HOLOCENE CHARCOAL-BASED ALLUVIAL FIRE
CHRONOLOGY AND GEOMORPHIC IMPLICATIONS IN
CABALLERO CANYON, SACRAMENTO MOUNTAINS,
NEW MEXICO

BY

JENNIFER NEW

THESIS
Submitted in Partial Fulfillment of the
Requirements for the Degree of

Master of Science
Earth and Planetary Sciences

The University of New Mexico
Albuquerque, New Mexico

May 2007
ACKNOWLEDGEMENTS

Thanks to Dr. Grant Meyer for bringing me into the Earth & Planetary Sciences Climate and Surface Processes Group at the University of New Mexico. Also, Grant introduced me to the Sacramento Mountains, and assisted with this research project. To my committee members Dr. Leslie McFadden and Dr. Dave Gutzler, I have appreciated your commentary and invaluable coursework.

Thanks also to the faculty and students of the Earth and Planetary Sciences Department and especially the Climate and Surface Processes group. Their help in the classroom and in the preparation of my presentations and thesis has been extremely valuable. I am especially indebted to Jeff Parker and Jed Frechette for help in the field.

Funding was provided by a Geological Society of America Graduate Student Research Grant, New Mexico Geological Society Grants-in-Aid, UNM Research, Project, and Travel Grant, and UNM Earth and Planetary Sciences Department Scholarships.

Hugs and kisses to Jeff and the dog.
HOLOCENE CHARCOAL-BASED ALLUVIAL FIRE CHRONOLOGY AND GEOMORPHIC IMPLICATIONS IN CABALLERO CANYON, SACRAMENTO MOUNTAINS, NEW MEXICO

BY

JENNIFER NEW

B.A., GEOLOGY/ENVIRONMENTAL STUDIES, WHITMAN COLLEGE, 2003

ABSTRACT OF THESIS

Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science
Earth and Planetary Sciences

The University of New Mexico
Albuquerque, New Mexico

May 2007
HOLOCENE CHARCOAL-BASED ALLUVIAL FIRE CHRONOLOGY AND GEOMORPHIC IMPLICATIONS IN CABALLERO CANYON, SACRAMENTO MOUNTAINS, NEW MEXICO

BY

Jennifer New

M.S., Earth & Planetary Sciences, University of New Mexico, 2007

ABSTRACT

Caballero Canyon is a 15.7 km², steep, west-draining watershed in the Sacramento Mountains. The high-relief nature of the watershed has the potential to enhance the geomorphic sensitivity and heighten the response to perturbations such as fire. The watershed is dominated by ponderosa pine and mixed-conifer forests with scattered stands of Gambel oak (Quercus gambelii). It has been hypothesized that these dense stands of oak were established after stand-replacing fire events. These oak brushfields may have filled openings created by such fires and, once established, repeatedly experienced severe stand-replacing fires. Because charcoal preserves cell structures unique to families or species of woody vegetation, charcoal fragments from the alluvial deposits and soil pits dug in Gambel oak stands were identified to address this issue. Nearly 70 percent of the charcoal identified in the alluvium and 80 percent of the charcoal from soil pits was from conifer wood. Therefore stand-replacing fires in this area occur primarily in conifer-dominated forests.

Alluvial valley fill deposits in Caballero Canyon contain fire-related deposits identified by their sedimentary characteristics and by high concentrations of charcoal. Fragments of charcoal from these deposits were radiocarbon dated, revealing patterns in fire-induced sedimentation activity for the last 2800 years. Both high-severity and lower-severity fires characterize the record from 2800 yr. B.P. to 1300 cal yr B.P. A 300-year hiatus in fire-induced sedimentation activity follows this period and in turn is abruptly terminated at 1000 yr. B.P by a spike in probability of fire-induced events. This spike corresponds to a time in climate proxy records with elevated temperatures and episodes of severe multidecadal drought, commonly referred to as the Medieval Warm Period. There are no fire-related sedimentation events during the last 300 years, corroborating tree-ring evidence that fire regimes just prior to Euro-American settlement were dominated by low-severity fires. This period, however, is anomalous when examined in the context of the late Holocene record.
# TABLE OF CONTENTS

Acknowledgements ................................................................................................................... iii

List of Figures ........................................................................................................................... viii

List of Tables ............................................................................................................................ ix

Introduction ............................................................................................................................... 1
  Rationale .................................................................................................................................... 3
  Fire and Climate ..................................................................................................................... 4
  Forest Composition ............................................................................................................... 5
  Alluvial Chronologies of Fire .............................................................................................. 6
  Geology of the Sacramento Mountains ................................................................................ 8

Methods ...................................................................................................................................... 9
  Modern Analogs for Fire-induced Sedimentation: Peñasco Fire ......................................... 9
  Caballero Canyon Alluvium .................................................................................................. 11
  Caballero Canyon Slope Colluvium ....................................................................................... 16
  Radiocarbon Dating Procedure ............................................................................................ 16
  Charcoal Identification ......................................................................................................... 17

Results ...................................................................................................................................... 19
  Caballero Canyon Alluvial Stratigraphy .............................................................................. 19
  Radiocarbon Dates .............................................................................................................. 19
  Charcoal Identification ........................................................................................................ 22

Discussion ................................................................................................................................ 23
  Fire-related Deposits and Stratigraphic Interpretations ....................................................... 23
  Radiocarbon Dates .............................................................................................................. 26
  Geomorphic implications ..................................................................................................... 32
  Charcoal Identification ........................................................................................................ 34
  Regional Climate Proxies ..................................................................................................... 35
  Holocene Climate ................................................................................................................ 36

Conclusions ............................................................................................................................... 43
List of Figures

Figure 1: Alluvial fan deposits that resulted from the 2002 Peñasco fire................. 9
Figure 2: An exposure of a thin 2002 Peñasco fire-related debris flow deposit
       burying a thick A horizon and Bk horizons. ..................................................... 10
Figure 3: A channel scoured by post-fire erosion in the years following the Peñasco
       fire....................................................................................................................... 10
Figure 4: Location map of Caballero Canyon......................................................... 12
Figure 5: Calibrated radiocarbon probability curves from fire-related stratigraphy. 
.................................................................................................................................. 21
Figure 6: An example of a “probable severe” fire deposit from stratigraphic section
       001....................................................................................................................... 24
Figure 7: An example of a deposit interpreted to be the result of a “possible severe”
       fire. ....................................................................................................................... 25
Figure 8: Examples of deposits interpreted as related to “non-severe” fire-related
       sedimentation events.......................................................................................... 26
Figure 9: Variation in cumulative probability curves as a result of grouping of
       radiocarbon dates. ............................................................................................... 30
Figure 10: Plots showing tree-ring based climate reconstructions and the summed
       probability of fire-related sedimentation in Caballero Canyon. ...................... 39
List of Tables

Table 1: Total number of charcoal samples identified and the relative concentrations of gymnosperm and angiosperm charcoal. ........................................ 22

Table 2: Stratigraphic units with greater than 50% angiosperm charcoal and their corresponding radiocarbon dates. ................................................................. 22

Table 3: Units from different stratigraphic sections interpreted to be from the same fire event .......................................................... 28
Introduction

Recent crown fires in conifer forests of the Sacramento Mountains and throughout the Southwest have razed forest stands and heightened the public’s awareness of the damage that they cause. In 2000, the Scott Able fire burned 6,600 ha in the Sacramento Mountains, and the Cerro Grande fire burned 17,200 ha near Los Alamos, New Mexico. In 2002, the Rio Peñasco fire burned 6,200 ha in the Sacramento Mountains, and the Rodeo-Chediski fire burned 190,000 ha near Show Low, Arizona, destroying 426 structures including 250 homes (National Interagency Coordinating Center, 2006). In addition to the direct impact of fire on vegetation and infrastructure, geomorphic responses to these severe fires have been widespread. Fire changes the hydrology of mountain slopes resulting in debris flows and sediment-charged flood events. These sediment transport events erode soil from slopes, initiate valley floor trenching or filling, damage roads and buildings, and can alter river ecosystems in the months and years following the fire (Bisson et al., 2003; Cannon et al., 2001a; Benda et al., 2003).

Studies conclude that these large fires are unique to the last few decades. These reports are based on tree-ring data that show that prior to the late 20th century, fire regimes for the last 500 years were characterized by frequent, low-severity events (e.g. Brown et al., 2001; Kaye and Swetnam, 1999). Forests in the Sacramento Mountains, for example, experienced frequent, low-severity fires with a recurrence interval between a few years to a decade, but direct evidence of pre-settlement stand-replacing fires has not been found (Brown et al., 2001). The recent severe fires in the Southwest are commonly attributed to anthropogenic alterations to forest density through land use and fire suppression (Allen et al. 2002; Brown et al., 2001; Covington and Moore, 1994).
In the late 19th and early 20th centuries, forests in the Southwest were exploited for their valuable resources. Railroad construction into the Sacramento Mountains was finished in 1898 and opened the range to intensive logging concentrated on the east side of the range, at the same time that cattle grazing stripped the herbaceous cover from the mountainsides (Brown et al. 2001, Kaye and Swetnam, 1999). The depletion of understory grasses reduced the spread of frequent low-severity surface fires. Coupled with active regional fire suppression over the last century, smaller, young trees survived, creating dense thickets in naturally open, ponderosa pine (*Pinus ponderosa*)-dominated stands (Swetnam and Betancourt, 1990, Covington et al. 1997). Now, near-continuous fuels produce the laddering effect that carries fire into the canopy (Brown et al., 2001; Fule et al., 1997).

Studies from Yellowstone National Park and southern Idaho extend the history of fire in the West and show that on millennial timescales, recent severe fires are not unprecedented. There have been climatically warm and dry periods in the past with similar fire regimes to the present (Pierce et al., 2004; Whitlock and Anderson, 2003; Meyer et al., 2002). This suggests that in addition to forest management practices, climate may be playing an equally important role in regulating fire regimes throughout the western United States and in the Sacramento Mountains (Westerling et al., 2006). The catastrophic nature of both the fires and resulting geomorphic response creates public alarm, especially as forests become increasingly developed. Therefore it is important to examine the past relationship between fire, climate, and geomorphic instability in the Sacramento Mountains to provide insight into natural fire patterns and their geomorphic consequences.
Rationale

Previous studies conducted by Meyer et al. (1995) and Pierce et al. (2004) described the geomorphic responses of small <4 km² watersheds to catastrophic fires by examining the sediment in small alluvial fans along larger drainage basins. Using a similar technique, this research focuses on Caballero Canyon, a 15.7 km² west-draining watershed in the Sacramento Mountains. The high-relief (~780 m) nature of the watershed has the potential to enhance the landscape sensitivity and heighten the response to perturbations such as fire. Alluvial valley fill is well exposed in an incised channel in the middle reach of the canyon. Up to five meters of natural exposure shows a variety of stratigraphy including layers of charcoal-rich sediment, alluvial gravels, and travertine deposits. The alluvium provides an opportunity to determine if there is a history of intense, stand-replacing canopy fires on the west side of the mountain range, and examine how the fire-related sedimentation is tied to the alluvial history of the canyon. A detailed investigation in this watershed provides an opportunity to gain deeper insight into geomorphic processes that have shaped this canyon which might be overlooked by a more spatially widespread study.

