris flows, hyperconcentrated flows, and sediment-laden water floods during a single event (e.g. Costa 1988). The latter cannot be easily distinguished from non-fire-related floods in settings with common low-severity fire and thus are not a data source for high-severity paleofire information on alluvial fans.

### Age control and event modelling

Age control was based on accelerator mass spectrometry radiocarbon dates on charcoal fragments or other charred organic material recovered from debris-flow units. Units with a less certain fire-induced origin were described but not dated. Samples were submitted to both the National Science Foundation–University of Arizona Radiocarbon Facility and Beta Analytic, Inc. To diminish inbuilt age potential (Gavin 2001), charcoal fragments with short residence time on the landscape were preferentially analysed, including burned needles, cone fragments and twigs. Rounded charcoal or burned interior wood were avoided, because they may indicate periods of reworking or long residence time respectively. Radiocarbon ages were calibrated to calendar years before present (cal years BP) using *Calib Rev. 5.0.2* (Stuiver and Reimer 1993) and reported with 2$\sigma$ age ranges.

Age data are presented in two formats for this study: (1) as probability curves from individual radiocarbon dates on charcoal and burned litter, plotted within each basin for identification of minimum recurrence timing within a specific area; and (2) as a summed mountain-wide probability distribution, as has been generated in similar studies (e.g. Meyer and Pierce 2003; Frechette and Meyer 2009). The summed probability curve in the present study provides only a cursory representation of fire behaviour in the study area, owing to the low number of samples ($n = 28$) and preferential preservation of young deposits. Considering the uncertainties associated with the $^{14}$C results, the resolution of the paleofire reconstruction is on the order of multidecadal or century scale.

### Forest composition reconstruction

In order to document PIPO and PIPO-MC stand-replacing fire, the fire must be linked directly to these forest types. As ecosystems in the study drainages vary spatially in response to elevation and moisture availability, reconstructing preburn vegetation is necessary to compare the fire behaviour with our current understanding of fire type and recurrence. For example, recurrent patch- to stand-scale ( $>$5 to $>$50 ha respectively) high-severity fire in pure PIPO forests would be considered anomalous with regard to current regional reconstructions (e.g. Covington and Moore 1994; Swetnam and Baisan 1996; Fulé *et al.* 1997; Heinlein *et al.* 2005), although perhaps less unusual for mixed conifer, for which a mixed-severity regime is reported on the north rim of Grand Canyon, Arizona (Fulé *et al.* 2003). We submitted charcoal for identification from 12 fire-related units collected throughout the study area to PaleoResearch Institute, Inc. (Golden, CO). We assume that the general preburn vegetation assemblage (but not the tree density) is accurately reflected in the species composition of both the downed materials and standing trees, and that macroscopic charcoal fragments are not transported from adjacent basins (Whitlock and Millspaugh 1996; Clark *et al.* 1998; Gardner and Whitlock 2001).

## Results

Debris-flow deposits comprise the majority of the depositional units described and sampled, for ~60–100% of total exposure thickness at each site. These units are predominantly matrix-supported diamictons with a matrix of poorly sorted very coarse sand to clay and little to no clast sorting or imbrication. Clast sizes range from boulders to pebbles.

Of the 56 depositional units described, 34 were ascribed a credible fire-related debris-flow origin. An additional 11 units were interpreted as likely or possibly fire-related deposits (debris flow and hyperconcentrated flows). Features that justified a fire-induced interpretation include charcoal concentrations analogous to modern deposits, and position directly overlying burned soil and litter layers. The average concentration of angular charcoal in preserved debris-flow deposits (133 mg charcoal $L^{-1}$ matrix) was similar to modern deposits (180 mg $L^{-1}$), with some deposits surpassing modern concentrations by nearly 50%. Units with significant soil formation were excluded from charcoal concentration measurements because the time necessary for soil formation could lead to a build-up of soil charcoal from local surface fires.

Radiocarbon dates were returned on 33 charcoal samples recovered from debris-flow deposits, burned soil layers and unburned soil units (Table 1). Eight samples were excluded from fire history reconstructions (reasoning for these exclusions is provided in the following section). The ages range from ~0 to 5600 cal years BP (Table 1) and fall within the following 2$\sigma$ intervals (rounded to the nearest decade): 0–280, 320–500 (one to two events), 680–960 (one to two events), 1080–1260, 1570–1700, 1720–1880, 2360–2700, 3220–3340 and 3900–4400 (one to two events) cal years BP (Fig. 4). These ages may include a centennial-scale 'inbuilt age', although we attempted to

**Table 1. Deposit ages and interpretations**

AA prefix signifies sample processed by the National Science Foundation–University of Arizona Facility; B signifies Beta Analytic, Inc. $^{14}$C age samples marked by superscript R were age-rejected owing to stratigraphic position or possible contamination. Deposit interpretations marked with a superscript NF were excluded from fire chronology (possible non-fire origin)

