Available online at www.sciencedirect.com

SCIENCE DIRECT

Forest Ecology and Management 178 (2003) 89–104

Forest Ecology and Management

www.elsevier.com/locate/foreco

Climatic controls on fire-induced sediment pulses in Yellowstone National Park and central Idaho: a long-term perspective

Grant A. Meyer*, Jennifer L. Pierce

Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131-1116, USA

Abstract

Fire management addressing postfire erosion and aquatic ecosystems tends to focus on short-term effects persisting up to about a decade after fire. A longer perspective is important in understanding natural variability in postfire erosion and sedimentation, the role of these processes in structuring habitat, and future expectations in light of a warming climate and environmental change. In cool high-elevation forests of northern Yellowstone National Park, stand ages indicate infrequent large stand-replacing fires. In warmer low-elevation forests of the Payette River region of Idaho, fire-scarred tree-rings record frequent low-severity fires before 1900; stand-replacing fires and resulting debris flows in recent decades are usually attributed to 20th-century fire suppression, grazing, and other land uses. In both areas, however, tree-ring records extend back only about 500 years. We use ^{14}C-dated geologic records to examine spatial and temporal patterns of fire-induced sedimentation and its relation to climate over the last 10 000 years. We review sedimentation processes in modern postfire events, which vary in magnitude and impact on stream systems depending on burn severity, basin geomorphology, and the timing and characteristics of postfire storms. Modern deposits also provide analogs for identification of fire-related deposits in alluvial fans. In Yellowstone, episodes of fire-induced sedimentation occurred at intervals of about 300–450 years during the last 3500 years, indicating a regime of infrequent high-severity fires. Millennial-scale variations in the fire-sedimentation record appear to relate to hemispheric-scale climatic change. Fire-related sedimentation is rare in Yellowstone during cooler episodes (e.g., the Little Ice Age ~1200–1900 A.D.), probably because effectively wetter conditions prevented most fires from spreading. During some of the same cool periods, the Payette region experienced light surface fires and frequent, small pulses of fire-induced sediment. Between 900 and 1200 A.D., however, large fire-related debris flows occurred in both study areas, coincident with the Medieval Warm Period. During that time, drought may have limited grass growth in xeric Payette-region forests, restricting surface fire spread and allowing understory shrubs and trees to create ladder fuels. Although fire suppression and land-use effects are clearly involved in recent catastrophic fires in the Payette region, a warming climate and severe drought are probable contributors to major stand-replacing fires and postfire sedimentation, both past and present. Restoration and maintenance of conditions prior to European settlement may be unrealistic because of the potent influence of climate, and the incidence of severe fires will likely increase in both areas with future warming.

Keywords: Fire; Conifers; Erosion; Debris flows; Climate; Drought; Yellowstone; Idaho

1. Introduction

In mountain landscapes, the connection between fire and major debris-flow and flash-flood events has been well established (e.g., Swanson, 1981; Wells,

* Corresponding author. Tel.: +1-505-277-5384; fax: +1-505-277-8843.
E-mail address: gmeyer@unm.edu (G.A. Meyer).

0378-1127/03/$ – see front matter
doi:10.1016/S0378-1127(03)00055-0

1987; Wohl and Pearthree, 1991; Meyer and Wells, 1997). These events initiate in small, steep tributary basins. Their physical effects propagate down stream systems and can range from mild to catastrophic, and from transient to persistent. Here we use catastrophic in the geological sense to mean major change, without the implication of negative (or positive) ecological impacts. Effects of flash-floods and debris flows vary with location in the drainage network and the timescale of consideration. Immediate impacts in small streams may include extreme turbulence and sediment concentrations that directly cause fish mortality, with deep scouring or major infilling of channels (e.g., Bozek and Young, 1994; Meyer and Wells, 1997; Minshall et al., 2001). Over periods of several years, impacts along larger streams may range from minor and transient loading with fine sediment to major aggradation of gravel (e.g., Benda et al., 1998). Persistent alteration of channel structure may occur through addition of large woody debris and boulders that remain immobile for centuries or more (e.g., Minshall et al., 1997; Meyer et al., 2001).

The importance of fire in sediment yield and aquatic habitat disturbance is a function of fire frequency and severity, as well as the geomorphic sensitivity of the landscape (i.e., susceptibility to postfire erosion) (Swanson, 1981; Meyer, in press). In steep mountain ranges that have both erodible soils and a regime of high-severity fires, extreme postfire runoff and mass failures produce a large proportion of the overall sediment flux. In contrast, fire is much less of a factor in low-relief landscapes with only light surface fires.

Clearly, weather and climate are major factors in both fire activity and postfire sedimentation over a wide range of timescales. In xeric conifer forests of the western USA, a few wet years may allow grasses and other fine fuels to build up, so that a subsequent drought year produces widespread fires (Swetnam and Betancourt, 1998; Veblen et al., 2000). Prior to fire suppression, light surface fires recurred at intervals of a few years to a few decades in generally open forest stands. In wetter high-elevation conifer forests as in Yellowstone, more rare and severe drought may be necessary for significant areas to burn (Balling et al., 1992a,b). Forest structure there is typically dense. Intervals of many decades to several hundred years may elapse between high-severity stand-replacing fires, and climate change over centuries and longer periods is important (Romme and Despain, 1989; Meyer et al., 1995; Millspaugh et al., 2000).

In this paper, we review postfire erosion and sedimentation processes, and explore changing landscape responses to fire in contrasting xeric and mesic conifer forests over periods of centuries to millennia. Although planning for the future over such timescales is beyond our capabilities, knowledge of linkages between climate, fire, and landscape response in the Holocene epoch (the postglacial period of the last ~10 000 years) is critical to understand the modern environment and the potential effects of climatic trends over the last few centuries. For example, tree-rings yield detailed, spatially explicit fire histories that are limited to the age of living trees, mostly less than 500 years. Many tree-ring records reveal fire regimes prior to European settlement in the western USA, but they do not extend back before the Little Ice Age, a time of minor glacial advances and generally cooler climates in the northern hemisphere beginning ca. 1200 A.D. (Grove, 1988, 2001; Luckman, 2000). Marked warming began in the late 1800s to early 1900s and continues in the late 20th century (Pollack et al., 1998; Esper et al., 2002). Given such climatic change, fire regimes may change markedly, even without major changes in forest composition (e.g., Meyer et al., 1995; Millspaugh et al., 2000). Therefore, geomorphic responses to fire that affect aquatic ecosystems may also vary from what historical observations and shorter fire histories suggest are characteristic of a given landscape. To provide a long-term perspective on such disturbances and to better understand the influence of climate, we compare a Holocene record of fire-related sedimentation in cool, high-elevation forests of northern Yellowstone National Park with one under development for warmer, low-elevation forests of the South Fork Payette River region in west-central Idaho (Fig. 1). In both areas, fire-related sediments are well-preserved in small alluvial fans. These fans are gently sloping, conical landforms formed where small tributary drainage become unconfined and deposit sediment as they enter larger stream valleys.