Much of the paleo-fire research conducted in the southwest has been concentrated in ponderosa pine and mixed-conifer forests. Within the mixed-conifer forests of the Sacramento Mountains dense stands of Gambel oak (*Quercus gambelii*) dominate swaths of land. The long-term fire history and dynamics of this woody plant are poorly understood (Floyd et al. 2000). These stands of oak may represent the first vegetation regenerated after a stand-replacing fire in a conifer forest, and the conifer species slowly encroach and reestablish their dominance. It has been suggested that these stands
repeatedly and preferentially burn because of their high-density growth patterns and rapid recovery, but this hypothesis is impossible to test using tree-ring methods (Swetnam pers. comm.). By identifying the types of wood preserved as charcoal in alluvial deposits, this study investigates the validity of these hypotheses and to determine whether severe burns in Gambel oak stands have generated sedimentation events that were recorded in the alluvial valley fill.

**Fire and Climate**

In present-day New Mexico, fires predominantly occur in the early summer, when conditions are warm but before the monsoonal rains of late June and July have added moisture to the system (Brown et al., 2001, Swetnam and Betancourt, 1998). During wet years, understory vegetation in ponderosa pine (*Pinus ponderosa*) forests provides more fuel for future fires. When a dry year follows a wet year, or series of wet years, fires tend to occur. Antecedent conditions are less important in mixed-conifer forests, possibly because the buildup of fine fuels is less important in their fire dynamics (Swetnam and Betancourt, 1998). In addition, studies have shown that the number of acres burned is partially regulated by the El Niño Southern Oscillation (ENSO) (Swetnam, 1990). In the Southwest, ENSO conditions generally correlate to wet winters, therefore the fuel is moist during the early summer and fires are naturally suppressed (Swetnam and Betancourt, 1990). The antiphase part of the ENSO cycle, La Niña, is manifested in the Southwest as winters with below-average precipitation, therefore the fuel is drier and fires are more probable.

Research in the last two decades has shown that patterns of fire and climate are closely linked on millennial time scales. There is strong evidence that the time period
often referred to as the Medieval Warm Period, a time when climate proxy records show episodes of unusually warm, dry conditions in the western United States, corresponds to a peak in fire activity and an abundance of severe fires (Meyer et al., 1992; Pierce et al., 2004; Cook et al., 2004). Given the current climate warming trends (Jones et al., 1999), it is important to examine records of the past to help predict how forest fire regimes will respond.

**Forest Composition**

Within the Sacramento Mountains, spatial variability in climate controls plant demography. Annual precipitation and temperature gradients allow for xeric forests at low elevations and more temperate forests at high elevations. Pinyon-juniper woodlands are found at low elevations and are dominated by alligator juniper (*Juniperus deppeana*) and pinyon pine (*Pinus edulis*). Ponderosa pine (*Pinus ponderosa*) with Gambel oak (*Quercus gambelii*) commonly found in the understory occur above the pinyon-juniper forests and in mesic canyons. At higher elevations, Douglas-fir (*Pseudotsuga menziesii*) and southwestern white pine (*Pinus strobiformis*) become more common forming a mixed-conifer forest (Brown et al., 2001).

Woody understory brush such as Rocky Mountain maple (*Acer glabrum*), mountain mahogany (*Cercocarpus montanus*), varieties of ash (*Fraxinus velutina* and *Fraxinus cuspidata*), rock spiraea (*Holodiscus dumosa*), quaking aspen (*Populus tremuloides*), southwestern chokecherry (*Prunus serotina*), hop tree (*Ptelea trifoliata*), wavy leaf oak (*Quercus undulata*), sawtooth buckthorn (*Rhamus serrata*), New Mexico locust (*Robinia neomexicana*), and New Mexico elder (*Sambucus cerulea*) can be found in the understory in varying concentrations (Tim Lowrey, UNM, pers. comm. 2005).
Stands of Gambel oak (*Quercus gambelii*) are scattered along the high elevation watersheds between 7900 and 8800 feet along the western border of the range. The oaks grow on slopes of varying incline and aspects with tree heights ranging from small shrubs to ~35 ft trees. The trees grow in groups of similar heights, and presumably similar ages, but within a stand multiple groups of different heights were found. Pockets of southwestern white pine (*Pinus strobiformis*) and ponderosa pine (*Pinus ponderosa*) are not uncommon in the predominantly Gambel oak thickets. Gambel oak has an interesting response to fire. After a severe fire that killed all aboveground vegetation in 1989 in Mesa Verde National Park, researchers noted that underground portions of Gambel oak survived and quickly resprouted within months (Floyd et al., 2000). After two years, the shrub cover had rebounded to pre-burn densities, with height being the only distinction between burned and unburned vegetation.

The study documenting fire-scarred trees in the Sacramento Mountains found that the fire frequency of low-severity surface fires on the west side of the range does not differ with elevation, as would be hypothesized based on differing forest compositions (Brown et al., 2001). However, a higher fire frequency was found on the west side of the range in comparison to the forests on the more gradually sloping east side. Fires may spread more readily with westerly prevailing winds. Also, with much steeper western slopes, there are shorter distances and fewer topographic breaks between stands. Brown et al. (2001) found no evidence of stand-replacing fires.

**Alluvial Chronologies of Fire**

Over a range of climates, fires can enhance sediment transport and deposition, especially in areas of high relief (e.g. Swanson, 1981; Florsheim, 1991; Meyer and Wells,
Fire decreases the ability of water to penetrate soil by clogging pore spaces with ash and fine sediment, and by coating grains with hydrophobic organic compounds (Moody and Martin, 2001). It also reduces ground cover of living and dead organic matter, exposing mineral soil to surface processes (Swanson, 1981). Reduced interception and evapotranspiration from loss of vegetation may increase soil moisture during wet seasons. Reducing surface roughness by burning forest litter and small plant stems, and by the removal of flow obstructions including trees, shrubs, and fallen logs, reduces infiltration and increases the erosive power of overland flow (Cannon et al., 2004). The effects of these changes on the vegetation and landscape enhance the chance that precipitation events will generate overland flow, increase channelized streamflow, hyperconcentrated flow, rilling and gullyling, and debris flows (Meyer et al., 1992). Also, after severe burns, root strength decreases and landslides may ensue, especially in moist regions such as the Pacific Northwest (Schmidt et al., 2001). The resulting deposits can be used to develop a stratigraphic record of fire-related sedimentation. A description of streamflow, hyperconcentrated flow, and debris flow and the identifying characteristics of their deposits can be found in Appendix A. In reality, there is a continuum between these processes.

Meyer et al. (1995) and Pierce et al. (2004) have shown that fire-induced alluvial deposits provide a means for extending fire history data back thousands of years. These studies used deposits from the past 10,000 years in Yellowstone National Park and central Idaho to document evidence of mixed-severity to stand-replacing fires and show that fire regimes may be closely linked to millennial-scale variations in climate. One implication is that, in addition to human land management, 20th century warming is
partly responsible for recent severe fires in this Northern Rocky Mountain study area (Meyer and Pierce 2003).

Exposures of alluvial valley fill sediment in Caballero Canyon provide a location to study fire-related sedimentation history in southern New Mexico. In addition, these exposures provide an opportunity to examine the overall geomorphic stability of this watershed.

**Geology of the Sacramento Mountains**

The Sacramento Mountains are an east-tilted fault block, bounded on the west side by the Alamogordo normal fault, an extension of the Rio Grande Rift (Koning et al. 2002). The west side of the range rises steeply above the Tularosa Basin and features a stepped profile with a large bench forming the most prominent step. Topography below the bench is characterized by steep, rugged ridges and canyons; at higher elevations the land is relatively unbroken. The bedrock geology of Caballero Canyon consists of limestones, dolostones, sandstones and shales that were the result of several transgressional and recessional sea level cycles through the Paleozoic (Pray, 1941; Raatz, 2001).
Methods

Modern Analogs for Fire-induced Sedimentation: Peñasco Fire

The identification and interpretation of fire-related alluvium can be difficult. Variation in the deposits can result from variations in fire severity, topography and slope, the bedrock geology, and the amount and intensity of rainfall in the years following the fire. Without a modern analogue that can be directly related to the study area, uncertainty arises in the interpretation of stratigraphy. The 2002 Rio Peñasco fire on the east side of the Sacramento Mountains provides the best modern analogue for sedimentary comparison. It burned 6,200 ha, many of them severely. Through the summer of 2005 and possibly more recently, tributary drainages to the Rio Peñasco have released debris flows initiated by summer monsoonal rains, providing modern deposits to examine (Fig. 1 & 2). Associated tributary channels have been deeply scoured (Fig. 3). The channel bottoms show only the remains of the debris flows, a relatively thin layer of gravel that has been reworked and imbricated by streamflow. These channels guide the sediment onto alluvial fans in valleys draining the east side of the mountain range.

Figure 1: Alluvial fan deposits that resulted from the 2002 Peñasco fire. A) Most deposits are clast-supported at the surface, deposited by debris flow with post-deposition reworking or streamflow. B) Where post-2002 debris-flow fan deposits have been incised or exposed by road cuts, matrix-rich deposits are more common.
Figure 2: An exposure of a thin 2002 Peñasco fire-related debris-flow deposit burying a thick A horizon and Bk horizons. Buried soils in the alluvial fans provide a record of stability between past debris flow events and have been studied in greater detail by Jed Frechette (2007). The contact between the debris flow and the soil development is just below the pen.

Figure 3: A channel scoured into footslope colluvium by post-fire erosion in the years following the Peñasco fire. Note the undercut fence posts hanging ~1.5 m in the air.

A model for sedimentary response to fire developed on the east side of the range should be applied with caution to the west side. Although the geology and meso-scale climate remain constant, forest transitions, slope angles, relief, and microclimates are appreciably different. The two landscapes may have different geomorphic responses to
fire, but these observations are nevertheless helpful in the interpretation of deposits from past fires.

**Caballero Canyon Alluvium**

Nine stratigraphic sections chosen for their accessibility and degree of exposure were described in the main channel draining Caballero Canyon. Exposures that are 1.5-5.5 meters in height were generated by arroyo incision into the valley alluvium in gently sloping sections of the canyon floor. Eight of the nine sections are located along a natural topographic bench at approximately 7200 ft elevation (Fig. 4). One section was described approximately one mile downstream at 6500 feet. It was chosen because of its interesting stratigraphy with prominent charcoal layers and different character from any others. A total of five soil pits were dug in the two primary patches of Gambel oak in Caballero Canyon. Three of the pits were approximately evenly spaced at 200 ft in elevation to capture soil variations within the oak stand.
Figure 4: Location map of Caballero Canyon A) in reference to the state of New Mexico (box in the south-central part of the state). B) The two sites where alluvial stratigraphy was described are shown as red dots. C) A topographic map showing the upper Caballero Canyon watershed (referenced in B by a box), with upper stratigraphic site shown by red dot.
Descriptions of the sediment were geared toward interpreting the depositional processes of the deposit (e.g. resulting from a debris flow, hyperconcentrated flow, or streamflow; Meyer and Wells, 1997), distinguishing between deposits of different character, and identifying soils and buried soil horizons. Units were divided based on changes in color, texture, percent of >2 mm diameter clasts, sorting, and percent charcoal. Each layer was evaluated for its thickness, character of the lower contact, degree of effervescence, degree of sorting, mean grain size, and the character of travertine within the unit. Clasts greater than 2 mm were judged on their roundness, orientation, size, and lithology. Soil descriptions included the soil texture, the moist and dry colors, and the sedimentary structures (App. B).