| Location | Stratigraphic unit | Deposit depth (m) | Laboratory ID | $\delta^{13}$C (‰) | $^{14}$C age ± 1σ | 2σ calibrated age range (area under curve) | | Deposit interpretation |
|---|---|---|---|---|---|---|---|---|
| Bull Basin A | BB-A1 | 0.0–0.8 | AA67719 | −24.7 | 736 ± 36$^{R}$ | 572–578 | (0.015) | Pumpkin Fire-related debris flow (2000) |
| | | | | | | 652–731 | (0.985) | |
| | BB-A2 | 0.8–1.0 | AA67730 | −25.2 | 151 ± 36 | 0–42 | (0.183) | Fire-related debris flow |
| | | | | | | 59–154 | (0.326) | |
| | | | | | | 166–234 | (0.314) | |
| | | | | | | 238–284 | (0.176) | |
| | BB-A3 | 1.0–1.5+ | AA67726 | −26.1 | 312 ± 36 | 300–473 | (1.000) | Fire-related debris flow |
| Bull Basin B | BB-B1 | 0.0–1.0 | AA67727 | −24.0 | 826 ± 37 | 676–795 | (0.989) | Fire-related debris flow |
| | | | | | | 879–883 | (0.005) | |
| | | | | | | 886–892 | (0.007) | |
| | BB-B2 | 1.0–1.5+ | AA67728 | −26.9 | 1712 ± 37 | 1541–1705 | (1.000) | Fire-related debris flow |
| Crater Springs A | CS-A1 | 0.0–0.4 | AA67718 | −23.2 | 410 ± 35 | 322–377 | (0.188) | Fire-related debris flow |
| | | | | | | 428–521 | (0.812) | |
| | CS-A2 | 0.4–0.7 | AA67720 | −21.9 | 800 ± 190 | 488–1147 | (0.996) | Fire-related debris flow |
| | | | | | | 1157–1170 | (0.004) | |
| | CS-A3 | 0.7–1.0 | AA67721 | −23.9 | 1185 ± 68 | 967–1264 | (1.000) | Fire-related hyperconcentrated flow |
| | CS-A4 | 1.0–1.8+ | AA67722 | −23.3 | 3610 ± 45 | 3734–3741 | (0.004) | Fire-related debris flow |
| | | | | | | 3776–3789 | (0.010) | |
| | | | | | | 3827–4011 | (0.893) | |
| | | | | | | 4028–4083 | (0.093) | |
| Crater Springs B | CS-B2 | 0.05–0.7 | B210938 | −25.8 | 370 ± 40 | 315–411 | (0.473) | Fire-related debris flow |
| | | | | | | 420–504 | (0.527) | |
| | CS-B3-BL | 0.7 (2 cm) | AA67723 | −23.9 | 406 ± 42 | 318–394 | (0.284) | Burned litter, charcoal layer or both; caps soil |
| | | | | | | 424–522 | (0.716) | |
| | CS-B3soil | 0.7–1.0 | AA67725 | −23.4 | 473 ± 36 | 478–548 | (1.000) | Soil (relative age confirmation) |
| | CS-B3 | 1.0–1.3+ | AA67724 | −21.9 | 1888 ± 38 | 1721–1899 | (0.988) | Fire-related debris flow |
| | | | | | | 1913–1920 | (0.012) | |

(*Continued*)

**Table 1. (Continued)**

| Location | Stratigraphic unit | Deposit depth (m) | Laboratory ID | $\delta^{13}$C (‰) | $^{14}$C age ± 1$\sigma$ | 2$\sigma$ calibrated age range (area under curve) | | Deposit interpretation |
|---|---|---|---|---|---|---|---|---|
| Crater Springs C | CS-C3 | 0.5–0.9 | B210939 | −26.4 | 990 ± 40 | 795–964 | (1.000) | Fire-related debris flow |
| Crowley Tank A | CT-A2 | 0.1–0.8 | B210940 | −13.7 | 1260 ± 40 | 1081–1114 | (0.084) | Fire-related debris flow |
| | | | | | | 1118–1282 | (0.916) | |
| | CT-A4 | 1.6–2.0+ | AA67714 | −24.0 | 1844 ± 40 | 1639–1641 | (0.002) | Fire-related debris flow |
| | | | | | | 1696–1878 | (0.998) | |
| Crowley Tank B | CT-B2 | 0.05–1.1 | AA67715 | −24.0 | 3805 ± 41$^{R}$ | 4013–4020 | (0.005) | Fire-related debris flow |
| | | | | | | 4083–4300 | (0.915) | |
| | | | | | | 4310–4316 | (0.004) | |
| | | | | | | 4324–4356 | (0.040) | |
| | | | | | | 4367–4406 | (0.036) | |
| | CT-B3-BL | 1.1 (1 cm) | AA67729 | −23.6 | 3510 ± 41 | 3649–3654 | (0.006) | Detrital charcoal; not burned *in situ*$^{NF}$ |
| | | | | | | 3688–3893 | (0.994) | |
| | CT-B4 | 1.2–1.4+ | AA67716 | −24.8 | 3689 ± 42 | 3903–4102 | (0.907) | Fire-related debris flow |
| | | | | | | 4109–4148 | (0.093) | |
| Crowley Tank C | CT-C2 | 0.3–0.9 | AA67717 | −24.2 | 3793 ± 43 | 3993–4039 | (0.050) | Fire-related debris flow |
| | | | | | | 4075–4298 | (0.911) | |
| | | | | | | 4327–4354 | (0.025) | |
| | | | | | | 4369–4384 | (0.011) | |
| | | | | | | 4396–4401 | (0.004) | |
| Crowley Tank D | CT-D2 | 0.9–1.2 | B210941 | −24.2 | 320 ± 40 | 302–481 | (1.000) | Hyperconcentrated flow$^{NF}$ |
| Pumpkin Center M | PC-MU-BL | 0.7 (23 cm) | AA67704 | −24.1 | 231 ± 41 | 0–30 | (0.113) | Charcoal layer$^{NF}$ |
| | | | | | | 139–222 | (0.401) | |
| | | | | | | 259–328 | (0.394) | |
| | | | | | | 359–368 | (0.005) | |
| | | | | | | 374–429 | (0.086) | |
| | PC-ML-BL | 1.0 (3 cm) | AA67705 | −22.5 | 271 ± 37 | 0–6 | (0.010) | Charcoal layer$^{NF}$ |
| | | | | | | 152–170 | (0.071) | |
| | | | | | | 281–338 | (0.413) | |
| | | | | | | 348–460 | (0.506) | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Pumpkin Center K | PC-K1 | 0.0–0.6 | B210943 | –23.6 | 150 ± 40 | 0–42 | (0.180) | Fire-related debris flow |
| | | | | | | 58–155 | (0.339) | |
| | | | | | | 166–284 | (0.481) | |
| | PC-K2 | 0.6–1.4 | AA67706 | –23.5 | 842 ± 38 | 682–799 | (0.907) | Fire-related debris flow |
| | | | | | | 814–826 | (0.019) | |
| | | | | | | 867–901 | (0.074) | |
| | PC-K3 | 1.4–1.7 | AA67707 | –22.1 | 1761 ± 38 | 1566–1741 | (0.909) | Fire-related debris flow |
| | | | | | | 1754–1785 | (0.057) | |
| | | | | | | 1790–1811 | (0.034) | |
| Pumpkin Center HM | PC-HM4 | 0.9–1.6 | AA67708 | –22.5 | 3017 ± 42 | 3078–3097 | (0.043) | Fire-related debris flow |
| | | | | | | 3101–3342 | (0.957) | |
| Pumpkin Center HL | PC-HL2 | 0.03–0.5 | B210942 | –24.3 | 2470 ± 40 | 2363–2419 | (0.118) | Fire-related debris flow |
| | | | | | | 2428–2623 | (0.600) | |
| | | | | | | 2628–2713 | (0.282) | |
| | PC-HL4 | 0.7–1.5 | AA67709 | –22.8 | 3283 ± 42$^{R}$ | 3403–3432 | (0.050) | Fire-related debris flow |
| | | | | | | 3437–3617 | (0.950) | |
| | PC-HL5 | 1.5–1.9+ | AA67710 | –22.4 | 3117 ± 47 | 3219–3229 | (0.017) | Fire-related debris flow |
| | | | | | | 3239–3443 | (0.983) | |
| Pumpkin Center L | PC-L3 | 0.1–0.3 | AA67711 | –22.5 | 1004 ± 38 | 795–875 | (0.302) | Fire-related debris flow (distal) |
| | | | | | | 878–884 | (0.007) | |
| | | | | | | 891–978 | (0.685) | |
| | | | | | | 1039–1044 | (0.006) | |
| | PC-L5 | 0.4–1.1 | AA67712 | –23.1 | 4851 ± 45$^{R}$ | 5472–5553 | (0.309) | Fire-related debris flow (distal) |
| | | | | | | 5571–5661 | (0.690) | |
| | | | | | | 5694–5696 | (0.001) | |
| | PC-L7 | 1.2–1.4+ | AA67713 | –24.1 | 1172 ± 38 | 977–1179 | (0.991) | Fire-related debris flow (distal) |
| | | | | | | 1214–1222 | (0.009) | |