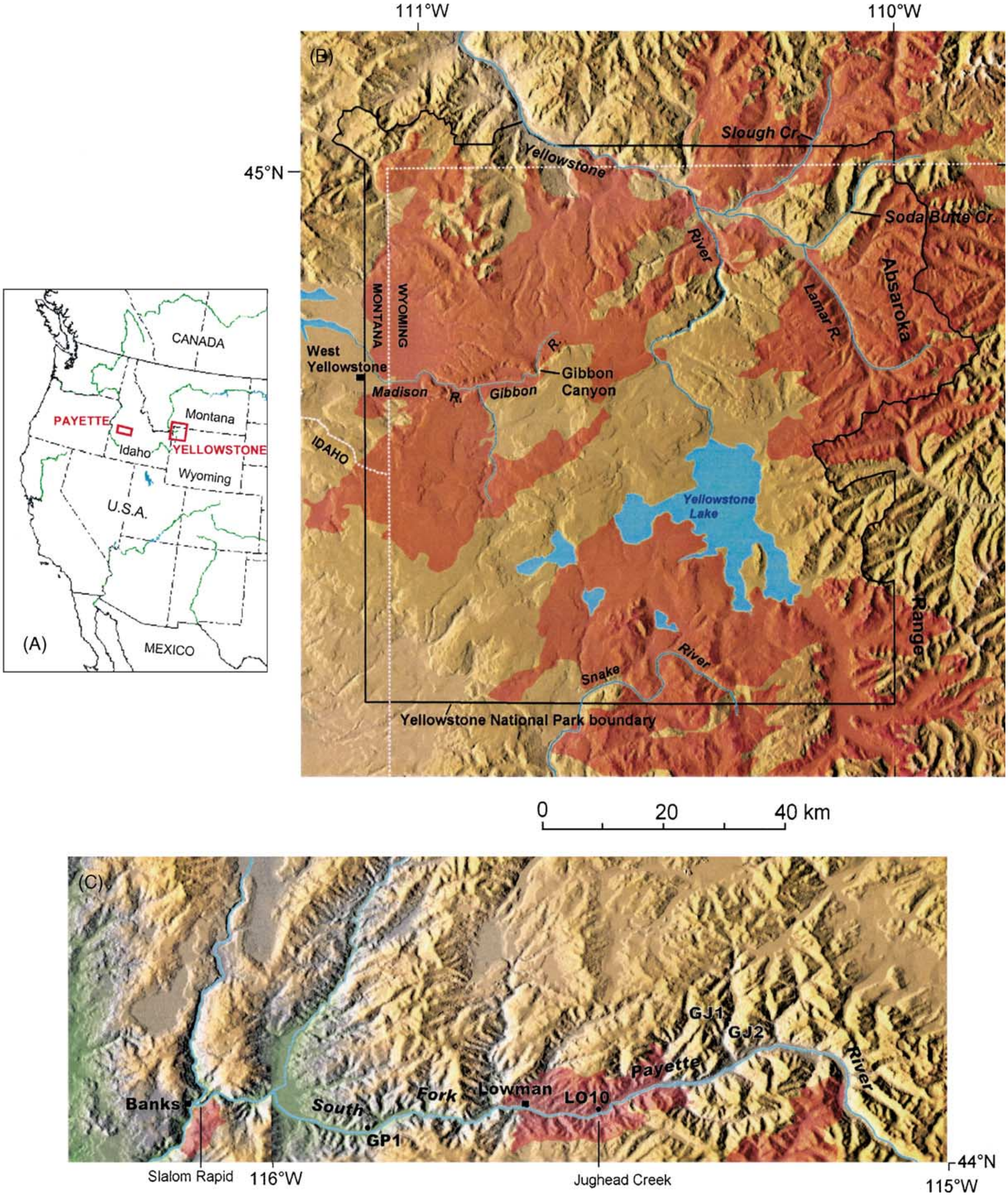


Fig. 1. (A) Index map showing the location of the two study areas in the western USA, (B) Yellowstone National Park study area showing 1988 burned area perimeters (red shading) and (C) South Fork Payette River study area, Idaho, showing 1994 (in southeast) and 1989 burned area perimeters (red shading) and study sites shown in Figs. 3 and 4. Digital shaded relief maps show elevation range from 1000 m (green, e.g., western Payette area) to 3000 m (red-brown, e.g., eastern Yellowstone area). Localities mentioned in the text and figures are shown.

2. Postfire erosion and deposition: processes and patterns

Fires help to initiate sediment transport events in small, steep mountain basins via two primary mechanisms (see also Wondzell and King, this volume). The first mechanism operates when intense precipitation, often in brief summer thunderstorms, produces widespread surface runoff on severely burned slopes. Water-repellent soils and (or) surface-sealing effects reduce infiltration rates dramatically, and smooth flow paths allow rapid runoff (Swanson, 1981; Meyer and Wells, 1997; Robichaud, 2000). Rill and sheetwash erosion strip fine sediment and ash from surface soil, sometimes generating small debris flows on slopes and in uppermost drainages (Wells, 1987; Cannon et al., 1998, 2001). The very large volume of runoff produces extreme discharges in low-order channels, with further sediment entrainment and generation of catastrophic flash floods to debris flows in main channels (Parrett, 1987; Meyer and Wells, 1997). Events of this nature are most common for 2–3 years following fire, before herbaceous revegetation. Runoff-generated debris flows and flash floods were widespread in Yellowstone after the 1988 fires (Meyer and Wells, 1997). They also occur in the Payette region of Idaho; for example, major runoff-generated debris flows were spurred by a heavy 1995 thunderstorm in tributary basins of the North Fork Boise River that burned in 1994 (Meyer et al., 2001). Low-severity fires that leave patches of litter and understory vegetation intact have limited effect because small, patchy runoff-generating areas and discontinuous overland flow paths allow re-infiltration (Lavee et al., 1995).

The second initiation mechanism may function after some lag time following fire, when tree roots decay and cohesive strength in colluvium is reduced (Schmidt et al., 2001). Failure becomes more likely upon saturation, often in more prolonged storms and snowmelt (e.g., Reneau and Dietrich, 1987; Gray and Megahan, 1981; Montgomery et al., 2000). In the Payette River and surrounding region, landslides were most common 4–10 years after burning or deforestation (Gray and Megahan, 1981). In some cases, saturation may also be promoted by reduced postfire evapotranspiration. Postfire saturation-failure events were much less common on the glacially scoured slopes of northern Yellowstone, where colluvium is thin, than in the weathered granitic terrain of the unglaciated lower Payette River basin. A 1996–1997 winter thaw and heavy rains provided a trigger for such failures, 7 years after the severe 1989 Lowman fire in the Payette basin (Meyer et al., 2001) (Fig. 2). Most of the failures on forested slopes occurred in burned areas (Shaub, 2001). In Yellowstone, most saturation-induced slope failures that occurred after the 1988 fires were prompted by melting of a heavy snowpack in 1996 (Meyer, in press).

With either initiation mechanism, the resulting sediment transport process may vary from dense, slurry-like debris flows to more dilute but nonetheless sediment-charged flash floods. A single event often progresses through a large range within this continuum, but one type of process may dominate depending on a variety of basin and storm characteristics (e.g., Meyer and Wells, 1997; Cannon, 2001). Debris flows are saturated flows with high sediment:water ratios that are controlled by both solid and fluid forces (Pierson and Costa, 1987; Iverson, 1997). A mixture of water and fine sediment forms the pore fluid, and strength is imparted largely by grain–grain friction. Debris flows have high density and high viscosity compared to flood flows. Where available for transport, large boulders and woody debris are typically concentrated in a non-liquefied mass that is shoved along at the flow front. Many debris flows become more dilute and progress into mud-rich floods toward the tail of the flow.

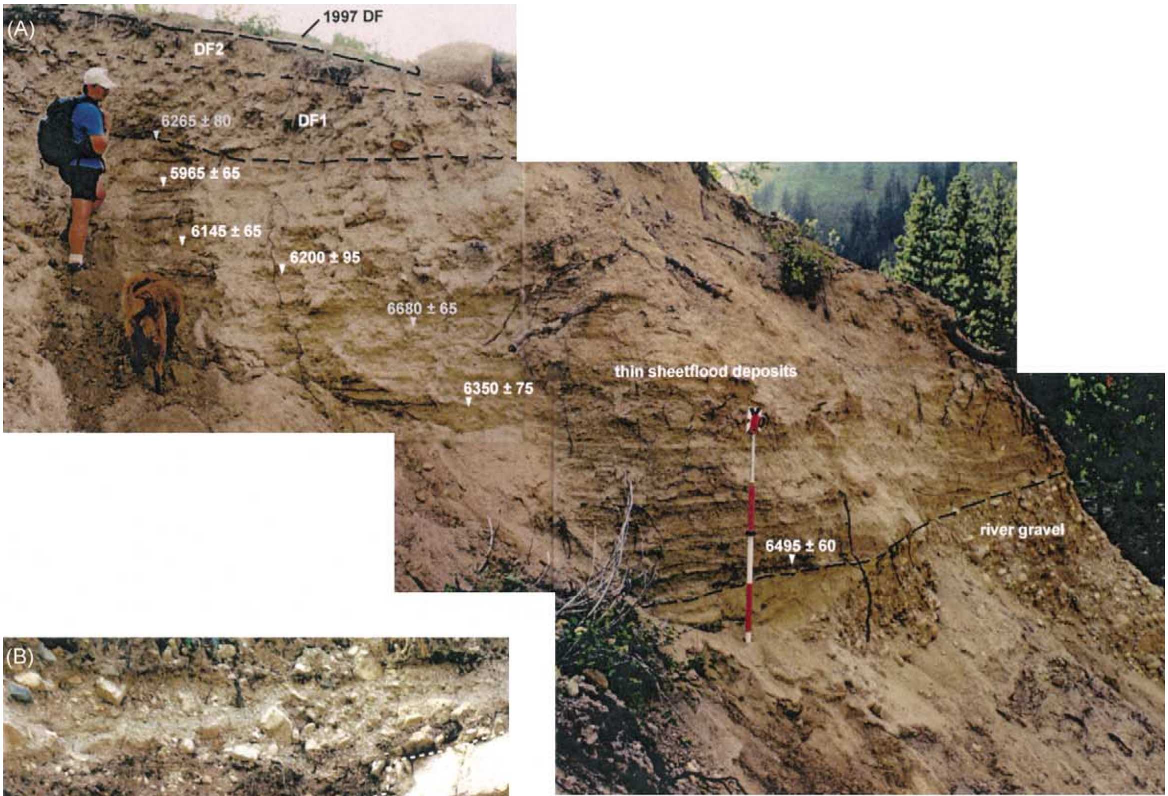
In general, debris-flow deposits are characterized by very poor sorting, variable content of gravel-sized clasts to large boulders, and a finer, generally muddy matrix (e.g., Costa, 1984, 1988). Debris flows emanating from burned basins onto alluvial fans often contain abundant charcoal and charred wood (Meyer et al., 1995; Meyer and Wells, 1997; Cannon, 2001) (Fig. 3B). Charcoal is especially common in gravel-poor "mudflow" deposits, which often represent matrix fluid that has segregated during movement and deposition of debris flows (Pierson, 1986). In debris-flow deposits with abundant gravel-sized material and a coarse sandy matrix, large charcoal fragments may be rare because of comminution during flow (Meyer and Wells, 1997; Cannon, 2001). Simple presence of charcoal does not indicate a fire-related origin, but abundant coarse, angular charcoal and dark mottles of fine charred material are diagnostic. Buried

