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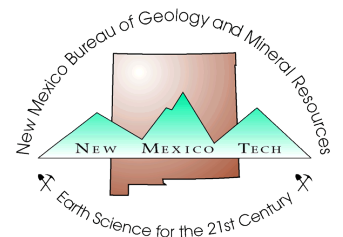
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Introduction

As highlighted in this issue's Gallery of Geology on page 24, large, severe wildfires have become part of the New Mexico late spring and early summer experience in the last few decades. Such fires have considerable relevance to geomorphologists, as erosion rates in mountainous landscapes are often dramatically increased in the several years after severe fires. Erosion and sediment transport often take place during major debris flows and flash floods (Fig. 1). These events are most commonly triggered by intense thunderstorm rainfall, as in New Mexico's summer monsoon, and very rapid runoff from slopes devoid of vegetation or forest litter. Although water-repellent soils formed by fire effects are often cited as the primary cause of increased runoff, the creation of extensive bare, smooth soil surfaces alone is more than sufficient—for example, consider the erosion that would occur on a plowed, smooth farm field at slope angles of 15–30° or more! The extreme flows that are generated can entrain huge volumes of sediment as they course down slopes and channels. Events of this nature affected a number of small, steep drainages in the Sacramento Mountains southeast of Cloudcroft after the 2002 Peñasco fire. Large quantities of mud- to boulder-sized sediment may be deposited on alluvial fans along the valley margins, and in some cases deep gullies are also cut in the fans. Major damage to roads, buildings, and property resulted in several locations in the Peñasco fire area, as valley-side alluvial fans are common sites for residential and other development.

Along with their importance in understanding geologic hazards and watershed impacts, sediments deposited on alluvial fans by postfire debris flows and floods also provide a means of assessing the timing and spatial distribution of past forest fires, and relations between fire and climate, in particular episodes of severe drought. These sediments are often rich in charcoal fragments from the burned area, which allows radiocarbon dating of fire-related sedimentation events thousands of years into the past, providing an important supplement to the more commonly available tree-ring fire histories. Tree-ring dating has provided a wealth of information on low-severity surface fires that scar trees, but leave them living. Such fires swept through the understory of many southwestern forests every few years to a few decades before European settlement and intensified grazing, logging, and fire suppression in the late 1800s (e.g., Brown et al. 2001). However, tree-ring fire-scar records extend back about 500 yrs at most, and do not provide data on severe fires that kill large stands of trees. Stand-destroying fires can be dated via the ages



FIGURE 1—Deposits of a debris flow from a tributary basin of lower Cox Canyon in the Sacramento Mountains. The tributary basin was severely burned in the 2002 Peñasco fire. Debris-flow deposits partially filled and dammed the main valley arroyo at this location (the arroyo wall is visible across the center of the photo). The surface deposits lack mud because of reworking by later flood flows.

of living trees that germinated after fire, but this reveals the last such fire only, and again is limited to about the last 500 yrs. Therefore, alluvial sediments can greatly extend fire histories, albeit with greater uncertainty in ages. Climatic change on time scales of a thousand years or more has strongly affected Earth environments over the Holocene Epoch, the ~12,000 yrs since the last episode of continental glaciation. Thus, the sensitivity of fire activity to climate change over such time scales is of great interest. It is also critical to understanding the potential impacts of future droughts on New Mexico's mountain forests, given that predicted warming over the next century has no precedent on the short time scales covered by tree-ring fire chronologies.

Fire and alluvial history in the Sacramento Mountains

South of Cloudcroft, the Sacramento Mountains are essentially a broad eastward-dipping cuesta, where the range crest and ridges on the eastern slope are capped by resistant limestone and dolomite of the Permian San Andres Formation. Below the San Andres Formation, the highly erodible Permian Yeso Formation forms slopes that have contributed large volumes of fine-grained Holocene alluvium to valleys. Abundant exposures of these alluvial sediments are present in both deep main valley arroyos that predate the Peñasco fire (Fig. 2), and in gullies cut in alluvial fans by recent postfire debris flows

and floods (Fig. 1). Deposits of modern post-fire events helped us to define criteria for recognition of fire-related sediments in the Holocene alluvium. Conifer forests of the Sacramentos range from spruce and fir near the range crest, through ponderosa pine and mixed conifers at middle elevations, to piñon-juniper stands near the lower forest border.