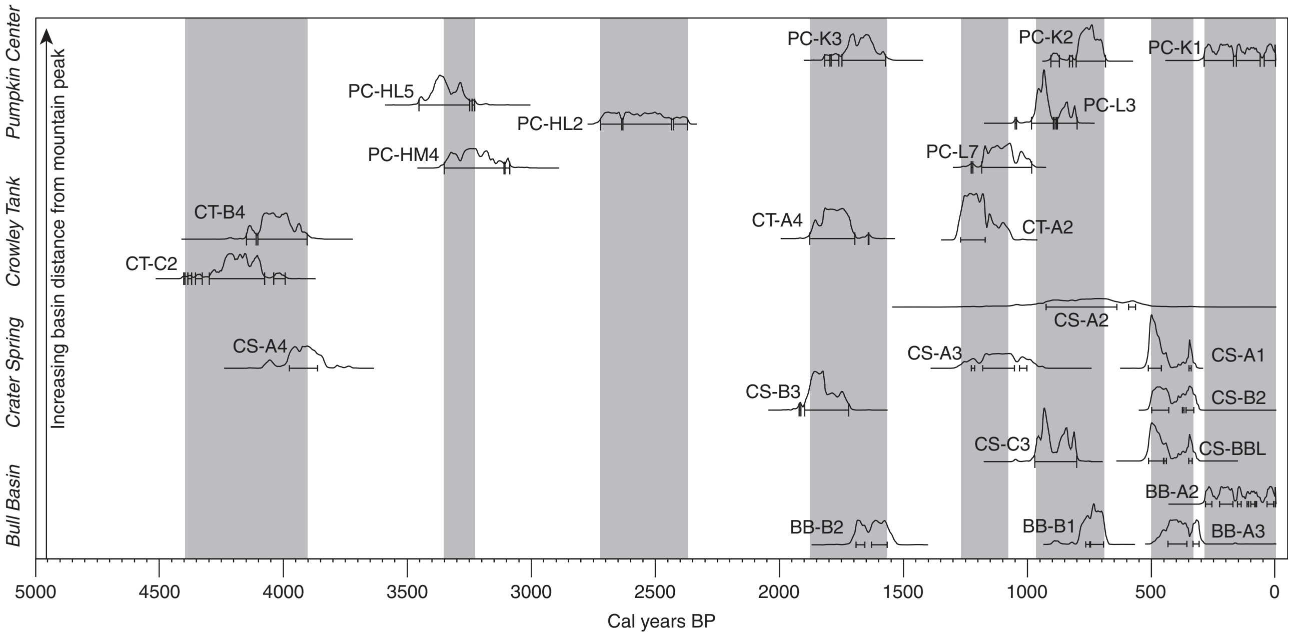

**Fig. 4.** Probability distributions for individual calibrated radiocarbon ages inferred to represent fire events in the study area during the late Holocene. Calibrations obtained using IntCal04 curve in *Calib 5.0* (Stuiver and Reimer 1993). *y* axis for individual curves represents probability (not to scale; area under curve = 1); brackets below curves delimit 2σ (95% confidence interval) age ranges. Charcoal fragments with low residence time on the landscape were dated whenever possible, including such materials as conifer needles, fascicles, cone scales and small twigs. Each grey bar signifies the age bracket on what is presumed to be an individual event, with the exception of the 680–960 and 3900–4400 cal years BP ranges, which may each bracket two discrete events owing to very low probability curve overlaps. Basins are arranged alphabetically along the vertical axis, corresponding with distance to source area from mountain peak, for rapid visual capture of mountain-wide events.

minimise this where possible by analysing materials with characteristics that suggest a low residence time on the landscape. Ages of samples collected from more than one basin cluster about the broader periods of 0–500, 700–1300 and 1600–1900 cal years BP (Figs 4, 5). With increasing age, fewer events are recognised in the stratigraphic record, but this likely reflects post-depositional modification, erosion of older deposits and limits of lateral exposure rather than a true decrease in the frequency of events.