Fig. 2. Contrasting effects of large fire-related debris flows on the South Fork Payette River channel: (A) *Mouth of "Jughead" Creek* (Fig. 1): Red bracket indicates 1.8 m tall person for scale. A large debris flow deeply scoured the "Jughead" Creek channel, slightly overtopped the flanking alluvial fan surfaces (Fig. 3), and flowed entirely across the South Fork Payette River channel onto the terrace in the foreground. Deposits in the river channel were rapidly removed because few boulders were transported. (B) *Slalom Rapid*: The steep, burned upper basin of a tributary that produced a large debris flow is visible at top. Remnant boulders of the debris flow remain on the opposite bank, and very large, stable, submerged debris-flow boulders form the rapid.

A horizons may contain significant charcoal and superficially resemble fire-related debris-flow deposits, but A horizons typically grade downward into lighter-colored material and may cut across stratigraphic units.

Floods from burned basins can transport voluminous sediment in suspension and traction, but by definition the sediment:water ratio is low enough that the fluid has essentially the same flow properties as water alone (Pierson and Costa, 1987). Hyperconcentrated flows display flow properties and deposit characteristics transitional between debris flows and floods (Costa, 1988; Meyer and Wells, 1997). Sheetflooding is a common process on alluvial fans, where relatively shallow, unconfined flow spreads broadly over the fan surface.

In hyperconcentrated and flood flows, deposition of different particle sizes is controlled by fluid forces that vary with changing flow velocity, depth, and slope, so deposits are typically better sorted than debris flows and often display stratification. Alluvial fan deposits range from boulder bars deposited in channeled flows to thin sheets of silty sand deposited by shallow sheetflooding on distal fans (Meyer and Wells, 1997; Cannon, 2001). In general, large charcoal fragments are uncommon in these deposits, but finer-grained sheetflood sediments may have hydrodynamically concentrated charcoal-rich layers (Fig. 3A).



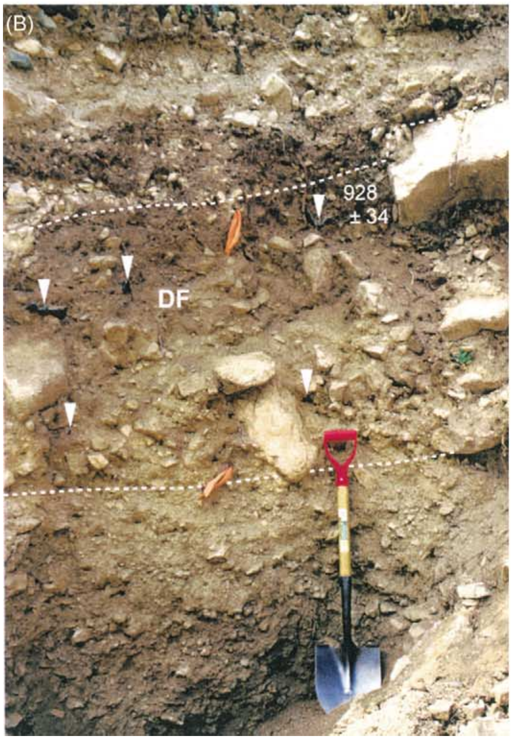


Fig. 3. (A) Early Holocene stratigraphic section at ''Jughead'' Creek (Figs. 1 and 2A) showing alluvial-fan deposits dominated by thin sheetflood units, capped by two older debris-flow (DF) units and a thin deposit of the 1997 debris flow. Red and white bands on prism pole are 30 cm long; foreshortening compresses the upper photo. Note thin dark charcoal concentration zones and burned soil surfaces with dates in radiocarbon years (^{14}C year B.P.) $\pm 1\ \sigma$. Dates in gray are stratigraphically ''inverted'', i.e., older than underlying ages, probably because older charcoal was eroded from pre-existing deposits into postfire flows. (B) Alluvial fan stratigraphic section at site GJ1 (Fig. 1) containing a fire-related debris-flow deposit (DF, bounded by dashed lines) with large charcoal fragments (white arrows). Tops of orange flags mark 1 and 2 m depth. The date of 928 ± 34 ^{14}C year B.P. calibrates to 1021–1211 A.D., within the Medieval Warm Period.

Both debris flow- and sheetflood-dominated events can produce major deposition on alluvial fans in the study areas (Meyer and Wells, 1997; Meyer et al., 2001), but smaller events are probably more often characterized by sheetflooding.

Charred forest litter layers may be preserved on alluvial fans when buried by debris-flow or flood deposits shortly after fire (Meyer et al., 1995; Meyer and Wells, 1997) (Fig. 3A). These burned soil surfaces are discrete, laterally extensive layers about 0.5–2 cm thick, predominantly composed of fine charred organic material, but often containing charred needles, twigs, and other recognizable macrofossil materials. If burned surfaces are not buried soon after fire, bioturbation and erosion mix and scatter the charred material. We consider depositional units directly overlying well-preserved burned surfaces to be probable fire-related sediments.

For all flow processes, sediment delivery to channels is strongly influenced by valley-floor geomorphology (e.g., broad glacial trough valleys promote trapping of sediment on valley-side alluvial fans because there is more space for accumulation away from mainstem streams). Debris-flow and flood events also have markedly different effects on channels depending on the sediment size delivered. For example, a massive 1997 debris flow at "Jughead" Creek deposited an estimated 11 000 m^3 of sediment in the South Fork Payette River channel, but the low percentage and submeter size of boulders resulted in minimal local channel change after high flows reworked the deposit (Meyer et al., 2001) (Fig. 3A). Farther downstream along the South Fork Payette River at Slalom Rapid, however, fire-related debris-flow boulders up to several meters in diameter increased the channel constriction, drop, and complexity, with upstream pool formation and bed-sediment accumulation (Fig. 3B). Given the truly extreme discharges required to move the largest boulders, some of these effects are likely to persist at least for centuries.

3. Northern Yellowstone National Park study area

Most of Yellowstone National Park lies at over 2000 m elevation and is covered by dense conifer forests. We focused on geomorphic responses to fire in the rugged Absaroka Range of northeastern Yellowstone National Park and other areas of local high relief, such as Gibbon Canyon (Fig. 1). Mean annual precipitation increases markedly with elevation in northeastern portion of the park, from 360 mm at Lamar Ranger Station (2000 m elevation) to 660 mm at Cooke City (2302 m elevation), and as much as 1300 mm at 3050 m elevation along the eastern park boundary (Dirks and Martner, 1982). Precipitation falls largely as snow, and an average of 70% of annual runoff in the Lamar River occurs during snowmelt in May and June. In summer, however, convective storms often deliver intense localized rainfall. Mean annual temperature is $\sim$1.8 °C at Lamar Ranger Station and decreases with elevation.

Climatic gradients in northern Yellowstone National Park are strongly reflected in vegetation patterns (Whitlock and Bartlein, 1993). The lower Lamar River and Soda Butte Creek valley floors are dominated by wet floodplain meadows and dry grasslands, with big sagebrush (*Artemisia tridentata*)—bunchgrass steppe communities on terrace and alluvial fan surfaces. As elevation increases, steppe communities and open Douglas-fir (*Pseudotsuga menziesii*) stands on foot slopes and south aspects are transitional to the dense mesic mixed-conifer communities that comprise most of the forest cover in northern Yellowstone. Lodgepole pine (*Pinus contorta*) predominates, but Douglas-fir, Engelmann spruce (*Picea engelmannii*), and subalpine fir (*Abies lasiocarpa*) are also common. Near upper treeline at ca. 2750–3050 m elevation, subalpine fir and whitebark pine (*Pinus albicaulis*) are the dominant conifer species.