In addition, the amount of charcoal was described using the following scale: very few (<<1% of volume), few (<1%), common (1-5%), many (5-25%), and very many (>25%) fragments. The angularity, size, and distribution of the charcoal were recorded. In units with common to very many, charcoal samples were taken in plastic baggies with care not to crush or touch the samples. The location of the samples within the stratigraphy was noted along with specific descriptions of the charcoal fragments.

The sedimentary and stratigraphic descriptions were employed in the designation and interpretation of fire-related deposits. It has been well documented that a variety of sediment transport processes ranging between debris flow, hyperconcentrated flow, and streamflow can be triggered as a result of slope instability caused by forest fire (Appendix A; Meyer and Wells, 1997). Due to the range in fire-related deposit characteristics and the atypical, mid-slope topographic position of the sediment
accumulation, the concentration of angular charcoal was one of the primary features used for their initial identification in the Caballero Canyon study site.

The “fire-related” deposits were classified as resulting from a “probably severe” fire if they were charcoal-rich coarse-grained debris-flow deposits, or fine-grained charcoal-rich deposits overlain by debris-flow deposits (Appendix A). In the Southwest these flows are generally triggered by sediment bulking resulting from rill erosion on steep slopes leading to deep incision that develops into a debris flow downslope (Meyer and Wells, 1997; Cannon et al., 2001b). Therefore, in order to initiate a debris flow, sufficient area in the watershed must be severely burned for overland flow to erode and entrain sediment in concentrations necessary to carry large clasts. These deposits that are positively identified as the result of debris-flows are poorly sorted or unsorted with cobble to boulder-sized clasts. They are typically matrix-supported, but the tops of the deposits may be clast-supported, a result of secondary reworking or kinetic sieving.

A deposit is classified as the result of a “possibly severe” fire if it met the same criteria as a severe event, but the relationships between the charcoal-rich deposits and coarse-grained deposits were more obscure. In addition, the mode of deposition for a few massive, fine-grained deposits with scattered gravel and charcoal was difficult to determine. It is possible that they were the result of fine-grained debris flows, but it is difficult to be definitive.

Deposits were also classified as the result of “non-severe” fires if they were entirely fine-grained. This classification is based on the assumption that if a fire burned a sufficient area, debris-flow or hyperconcentrated flow processes would result in the transport of pebbles, cobbles, or boulders. Therefore “non-severe” fires must have
burned areas exceeding a threshold for producing a sedimentation event, yet insufficient
to develop into a catastrophic event. Unfortunately this threshold is qualitative, as no
modern fires on this west side of the Sacramento Mountains are available to quantify
these assumptions. Debris flows can result in gravel-poor facies (Meyer and Wells,
1997), however without poorly-sorted gravels it is difficult for them to be identified
confidently.

In some cases “non-severe” fire-related deposits were further classified as pool-
fills or burned soil surfaces. The modern channel has a stepped profile, where the steep
sections are characterized by travertine accumulation. The low-gradient pool sections are
filled with grasses. These pools trap fine-grained sediment and may trap reworked
charcoal, or collect charcoal-rich sediment after a non-severe fire. Meyer et al. (1995)
identified burned soil surfaces in fire-related alluvium as thin layers with high charcoal,
needle, and seed concentrations. These layers were often overlain by fire-related deposits
that were triggered by the same fire event. Similar deposits were found in Caballero
Canyon.

The valley floor of Caballero Canyon is a very dynamic environment as indicated
by channel scour and filling, travertine deposition, and a wide range in the character of
sediment deposits. This makes it very difficult to laterally trace deposits between
stratigraphic sections, but provides an opportunity to examine the history of arroyo
incision and filling. The designations as “probably severe” and “possibly severe” were
further refined based in part on the number of stratigraphic sections that included units
from a particular fire-related sedimentation event. The more sections in which a deposit
was found, the larger and more extensive the deposit, and therefore, the more likely it
was to be the result of a severe fire. Radiocarbon dating allowed for the grouping of deposits of the same age and similar sedimentary characteristics.

**Caballero Canyon Slope Colluvium**

Five soil pits were excavated into the slope colluvium on the steep, high-elevation slopes of the watershed. Three were approximately evenly spaced by elevation to investigate variations in soil development with slope position within the patches of oak. The same analyses were conducted as on the alluvium. Charcoal fragments from the colluvium were radiocarbon dated to determine whether the charcoal found in the upper watershed corresponded to a fire that produced a sedimentation event. In addition the ages give insight into recent fire activity within the stands.

**Radiocarbon Dating Procedure**

Charcoal samples for radiocarbon dating were primarily angular fragments of carbonized wood preserved in the alluvium of fire-related stratigraphic units. Small twigs or seeds were dated whenever possible to eliminate the chance of inbuilt ages caused by the dating of an inner ring of an old tree. For example, alligator juniper (*Juniperus deppeana*) in the area are known to live up to 500 years (Loehle, 1988) and the dating of an inner ring would yield an age hundreds of years older than the fire event that released that fragment into the sedimentary record. Charcoal reworking through erosion and redeposition as well as bioturbation may also cause anomalous ages.

Forty-six samples were pretreated at the University of New Mexico using the procedures developed by the University of Arizona Accelerator Mass Spectrometer (AMS) lab. These samples were taken to the University of Arizona for combustion and radiocarbon analysis. Three samples were pretreated and analyzed at Beta Analytic in
Miami, FL. Ages were converted from radiocarbon age to calibrated calendar years with CALIB 5.0 to facilitate comparison with other calendar year proxy records (Stuiver and Reimer, 1993).

**Charcoal Identification**

The premise behind identifying the charcoal in sediment deposits was to determine whether Gambel oak patches burn more often than the surrounding mixed-conifer forests. Tree species can be distinguished by examining the cell structure of wood (Hoadley, 1990). Although charcoal is more fragile, these signature features are preserved during carbonization, allowing charcoal to be identified in the same fashion (February, 2000) (App. C). A vegetation survey conducted by Prof. Tim Lowrey, a botanist at the University of New Mexico, included the collection of samples from all woody species in the study area (App. D). These samples were burned for comparison with fragments recovered in the alluvial stratigraphy. Charcoal fragments collected from fire-related stratigraphy were identified with the help of Lisa Huckell, a paleoethnobotanist at the University of New Mexico using a Zeiss 50x microscope. This magnification is sufficient to discern between gymnosperms from angiosperms, but higher magnification is needed to further divide between many families, genera, and species.

Ten samples from each layer interpreted as related to a fire-induced sedimentation event were identified. In seven cases 10 identifiable charcoal fragments were not available. In these cases all samples collected were identified. In section 009, eight of nine units had no sufficiently large fragments for identification. In these cases no samples were identified.
Larger charcoal fragments fractured into multiple pieces during collection. Care was taken to have each sample represented only once in the identification data. It is possible that multiple fragments from a single tree were deposited in close proximity within the sediment, and thus would skew the representation of species within a deposit.
Results

Caballero Canyon Alluvial Stratigraphy

Annotated stratigraphic section photographs are shown in Appendices E-G. These contain brief unit descriptions and charcoal sample locations with radiocarbon-year ages, and illustrate relations between dated units in a comprehensive manner. These figures are very useful in considering the discussion that follows. The alluvial fill in Caballero Canyon contains stratigraphic evidence of multiple episodes of aggradation and incision and a variety of fire-related sediment deposits. The description of nine stratigraphic sections exposed within the main channel of the canyon revealed 37 units that contained enough charcoal to be classified as fire-related deposits. Samples from all of these units were radiocarbon dated. Twenty-nine such units were found in stratigraphic sections located on the topographic bench at 7200 ft elevation (2194 m) (App. E). Eight were found approximately 1 mile downstream in an exposure at approximately 6500 ft (App. F). In an undescribed section, located approximately halfway between the two site locations, a layer of very charcoal-rich sediment was found at the base of a ~6 m, vertical exposure and radiocarbon dated (App. G).

Radiocarbon Dates

Forty-nine charcoal fragments or groups of fragments from each unit identified as fire-related were radiocarbon dated and the date calibrated. The dates are plotted in calibrated years before 1950 (Fig. 5 a&b). The uncalibrated results from the radiocarbon analyses are available in Appendix H. The calibrated radiocarbon probability curves are plotted by depth to allow for many curves to be individually viewed on the same time scale (Fig. 5 a&b).
The radiocarbon dates from the Gambel oak patches in the upper watershed (shown in green, Fig. 5 b) were mostly very young. One exception (UpCab2) has a probability peak at approximately 525 cal years B.P. Note that multiple dates were obtained from single fire-related deposits in a few sections.

The record of fire-related sediment deposits for this canyon spans 2,800 cal years (Fig. 5). Due to episodic cutting and filling of Caballero Canyon’s valley floor, each stratigraphic section recorded an overlapping but different time span. Deposit ages from most stratigraphic sections fall into the age range of 300 to 1000 calibrated years B.P. (Fig. 5 b). The oldest dates came from section 009, an exposure approximately 1 mile downstream from other stratigraphic sections (Fig. 4). Sections 005 and 008 contained older units from the time period between 1200 and 2000 cal yr B.P. These sections were in close proximity and on opposite sides of the arroyo. Section 008 is in a small tributary exposure off the main arroyo.
Figure 5: Calibrated radiocarbon probability curves from fire-related stratigraphy. Dates are vertically arranged according to their depth below the modern floodplain. The top of the stratigraphic section Section 009 was not measured from the floodplain. The relative probability curves are color-coded by stratigraphic section. The two figures are plots of the same data, B is an enlarged version of the last 1000 cal yr B.P.
In seven cases the results from radiocarbon analysis produced dates that were anomalous with respect to other dates from the section (i.e., younger dates underneath older dates). This may have resulted from bioturbation, inbuilt age, sediment reworking, or insufficient pretreatment of highly contaminated samples.

**Charcoal Identification**

A total of 326 samples were examined under a microscope and classified into angiosperm or gymnosperm groups (Table 1). Many of the samples were very small (a few millimeters in diameter), or poorly preserved, and this was the most precise designation possible. Out of the 99 samples identified as angiosperm, 22 were positively identified as *Quercus* spp. and 10 as mountain mahogany (*Cercocarpus montanus*). These are the two most common angiosperm species in the basin, and the relative concentrations of charcoal fragments may reflect their relative abundance. Many samples were narrowed to two or three possible genera or species, or labeled as undifferentiated if angiosperm was the most precise designation possible (App. C). Some units had greater than average concentrations of angiosperm charcoal (Table 2).

**Table 1: The total number of charcoal samples identified and the relative concentrations of gymnosperm and angiosperm charcoal.**

<table>
<thead>
<tr>
<th>Gymnosperms</th>
<th>Sample Count</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>227</td>
<td>69.6</td>
</tr>
<tr>
<td>Angiosperms</td>
<td>99</td>
<td>30.4</td>
</tr>
<tr>
<td><strong>Total Sum</strong></td>
<td><strong>326</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

**Table 2: The stratigraphic units with greater than 50% angiosperm charcoal and their corresponding radiocarbon dates.**

<table>
<thead>
<tr>
<th>002N</th>
<th>003I</th>
<th>005S</th>
<th>007F</th>
<th>007K</th>
<th>007M</th>
<th>008G</th>
</tr>
</thead>
<tbody>
<tr>
<td>n=</td>
<td>%</td>
<td>n=</td>
<td>%</td>
<td>n=</td>
<td>%</td>
<td>n=</td>
</tr>
<tr>
<td>Gymnosperm</td>
<td>5</td>
<td>50</td>
<td>4</td>
<td>57</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Angiosperm</td>
<td>5</td>
<td>50</td>
<td>3</td>
<td>43</td>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>Radiocarbon date (¹⁴C yr B.P.)</td>
<td>646±38</td>
<td>894±36</td>
<td>1,932±46</td>
<td>703±44</td>
<td>841±36</td>
<td>1,010±32</td>
</tr>
<tr>
<td></td>
<td>843±32</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Discussion

Fire-related Deposits and Stratigraphic Interpretations

With no modern analog on the west side of the Sacramento Mountains, the interpretation of the sediment in Caballero Canyon is less straightforward. The majority of the Peñasco fire-related deposits were gravel-rich debris-flow remnants, with low concentrations of charcoal. Sediment generated after the Peñasco fire was deposited on steeply-sloping alluvial fans that have formed at the mouth of small canyons. In comparison, Caballero Canyon is a much larger basin with greater relief than those basins that burned in 2002. The alluvium was deposited on a confined, gently sloping bench. The sediment in Caballero Canyon has relatively abundant charcoal compared to sediment resulting from the Peñasco fire, yet compared with descriptions of sediment from Idaho and Yellowstone (Meyer per. comm., 2006), the charcoal concentrations are relatively low.