Charcoal from only three tree genera was identified in fire-related deposits: *Pinus*, *Pseudotsuga* and *Populus* (Fig. 6). *Picea* and *Abies* are currently present at higher elevations in the study area, but were not identified in our charcoal record. Charcoal vitrification, which is thought to occur in response to burning green or living tissues with high sap content, was observed in *Pinus*, *Pseudotsuga* and unidentified conifer charcoal fragments (Fig. 6).

### *Interpretation caveats*

Overall, 1σ errors on calibrated radiocarbon dates range from 39 to 300 years. A date on a modern debris flow at site BB-A yielded an age of 660–699 cal years BP, indicating that reworking of old charcoal or extended preservation of wood or charcoal on the landscape is possible. Given the modern deposition of this unit, the date was rejected, but it is useful for understanding the range of age errors. An additional four dates were rejected based on age discrepancies, violations of the law of superposition, or obvious charcoal rounding.

Because shifts between debris and hyperconcentrated flows are common during movement and deposition (e.g. Iverson 2001), clast-supported hyperconcentrated-flow deposits with poor to moderate clast sorting, and low to moderate imbrication were also assigned a fire-related origin where angular charcoal concentrations were similar to fire-related debris-flow units. One hyperconcentrated unit (CT-D2) was not assigned a fire-related origin because it did not contain charcoal; intense rainfall may have generated this flow in the absence of severe fire, a possibility that cannot be excluded for producing debris flows in this area.

Three of the dated charcoal samples (CT-B3-BL, PC-MU-BL, PC-ML-BL; Table 1) were collected from lenses within a single stratigraphic unit. Unlike charcoal layers that cap soils, these lenses neither bear a relationship to stable surfaces, nor contain large, angular charcoal pieces. Instead, they may represent hydrodynamically concentrated charcoal that cannot be unquestionably assigned a fire-related origin (rainfall-induced fluvial processes may also produce these concentrations). The ages of these charcoal layers were therefore excluded from fire history reconstructions, and reinforce the necessity of interpreting charcoal layers in the context of depositional processes; burn lenses alone are not indicative of stand-replacing fire.

## Discussion

### *Fire history interpretation*

#### *Temporal variability*

High-severity fires appear to have been common in the study area over the 4400-year period of reliable record. Vitrified