Even-age stands 150–350 years or more in age are common in higher-elevation forests of the park, indicating that they last burned in extensive lethal fires, as in 1988 (Romme, 1982; Romme and Despain, 1989). Fire spread in Yellowstone region is strongly dependent on weather, most importantly drought and wind conditions during the summer fire season (Romme and Despain, 1989; Balling et al., 1992a,b). The 1988 Yellowstone fires occurred during the most severe summer drought since the instrumental record began in 1895 (Balling et al., 1992a,b). Many low-order drainage basins in northern Yellowstone National Park were almost entirely burned by intense stand-replacing fires. The effect of fire suppression on fuel buildup and thus the severity and extent of the 1988 fires was probably small, given the relatively brief period over which fire-fighting was effective (Romme and Despain, 1989; Balling et al., 1992a) and the dense character of most higher-elevation stands even in the late 1800s (Meagher and Houston, 1998).

In the Absaroka Range, the Lamar River and its major tributaries Soda Butte Creek and Slough Creek flow down large glacial trough valleys (Pierce, 1979; Meyer et al., 1995). These streams are fed by numerous small (<4 km^2) steep tributary basins with total relief of 500–1000 m. Poorly consolidated and erodible andesitic volcaniclastic rocks form most of the steep upper slopes (e.g., Prostka et al., 1975). During storms, exposed bedrock slopes and cliffs generate substantial surface runoff in many basins even in the absence of fire. Nonetheless, the 1988 fires greatly increased runoff generation and erosion on burned slopes, with numerous debris flows and flash floods as a result (Meyer and Wells, 1997). Sediments deposited on alluvial fans provided modern analogs for identification of fire-related deposits in Holocene fan sections (Meyer et al., 1995).

4. Payette River study area

The central Idaho study area is located in the South Fork Payette River canyon below Grandjean, at lower elevation (1000–2000 m) than the Yellowstone National Park study area (Fig. 1). Mean annual precipitation varies from about 600 mm in valleys to 1000 mm at higher elevations, and occurs predominantly in the colder months. Runoff is dominated by snowmelt in March to May, but thaws and large cyclonic storms sometimes generate major winter floods (Meyer et al., 2001). A pronounced summer dry period is conducive to frequent fires at lower elevations. Sparse ponderosa pines (*Pinus ponderosa*), shrubs, grasses, and forbs cover dry low-elevation and south-facing slopes. Ponderosa pine mixed with Douglas-fir cover middle elevations and more shaded aspects, and dense forests of mixed conifers mantle higher, north-facing slopes.

Because only the uppermost valley was glaciated in the Pleistocene (Stanford, 1982), the valley floor is generally narrower than those of northeastern Yellowstone National Park. Nonetheless, many small tributary alluvial fans are preserved, especially where they have built onto river terraces bordering the present channel. Unglaciated slopes along the canyon are typically mantled by thick colluvium derived from granular disintegration of weathered Idaho batholith granitic rocks. Although infiltration rates are typically high in unburned areas, postfire surface runoff is greatly enhanced and can readily erode the cohesionless grussy colluvium (Megahan and Molitor, 1975; Robichaud, 2000). Thick colluvium in slope hollows is also prone to landsliding after fires, when tree roots decay and the associated cohesive strength in colluvium is lost (Gray and Megahan, 1981; Clayton and Megahan, 1986; Schmidt et al., 2001).

Tree-ring studies indicate that from 1700 to 1900, low-elevation forests of central Idaho typically experienced frequent, low-severity fires (Steele et al., 1986; Barrett, 1988; Barrett et al., 1997) that removed small trees and other fine fuels while allowing mature trees to survive. Mean fire return intervals (MFIs) were about 10–22 years for dry ponderosa pine stands and somewhat longer (15–36 years) for ponderosa pine–Douglas-fir stands in moister sites. After 1900, organized fire suppression was conducted by Europeans to protect timber resources and settlements, and locally focused livestock grazing limited the spread of surface fires through dry grasses. Reduced fire frequency promoted survival of young conifers and resulted in a denser structure in many stands. Therefore, recent large stand-replacing burns are usually attributed to forest management and land use (e.g., Steele et al., 1986), as are associated debris flows and floods. Over longer timescales, however, the range of fire regimes in ponderosa pine forests and their potential alteration by climatic variations are not well understood.

5. Radiocarbon dating

Charcoal samples from fire-related deposits were ^{14}C-dated, in part using conventional decay-counting methods but mostly by accelerator mass spectrometry (AMS) at the NSF-Arizona Laboratory. Individual charcoal fragments were selected for dating to avoid mixing of charcoal ages, and small twigs, cone fragments, needles, grass stems, and seeds were selected where possible to avoid samples with potentially large ‘‘inbuilt’’ ages (i.e., samples that were formed significantly before the time of fire; Gavin, 2001). Rootlets and other macroscopic organic contaminants were removed under a low-power microscope. Samples were pretreated at the dating laboratories using standard acid and base washes to remove soluble organic contaminants. Radiocarbon ages (reported herein as ^{14}C year B.P.) were calibrated to calendar years (reported herein as cal. year B.P.) using the program CALIB 4.3 (e.g., Stuiver and Reimer, 1993).

To test the precision of radiocarbon ages, five individual charcoal fragments from a single debris-flow in Yellowstone National Park were dated by AMS ^{14}C techniques (Meyer et al., 1995). Four of the five ages were indistinguishable from their mean (2508 ± 28 ^{14}C year B.P.) at the 95% level of confidence (Ward and Wilson, 1978; Table 1), with one older age of 2825 ± 55 ^{14}C year B.P. The consistency of the ages also supports the hypothesis that debris-flow deposits inferred to be fire-related do indeed represent a response to a single fire. Older wood from inner rings and dead timber may be charred and incorporated in debris flows, and older charcoal may be reworked from soils and alluvial deposits by erosion in a postfire event, so some fragments with older ages are expectable (Fig. 3A).

6. Fire-induced sedimentation records

6.1. Northern Yellowstone National Park high-elevation conifer forests

Fire-related deposits make up about 30% of the total thickness of the alluvial-fan sediments examined in northern Yellowstone National Park (Meyer et al., 1995). Because many postfire flood deposits lack features to identify them as fire-related, the actual percentage may be greater. The proportion of fire-induced sediment is also likely to be highly variable between small basins, given differences in amount of forest cover, bedrock erodibility, and basin morphology. For example, basins with a high percentage of forest cover and gentler slopes produce little sediment unless burned, but very steep basins with erodible cliffs clearly produce abundant sediment in storm runoff without fire (Meyer, 2001).

Twenty fire-related debris flows and 30 probable fire-related units (mostly hyperconcentrated-flow and sheetflood deposits) were dated in alluvial-fan stratigraphic sections in the Soda Butte Creek and Slough Creek drainage basins in the northeastern Yellowstone National Park area, and in Gibbon Canyon in northwestern part of the park (Meyer et al., 1995; Fig. 4). Because natural exposures were limited to between 2 and 6 m, most stratigraphic sections contained only late Holocene sediments. Representation of events was consistent from the present back to 3500 cal. year B.P., but decreased with age prior to that time. Fire-related sedimentation was most active within the intervals of 8600–8000, 6400–5900, 5450–4350, 3900–3000, 2750–1600, and 1250–750 cal. year B.P. (Fig. 4).

Spectral analysis of the fire-related sedimentation probability record over the last 3350 years shows that over the northern Yellowstone National Park study area, fire-related events tend to recur at intervals of 300–450 years. At a given site, intervals of 700–1000 years between fire-related deposition are common. These data are consistent with a regime of large, infrequent stand-replacing fires and attendant large debris flows and flash floods. Larger variations in fire-related sedimentation on millennial-scale cycles of approximately 1300 years are prominent, suggesting a climatic control (Meyer et al., 1995). Fire-related debris-flow deposition peaked between 2350–2050 and 900–750 cal. year B.P., also times of increased fire activity as inferred from lake-sediment charcoal records. The latter period falls in a period between 900 and 1200 A.D. of unusually warm spells and locally extreme droughts in the northern hemisphere, often termed the Medieval Warm Period (Lamb, 1977; Hughes and Diaz, 1994; Stuiver and others, 1995; Crowley, 2000; Esper et al., 2002). Widespread and severe multidecadal droughts occurred in the western USA during this interval (Stine, 1994; Woodhouse and Overpeck, 1998; Benson et al., 2002). The former period corresponds to the Roman warm period identified in European climate history (Lamb, 1977) and Atlantic region paleoclimatic records (Bianchi and McCave, 1999; McDermott et al., 2001; Bond et al., 2001). During both periods, warmer temperatures and severe droughts likely promoted extensive fires in Yellowstone region. With heightened fire-related sedimentation, tributary alluvial fans built over mainstem floodplains, narrowing the active fluvial valley floor.