Two sets of deposits in the Caballero Canyon drainage were confidently identified as related to a “probable severe” fire. Those events had debris-flow sedimentary characteristics, and were recorded in several stratigraphic sections. This indicates a relatively large depositional event. For example, three units described in section 001 combined to have the characteristics of a “probable severe” fire deposit (Fig. 6). The bottom fine-grained unit (E) may represent a debris-flow “precursor surge” (Pierson, 1986) or an early phase of a debris-flow event of muddy streamflow (Wells and Harvey, 1987) that carried charcoal-rich fine-grained sediment prior to the larger debris flow (G). Although the debris-flow deposit has a very low concentration of charcoal, the coarse-grained debris flow may have ground up fragile charcoal during flow. Later, after the
debris flow was deposited, more dilute flow material washed fine-grained material from the upper 14 centimeters (F), reworking and imbricating the gravel. A modern analog (Fig. 1b) shows fine-grained material buried by a poorly-sorted debris flow deposit and a nearby clast-supported gravel deposit (Fig. 1a) that likely underwent secondary reworking.

![Image](image.png)

**Figure 6:** An example of a “probable severe” fire deposit sequence from stratigraphic section 001. Unit E is a charcoal-rich, fine-grained deposit that is overlain by a poorly-sorted matrix-rich gravel (G) deposit and a well-sorted and clast-supported gravel (F). Black lines on the orange scale are spaced at 10 cm intervals.

Units classified as the result of a “possible severe” fire required more interpretation than those labeled “probable severe.” An example is in section 004, where a thin fine-grained deposit with a concentration of charcoal (D) is at the base of a channel scour-fill sequence (B and C) (Fig. 7). The sediment is bioturbated, suggesting that it was not immediately buried by the overlying gravel. A sequence of events beginning with the scouring of a channel similar to the modern analog (Fig. 3) can be used to help classify these deposits. After scouring, gravel and small boulders filled the channel by a
combination of hyperconcentrated flow and streamflow. There is no characteristic matrix-rich gravel, and bioturbation creates uncertainty in the relationship between the fine-grained deposit and the gravels.

Figure 7: An example of a deposit interpreted to be the result of a “possible severe” fire. Section 004 has a charcoal-rich layer (D) overlain by a series of fill deposits (B and C). Black lines on the scale are spaced at 10 cm intervals.

The “non-severe” classification is reserved for fine-grained deposits with relatively high concentrations of charcoal, and in some cases these deposits were further classified as burned soils or pool-fills. These are somewhat more difficult to interpret because other than the presence of charcoal, there is nothing to distinguish them from other non-fire related deposits (Fig. 8). Since these units can not be definitively related, the fine-grained unit is classified as “non-severe.”
Figure 8: Examples of deposits interpreted as “non-severe” fire-related sedimentation events (G and I). There are no gravels associated with these charcoal-rich deposits. Black lines on the scale are spaced at 10 cm intervals.

One thin, hydrophobic, continuous layer (007K) with a high concentration of charcoal was classified as a burned soil. Seeds and needles are absent and a unit with 20% gravel but very little charcoal overlies the burned soil. Since these units can not be definitively related, the fine-grained unit is classified as “non-severe.”

Radiocarbon Dates

The cut and fill nature of the alluvial system in Caballero Canyon makes it difficult to correlate units throughout the study reach prior to radiocarbon dating samples. Deposits from the same event may have been dated more than once with samples from different sections. To reduce this repetition, units were grouped according to their radiocarbon date and a statistical significance test was conducted using CALIB 5.0 to ensure that at a 95% confidence level the dates from each group were the same (App. I). Dates in this study had $1\sigma$ values that ranged from ± 31 to ± 55 uncalibrated radiocarbon years. Therefore this test alone is not sufficient to identify repeated stratigraphy. The sedimentologic characteristics of each layer were analyzed and groups were further refined. Through this procedure I found that there are at least 10 events that were likely dated more than once (Table 3).
It must be noted that sedimentary characteristics vary between locations and therefore there is a large degree of uncertainty in these groupings (App. I). Despite uncertainties, this procedure serves to provide a minimum value for the number of fire-related events in Caballero Canyon. Depending on the initial interpretation of the deposits and the number of sections in which an interpreted group shows up, each group was reanalyzed and determined to be the result of a probable severe, possible severe or non-severe fire event.
<table>
<thead>
<tr>
<th></th>
<th>Independents</th>
<th>Anomalous</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-severe</td>
<td>Probable severe</td>
<td>Possible severe</td>
</tr>
<tr>
<td>001C</td>
<td>001G</td>
<td>002C</td>
</tr>
<tr>
<td>584</td>
<td>39</td>
<td>690</td>
</tr>
<tr>
<td>003E</td>
<td>001E</td>
<td>002D</td>
</tr>
<tr>
<td>622</td>
<td>32</td>
<td>531</td>
</tr>
<tr>
<td>003H</td>
<td>002I</td>
<td>007D</td>
</tr>
<tr>
<td>562</td>
<td>38</td>
<td>627</td>
</tr>
<tr>
<td>005H</td>
<td>003K</td>
<td>008A</td>
</tr>
<tr>
<td>612</td>
<td>37</td>
<td>576</td>
</tr>
<tr>
<td>005L</td>
<td>009U</td>
<td>UpCab1-Non</td>
</tr>
<tr>
<td>557</td>
<td>37</td>
<td>2258</td>
</tr>
<tr>
<td>Und.Bbark</td>
<td>005S-Non</td>
<td>009G</td>
</tr>
<tr>
<td>2234</td>
<td>33</td>
<td>1932</td>
</tr>
<tr>
<td>004G</td>
<td>398</td>
<td>31</td>
</tr>
</tbody>
</table>

Table 3: The numbered columns list units from different stratigraphic sections that were interpreted to be from the same fire event. The numbers in the first row are arbitrary. The uncalibrated radiocarbon dates for each unit is below each unit name with the 1σ uncertainty.
There were six fire-related deposits that did not fit into groups herein termed independent dates. The units interpreted as independent from 007 and 008 were all originally interpreted as the result of non-severe fires. In addition, these two sections are located in small tributary gullies that drain into the main arroyo. It is likely that the fires that produced these units were either located in a side drainage to the south of the main watershed, or the fine-grained sediment was eroded out of the trunk channel preserving the remnants of these fire-related deposits exclusively in the tributaries.

The independent date from 005S is at the base of the stratigraphic section, across the main arroyo from section 008. The other independent date is from the upper watershed, in a patch of Gambel oak. This piece of charcoal that was dated could have been from a small fire that didn’t result in a release of sediment.

Seven radiocarbon dates, labeled anomalous in Table 3, were interpreted as either too young or too old in comparison to radiocarbon dates from stratigraphically higher or lower positions. Comparing ages and sedimentary characteristics of individual units between stratigraphic sections helped identify these anomalous dates. Causes include bioturbation, “inbuilt age,” dating a burned root, or in three cases, problems with sample preparation (App. J). Three units were dated twice using different charcoal fragments (002I, 002N, and 007M). Based on stratigraphy and dates from neighboring sections, and dates within the same section, the most reasonable dates were chosen.
Figure 9: Variation in cumulative probability curves as a result of grouping of radiocarbon dates. A) The black line is the summed probability of all radiocarbon dates. Those interpreted as “anomalous” were removed to produce the gray dashed line. The black dashed line was generated by summing the average ages of grouped stratigraphy (Table 3). B) As a sensitivity analysis, the youngest and oldest dates are plotted with “independent” dates. C) The data were divided by the interpreted severity and “probable severe” and “non-severe” are plotted.

The radiocarbon data can be represented in several ways (Fig. 9). First, all of the individual probability curves were summed and anomalous dates were removed (Fig. 9a). Sedimentation events that spanned several stratigraphic sections create an enhanced zone of probability when they are summed together. An attempt was made to minimize the effect of groups of four or five radiocarbon dates likely representing the same event on the summed probability curve. The black dashed line was generated by finding the mean probability of each year for individual groups, then summing the probability of all groups (Fig. 9a). Each group of radiocarbon dates is therefore given even weight.
The summed probability curves vary if the youngest date or the oldest date from each group is plotted (Fig. 9b). This sensitivity analysis was conducted to determine how much the cumulative curves are affected by age errors. These lines include the “independent” dates. In most cases the peaks in the probability curves are shifted very little, usually less than 50 years. Overall there is no major change in the timing of peak probability. Inbuilt age causes radiocarbon dates to be older than the fire event and is the most probable error affecting the sampled material. The plot of the youngest dates therefore is probably the most representative of the timing of fire.

Between approximately 500 and 700 cal. yr B.P. the peaks are strongly out of phase, a product of fluctuations in atmospheric carbon dioxide. Between 2000 and 2350 cal yr B.P. the oldest and youngest dates from one group do not overlap. The other dates in the group all overlap both the oldest and the youngest date. Given that there are no inverted ages, there is probably more than one fire recorded in the sediment of this group.

Finally, the dates were divided into probable severe, possible severe and non-severe groupings based on interpretations of stratigraphy and radiocarbon dates (App. I). The majority of the dates fell into the “possibly severe” category. These are included in the plots a and b but not shown in c. Two groups for a total of 8 radiocarbon dates were interpreted as the result of severe fires. Three groups with a total of 8 radiocarbon dates, and 5 independent dates were interpreted as the result of non-severe fires. The peaks of the independent dates have higher probability values than the group dates because these dates were not averaged and the probability is focused in a narrower range.
**Geomorphic implications**

The alluvium in Caballero Canyon provides a record of the overall degree of geomorphic stability of the watershed. In places, nearly 5.5 m of sediment accumulated over the last 2000 cal yr B.P. Throughout all stratigraphic sections many of the deposits are less than 20 cm thick. Therefore to get meters of accumulation, many sedimentation events have occurred. In addition, evidence of multiple episodes of cutting and filling has been preserved.

The oldest paleo-channel was found adjacent and downstream of section 008. Only ~10 cm of incision preceded the deposition of travertine that lines the 2 m wide channel. Sediment that once filled the channel has been stripped by more recent erosion, and the resistant travertine has prevented further incision. Cutting, travertine deposition, and filling happened between 1428 and 1361 cal yr B.P. (dates 008G2 and 008E1), using the weighted mean of calibrated radiocarbon dates here and below.