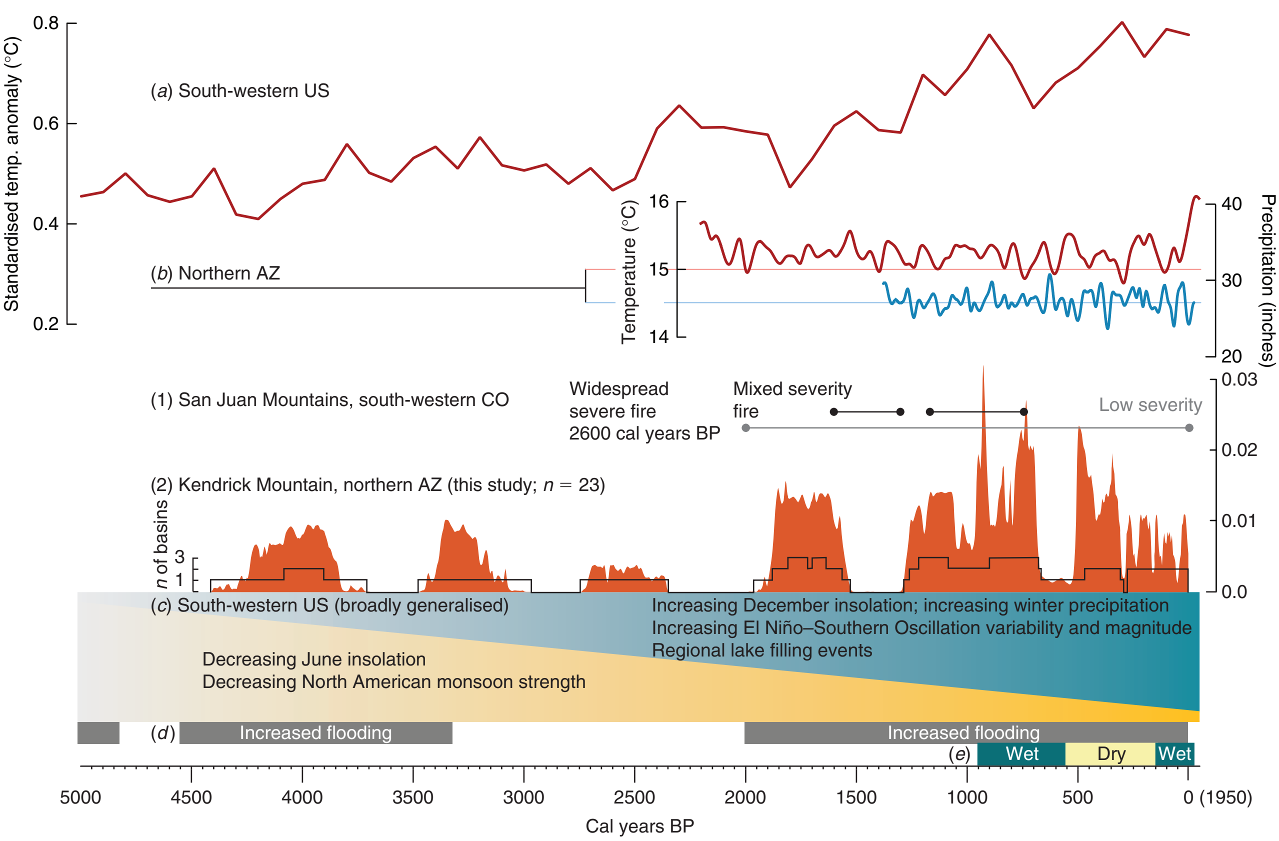

**Fig. 5.** Climate and fire proxies for the south-western USA shown with summed probability curve for charcoal ages at Kendrick mountain (2). Paleoclimate proxies include (*a*) palynological temperature reconstruction (Viau *et al.* 2006); (*b*) dendroclimatic temperature and precipitation reconstruction from sites on the San Francisco Peaks, Flagstaff, AZ, Navajo Mountain, central AZ–CO border, and Canyon de Chelly, north-eastern AZ (Salzer and Kipfmueller 2005; 25-year smoothing applied); (*c*) broadly generalised trends in insolation values, precipitation sources and resulting lake levels throughout the southern Colorado Plateau, and throughout the south-western US (Anderson 1993; Weng and Jackson 1999; Holmgren *et al.* 2007; Donders *et al.* 2008; Shuman *et al.* 2009); (*d*) south-western USA flood probability from multiple sources of dates on slack-water deposits and alluvial deposits (Harden 2007); and (*e*) pooled north-western New Mexico dendroclimatic record showing long-term periods of increased and decreased effective moisture (Grissino-Mayer and Swetnam 2000). Regional geomorphic-based fire history studies show little agreement with Kendrick, with the exception of Bigio (2006; Bigio *et al.* 2010) from southern Colorado (1). Increasing fire frequency during the last 2000 years may be related to increasing overall temperatures and effective moisture, increased winter precipitation (growing-season moisture), and reduced summer rainfall allowing for increased hillslope and channel sediment storage, as well as increased irregularity of high-magnitude precipitation. With a stronger monsoon active during the middle to late Holocene, the ~750-year event timing between 4.5 and 2 thousand years ago (ka) may reflect the time necessary for sediment storage to permit debris flows in response to fire.

charcoal in several deposits supports the interpretation of severe fires by indicating that the charcoal produced during the fire was not solely from downed woody materials. Single fire events at the basin scale appear in the geomorphic record as frequently as 25 years apart (without potential in-built age errors), and as infrequently as 2150 years apart. Average recurrence intervals for mountain-wide fire events appear to have decreased from ~600 years during the early part of the record, to 200–400 years during the last 2000 years.

These data are an incomplete record of high-severity fires on Kendrick Mountain during the last 4400 years. A high-severity fire might not have been recorded if the length of time between fires was too brief to permit sediment accumulation in channels necessary for a debris flow, if subsequent erosion removed the fire-related deposit, or if the deposit was not exposed and sampled in this study. Because the accumulation rate for fire fuels could therefore outpace sediment production and accumulation, our fire return intervals may underestimate the true recurrence of stand-replacing fire. However, even as a minimum estimate for fire events, our record is significant in providing a longer context for modern fire behaviour than is currently available from dendrochronologic reconstructions.

### *Prefire forest composition*

Charcoal assemblages in the deposits are interpreted to be *Pinus ponderosa* and *Pseudotsuga menziesii*, indicating that species composition has not varied significantly in the study area over the late Holocene. *P. ponderosa* appears in lacustrine records throughout the region as early as 11 thousand years ago (ka), and reached modern population levels and spatial distribution before the middle Holocene, thought to be linked to initial North American monsoon initiation and increasing temperatures. Although another common *Pinus* sp., *Pinus flexilis*, is found less commonly in late Holocene lake sediments from similar