Fire-related sedimentation was minimal during the Little Ice Age, which is variously considered to extend

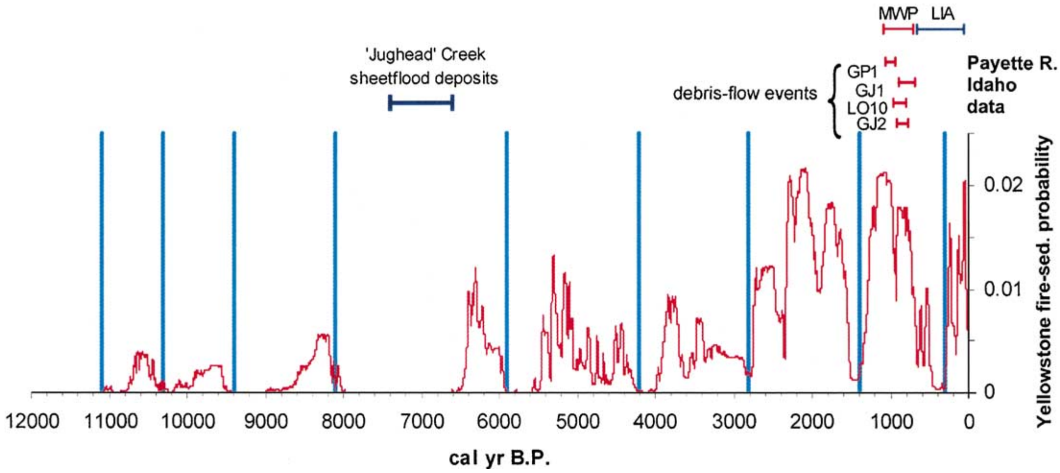


Fig. 4. Records of fire-related sedimentation. A probability spectrum (solid red line) was created by summing probability distributions for 50 calibrated radiocarbon dates on fire-related events in Yellowstone National Park (Meyer et al., 1995). The overall lower probability values in the earlier record mainly reflects lesser exposure of fan sediments with age, not necessarily a decline in the frequency of events. Vertical blue lines represent minimum temperatures in the North Atlantic (Bond et al., 1997), which consistently correspond to times of minimal fire-related sedimentation in Yellowstone. Heavy horizontal bars indicate preliminary age data for fire-related sedimentation in the Payette study area, Idaho. The "Jughead" Creek bar brackets the interval of frequent small sheetflood events (RI ∼33–80 year; Fig. 3A), and GP1, LO10, GJ1 and GJ2 denote calibrated ages (2 sigma ranges) for large fire-related debris flows at these sites. All four debris-flow ages fall within the Medieval Warm Period (MWP, red bar at top), which precedes the Little Ice Age (LIA, blue bar at top).

from about 1200 or 1500 A.D. to about 1900 A.D. (Grove, 1988; Bradley and Jones, 1995; Fig. 4). Although temperatures were not uniformly cold during the Little Ice Age, it is represented by widespread glacial advances in western North America (Davis, 1988; Luckman, 2000). This and preceding cold episodes are also expressed in millennial-scale cycles of iceberg drift in the North Atlantic region (Bond et al., 1997, 2001) that very consistently correspond to minima in fire-related sedimentation in Yellowstone National Park. During these same episodes, mainstem streams in northern portion of the park were broadening their floodplains by lateral erosion, probably because of sustained high snowmelt runoff (Meyer et al., 1995). Fire activity was apparently suppressed by cool, effectively wetter conditions overall and reduced evapotranspiration in summer.

Overall, fire-related sedimentation in Yellowstone is clearly linked to hemispheric-scale climatic variations, where temperature is the primary driver of effective moisture conditions that control the probability of major fires. Winter precipitation apparently increased during some cooler episodes, and greater snowpacks reduced summer drought by increasing soil moisture and slowing land-surface heating. Increasing summer temperature and decreasing winter precipitation were the principal factors in a trend of increasing summer drought over the 20th century that led to the 1988 drought and fires (Balling et al., 1992a,b), and which continues to the present. Summer precipitation exhibits high interannual variability and so is probably more important in short-term control of summer drought conditions than in long-term trends.

6.2. Payette River area low-elevation forests

The record of fire-induced sedimentation in the Idaho study area is under development, but preliminary results show some clear contrasts with Yellowstone. An early Holocene alluvial-fan stratigraphic section at "Jughead" Creek contains multiple thin, charcoal-rich sheetflood deposits and burned soil surfaces (Fig. 3A, see for details Meyer et al., 2001). Radiocarbon dates from this sequence show that from 7400 to 6600 cal. year B.P., between 10 and 24 small fire-induced sheetfloods occurred in the 0.5 km^2 Jughead Creek basin, yielding a recurrence interval of about 33–80 years (Fig. 4). This probably represents a minimum recurrence interval for fires, since low-severity burns often do not produce a geomorphic response (Lavee et al., 1995) and not all fire-related events are recognizable in the stratigraphic record. These small fire-induced sheetfloods occurred with a much higher frequency than observed for fire-induced events at any site in Yellowstone National Park, and imply frequent, low-severity fires. Similar stratigraphic sequences are present in several Payette area fans that are as yet undated, but very likely to be less than 4000 years. These observations suggest that a regime of frequent small fire-related sedimentation events has been common in the last several millennia.

Other deposits and stratigraphic sections, however, suggest that periods of more severe fires have occurred. At site LO10, a fan below a south-facing basin with open ponderosa pine forest contains a burned soil surface that underlies a thick debris flow and dates to 929 ± 56 ^{14}C year B.P. A charcoal-rich debris flow from a higher-elevation ponderosa and mixed-conifer basin yielded a very similar age of 928 ± 34 ^{14}C year B.P. at site GJ1 (Fig. 3B). These events occurred between 951 and 715 cal. year B.P. (2σ age range for LO10), and probable fire-related debris flows also date around this time at two other sites in the South Fork Payette basin, including one low-elevation site with few trees (GP1) (Fig. 4). The apparent coincidence of fire-related debris flows in different vegetation types suggests an episode of high-severity fires and major geomorphic response. This episode corresponds to the Medieval Warm Period, already noted as a time of major fire-related debris-flow activity in Yellowstone National Park (Meyer et al., 1995) and of increased fire activity in a variety of conifer forests in northwestern USA (Whitlock et al., this volume). Although large fire-related debris-flow deposits are not as common as in the Yellowstone region, such events have been a significant component of fire-induced geomorphic activity in the Payette area. At Jughead Creek, two debris-flow units cap the section; however, neither is clearly fire-related (Fig. 3A).

7. Discussion

Climate, elevation, and forest type are well-known primary controls over fire severity and return intervals (e.g., Arno, 1980; Barrett, 1988, 1994; Swetnam and Baisan, 1996; Barrett et al., 1997; Veblen et al., 2000). In general, fire return intervals are shorter for xeric low-elevation forests and longer for mesic high-elevation and subalpine forests in the Rocky Mountain region. Adaptations of conifers to fire clearly reflect these variations in regime. For example, mature ponderosa pines of xeric environments have high open crowns, thick fire-resistant bark, high foliar moisture, and deep roots to survive frequent surface fires, as in the Payette area (Swetnam and Baisan, 1996; DeBano et al., 1998; Keeley and Zedler, 1998). In contrast, lodgepole pines common in high-elevation Yellowstone forests typically have thin bark, low branches, and high stand densities that make them susceptible to infrequent high-severity fires. These conifers have some proportion of serotinous cones and are well adapted to re-establish after such burns (DeBano et al., 1998), as they have after the 1988 Yellowstone fires (Anderson and Romme, 1991).

It is therefore not surprising that the typical frequency and magnitude of fire-related sedimentation events in the Yellowstone and Payette environments reflect their climatic and ecologic differences. In cool and mesic forests of northern Yellowstone National Park, hundreds of years typically pass between major fire-related debris flows and flash floods because fires are infrequent and catastrophic. In the warm and xeric Payette area, many alluvial fans appear to record frequent small fire-induced sediment pulses generated by light surface fires, and some proportion of such burns likely produces no significant geomorphic response. Nonetheless, recent large debris flows following severe fires are not unprecedented, as evidence exists for major postfire sedimentation events at several sites between 950 and 715 cal. year B.P.