We focused our investigations along the valleys of the Rio Peñasco and lower Cox Canyon in the eastern Sacramentos (Frechette and Meyer 2009), and in Caballero Canyon west of the range crest (New 2007). Fire-related deposits dating to as much as 8000 yrs ago were discovered, interbedded with deposits with no clear evidence of an origin in a burned area. The most active period of fire-related sedimentation occurred from about 6000 to 4000 yrs ago, as is highlighted in Figure 3. Although it does not stand out markedly as a dominant peak in the fire-related sedimentation curve, this interval saw fans build rapidly with several meters of accumulated sediment including thick, charcoal-rich debris-flow deposits (Fig. 2, inset). This evidence for severe fires is consistent with a generally warmer middle Holocene climate, characterized by widespread and persistent drought conditions in the Southwest and in the interior western United States in general (Buck and Monger 1999; Shuman et al. 2009). However, it may also reflect a higher variability in precipitation and (or)

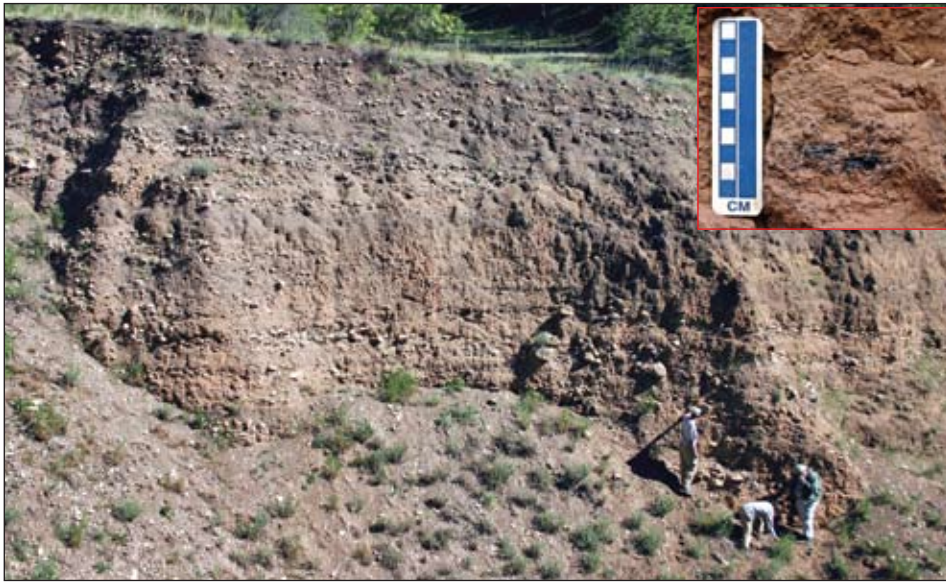


FIGURE 2—More than 10 m (32 ft) of sediment in the toe of an alluvial fan is exposed in this main valley arroyo along the Rio Peñasco. The fan deposits range in age from about 8000 to 650 yrs before present. Darker layers represent organic-enriched soils that developed during times of slow sediment accumulation. The middle part of the section with little soil development starting above the persons' heads dates to about 6000–4000 yrs ago, when rapid fire-related aggradation occurred. Inset shows abundant charcoal fragments in a muddy, poorly sorted fire-related debris-flow deposit from this section.

temperatures at this time (e.g., Asmerom et al. 2007), which would allow forests to grow more dense during wetter intervals that minimize the occurrence of surface fires. Severe crown fires would then be more likely during major droughts.

Evidence for severe fires in charcoal-rich debris flows in the Sacramento Mountains became substantially less common after 4,000 yrs ago, probably because of the climatic cooling associated with declining summer solar radiation in the Northern Hemisphere, and advances of mountain glaciers in the western USA and elsewhere known as the Neoglacial. However, episodic fire-related sedimentation punctuated this time interval, most notably around 650 yrs ago (Fig. 3). This peak in fire-related sedimentation is associated with the “Great Pueblo Drought” of AD 1276–1297, a period of persistent, severely dry conditions that was noted in some of the earliest climate reconstructions using tree rings (Douglass 1929). This megadrought centered on the Four Corners area but affected a much larger region of the Southwest (Cook et al. 2007). It came at the end of a period of generally warmer climate in the western USA from about AD 900–1300 known as the Medieval Climatic Anomaly (Fig. 3). There is also substantial evidence from tree rings, lake levels, and other paleoclimatic records of unusually large fluctuations between wet and dry conditions during this time, which could again promote dense growth of conifer stands followed by extensive severe fires. Prior work in Yellowstone National Park and in central Idaho has also shown the Medieval Climatic Anomaly to be a time of major fire-related debris-flow activity and building of alluvial fans (Meyer et al. 1995; Pierce et al. 2004), illustrating the widespread effects of drought in this interval. The most prominent episode