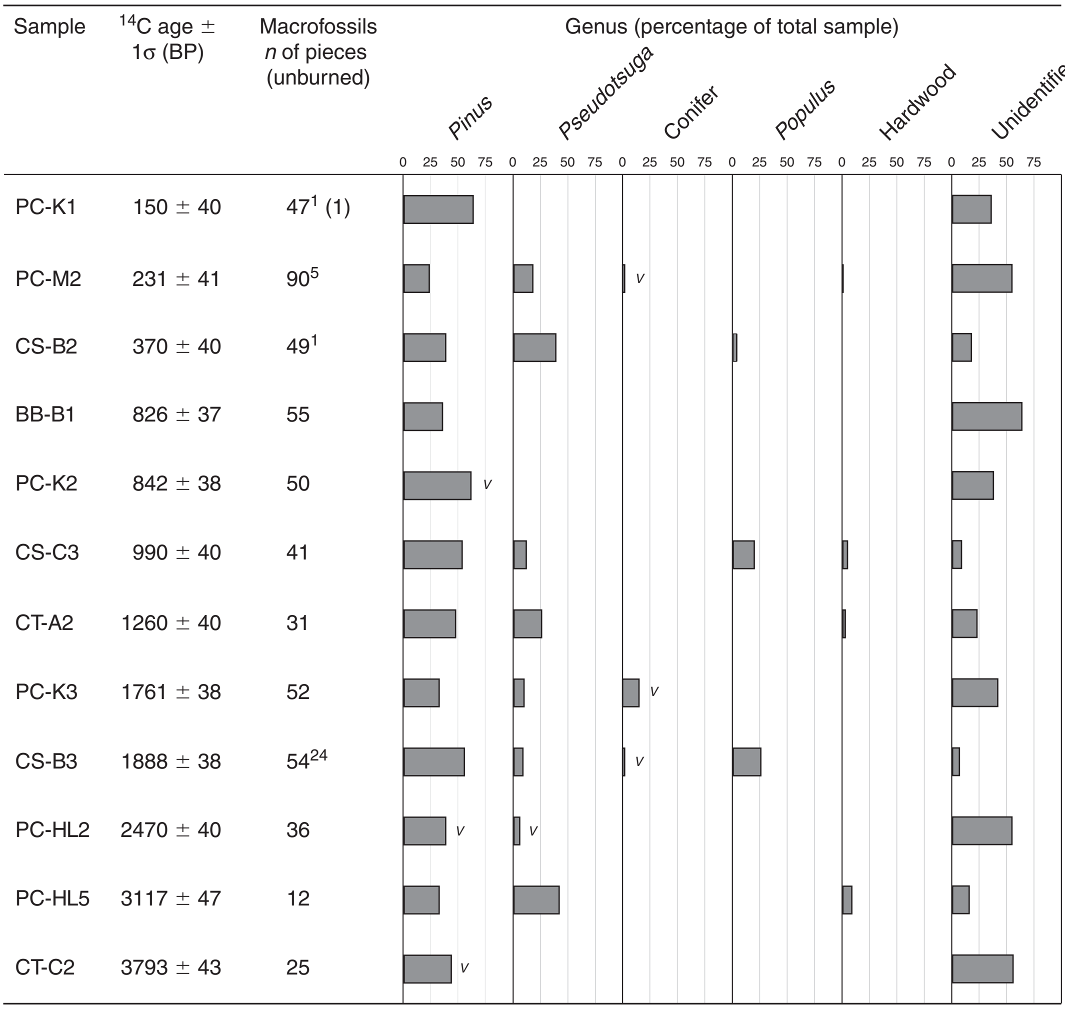

**Fig. 6.** Macrofossil identification for fire-related debris flow deposits in the study area. Superscript numbers indicate the number of partially charred fragments in the sample. The PC-M2 sample was not dated and so does not appear in Table 1; age is from stratigraphically identical detrital charcoal sample PC-MU-BL. A superscript *V* next to genus percentage of total sample data indicates that vitrified materials were recovered from sample.

elevations in the region (e.g. Weng and Jackson 1999); a warm and dry mid-Holocene on the southern Colorado Plateau (e.g. Anderson 1993; Hasbargen 1994; Weng and Jackson 1999) would make *Pinus flexilis* unlikely to have found significant refuge at the Kendrick Mountain elevations since the early Holocene in numbers significant enough for the charcoal record.

A predominant mix of *Pinus ponderosa* and *Pseudotsuga menziesii* is a forest composition not typically associated with stand-replacing fire, as both species are well adapted to low-severity fire (e.g. Flint 1925; Starker 1934; Agee 1998). *P. menziesii*, although often associated with longer fire-free intervals than *P. ponderosa*, also exhibits *P. ponderosa*'s 'resister' survival strategy for moderate- or low-severity wildfires (e.g. survival classification system of J. S. Rowe, summarised in Barnes *et al.* 1998). However, very young *P. menziesii* trees survive fire through avoidance; fire-free intervals on the order of several decades are necessary for tree establishment (e.g. Agee 1993). Despite a recent anthropogenic encroachment of *P. menziesii* into forests historically dominated by *P. ponderosa* through fire exclusion (e.g. Cocke *et al.* 2005), its appearance in our prehistoric fire record suggests that natural fire-free intervals have persisted on the order of decades to centuries, at least at the patch scale.

### Regional fire history comparison

Comparing our reconstruction with other regional fire history records (Fig. 1) is difficult, because dendrochronological data sources record contrasting fire types, and because the low temporal resolution of our radiocarbon dates makes a direct comparison of fire year impossible. Our results seem more consistent with temporally variable, high-severity burns reported for mixed-severity fire regimes in mixed-conifer forests of the Grand Canyon's North Rim (Fulé *et al.* 2003) – although dominant tree species differ somewhat from our study – than with annual to decadal fire return intervals reported for relatively flat or gentle hilly terrain (e.g. Covington and Moore 1994; Covington *et al.* 1997; Fulé *et al.* 1997). A similar surface-fire regime has been reconstructed from fire-scarred trees for nearby PIPO-MC sites on the San Francisco Peaks in northern Arizona (Fig. 1; Heinlein *et al.* 2005). However, the magnifying effect of steep or complex terrain may foster high-severity fires that cannot be identified in dendrochronological studies, as the record would have been destroyed in the fire.

Lentile *et al.* (2006) report that slope influences burn severity in a modern mixed-severity mosaic, and Iniguez *et al.* (2008) demonstrated that landscape-scale topography is a major control on fire behaviour. Recent research in the La Frontera region of the south-western USA has also suggested that stand-replacing fires can be a natural part of rugged PIPO ecosystems, probably occurring as part of a mixed-severity regime. Swetnam *et al.* (2001) reconstructed a mixed-severity fire regime for the PIPO and PIPO-MC forests in the complex terrain of the Animas Mountains, New Mexico, in which surface fire is less synchronous between tree stands and mountain-wide, high-severity burns occur occasionally. The authors reported that the patches of crown fire produced in the 1989 fire in the Animas Mountains are a good analogue for prehistoric mixed-severity fires. Even in low-density tree stands, stand-replacing fire can occur through excessive fuels accumulation in areas with natural topographic barriers to the spread of surface fire.

Iniguez *et al.* (2009) described a historical stand-replacing fire in 1867 on Rincon Peak in southern Arizona, reconstructed from combined lines of dendrochronological evidence. Contemporaneous tree deaths and regenerations suggested repeated, small (~60 ha) stand-replacing fire events on a single mountain, amounting to at least three severe fires over the past 250 years. In the San Juan Mountains of southern Colorado, Bigio (2006) identified a massive late-Holocene fire-related debris flow in an area dominated by small depositional events and surface fires, suggesting that the surface fire regime was occasionally punctuated by high-severity fire events. And in southern New Mexico, Frechette and Meyer (2009) identified fire-related deposition from mixed- and high-severity fires throughout the late Holocene. On a regional scale, severe fires in identical forest types are not uncommon. Increased fuels preheating through vertical crown arrangement or 'stacking' on slopes may permit full fuel consumption from both ground and crown sources, and could explain some of the discrepancy between the fire-scar records and geomorphic fire histories.