To estimate average annual sediment yield during the 7400–6600 cal. year B.P. period of frequent small sheetfloods, we reconstructed the form and mass of the abandoned early Holocene fan at Jughead Creek (Meyer et al., 2001; Fig. 5). The estimated sediment yield is comparable to that obtained from sediment traps and gauges in similar drainage basins in central Idaho; however, these modern measurements do not include major debris flows or floods (Clayton and Megahan, 1986). Sediment yield at Jughead Creek may be underestimated because of sediment lost to the fan, but it is still much lower than average sediment yields estimated for a number of basins in central

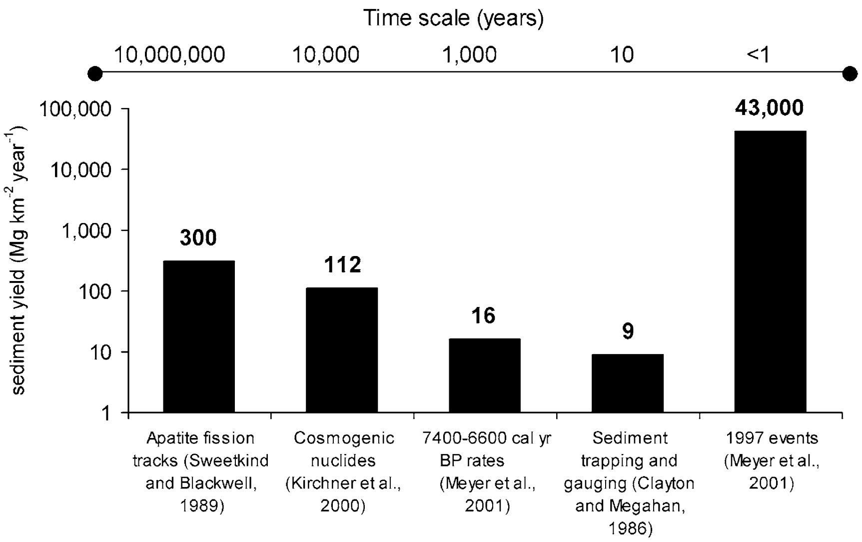


Fig. 5. Estimates of sediment yield in the Payette and central Idaho region averaged over different time scales and from different techniques (note log scale). Very large sediment yields were measured in single 1997 debris-flow and sheetflood events in two 0.5 km^2 basins in the Payette area. Low rates from modern sediment trapping and gauging and during the 7400–6600 cal. year B.P. interval do not include such large events, but the 10 000-year average based on cosmogenic nuclides is an order of magnitude higher and implies that large sedimentation events must occur episodically, possibly related to severe fires. Rates over the last several tens of millions of years are based on apatite fission-track thermochronology and show that over very long timescales, the modern and 7400–6600 cal. year B.P. measurements are also relatively low (Sweetkind and Blackwell, 1989).

Idaho over the last 10 000 years using cosmogenic nuclide abundances in sediments (Kirchner et al., 2001, Fig. 5). The higher 10 000-year average sediment yields imply that episodes of accelerated sedimentation must have occurred, probably in major events. One possibility is that episodes of large, stand-replacing fires resulted in major pulses of sediment, most likely in extreme droughts. We currently have evidence for such events in the Payette area during the Medieval Warm Period (Fig. 4). Extreme winter storms with prolonged rainfall and snowmelt (as in 1996–1997) may also generate major sediment pulses, but their effect is greater when slopes are burned (Shaub, 2001).

Our working hypothesis, then, is that fire regimes and sedimentation in the ponderosa pine forests of the Payette area are modulated by centennial- to millennial-scale climatic change. In the cool and effectively wetter Little Ice Age, frequent low-severity fires were common and probably accompanied by small fire-related sedimentation events. The 7400–6600 cal. year B.P. period of frequent minor fire-induced sedimentation at Jughead Creek corresponds to a time of floodplain widening and a lack of dated fire-induced sedimentation in Yellowstone, also suggesting effectively wetter conditions (Meyer et al., 1995). Although the early Holocene (11 000–7000 cal. year B.P.) was generally a time of summer warmth and drought (Whitlock et al., this volume), paleoclimatic records in interior western North America often indicate a wetter climate interval around 7400–6600 cal. year B.P. (e.g., Gaylord, 1990; Vance et al., 1992; Yansa, 1998). On shorter timescales, non-lethal fires in ponderosa stands are often associated with cooler temperatures and greater precipitation 1–4 years prior to the fire year (Swetnam and Betancourt, 1998; Veblen et al., 2000). With these antecedent conditions, abundant understory grass and forbs provide fuel for surface fires during the summer dry season in the Payette area.

The effects of severe, prolonged drought on vegetation and fire in ponderosa pine forests are less understood. We hypothesize that grass growth is suppressed by such droughts, so that a lack of fine fuels reduces the spread of surface fires. The lack of surface fires would increase stand density if young conifers already established survived drought and filled gaps, providing ladder fuels. When fires then start during severe drought conditions, there is an increased likelihood of high-severity crown fire, especially with high winds. In a similar manner, reduced grass cover (usually attributed to grazing) has been invoked to explain diminished surface fires and a widespread increase in density of xeric *Juniperus* spp. woodland in the interior northwestern USA (e.g., Miller and Rose, 1999). Similar changes in grass and juniper density have occurred, however, where grazing and other anthropogenic effects have been minimal (Knapp and Soule, 1998), suggesting that 20th century warming may be a factor.

Spatial variations in fire frequency also support the hypothesis that climate change may have substantial effects on fire regimes in xeric forests. Even within ponderosa pine forests, fire frequencies tend to be higher in low-elevation stands than those at higher elevations (Swetnam and Baisan, 1996; Veblen et al., 2000). At elevations of 2100–2520 m in central Colorado, Brown et al. (1999) found evidence of both low-severity surface fires and large, stand-replacing burns in ponderosa pine—Douglas-fir forests, representing a greater range of variability in fire regimes than typical of warmer ponderosa pine forests in the southwestern USA (e.g., Swetnam and Baisan, 1996; Brown et al., 2001). In addition, no fires were recorded over large parts of the Colorado study area between 1723 and 1851. In central Idaho, major stand-replacing burns occurred in the drought years of 1910 and 1919, including some in ponderosa pine forests (Barrett, 1988; Barrett et al., 1997). These catastrophic fires occurred before effective fire-fighting efforts and therefore cannot be attributed to fire suppression.

Although interior ponderosa pines can attain ages of at least 1047 years (the oldest documented tree, found in Colorado), most are significantly less than 700 years old (Schubert et al., 1981; Lanner, 1983). This suggests that in addition to senescence, environmental conditions prior to 700 years ago may have caused mortality of many trees. We speculate that many ponderosa stands may have experienced lethal fires during severe droughts within Medieval Warm Period ~1050–750 years ago. If so, associated aquatic ecosystems may have been subjected to large pulses of sediment, as suggested by the several large debris flows during that interval in the Payette study area.

Considerable uncertainty remains over how changes in the frequency, intensity, and depth of storm precipitation vary with changes in large-scale climatic conditions, and thus interact with drought and fire in producing sedimentation events at the local scale. Large-scale temperature changes may play a key role in such activity. Meyer et al. (1995) hypothesized that summer convective storms are more intense during warm periods in Yellowstone, but also note that summer precipitation is highly variable on interannual to decadal timescales. Severe summer drought and catastrophic fire is often followed locally by sufficient storm precipitation to generate debris flows and flash floods. In the Yellowstone region over the last few hundred years, very large floods on mainstem streams occurred during unusual late-spring to early-summer warming, with rapid snowmelt and heavy precipitation (Meyer, 2001). Saturation-induced landslides are often associated with such events, in both burned and unburned areas. It is possible that these unusual short-term warm events become more frequent during large-scale warm climatic periods that last for centuries. Further work employing data on historical and Holocene climates is necessary to examine these hypothesized links.

8. Conclusions and implications for management

The occurrence of catastrophic fires in Yellowstone high-elevation forests is clearly dependent on climatic variations, as is the attendant disturbance in stream ecosystems. Like many river flood records (e.g., Klemeš, 1989; Redmond et al., 2002), fire-related sedimentation is nonstationary because of climate change, and the probability of events changes markedly on centennial to millennial timescales. Although fire suppression and other land-use effects are clearly significant in recent catastrophic fires in the Payette region ponderosa forests, preliminary dating of alluvial-fan sediments also hints at major postfire sedimentation events in the past that are linked to variations in climate.

The dramatic, widespread warming of climate observed in the late 20th century was a major factor in the 1988 fires in Yellowstone (Balling et al., 1992a,b; Meyer et al., 1995), and probably augmented recent catastrophic fires in a variety of conifer forests in the western United States. Given projected temperature increases in the future, severe summer drought is strong possibility in mountain ranges of the US continental interior, and a high risk of catastrophic fires will likely be maintained. Forest restoration efforts often use forest density and fuel structure prior to European settlement as a standard, especially in ponderosa pine forests (e.g., Covington et al., 1997). Although such management may reduce the potential for stand-replacing fires, pre-settlement forests developed largely in cooler climates during the Little Ice Age, and strict restoration and maintenance of pre-settlement conditions may be difficult in the face of global warming. Management of both forests and associated aquatic ecosystems should consider possible future trajectories as influenced by climatic change, a difficult task in view of large uncertainties inherent in model predictions of future climate (e.g., Gutzler, 2000; Whitlock et al., this volume). A better understanding of past climate, fire, and ecological relationships and the range of variability over Holocene timescales may be useful in preparing for an uncertain future.