Just downstream and across the arroyo, stratigraphy in section 005 shows a gravel-filled paleo-channel. The date taken from the top of this deposit came from a sample that was difficult to pre-treat for radiocarbon analysis and resulted in an age that is much too young in comparison to other bracketing ages (App. E). Incision and filling must have occurred between 1348 and 700 cal yr B.P. (005R1 and 005O2), bracketed by the nearest ages above and below the deposit.

Spatially, sections 008 and 003 lie in very close proximity. The modern tributary channel that exposes section 008 cuts a few meters upstream nearly into the sediment behind section 003. However, the ages of their deposits are very different. Radiocarbon dates from section 008 range from 1646 to 782 cal yr B.P. (008O4 and 008A1b). One
date at the base of 003 is 802 (003N1) cal yr B.P. but all others are younger. The
elevation of the youngest unit from 008 (782 cal yr B.P.) is approximately the same as
elevation of a unit from 003 with a weighted mean age of 555 cal yr B.P. The elevation of
the oldest unit from 008 (1646 cal yr B.P.) is about the same as the oldest unit from 003
(802 cal yr B.P.). Although no direct evidence of a paleochannel was found, it may be
that a wide arroyo was cut during the time overlapping the youngest date from 008 and
the oldest date from 003, around 860 $^{14}$C yr B.P. Better stratigraphic evidence is needed
to test this hypothesis.

In section 004 a weighted mean age of 516 cal yr B.P. comes from a deposit
immediately underlying channel-fill deposits. It is difficult to determine whether this
deposit is at the base of the channel fill or if the channel incision cut down to just above
this deposit. The date provides a maximum age of channel incision and a possible age for
filling. This channel was approximately 1.5 m wide and cut into deposits that were 100-
200 cal years older.

The oldest radiocarbon dates are from the section downstream of most sites. Here
a weighted mean age of 2620 cal yr B.P. is from a deposit very near bedrock. This
implies that any older sediment has been eroded and removed from the sedimentary
record.

Along the Rio Peñasco on the east side of the Sacramento Mountains, the most
active period of sedimentation in the last 8000 years was between 6000 and 4000 cal yr
B.P., and no evidence is seen for cutting and filling in the main valley alluvium, except
for modern arroyos (Frechette, 2007). It is clear that Caballero Canyon is somewhat
more sensitive to environmental perturbations because of the diverse activity that is
recorded from the last 3000 years. Perhaps during climate fluctuations that are not represented in the record, such as the time with increased sediment accumulation on the east side of the mountain range, sediment in the canyon was deposited and later removed from the record. It must be noted, however, the exposures used to describe stratigraphy in the canyon cover only a small part of the valley width and older sediment may exist.

**Charcoal Identification**

The results of the charcoal identification show that 70% of the charcoal fragments are gymnosperms. This leads to several possible interpretations. First, perhaps the area burned by oak fires is insufficient to produce enough runoff to initiate sedimentation events. If the forest surrounding the burn remained intact, water velocities could be reduced by logs and trees, dissipating its energy, allowing reinfiltration, and preventing the charcoal and sediment-rich water from reaching the study site. In addition, oak roots survive even when all above-ground vegetation burns allowing for rapid regrowth (Floyd et al., 2000). These roots may help to stabilize the slope after fires, and the fast recovery limits the time for a postfire sedimentary response.

Second, perhaps angiosperm charcoal was pulverized before sediment deposition. The angiosperm charcoal is more fragile than the gymnosperm charcoal because of the large conduits for water called vessels. In the samples used for identification it was commonly found that angiosperm charcoal was often more damaged from combustion and transport than gymnosperm charcoal. Oak has especially large vessels and charcoal often fractures along the rows of these channels. In addition, although the sample size was small, 80% of the charcoal found in the oak patches on the flanks of the upper
watershed was gymnosperm, suggesting that these oak patches are not repeatedly and preferentially burning.

The patches may represent oak replacement after a stand-replacing fire in the mixed-conifer forest. Along the fringe of one large patch, tall (and presumably old) Gambel oak were found growing under the conifer-dominated canopy. This may be evidence for the reestablishment of conifer forest.

As mentioned previously, a relatively few number of samples were identified from each fire-related sediment deposit. Therefore, the most robust interpretations can be made from the combined data. Group 4 in the dated alluvial stratigraphy has two units with a high concentration of angiosperm charcoal. Perhaps these represent a fire that burned a large oak patch. The two other layers from this same group are dominated by gymnosperm charcoal. Out of 40 samples identified from the four layers, 40% are angiosperm and 60% are gymnosperm.

Finally, three layers interpreted as independent had relatively high concentrations of angiosperm charcoal, although one of these layers had very few samples identified. These layers were all interpreted as non-severe, consistent with the idea that burning an oak patch would produce a less-severe sedimentary response. No definite conclusions can be drawn based on the relatively small number of samples, but perhaps it leaves open the possibility that occasionally oak patches burn without the flames spreading to the surrounding conifer forest.

**Regional Climate Proxies**

On short timescales, tree ring-based climate proxy records have high temporal resolution and can be calibrated to modern precipitation and temperature values. These
records are very effective at capturing yearly, decadal and sometimes centennial climate fluctuations; however, most of these records are composites of living and dead trees whose life spans are generally 200 to 400 years long (Esper et al., 2002). For chronologies in which the lifespan of the trees is substantially shorter, difficulties arise in preserving long-term climate variability. Biological growth signals that describe the trend for ring widths to decrease with increasing age, are often assumed to be a smooth mathematical growth function. These signals are removed from ring-width measurements, limiting the resolvable wavelength to the age of the trees (Cook et al., 1995).

Longer records from this region have much less detail but tend to preserve longer-scale climate fluctuations. These proxies come from a variety of sources including playa lake sediment (Castiglia and Fawcett, 2006; Parker, 2005; Krider, 1998), alluvial stratigraphy (Nordt, 2003), stable isotopes in soils (Buck and Monger, 1999), packrat middens (Holmgren et al., 2003) and speleothems (Rasmussen, et al., 2006; Asmerom et al, 2007).

**Holocene Climate**

Holocene climate has been reconstructed using a variety of proxy records in the Four Corners region. The middle Holocene, the interval between approximately 7500 and 4000 cal yr B.P., was first characterized by Antevs (1948) as warmer and drier than today based on lake chronology and arroyo geomorphology in the Great Basin region. His interpretations have been refined by more recent studies, but variability in the timing of climate shifts stem either from the influence of local climate or as a result of biases from different proxies. Buck and Monger (1999) found an abrupt shift in soil $\delta^{13}$C
between 9000 and 7000 cal yr B.P. indicating that in the northern Chihuahuan Desert C4 grasses were abruptly replaced by C3 shrubs, marking decreased effective moisture. Paleolake levels in the Southwest were low during this time (Waters, 1989; Hawley, 1993). Fall et al. (1997) used pollen from high-elevation basins in western Colorado to trace timberline fluctuations and found, based on modern elevation-temperature gradients, that between between 9000 and 6000 cal yr B.P. temperatures were 1.5°C warmer than today. Oxygen isotopes measured from speleothems in the Guadalupe Mountains, New Mexico had very high δ¹⁸O values between 10,000 and 7000 cal yr B.P., suggesting a very dry period (Asmerom et al., 2007). After 7000 cal yr B.P. δ¹⁸O values decreased presumably associated with an increase in precipitation.

Several studies found a shift in climate between 5000 and 4000 cal yr B.P. For example, Krider (1998) documented a lacustrine aggradation event prior to 5300 cal yr B.P. interpreted to mark a climatic change in the Animas Valley, New Mexico. Nordt (2003) summarized that a shift in climate occurred at 5700 cal yr B.P., supported in his study by evidence of erosion into a paleosol, marking a transition from a warmer and drier climate to a generally cooler and wetter climate. This corresponds to a time with high magnitude floods in Arizona (Ely et al., 1993), lacustrine sediment deposition in the Laguna El Fresnal basin (Parker, 2005), and major fire-related fan aggradation in the eastern Sacramento Mountains (Frechette, 2007).

Starting around 4000 cal yr B.P., upper treeline in western Colorado began to recede to lower elevations, suggesting that temperatures began to cool at that time (Fall et al., 1997). Thompson et al. (1993) summarized that Holocene moisture levels in the Great Basin were highest between 3800 and 2000 cal yr BP. Major vegetation changes
were documented at both 4000 and 2200 cal yr B.P. in soil carbonate isotopes and packrat midden records (Van Devender, 1990, 1995; Buck and Monger, 1999). At 4000 cal yr B.P. C4 grass levels increased, and at 2200 cal yr B.P. grass populations declined, indicating a climate with first more and then less effective precipitation. Higher resolution speleothem records from the Guadalupe Mountains in south-eastern New Mexico show increased stalagmite growth and large negative $\delta^{18}O$ values at 3300 cal yr B.P. and 2700 cal yr B.P. suggesting a wet climate (Asmerom et al., 2007). At approximately 2200 cal yr B.P. the $\delta^{18}O$ values become smaller, suggesting a decrease in precipitation.

These studies provide insight into the climate for the Holocene millennia that lead into the Caballero Canyon record beginning 2800 cal yr B.P. (Fig. 10). According to these records, the climate at this time was relatively cool and wet (Asmerom et al., 2007). A transition to a warmer and drier climate occurred around 2200 cal yr B.P. Around this transition, two to three fires are recorded in the alluvium of Caballero Canyon including one severe fire with a date centered on 2550 cal yr B.P. (Fig. 10). These are the oldest fire-related sediment deposits identified in this canyon and all were found downstream of most dated deposits. The base of the stratigraphic section that contained these deposits is very near bedrock, and any possible older Holocene sediments have been stripped. More recently, the modern arroyo has cut back down to the bedrock, exposing the stratigraphy. Older stratigraphy exists below the remainder of the stratigraphic sections, but the total thickness of the alluvium is unknown.
Figure 10: Plots showing tree-ring based climate reconstructions and the summed probability of fire-related sedimentation in Caballero Canyon.  A) A reconstruction of precipitation from south-central New Mexico tree-ring chronologies (Grissino-Mayer et al., 1997).  B) A tree-ring reconstruction of drought for southern New Mexico. Data are in the form of summer (June -August) average Palmer Drought Severity Index. Negative PDSI values indicate dry conditions, while positive values indicate wet conditions.  C) The Drought Area Index is a percentage of the number of PDSI grid point reconstructions in the western U.S. that exceeded a drought threshold in a given year. The number of grid points (each representing the same land area) exceeding the threshold was divided by the total number of grid points in the study area. This provides an estimate of the percent of the western U.S. affected by drought. D) The total number of individual calibrated radiocarbon curves summed in each segment of the blue line in E. E) Radiocarbon data on fire-related sedimentation from Caballero Canyon treated to minimize bias from age errors and multiple ages on single events. The blue line is the summed probability of all dates with the exception of eight dates deemed anomalous. The solid black line shows the independent dates and the youngest dates from groups described in earlier sections. This line should be interpreted as a minimum summed probability. The red line shows the dates of “probable severe” fire-related deposits.
Later, between 1700 and 1300 cal yr B.P. one or two fires caused sedimentation events that deposited sediment in sections 008 and 005 as described previously. These occurred during an extended dry period recorded in the summer-season Palmer Drought Severity Index (PDSI), a proxy measure of drought and wetness over the Western United States (Cook et al., 2004). The number of chronologies for this tree-ring based record decreases with time; therefore this section of the record should be interpreted with caution. It does, however, line up well with a small peak in fire activity recorded in the study area.