of postfire debris flows in these areas, however, is correlated with the AD 1140–1162 megadrought, considered to be the worst in North America in the last two millennia (Cook et al. 2007). Fire-related deposits dating to the time of the mid-1100s megadrought are found in the Sacramento Mountains (Fig. 3), but are less common than those emplaced after fires in the late AD 1200s. Overall, the occurrence of major droughts, severe fires, and debris flows across the interior western USA is consistent with an inference of generally higher temperatures during the Medieval Climatic Anomaly.

The effects of warmer climate and severe drought notwithstanding, fire-related sedimentation in the Sacramentos over most of the Holocene is characterized by relatively small and sporadic events, consistent with a regime of low-severity surface fires, with the occasional patch of higher-severity crown fires. Likewise, tree-ring fire-scar records in the Sacramentos show that frequent, low-severity surface burns dominated fire activity throughout the range of forest types, from the beginning of the record about AD 1580 to the late 1800s (Brown et al. 2001). This period falls within the generally cooler and effectively moister climate of the Little Ice Age (e.g., Cook et al. 2007) (Fig. 3). A regime of low-severity fires makes sense during the Little Ice Age, as reduced temperatures and evapotranspiration would promote grass growth to fuel surface fires, as well as limit the potential for reducing moisture levels in the forest canopy to the point where extensive, high-severity crown fires could occur. Since the late 1800s, fire suppression and other land uses greatly limited surface fire activity, and the resulting denser forest stands—along with a warming climate, especially in the last several decades—have

created conditions that are ripe for extensive stand-destroying crown fires.

An interesting aspect of Sacramento Mountains forests are the large, dense stands of Gambel oak that are especially prominent on the upper western slopes of the range. Professor Thomas Swetnam of the University of Arizona Laboratory of Tree-ring Research has hypothesized that these brushy patches represent areas where severe crown fires destroyed conifer stands and Gambel oak recolonized. Identification of charcoal fragments found in soils under oak brush in Caballero Canyon suggest that some past fires at these sites were indeed in conifer stands (New 2007), but further work is necessary to test this hypothesis.

Another question we considered in our Sacramento Mountains work is whether the deep arroyos found along many valley reaches may, at least in part, stem from land uses such as railroad logging and intensive grazing, especially along the eastern flank of the range. The main valley arroyos pre-date modern severe wildfires, but the timing of their initiation is largely unknown. At lower elevations in the Southwest and on the Colorado Plateau, most valley-filling alluvial sequences show clear evidence of alternating episodes of arroyo cutting and valley filling, especially in the last 4000 yrs (e.g., Waters and Haynes 2001; Love 1983). We found no clear evidence of past arroyo incision in the exposures examined for fire-related deposits in the eastern Sacramento Mountains. We also found no place where gravelly deposits filled a deep paleochannel in finer-grained valley fill, as occurred in modern times after the Peñasco fire (Fig. 1). Such a relationship should have been obvious despite imperfect exposures along many present arroyos. Some evidence exists for paleo-arroyo cutting in Caballero Canyon on the west slope, however. The lack of clear precedence for modern arroyos in the eastern Sacramentos suggests that 19–20th century land use may have been an important factor. However, we again need to investigate this question further, including dating the initiation of the present episode of arroyo cutting, and conducting a focused search for paleochannels.

Implications of long-term fire-climate relations

As in other studies of Holocene fire-climate relations (e.g., Pierce et al. 2004), our work in the Sacramento Mountains shows that fire behavior is highly sensitive to relatively modest climatic change. With the high probability of increased temperatures and episodes of severe drought over the next century, catastrophic wildfires and their accompanying debris flows and flash floods will become even more likely in New Mexico’s mountain forests. Thinning of over-dense stands that have resulted from fire suppression, especially in ponderosa pine forests, can reduce