Acknowledgements

We wish to thank Ralph Mason, Chris Inoue, Danny Katzman, John Rogers, Del and Sandy Fadden, Frank Pazzaglia, Tim Lite, Lydia Rockwell, Sarah Caldwell, Wallace Pierce-Andersen, and Molly Watt for aid in field work; our colleagues Spencer Wood, Steve Wells, Tim Jull, and Charlie Luce for many helpful discussions; and John Varley (National Park Service—Yellowstone) and Kari Grover-Wier (US Forest Service) for cooperation and logistical assistance. We are grateful to the Western Regional Climate Center for historical climate information at http://www.wrcc.dri.edu/. Reviews by Cathy Whitlock, Andrew Marcus, Steven Wondzell, and Bob Gresswell improved the clarity and quality of the manuscript. This work was supported by National Science Foundation grants EARs 9005058 and 0000905 to Meyer, and EAR 9730699 in support of dating at the NSF—Arizona AMS Laboratory.

References

Anderson, J.E., Romme, W.H., 1991. Initial floristics in lodgepole pine (*Pinus contorta*) forests following the 1988 Yellowstone fires. Int. J. Wildland Fire 1, 119–124.

Arno, S.F., 1980. Forest fire history in the northern Rockies. J. Forest. 78, 450–465.

Balling Jr., R.C., Meyer, G.A., Wells, S.G., 1992a. Climate change in Yellowstone National Park: is the drought-related risk of wildfires increasing? Clim. Change 22, 34–35.

Balling Jr., R.C., Meyer, G.A., Wells, S.G., 1992b. Relation of surface climate and burned area in Yellowstone National Park. Agric. For. Meteorol. 60, 285–293.

Barrett, S.W., 1988. Fire suppression's effects on forest succession within a central Idaho wilderness. West. J. Appl. For. 3, 76–80.

Barrett, S.W., 1994. Fire regimes on andesitic mountain terrain in northeastern Yellowstone National Park, Wyoming. Int. J. Wildland Fire 4, 65–76.

Barrett, S.W., Arno, S.F., Menakis, J.P., 1997. Fire episodes in the Inland Northwest (1540–1940) based on fire history data. General Technical Report INT-GTR-370. USDA Forest Service, Intermountain Research Station, Ogden, UT, 17 p.

Benda, L.E., Miller, D.J., Dunne, T., Reeves, G.H., Agee, J.K., 1998. Dynamic landscape systems. In: Naiman, R.J., Bilby, R.E. (Eds.), River Ecology and Management: Lessons from the Pacific Coastal Ecoregion. Springer, New York, pp. 261–288.

Benson, L., Kashgarian, M., Rye, R., Lund, S., Paillet, F., Smoot, J., Kester, C., Mensing, S., Meko, D., Lindstrom, S., 2002. Holocene multidecadal and multicentennial droughts affecting Northern California and Nevada. Quat. Sci. Rev. 21, 659–682.

Bianchi, G.G., McCave, I.N., 1999. Holocene periodicity in North Atlantic climate and deep-ocean flow south of Iceland. Nature 397, 515–517.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., Bonani, G., 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. Science 278, 1257–1266.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., Bonani, G., 2001. Persistent solar influence on North Atlantic climate during the Holocene. Science 294, 2130–2136.

Bozek, M.A., Young, M.K., 1994. Fish mortality resulting from delayed effects of fire in the greater Yellowstone ecosystem. Great Basin Nat. 54, 91–95.

Bradley, R.S., Jones, P.D. (Eds.), 1995. Climate Since 1500 A.D. Routledge, London.

Brown, P.M., Kaufmann, M.R., Shepperd, W.D., 1999. Long-term, landscape patterns of past fire events in a montane ponderosa pine forest of central Colorado. Landscape Ecol. 14, 513–532.

Brown, P.M., Kaye, M.W., Huckaby, L.S., Baisan, C.H., 2001. Fire history along environmental gradients in the Sacramento Mountains, New Mexico: influences of local patterns and regional processes. Ecoscience 8, 115–126.

Cannon, S.H., 2001. Debris-flow generation from recently burned watersheds. Environ. Eng. Geosci. 7, 321–341.

Cannon, S.H., Kirkham, R.M., Parise, M., 2001. Wildfire-related debris-flow initiation processes, Storm King Mountain, Colorado. Geomorphology 39, 171–188.

Cannon, S.H., Powers, P.S., Savage, W.Z., 1998. Fire-related hyperconcentrated and debris flows on Storm King Mountain, Glenwood Springs, Colorado. Environ. Geol. 35, 210–218.

Clayton, J.L., Megahan, W.F., 1986. Erosional and chemical denudation rates in the southwestern Idaho batholith. Earth Surf. Process. 11, 389–400.

Costa J.E., 1984. Physical geomorphology of debris flows. In: Costa, J.E., Fleisher, P.J. (Eds.), Developments and Applications of Geomorphology. Springer, Berlin, Chapter 9, pp. 268–317.

Costa, J.E., 1988. Rheologic, geomorphic, and sedimentologic differentiation of water floods, hyperconcentrated flows, and debris flows. In: Baker, V.R., Kochel, R.C., Patton, P.C. (Eds.), Flood Geomorphology. Wiley, New York, pp. 113–121.

Covington, W.W., Fule, P.Z., Moore, M.M., Hart, S.C., Kolb, T.E., Mast, J.N., Sackett, S.S., Wagner, M.R., 1997. Restoring ecosystem health in ponderosa pine forests of the southwest. J. Forest. 95, 23–29.

Crowley, T.J., 2000. Causes of climate change over the past 1000 years. Science 289, 270–277.

Davis, P.T., 1988. Holocene glacier fluctuations in the American Cordillera. Quat. Sci. Rev. 7, 129–157.

DeBano, L.F., Neary, D.G., Ffolliott, P.F., 1998. Fire's Effects on Ecosystems. Wiley, New York.

Dirks, R.A., Martner, B.E., 1982. The climate of Yellowstone and Grand Teton National Parks. USDI-National Park Service Occasional Paper 6, 26 p.

Esper, J., Cook, E.R., Schweingruber, F.H., 2002. Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. Science 295, 2250–2253.

Gavin, D., 2001. Estimation of inbuilt age in radiocarbon ages of soil charcoal for fire history studies. Radiocarbon 43, 27–44.

Gaylord, D.R., 1990. Holocene paleoclimatic fluctuations revealed from dune and interdune strata in Wyoming. J. Arid Environ. 18, 123–138.

Gray, D.H., Megahan, W.F., 1981. Forest vegetation removal and slope stability in the Idaho batholith. Research Paper INT-271. USDA Forest Service, Intermountain Forest and Range Experiment Station, 23 p.

Grove, J.M., 1988. The Little Ice Age. Methuen, London.

Grove, J.M., 2001. The initiation of the "Little Ice Age" in regions round the North Atlantic. Clim. Change 48, 53–82.

Gutzler, D.S., 2000. Evaluating global warming a post-1990s perspective. GSA Today 10, 1–7.

Hughes, M.K., Diaz, H.F., 1994. Was there a Medieval Warm Period, and if so, where and when? Clim. Change 26, 109–142.

Iverson, R., 1997. The physics of debris flows. Rev. Geophys. 35, 245–296.

Keeley, J.E., Zedler, P.H., 1998. Evolution of life histories in Pinus. In: Richardson, D.M. (Ed.), Ecology and Biogeography of Pinus. Cambridge University Press, Boston, pp. 219–250.

Kirchner, J.W., Finkel, R.C., Riebe, C.S., Granger, D.E., Clayton, J.L., King, J.G., Megahan, W.F., 2001. Mountain erosion over 10 yr, 10 k.y., and 10 m.y. time scales. Geology 29, 591–594.

Klemeš, V., 1989. The improbable probabilities of floods and droughts. In: Starosolszky, Ö., Melder, O.M. (Eds.), Hydrology of Disasters. James and James, London, pp. 43–51.

Knapp, P.A., Soule, P.T., 1998. Recent *Juniperus occidentalis* (western juniper) expansion on a protected site in central Oregon. Glob. Change Biol. 4, 347–357.

Lamb, H.H., 1977. Climate: present, past and future, vol. 2, Climatic History and the Future. Methuen, London.

Lanner, R.M., 1983. Trees of the Great Basin: A Natural History. University of Nevada Press, Reno, NV.

Lavee, H., Kutiel, P., Segev, M., Benyamini, Y., 1995. Effect of surface roughness on runoff and erosion in a Mediterranean ecosystem: the role of fire. Geomorphology 11, 227–234.