A hiatus in the fire-sedimentation record beginning at 1300 cal yr B.P. and ending at approximately 1000 cal yr B.P. follows this peak, an occurrence that can be explained in several ways. It must be remembered that this record is from only one watershed and should not be interpreted as a complete history of severe fire in the Sacramento Mountains. On the east side of the Sacramento Mountains, data from a number of sites show a consistent moderate level of fire activity between 1800 and 800 cal yr B.P., except for a short gap ca. 1500 cal yr B.P. (Frechette, 2007). The Sacramento Mountains are a large range, so perhaps simply by chance there was no fire large enough to result in a sedimentation event in Caballero Canyon during this time. Or, perhaps there were burns in the watershed, but no precipitation events intense enough to trigger debris flows or hyperconcentrated flows within the postfire period of instability. Although the Drought Area Index time series (DAI, a measure of the spatial extent of reconstructed drought in the West) (Cook et al., 2004) does not span the hiatus, the segment that overlaps shows a time with relatively low percent of the grid points in the western U.S. in
drought. This suggests that the climate might have been cool and wet enough to prevent fires from spreading, although this differs from the findings of Frechette (2007).

A peak in fire probability centered on 930 cal yr B.P. ends the hiatus. This peak falls near the beginning of the interval known as the Medieval Warm Period (MWP), a period that shows increased aridity spanning 400 years between approximately 1050 and 650 cal yr B.P. (Cook et al., 2004). The DAI shows that multidecadal droughts during this time were common and widespread throughout the western U.S. Within this period, four prominent peaks in aridity occur at 1014, 916, 800, and 697 cal yr B.P. The first fire-related sedimentation event after the hiatus is nearly coincident with the second peak in aridity (916 cal yr B.P.) recognized by Cook et al. (2004). Within the DAI record there is a decrease in pervasive drought between approximately 900 and 875 cal yr B.P. that corresponds to a low fire probability based on radiocarbon dates from this study. The probability curve steps up just after 800 cal yr B.P., marking an increase in the probability of fire during the time between two major peaks in aridity (800 and 697 cal yr B.P.). The largest peak in fire-related sedimentation events spans 200 years between 700 and 500 cal yr B.P. The summed peak overlaps with the widespread aridity in the western U.S. as measured by the DAI, but extends until 300 cal yr B.P. The probability peak during this time period is much higher than others because these fire deposits were dated in multiple stratigraphic sections. When interpreting these data it must be remembered that each radiocarbon date only represents one fire sedimentation event or group of events following a single fire. These sedimentation events typically happen within several years following the fire, even though the probability distribution can span a century or more.
A 1,373 year tree-ring based precipitation reconstruction from the southern Rio Grande Basin shows that the most severe drought, both in magnitude and duration, occurs between 678 and 654 cal yr B.P. (Fig 10; Grissino-Mayer et al., 1997). This period of extreme aridity marks the beginning of the largest radiocarbon probability peak of fire-related sedimentation. A minimum of two fires resulted in sedimentation events with radiocarbon probability curves that overlap this drought. One was interpreted as the result of a “probable severe” fire and the other a result of a “non-severe fire” (Fig. 10). Perhaps these fires are related to the 24-year drought that was recorded in regional tree-ring reconstructions. The second prominent decades-long drought between 400 and 345 cal yr B.P. corresponds to the youngest major peak in fire-related sedimentation (Grissino-Mayer et al., 1997).

The radiocarbon probability curves that span the last 300 years are from charcoal extracted from soil pits in Gambel oak patches high on the flanks of the watershed. These are not “fire-related” sediment deposits. The charcoal was radiocarbon dated to determine whether they correlate with charcoal found in the alluvium. Two of the radiocarbon dates have calibrated probability curves that span 300 years. One curve spans nearly 500 years. It is impossible to determine the severity of fires because they are not associated with alluvial deposits.
Conclusions

The alluvial stratigraphy of Caballero Canyon provides evidence of severe, stand-replacing fires on the west side of the Sacramento Mountains. The stratigraphy is complicated and only two sets of deposits were confidently identified as related to a “probable severe” fire. The first has a calibration curve centered on 2550 cal yr B.P., a time that may have coincided with a transition from a relatively cool and wet climate to a time that was generally warmer and drier. The second is centered on 650 cal yr B.P. during the most severe and persistent drought recorded in a 1,373 yr tree ring record for the southern Rio Grande Basin (Grissino-Mayer et al., 1997) at the end of the interval known as the Medieval Warm Period, a time that shows increased aridity throughout the West (Cook et al., 2004).

Fire-related deposits that are conservatively interpreted as “possibly severe” account for a minimum of six events and “non-severe” account for five events. These represent fire events that occurred throughout the record, including the Medieval Warm Period. More detailed interpretations with regards to the relation of fire events to climate are difficult given the large time uncertainty associated with radiocarbon dates.

Stratigraphy from multiple episodes of channel incision and filling are exposed along the arroyo in the canyon. In general, the timing of the cutting and filling is poorly constrained with the exception of one filling event at 472 ± 32 $^{14}$C yr B.P.

Identification of charcoal fragments from the alluvium suggests that fires in conifer forests are the cause of fire-related sedimentation events. The hypothesis that severe fires repeatedly and preferentially burn in stands of Gambel oak cannot be substantiated, but it may also not be completely ruled out.
References Cited


Frechette, J., 2007, Millennial-scale changes in fan deposition and fire severity in ponderosa pine forests, Sacramento Mountains, New Mexico, New Mexico: University of New Mexico.


National Interagency Coordination Center, 2006, Wildland Fire Statistics.


Pray, L. C., 1961, Geology of Northern Sacramento Mountains Escarpment, Otero County, New Mexico.


Van Devender, and Roger, T., 1990, Late Quaternary vegetation and climate of the Chihuahuan Desert, United States and Mexico, in Betancourt, J. L., Van


Appendices

Appendix A: A description of three types of sediment transport processes that may result from fire and the identifying characteristics of their deposits.

- Streamflow and Sheetflood
  In conditions where sediment is transported by streamflow, turbulence is the support mechanism that carries sediment by suspension, rolling, and saltation (Costa, 1988). The water flows as a Newtonian fluid, there is no yield or shear strength, and the flow is fully turbulent except a thin layer near the bed (Smith and Lowe, 1991). Some shear strength can be added to the flow with increasing concentrations of fine sediment during events with large sediment loads (Costa, 1988). Streamflow transports relatively small amounts of sediment and deposition of the sediment happens “grain by grain” as the solids fall out of suspension or energy decreases enough to halt rolling and saltation (Florsheim et al., 1991).
  Deposits from streamflow take on different forms depending on discharge conditions and the size of transported material. Deposits can include massive or cross-bedded sands (Smith and Lowe, 1991). They can also included imbricated gravel, that are associated with lenses and thin beds of sand. Depending on the source of gravel the clasts can be angular to well-rounded. Often gravel deposits are clast supported (Florsheim et al., 1991) however, material that is transported in high-energy conditions can be much more poorly sorted, have more angular grains, and lack well-defined cross-beds (Smith and Lowe, 1991).

-Hyperconcentrated flow
  There are a variety of physical properties that researchers have used to define the term hyperconcentrated flow. Sediment concentrations by weight (40-70%) and volume (20-47%) (Beverage and Culbertson, 1964), yield strength (Pierson and Costa, 1987), suspension and deposition mechanisms (Smith, 1986). In general, hyperconcentrated flow is intermediate between streamflow and debris flow. It is turbulent and spans a continuum between Newtonian (Costa, 1988) and non-Newtonian flow (Smith and Lowe, 1991) but has measurable shear strength (Costa, 1988). The fluid density and viscosity are greater than streamflow, fine sediment remains suspended longer, and sediment is transported farther (Costa, 1988). Mechanisms of sediment suspension and transport include a combination of buoyancy, grain collision, and turbulence (Beverage and Culbertson, 1964). As fine sediment concentrations increase, the importance of grain collisions increases while the turbulence decreases (Costa, 1988). As the flow’s velocity decreases, the coarser solids drop out of suspension and are deposited.
  The deposits that result from hyperconcentrated flow events, like the processes that move sediment, have characteristics both of streamflow and debris flow. Sand and granule deposits can be massive or show weak normal or reverse grading and have cobbles or boulders scattered. Gravel deposits are generally in normally graded units and are not imbricated (Smith and Lowe, 1991).
Debris flow

Unlike streamflow and hyperconcentrated flow, in debris flows solid particles and water move as a single body as a non-Newtonian flow. Like more water-rich sediment transport processes, these flows can travel long distances over relatively shallow slopes. The mechanisms for debris flows to travel long distances, are different however, they include the vibrational kinetic energy of the solid grains, and the pressure of pore fluid that acts to lubricate grain interactions (Iverson, 1997). They have strength and resist shear. Solids in the flows make up 70-90% of the weight (47-77% of the volume) (Costa, 1988). Large clasts are carried by the fine-grained matrix. Some flows are generated by mass failure of saturated slope material often attributed to reduced evapotranspiration rates and subsequent increase in soil moisture and loss of root strength in the years following a fire (Swanson, 1981; Iverson, 1997). More commonly in the Southwest, flows are triggered by sediment bulking resulting from rill erosion on steep slopes leading to deep incision and developing into a debris flow downslope (Meyer and Wells, 1997, Cannon et al., 2001b). These events end with the deposition of sediment occurring as a single event, when the internal shear stress no longer exceeds the yield strength of the flow (Florsheim et al., 1991). Once sediment is entrained water and solids move contiguously and unlike more water laden events, the coarsest particles can’t drop out (Costa, 1988).

Deposits from these events have a range of characteristics depending on the water content, sediment that was transported, and the spatial location within a single flow. They are poorly sorted, generally have angular clasts that span the sediment size continuum from clay to boulders (Florsheim et al., 1991). Deposits are unstratified but they can have normal or reversed grading. Clasts may be imbricated or somewhat aligned, this happens along lobe fronts where clasts are stacked on top of each other.
Appendix B: Features noted in alluvial and soil descriptions

<table>
<thead>
<tr>
<th>Depth</th>
<th>Thickness</th>
<th>Lower Contact</th>
<th>Effervescence</th>
<th>Soils Texture</th>
<th>Matrix/clast supported</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth below the surface measured in cm</td>
<td>total thickness of the unit</td>
<td>Defines the character of the boundary between the described unit and the underlying unit</td>
<td>Reactivity to hydrochloric acid to evaluate the amount of calcium carbonate</td>
<td>field test measuring the relative proportions of sand, silt, and clay using guidelines from Birkeland (1999)</td>
<td>Characterization of sedimentary support</td>
</tr>
</tbody>
</table>

- A/Abrupt: 0-2cm
- C/clear: 2-5cm
- S/straight
- W/wavy: width>depth

<table>
<thead>
<tr>
<th>Percent gravel</th>
<th>5 largest clasts</th>
<th>Mean grain size</th>
<th>clast description</th>
</tr>
</thead>
<tbody>
<tr>
<td>the relative proportions of gravel and fine-fraction sediment</td>
<td>measure of the B-axis on the 5 largest clasts</td>
<td>visual approximation of the average grain size</td>
<td>gravel lithology and angularity</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Color</th>
<th>Sedimentary Structure</th>
<th>Charcoal Notes</th>
<th>Notes/interpretations</th>
<th>Sample Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet and dry color determined by visual comparison with a Munsell soil color chart</td>
<td>soil structure and bedding</td>
<td>visual analysis of the angularity, size and distribution of charcoal</td>
<td>additional pertinent information and preliminary interpretations of the unit</td>
<td>sample description including size, location of extraction, and angularity</td>
</tr>
</tbody>
</table>
Appendix C: Complete descriptions of charcoal identification samples (cd).