An alternative interpretation of our data is that centennial-scale high-severity fires were initiated in spruce-fir forests, such as those currently present at the highest elevations in our study area, and spread vertically and laterally to the PIPO and PIPO-MC forests. Forests with these mixed PIPO and Douglas-fir associations vary widely in fire severity from low-severity surface fires occurring on the order of 52–76 years, to stand-replacing fires with much longer recurrence intervals (e.g. Agee 1990, Brown *et al.* 1999); However, spruce and fir species were not identified in the late Holocene deposit charcoal assemblage. The presence of debris-flow deposits in PIPO-dominated basins and the prominence of *Pinus* and *Pseudotsuga* in the recovered charcoal imply that PIPO and PIPO-MC forests could easily support stand-replacing fire during the late Holocene.

The record from Kendrick Mountain, in conjunction with previous regional studies, would suggest a temporally and spatially variable mixed fire regime in southern PIPO and transitional PIPO-MC forests during the late Holocene. A regime of frequent, patchy, low- to moderate-severity fires, as demonstrated by the dendrochronologic reconstructions of surface fires, is punctuated by infrequent high-severity fires that occur when initiations are coupled with fugacious thresholds of both reduced vegetation moisture and heavy fuel accumulations. The influence of topography is two-fold: vertical crown stacking magnifies fire severity, whereas complex topography permits fuels accumulation in forest types that carry laterally contiguous surface fires in lower-gradient terrain.

## Discussion

### *Fire–climate associations*

The fundamental relationships between fire behaviour and climate are complex. Climatic phenomena have been shown to affect fire regimes throughout the western USA, ranging in scale from hemispheric temperature shifts to interannual precipitation oscillations (e.g. Simard *et al.* 1985; Swetnam and Betancourt 1990; Millspaugh and Whitlock 1995; Grissino-Mayer and Swetnam 2000; Millspaugh *et al.* 2000; Kitzberger *et al.* 2001). The resolution of the Kendrick Mountain radiocarbon dates is too coarse to compare with annual dendroclimatic reconstructions, but we can compare the occurrence of high-severity fires with multidecadal to multicentennial climatic trends.

Effective moisture has a strong influence on wildfire, both in terms of recurrence patterns and fire spread. In environments where growing season moisture is abundant, temperature appears to be the dominant control on effective moisture, thereby regulating fire occurrence in systems that do not experience habitual low-severity fire. For example, in northern Rocky Mountain mixed-conifer forests, late Holocene stand-replacing-fire occurrence tended to increase during the Medieval Warm Period (MWP, c. 1000–1300 AD), and decrease during the Little Ice Age (LIA, c. 1400–1800 AD) (Meyer *et al.* 1995; Meyer and Pierce 2003; Pierce and Meyer 2008). Parallel scenarios occurred during the Roman Warm and Dark Ages Cold Periods (Meyer *et al.* 1995; Meyer and Pierce 2003).

In addition to fire frequency, fire *type* has also been shown to shift with climatic influence. In contrast to mixed-conifer forests, Pierce (2004) documented a transition from frequent, low-severity surface fire during cooler periods to infrequent, high-severity fire during warmer periods in Rocky Mountain PIPO and PIPO-MC forests. The inference is that increased effective moisture during cooler periods limits severe fires, whereas warm periods permit fuel desiccation that leads to larger and more severe fires. Although the fire regime patterns and climate variations in southern PIPO forests do not match those of their northern counterparts, the inference for climatic influence over fire through effective moisture is meaningful nevertheless.

### *4500–2000 cal years BP fires*

Over the south-western USA at large, Viau *et al.* (2006) reconstructed 100-year average July temperatures for the Holocene using pollen assemblages. Their reconstruction shows an overall temperature increase for this region since the early

Holocene through the present, which is reflected in the arrival of C3 desert shrubs in the Chihuahuan Desert (stressing warming winter temperatures; Holmgren *et al.* 2007) and expansions of *Pinus edulis* throughout the south-western highlands (e.g. Anderson *et al.* 2008) after ~5000 years BP. A drop in regional effective moisture also ushered in this period of the fire history record as the North American monsoon reached an insolation-induced peak during the early-mid Holocene transition, despite a corresponding increase in El Niño–Southern Oscillation (ENSO) magnitude and variability (e.g. Holmgren *et al.* 2007). During mid-Holocene time, regional lakes record lengthy periods of lowered volume, or full conversion to terrestrial vegetation (e.g. Anderson 1993; Weng and Jackson 1999).

Between 4500 and 2000 years BP, the ~750-year gap between major fire-related deposition during a period of generally warm and dry conditions likely reflects the time needed for storage of both fuels and sediment on hillslopes or in channels before a major fire can be preserved in the geomorphic record. Between major events, overall dry conditions may have promoted more frequent fires that were not preserved in our sampled sedimentary record.