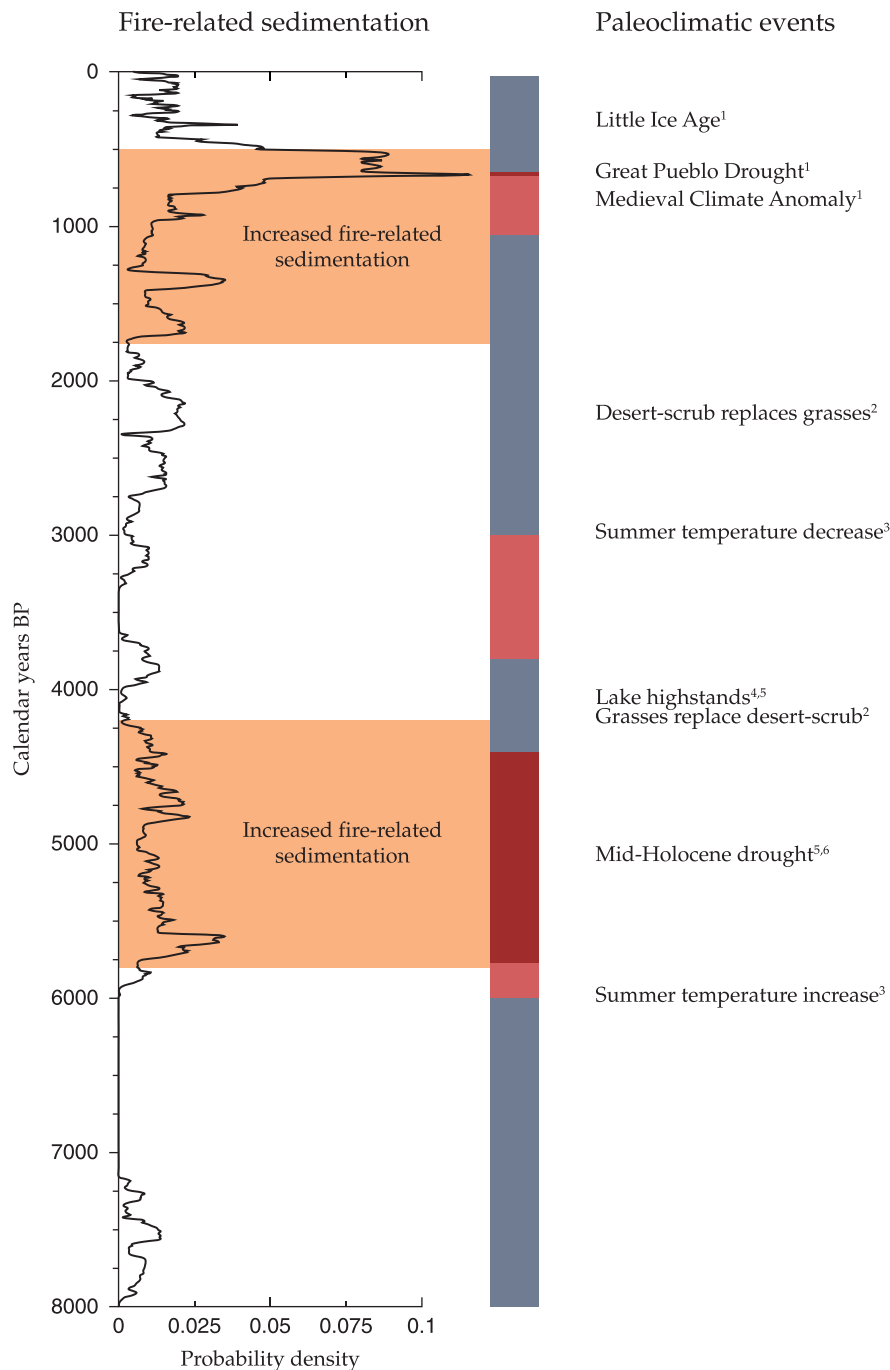


FIGURE 3—Record of fire-related sedimentation in the Sacramento Mountains compared to simplified Holocene paleoclimatic events from the western USA. The curve at left shows the relative probability of fire-related sedimentation, and was constructed by summing probability distributions for calibrated radiocarbon ages on individual fire-related sedimentation events. Periods of increased fire-related sedimentation are inferred based on both radiocarbon age distributions and the nature of stratigraphic evidence for fires. References for paleoclimatic information: ¹Cook et al. 2007, ²Buck and Monger 1999, ³Viau et al. 2006, ⁴Castiglia and Fawcett 2006, ⁵Shuman et al. 2009, and ⁶Davis and Shafer 1992.

the impact of wildfires, but this is a very large and expensive task that can have impacts of its own, for example, in roadless areas, and there is limited commercial value to the small-diameter trees that must be removed. Public awareness of the hazards that stem directly from development in fire-prone forests, as well as those from postfire debris flows and flash floods on alluvial fans, is key to reducing risks to life and property.

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