Appendix D: List of woody species found in the study area.

<table>
<thead>
<tr>
<th>Scientific</th>
<th>Common</th>
<th>Family</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hardwoods</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Acer glabrum</em></td>
<td>Rocky Mountain maple</td>
<td>Aceraceae</td>
</tr>
<tr>
<td><em>Sambucus cerulea</em></td>
<td>New Mexico Elder</td>
<td>Caprifoliaceae</td>
</tr>
<tr>
<td><em>Robinia neomexicana</em></td>
<td>New Mexico Locust</td>
<td>Fabaceae</td>
</tr>
<tr>
<td><em>Quercus gambelii</em></td>
<td>Gambel oak</td>
<td>Fagaceae</td>
</tr>
<tr>
<td><em>Quercus undulata</em></td>
<td>wavy leaf oak</td>
<td>Fagaceae</td>
</tr>
<tr>
<td><em>Fraxinus velutina</em></td>
<td>ash</td>
<td>Oleaceae</td>
</tr>
<tr>
<td><em>Fraxinus cuspidata</em></td>
<td>ash</td>
<td>Oleaceae</td>
</tr>
<tr>
<td><em>Rhamnus serrata</em></td>
<td>Sawtooth buckthorn</td>
<td>Rhamnaceae</td>
</tr>
<tr>
<td><em>Cercocarpus montanus</em></td>
<td>mountain mohagony</td>
<td>Rosaceae</td>
</tr>
<tr>
<td><em>Holodiscus dumosa</em></td>
<td></td>
<td>Rosaceae</td>
</tr>
<tr>
<td><em>Prunus serotina</em></td>
<td>SW chokecherry</td>
<td>Rosaceae</td>
</tr>
<tr>
<td><em>Ptelea trifoliata</em></td>
<td>hop tree</td>
<td>Rutaceae</td>
</tr>
<tr>
<td><em>Populus tremuloides</em></td>
<td>quaking aspen</td>
<td>Salicaceae</td>
</tr>
<tr>
<td><strong>Softwoods</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Juniperus deppeana</em></td>
<td>alligator juniper</td>
<td>Cupressaceae</td>
</tr>
<tr>
<td><em>Pinus edulis</em></td>
<td>pinon pine</td>
<td>Pinaceae</td>
</tr>
<tr>
<td><em>Pinus ponderosa</em></td>
<td>Ponderosa Pine</td>
<td>Pinaceae</td>
</tr>
<tr>
<td><em>Pinus strobiformis</em></td>
<td>sw white pine</td>
<td>Pinaceae</td>
</tr>
<tr>
<td><em>Pseudotsuga menziesii</em></td>
<td>Douglas fir</td>
<td>Pinaceae</td>
</tr>
</tbody>
</table>

Appendix E: Figure of stratigraphic sections 001-008 (cd).

Appendix F: Figure of stratigraphic section 009 (cd).

Appendix G: Photo of the undescribed section with 1 radiocarbon date (cd).
Appendix H: List of uncalibrated radiocarbon dates.

Results from Radiocarbon Analyses
University of Arizona AMS lab

<table>
<thead>
<tr>
<th>AA#</th>
<th>Sample ID</th>
<th>d13C</th>
<th>F</th>
<th>uncertainty</th>
<th>Radiocarbon age</th>
<th>uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA69529</td>
<td>001-C3b</td>
<td>-23.7</td>
<td>0.9298</td>
<td>0.0045</td>
<td>584</td>
<td>39</td>
</tr>
<tr>
<td>AA71044</td>
<td>001E1</td>
<td>-21.5</td>
<td>0.936</td>
<td>0.0037</td>
<td>531</td>
<td>32</td>
</tr>
<tr>
<td>AA71045</td>
<td>002C1</td>
<td>-21.6</td>
<td>0.955</td>
<td>0.0038</td>
<td>368</td>
<td>32</td>
</tr>
<tr>
<td>AA71046</td>
<td>002D2</td>
<td>-25.7</td>
<td>0.951</td>
<td>0.0037</td>
<td>402</td>
<td>31</td>
</tr>
<tr>
<td>AA71047</td>
<td>002I1</td>
<td>-24.4</td>
<td>0.913</td>
<td>0.0039</td>
<td>727</td>
<td>34</td>
</tr>
<tr>
<td>AA69530</td>
<td>002I2</td>
<td>-24.3</td>
<td>0.925</td>
<td>0.0044</td>
<td>627</td>
<td>38</td>
</tr>
<tr>
<td>AA69531</td>
<td>002N2</td>
<td>-24.2</td>
<td>0.9227</td>
<td>0.0044</td>
<td>646</td>
<td>38</td>
</tr>
<tr>
<td>AA71048</td>
<td>002N2b</td>
<td>-25.5</td>
<td>0.9</td>
<td>0.0036</td>
<td>843</td>
<td>32</td>
</tr>
<tr>
<td>AA71049</td>
<td>003E1</td>
<td>-23.4</td>
<td>0.925</td>
<td>0.0037</td>
<td>622</td>
<td>32</td>
</tr>
<tr>
<td>AA69532</td>
<td>003H1</td>
<td>-22.8</td>
<td>0.9325</td>
<td>0.0045</td>
<td>562</td>
<td>38</td>
</tr>
<tr>
<td>AA69533</td>
<td>003I2</td>
<td>-21.4</td>
<td>0.8946</td>
<td>0.0041</td>
<td>894</td>
<td>36</td>
</tr>
<tr>
<td>AA69534</td>
<td>003K3</td>
<td>-24.9</td>
<td>0.9309</td>
<td>0.0041</td>
<td>576</td>
<td>36</td>
</tr>
<tr>
<td>AA69535</td>
<td>003N1</td>
<td>-21.5</td>
<td>0.8967</td>
<td>0.0044</td>
<td>876</td>
<td>39</td>
</tr>
<tr>
<td>AA71050</td>
<td>004D1b</td>
<td>-22.1</td>
<td>0.942</td>
<td>0.0037</td>
<td>472</td>
<td>32</td>
</tr>
<tr>
<td>AA71051</td>
<td>004G2bg</td>
<td>-22.8</td>
<td>0.951</td>
<td>0.0037</td>
<td>398</td>
<td>31</td>
</tr>
<tr>
<td>AA69536</td>
<td>005H2</td>
<td>-23.3</td>
<td>0.9267</td>
<td>0.0043</td>
<td>612</td>
<td>37</td>
</tr>
<tr>
<td>AA69537</td>
<td>005L1</td>
<td>-21.7</td>
<td>0.933</td>
<td>0.0044</td>
<td>557</td>
<td>37</td>
</tr>
<tr>
<td>AA71052</td>
<td>005N1</td>
<td>-22.8</td>
<td>0.918</td>
<td>0.0037</td>
<td>685</td>
<td>32</td>
</tr>
<tr>
<td>AA69538</td>
<td>005O2</td>
<td>-24.2</td>
<td>0.9094</td>
<td>0.0046</td>
<td>763</td>
<td>41</td>
</tr>
<tr>
<td>AA71053</td>
<td>005Q2b</td>
<td>-24.3</td>
<td>0.922</td>
<td>0.0037</td>
<td>647</td>
<td>32</td>
</tr>
<tr>
<td>AA69539</td>
<td>005R1</td>
<td>-22.6</td>
<td>0.8353</td>
<td>0.0051</td>
<td>1,446</td>
<td>48</td>
</tr>
<tr>
<td>AA69540</td>
<td>005S1b</td>
<td>-24.2</td>
<td>0.7862</td>
<td>0.0045</td>
<td>1,932</td>
<td>46</td>
</tr>
<tr>
<td>AA71055</td>
<td>007D1</td>
<td>-23.2</td>
<td>0.953</td>
<td>0.0037</td>
<td>387</td>
<td>31</td>
</tr>
<tr>
<td>AA69541</td>
<td>007F1</td>
<td>-23.4</td>
<td>0.9163</td>
<td>0.005</td>
<td>703</td>
<td>44</td>
</tr>
<tr>
<td>AA69542</td>
<td>007K1b</td>
<td>-23.8</td>
<td>0.9006</td>
<td>0.0041</td>
<td>841</td>
<td>36</td>
</tr>
<tr>
<td>AA69543</td>
<td>007M3</td>
<td>-21.7</td>
<td>0.91</td>
<td>0.0048</td>
<td>757</td>
<td>43</td>
</tr>
<tr>
<td>AA71054</td>
<td>007M6</td>
<td>-23.8</td>
<td>0.881</td>
<td>0.0035</td>
<td>1,010</td>
<td>32</td>
</tr>
<tr>
<td>AA69544</td>
<td>008A1b</td>
<td>-24.3</td>
<td>0.8994</td>
<td>0.0062</td>
<td>852</td>
<td>55</td>
</tr>
<tr>
<td>AA71056</td>
<td>008E1</td>
<td>-24.2</td>
<td>0.832</td>
<td>0.0034</td>
<td>1,476</td>
<td>33</td>
</tr>
<tr>
<td>AA69545</td>
<td>008G2</td>
<td>-23.7</td>
<td>0.8266</td>
<td>0.0041</td>
<td>1,530</td>
<td>40</td>
</tr>
<tr>
<td>AA69546</td>
<td>008I1</td>
<td>-20.9</td>
<td>0.8154</td>
<td>0.0037</td>
<td>1,640</td>
<td>36</td>
</tr>
<tr>
<td>AA69547</td>
<td>008K2</td>
<td>-22.1</td>
<td>0.818</td>
<td>0.0046</td>
<td>1,614</td>
<td>45</td>
</tr>
<tr>
<td>AA69548</td>
<td>008O4</td>
<td>-23</td>
<td>0.8056</td>
<td>0.0037</td>
<td>1,737</td>
<td>37</td>
</tr>
<tr>
<td>AA71057</td>
<td>009A2</td>
<td>-23.8</td>
<td>0.771</td>
<td>0.0032</td>
<td>2,085</td>
<td>33</td>
</tr>
<tr>
<td>AA71091</td>
<td>009G1</td>
<td>-23.5</td>
<td>0.745</td>
<td>0.0031</td>
<td>2,363</td>
<td>34</td>
</tr>
<tr>
<td>AA71063</td>
<td>009K1</td>
<td>-26.1</td>
<td>0.763</td>
<td>0.0032</td>
<td>2,168</td>
<td>34</td>
</tr>
<tr>
<td>AA71092</td>
<td>009Q1</td>
<td>-24.9</td>
<td>0.767</td>
<td>0.0032</td>
<td>2,130</td>
<td>33</td>
</tr>
<tr>
<td>AA71093</td>
<td>009S1</td>
<td>-23.5</td>
<td>0.762</td>
<td>0.0032</td>
<td>2,180</td>
<td>33</td>
</tr>
<tr>
<td>AA71094</td>
<td>009U1</td>
<td>-26.2</td>
<td>0.755</td>
<td>0.0032</td>
<td>2,258</td>
<td>34</td>
</tr>
<tr>
<td>AA71089</td>
<td>009V2</td>
<td>-26.1</td>
<td>0.737</td>
<td>0.0031</td>
<td>2,443</td>
<td>34</td>
</tr>
<tr>
<td>AA71095</td>
<td>009X1A</td>
<td>-25.3</td>
<td>0.735</td>
<td>0.0031</td>
<td>2,469</td>
<td>33</td>
</tr>
<tr>
<td>AA71060</td>
<td>Sept001b</td>
<td>-22.6</td>
<td>0.984</td>
<td>0.0039</td>
<td>125</td>
<td>31</td>
</tr>
<tr>
<td>AA71061</td>
<td>Sept002A</td>
<td>-24.5</td>
<td>0.983</td>
<td>0.0039</td>
<td>132</td>
<td>32</td>
</tr>
<tr>
<td>Beta</td>
<td>13C/12C</td>
<td>Measured Radiocarbon age and uncertainty</td>
<td>Conventional Radiocarbon Age</td>
<td>Uncertainty</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------</td>
<td>---------</td>
<td>-----------------------------------------</td>
<td>-------------------------------</td>
<td>-------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AA71062</td>
<td>UndsBbark</td>
<td>-24.1</td>
<td>0.757</td>
<td>0.0032</td>
<td>2,234</td>
<td>33</td>
</tr>
<tr>
<td>AA71059</td>
<td>UpCab1</td>
<td>-22.2</td>
<td>0.966</td>
<td>0.0038</td>
<td>275</td>
<td>32</td>
</tr>
<tr>
<td>AA71058</td>
<td>UpCab2</td>
<td>-23.8</td>
<td>0.94</td>
<td>0.0039</td>
<td>496</td>
<td>33</td>
</tr>
</tbody>
</table>