### *2000–0 cal years BP fires*

During the latest Holocene, the overall warming trend appears contemporaneous with an increase in effective moisture on the southern Colorado Plateau, particularly during the most recent 2000 years (e.g. Anderson 1993; Hasbargen 1994). Weng and Jackson (1999) suggested that reduced summer insolation fostered increased effective moisture through a reduction in summer evaporation rates. Anderson *et al.* (2008) hypothesise that higher regional moisture levels during the transition to the late Holocene were manifested as an increased cool-season precipitation (e.g. Toney and Anderson 2006), which provided the moisture source for excessive spring fuels growth. Flood probability also rose sharply in this region during the most recent 2000 years (Ely 1997; Harden 2007). There is some evidence to suggest that this increase is a function of an increasingly intensified ENSO system since ~3000 years (e.g. Donders *et al.* 2008; *Pinus edulis* increase of Toney and Anderson 2006; increased bedrock canyon flooding of Ely 1997), associated with increasing winter insolation. Strong El Niño phases are typically associated with increased winter precipitation by facilitating the incursion of moist subtropical air currents to the south-west (Harvey *et al.* 1999; Chappell and Grove 2000). Fire ignition is curtailed during wetter El Niño phases, but increases during La Niña phases (e.g. Swetnam and Betancourt 1990), which may be further amplified during negative phases of the Pacific Decadal Oscillation (PDO) (MacDonald and Case 2005). Greater ENSO amplitude may therefore produce fewer favourable fire years, leading to an overall increase in spatially-extensive or severe fire events during this period.

The Kendrick fire record also shows that the majority of depositional events due to severe fires overlap with multi-decadal cooler deviations from the overall warming trend (Fig. 5*a*). A general increase in cool-season moisture, coupled with temporary reductions in summer temperatures could play an important role in the timing of severe fires. Cooler temperatures delay spring melt and reduce evapotranspiration, thereby extending moisture availability for significant fuels growth. Moist ground conditions curb the ignition and spread of surface fire, thereby leading to further biomass production for ignition during dry years. This general pattern might further account for the apparent increase in severe fires in the xeric vegetation communities on Kendrick Mountain during the period 2000–0 cal years BP, and more frequent and synchronous fire throughout high-elevation mixed-conifer forests of southern Colorado and northern New Mexico (Anderson *et al.* 2008) between 2000–1000 cal years BP. Although the timing of fire-related deposition likely continues to reflect limits on sediment production and storage during this period, enhanced storm intensity might have produced more frequent depositional events than during the preceding 200–4500-cal years BP period.

Broad errors inherent in radiocarbon dates on charcoal preclude further comparison of fire events with higher-resolution climatic records. During the last 2000 years, high-resolution climate reconstructions show rapid vacillation between warm, cool, wet, and dry, although decadal periods of regionally synchronous trends are common (e.g. Grissino-Mayer 1996; Cook and Krusic 2004; Salzer and Kipfmueller 2005; Fig. 5*b*, *e*). Effective moisture availability associated with the MWP and LIA appears opposite to trends recorded in the northern Rockies. In contrast to the well-defined reduced and increased effective moisture availability during the MWP and LIA respectively in the northern Rocky Mountains, the south-west USA experienced higher precipitation during the period 1000–1400 AD (950–550 cal years BP), followed by below-average precipitation from 1400 to 1790 AD (550–140 cal years BP) (Grissino-Mayer and Swetnam 2000; Fig. 5*e*). The San Francisco Peaks in Arizona (Salzer and Kipfmueller 2005; Fig. 5*b*) and the broader south-western region (e.g. Ni *et al.* 2002) do not show a strong climatic expression of the MWP or LIA.

Asynchrony between climate records and fire timing for individual study sites is expected. Gavin *et al.* (2006, 2007) reported little coincidence in timing of fire events over a 5000-year period in Canadian forests. As variability in timing and source of ignition, as well as fuel availability are most influential on any fire episode, synchrony between fires and broad climatic trends only appears within large sample sets distributed over broad areas. Gavin *et al.* (2007) stressed the importance of limiting the spatial extent of implied fire–climate associations for any climatic regime, which may help explain the lack of a clear climatic correlation for the Kendrick Mountain fires. Rather, we infer that the appearance of severe fire in the geomorphic record is more strongly controlled by sediment storage and fire fuel dynamics rather than directly influenced by a single climatic phenomenon, as these deposits were formed during periods of both enhanced and reduced effective moisture throughout the region.

## Conclusions

The geomorphic record of fires on Kendrick Mountain reflects the most extreme portion of the overall fire regime. Although the evidence indicates that severe wildfire was an important influence on the pre-European-settlement landscape in transitional PIPO and PIPO-MC, the deposits were not emplaced simply in response to severe wildfire events punctuated by extended fire-free intervals. Rather, we suggest that they resulted from high-severity burns within a complex burn mosaic influenced by topography and ecologic framework. The size of these fires, inferred from modern analogues of debris-flow initiation related to spatial burn extent, implies that prehistoric high-severity wildfire burned at the patch scale or larger as part of the natural fire regime.

Fires are recorded in our study area with a frequency of several centuries, ranging from 600 to 200 years for multiple-basin events. Temporal fire patterns in the study area do not appear to be correlated with proxy climate records, in contrast to studies from similar forest types in the northern USA. Instead, we suggest that the apparent fire timing is related to internal thresholds (primarily sediment storage or fire fuels accumulation), although effective moisture may exert a secondary control during the last 2000 years. During the latest Holocene, a shift from predominantly summer moisture in an overall warm and dry climatic setting to a regime of greater variability – particularly in winter moisture – may have promoted more frequent fires and fire-related sedimentation. The geomorphic-derived fire interval must be interpreted as a minimum; fires will not induce significant geomorphic response in burned watersheds when the necessary conditions are not met (i.e. fuel production rates outpace sediment storage; rainfall below thresholds for producing runoff; burned area of insufficient size), or subsequent fluvial processes have removed fire-related deposits.

This research calls for inclusion of stand-replacing fire episodes on centennial scales when characterising the natural range of variability in the late Holocene fire regime for these forest types. This work also stresses the importance of point-source fire history reconstructions over a broader characterisation of the regional fire regime, as variability in terrain may exert a strong control on fire behaviour, producing fire types not expected for certain forest types. A more complete record of fire-related sedimentation might be recovered from alluvial fans to evaluate the role of climate in perturbing long-term surface fire patterns, as has been documented in similar fire-related geomorphic studies.

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