Luckman, B.H., 2000. The Little Ice Age in the Canadian Rockies. Geomorphology 32, 357–384.

McDermott, F., Mattey, D.P., Hawkesworth, C., 2001. Centennial-scale Holocene climate variability revealed by a high-resolution speleothem $\delta^{18}O$ record from SW Ireland. Science 294, 1328–1331.

Meagher, M., Houston, D.B., 1998. Yellowstone and the Biology of Time. University of Oklahoma Press, Norman, OK.

Megahan, W.F., Molitor, D.C., 1975. Erosional effects of wildfire and logging in Idaho. In: Proceedings of the Symposium on Watershed Management. American Society of Civil Engineers, Irrigation and Drainage Division, Logan, UT, pp. 423–444.

Meyer, G.A., 2001. Recent large-magnitude floods and their impact on valley-floor environments of northeastern Yellowstone. Geomorphology 40, 271–290.

Meyer, G.A., in press. Yellowstone fires and the physical landscape. In: Wallace, L.L. (Ed.), After the Fires: Over a Decade of Research on the Yellowstone Fires. Yale University Press, New Haven, CT.

Meyer, G.A., Wells, S.G., Jull, A.J.T., 1995. Fire and alluvial chronology in Yellowstone National Park: climatic and intrinsic controls on Holocene geomorphic processes. Geol. Soc. Am. Bull. 107, 1211–1230.

Meyer, G.A., Wells, S.G., 1997. Fire-related sedimentation events on alluvial fans, Yellowstone National Park, USA. J. Sediment. Res. A 67, 776–791.

Meyer, G.A., Pierce, J.L., Wood, S.H., Jull, A.J.T., 2001. Fires, storms, and sediment yield in the Idaho batholith. Hydrol. Process. 15, 3025–3038.

Miller, R.F., Rose, J.A., 1999. Fire history and western juniper encroachment in sagebrush steppe. J. Range Manage. 52, 550–559.

Millspaugh, S.H., Whitlock, C., Bartlein, P.J., 2000. Variations in fire frequency and climate over the past 17 000 year in central Yellowstone National Park. Geology 28, 211–214.

Minshall, G.W., Robinson, C.T., Lawrence, D.E., 1997. Postfire responses of lotic ecosystems in Yellowstone National Park, USA. Can. J. Fish. Aquat. Sci. 54, 2509–2525.

Minshall, G.W., Brock, J.T., Andrews, D.A., Robinson, C.T., 2001. Water quality, substratum and biotic responses of five central Idaho (USA) streams during the first year following the Mortar Creek fire. Int. J. Wildland Fire 10, 185–199.

Montgomery, D.R., Schmidt, K.M., Greenberg, H., Dietrich, W.E., 2000. Forest clearing and regional landsliding. Geology 28, 311–314.

Parrett, C., 1987. Fire-related debris flows in the Beaver Creek drainage, Lewis and Clark County, Montana. US Geol. Surv. Water-supply Paper 2330, 57–67.

Pierce, K.L., 1979. History and dynamics of glaciation in the northern Yellowstone National Park area. US Geol. Surv. Prof. Paper 729-F.

Pierson, T.C., 1986. Flow behavior of channelized debris flows, Mount St. Helens, Washington. In: Abrahams, A.D. (Ed.), Hillslope Processes. Allen and Unwin, Boston, pp. 269–296.

Pierson, T.C., Costa, J.E., 1987. A rheologic classification of subaerial sediment-water flows. In: Costa, J.E., Wieczorek, G.F. (Eds.), Debris Flows/Avalanches. Geol. Soc. Am. Rev. Eng. Geol. 7, 1–12.

Pollack, H.N., Huang, S.P., Shen, P.Y., 1998. Climate change record in subsurface temperatures: a global perspective. Science 282, 279–281.

Prostka, H.J., Ruppel, E.T., Christiansen, R.L., 1975. Geologic map of the Abiathar Peak Quadrangle, Yellowstone National Park, Wyoming. US Geol. Surv. Geol. Quad. Map GQ-1244, 1:62,500.

Redmond, K.T., Enzel, Y., House, P.K., Biondi, F., 2002. Climate variability and flood frequency at decadal to millennial scales. In: House, P.K., Webb, R.H., Baker, V.R., Levish, D.R. (Eds.), Ancient Floods, Modern Hazards: Principles and Applications of Paleoflood Hydrology. American Geophysical Union, Washington, DC, pp. 21–45.

Reneau, S.L., Dietrich, W.E., 1987. The importance of hollows in debris-flow studies; examples from Marin County, California. In: Costa, J.E., Wieczorek, G.F. (Eds.), Debris Flows/Avalanches. Geol. Soc. Am. Rev. Eng. Geol. 7, 165–180.

Robichaud, P.R., 2000. Fire effects on infiltration rates after prescribed fire in northern Rocky mountain forests. USA. J. Hydrol. 231, 220–229.

Romme, W.H., 1982. Fire and landscape diversity in subalpine forests of Yellowstone National Park. Ecol. Monogr. 52, 199–221.

Romme, W.H., Despain, D.G., 1989. Historical perspective on the Yellowstone fires. Bioscience 39, 695–699.

Schmidt, K.M., Roering, J.J., Stock, J.D., Dietrich, W.E., Montgomery, D.R., Schaub, T., 2001. The variability of root cohesion as an influence on shallow landslide susceptibility in the Oregon coast range. Can. Geotech. J. 38, 995–1024.

Schubert, G.H., Wellner, C.A., Hudson, R.H., Barrett, J.W., 1981. Interior ponderosa pine. In: Choices in Silviculture for American Forests. Society of American Foresters, Washington, DC, pp. 54–63.

Shaub, S., 2001. Landslides and wildfire: an example from the Boise National Forest. Masters Thesis. Boise State University, Boise, Idaho, 85 p.

Stanford, L.R., 1982. Surficial geology of the upper South Fork Payette River area, south central Idaho. Idaho Geological Survey Technical Report 82-7.

Steele, R., Arno, S.F., Geier-Hayes, K., 1986. Wildfire patterns change in central Idaho's ponderosa pine–Douglas-fir forest. West. J. Appl. For. 3, 76–80.

Stine, S., 1994. Extreme and persistent drought in California and Patagonia during mediaeval time. Nature 369, 546–549.

Stuiver, M., Reimer, P.J., 1993. Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. Radiocarbon 35, 215–230.

Swanson, F.J., 1981. Fire and geomorphic processes. In: Mooney, H.A., Bonnicksen, T.M., Christensen, N.L., Lotan, J.E., Reiners, W.A. (Eds.), Fire Regimes and Ecosystem Properties. USDA Forest Service General Technical Report WO-26. Washington, DC, pp. 401–420.

Sweetkind, D.S., Blackwell, D.D., 1989. Fission-track evidence of the Cenozoic thermal history of the Idaho batholith. Tectonophysics 157, 241–250.

Swetnam, T.W., Baisan, C.H., 1996. Historical fire regime patterns in the southwestern United States since 1700. In: Allen, C.D. (Ed.), Fire Effects in Southwestern Forests. Proceedings of the Second La Mesa Fire Symposium. US Forest Service General Technical Report RM-286. pp. 11–32.

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

Vance, R.E., Mathewes, R.W., Clague, J.J., 1992. 7000 year record of lake-level change on the northern Great Plains: a high-resolution proxy of past climate. Geology 20, 879–882.

Veblen, T.T., Kitzberger, T., Donnegan, J., 2000. Climatic and human influences on fire regimes in ponderosa pine forests in the Colorado Front Range. Ecol. Appl. 10, 1178–1195.

Ward, G.K., Wilson, S.R., 1978. Procedures for comparing and combining radiocarbon age determinations: a critique. Archaeometry 20, 19–31.

Wells II, W.G., 1987. The effect of fire on the generation of debris flows. In: Costa, J.E., Wieczorek, G.F. (Eds.), Debris Flows/Avalanches, vol. 7, Geol. Soc. Am. Rev. Eng. Geo. pp. 105–114.

Whitlock, C., Bartlein, P.J., 1993. Spatial variations of Holocene climatic change in the Yellowstone region. Quaternary Res. 39, 231–238.

Wohl, E.E., Pearthree, P.A., 1991. Debris flows as geomorphic agents in the Huachuca mountains of southeastern Arizona. Geomorphology 4, 273–292.

Woodhouse, C.A., Overpeck, J.T., 1998. 2000 years of drought variability in the central United States. B. Am. Meteorol. Soc. 79, 2693–2714.

Yansa, C.H., 1998. Holocene paleovegetation and paleohydrology of a prairie pothole in southern Saskatchewan, Canada. J. Paleolimnol. 19, 429–441.