**Beta Analytic Lab**

<table>
<thead>
<tr>
<th>Beta</th>
<th>13C/12C</th>
<th>Measured Radiocarbon age and uncertainty</th>
<th>Conventional Radiocarbon Age</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>193090</td>
<td>Grant's Date</td>
<td>-21.3/o/o</td>
<td>1720</td>
<td>40</td>
</tr>
<tr>
<td>009Z</td>
<td>-25.9/o/o</td>
<td>2560</td>
<td>50</td>
<td>2550</td>
</tr>
<tr>
<td>001G</td>
<td>22.2/o/o</td>
<td>650</td>
<td>50</td>
<td>690</td>
</tr>
</tbody>
</table>
Appendix I: Description of grouped stratigraphy.

Grouping:
The following section groups the descriptions of units that have approximately the same radiocarbon age.

Severe fire events interpretations: I analyzed the different groups and depending on their association with layers of poorly sorted gravels and the number of sections that recorded the fire I determined if the sediment is representative of a probable severe, possible severe or non-severe fire-related sedimentation event.

Group 1-non-severe, all units are associated with travertine and fine-grained deposits.
They may represent a pool fill that collected charcoal as it washed off the slopes. They all underlie at least a thin layer of travertine.
001 C: A 9cm thick unit, the upper 5cm is indurated travertine with a concentration of angular scattered charcoal in lower 4cm. It underlies a debris flow unit but the lower charcoal stratum is probably not directly related to the debris flow deposit with the travertine separating the two. Interpretation: The lower charcoal-rich layer may be a pool fill. The modern channel is essentially stepped with flat pools and steep riffles. The pools trap fine-grained sediment and in the past they could have trapped charcoal that was flushed from a minor fire in the watershed. Travertine was later deposited on the surface.
002 I-15cm thick fine-grained layer with common to many charcoal, and only ~1% gravel. It underlies a poor to medium sorted, slightly imbricated gravel. It may be a fine-grained debris flow but it is difficult to interpret. Due to the high concentration of charcoal I consider this a probable fire-related deposit but only a possibly related to a severe fire.
003 E- 12cm thick fine-grained layer with ~5% gravel and common angular charcoal. Millimeter-sized travertine granules are found in varying concentrations, they may have been transported from upstream. The thickness of the layer pinches and swells between the upper and lower bounding travertine layers. Interpretation: pool fill that collected charcoal, gravel, and some ripped-up travertine after a fire in the watershed.
003 H-21cm thick layer with common to many charcoal and10-20% gravel. Gravel is concentrated in small lenses. The fine-grained portion is clay-rich making the sediment very hard but there is no evidence of pedogenesis. Interpretation: possible pool fill but it could also be the result of a hyperconcentrated flow.
003E and H have significantly the same date. I suspect that these are probably the same fire because not only are they in close proximity to each other, the other interpretations of having H and K the same don’t make sense with stratigraphy. There are large roots in this area that have bioturbated units. The one problem is that there is a travertine unit in between that thickens upstream but perhaps E is reworked or H was bioturbated down.

Group 2: probable severe fire-lots of gravel, recorded in many sections
001 G- A 40cm poorly sorted layer with 75-85% gravel and no imbrication. Clasts have B-axes up to 17cm. Where the section was described there were relatively few pieces of charcoal, however, downstream a couple meters the deposit could be traced to an area
that had a high concentration of charcoal. In addition there was a buried partially charred log. This deposit looks very similar to deposits seen on the east side of the Sacramento Mountains following the 2002 Rio Penasco fire. These are described in the results section of this thesis. Interpreted as a debris flow and a probable fire-related deposit. **001E**- 9cm of fine-grained sediment with 1-2% gravel. The charcoal concentration varies-in places 1-2cm fragments and flecks are common in other places there are only few 1-2mm flecks. The unit thickens downstream and % gravel increases. This layer is probably related to the overlying gravel unit that I interpreted as a debris flow, and there is a thin discontinuous black layer that may be a burned soil at the top of the fine-grained unit, just below the gravel. Interpretation: probable fire-related deposit.

Notes: I think that units F, G, and E are from the same fire event. The difference between F and G is the amount of matrix (F is clast supported). It makes sense that the upper portion of a gravel layer has its matrix washed out by later rain and water flowing through. Both of the dates from E and G match up with dates from other sections. Without evidence of G being a root I’ll assume that E is young because the humates weren’t removed. Therefore throw out E and use G as the date for these units. **003 K**- 7cm thick layer with few-common charcoal, 10-85% non-imbricated, poorly sorted gravel. Interpretation: fire-related debris flow. Has similar date to 003H. One would think that if it was a severe event that there would be more dates in other sections to match. Also, there are many layers between it and H including a section of interbedded travertine and SL making me think that they must be separate fires. This date is too young. The pretreatment note says that humates were not completely cleared. It is probably a separate fire event but I don’t think I have a good date on it. However, this unit corresponds to the 004G whose date I determined didn’t make sense. Because I don’t have any good reason other than: it doesn’t seem right for a date so young to be next to a much older date, I should probably keep it because it fits with what I have in 004. There must have been a break in time between ~580 years and 870 years ago where there was stability here (or material was removed). **005 L**- 6cm thick layer with few to locally many angular charcoal and <1% gravel. The overlying unit has 70-80% gravel with no imbrication. This could be a sequence of hyperconcentrated flow followed by a debris flow as a result of a fire.

**002I**- 15cm thick, fine-grained layer with common to many charcoal, and only ~1% gravel. It underlies a poor to medium sorted, slightly imbricated gravel. It may be a fine-grained debris flow but it is difficult to interpret. Due to the high concentration of charcoal I consider this a probable fire-related deposit but only a possibly related to a severe fire.

**Group 3:** possible severe event: it doesn’t show up in very many sections but they all underlie a gravel unit and have enough charcoal to be considered a fire unit. **002 C:** Very bioturbated 14cm thick fine-grained layer with common angular charcoal I predicted that C and D were from the same fire and that C is an A horizon. Overlain by poorly sorted gravel. **002 D**- 17cm thick fine-grained layer that has few-common charcoal. The top 3cm is travertine-rich and the bottom (~2cm) is darker due to more charcoal.
Interpretation of C and D: I would say that these are possible severe fire-related units but not certain because although there is a lot of charcoal, there aren’t characteristic sedimentary packages (e.g. debris flow).

**007 D**-30cm thick layer with few-common charcoal flecks that are up to 2cm in size. The layer is bioturbated, there is no gravel, but it underlies a layer with 5-40% gravel that is poorly sorted. This follows the idea of charcoal washing down to be covered by a debris flow.

---

**Group 4:** all units are hard to interpret, **non-severe or possibly severe**-002N is not associated with any gravel but 003N, and 007K underlie gravels and 008A has gravel in the deposit.

**002 N**-16cm thick massive, fine-grained layer with evenly dispersed common charcoal, <1% gravel, and clay loam texture. It is hard to interpret with the strange soil texture and it is possibly a pool infilling after a fire. I call this a possible fire and it seems to be the result of a non-severe event.

**003 N**-11cm massive layer with common charcoal, no gravel and high concentration of clay. Interpretation: likely a pool-fill because of the high clay concentration but possibly a fine-grained debris flow or the outwash from a coarse-grained debris flow.

**007 K**-2cm thick layer with common charcoal. It is a dark layer that is interpreted as a burned soil. It is only 2cm thick and is continuous up and down stream. The layer above it has 20% gravel with very few charcoal flecks. If it is not a soil then it is the result of a concentration of charcoal. Based on some of the other units that have the same date, this might not be a burned soil but rather the result of a concentration of charcoal. Age seems a little old, the date came from many fine fragments.

**008 A**-82cm thick layer with few-common scattered charcoal, <10% gravel, and large pieces of charcoal up to 5cm in length. The way that the charcoal is scattered, not concentrated in discrete locations makes me think that it is a fine-grained debris flow deposit. However, it could be a cumulic soil that has had charcoal bioturbated into it.

---

**Group 5:** **possible severe fire**-don’t see date anywhere except upper watershed, but it is under a lot of gravel and filling of a channel, maybe you don’t see it anywhere else because the channel isn’t exposed anywhere else in the modern arroyo. It isn’t exposed on the other side of the modern arroyo but maybe the rest of it was washed away in the modern arroyo incision. In any case there must have been a lot of activity during and after this time because the channel filled to the modern floodplain surface (because younger dates are found in group 3 and since the time of group 3 the arroyo has incised all the way back through and past 004 infilling by a few feet.

**004 D**-7cm thick layer with common charcoal that are mostly mm-sized flecks. The layer has no gravel, bioturbation, and areas of very high charcoal concentrations. The relationship between it and the overlying well-sorted gravel is difficult to determine. Interpretation: Either a fine-grained deposit that immediately preceded the deposition of the overlying gravel or a layer that was scoured into prior to gravel deposition. This must be part of the scour because it is younger than all units just downstream in section 003.

**Upper Cab2**
**Group 6: possible severe fire.** Only seen in 2 different sections

*005N* - 6cm thick gravel that is both matrix and clast supported in places. There is weak imbrication and there are fine layers that have common charcoal flecks. The relationship between the gravels and fine material is complex. M is a layer that has 25-35% gravel with moderate sorting- It has a red coloring and may be from tributary input. M has few charcoal flecks.

*005O* - 23cm thick, it has <1% gravel, and few-common charcoal. It is massive and doesn’t have any clear sedimentologic characteristics that would provide evidence of a fire. It was only the presence of charcoal that led me to radiocarbon date this unit. Perhaps it is another pool fill.

Notes on 005:
It seems like L and N should be the same but they tested to be significantly different. 005N and 005O tested to be the same. M and N have the same percentage of sandstone and limestone, perhaps they are related. N is a fill deposit into a scour that cut into O but that is no reason for them not to be related. There aren’t any good indications of O being fire-related except lots of charcoal. Maybe this is a case where fine-grained sediment washed down first and then the coarser sediment from M and N came down. Because L is different from N, and I have no reason to believe that L is a young date from the pretreatment records, I interpret it to be the record of another fire. However, due to the stratigraphy in between 005H and L, I need to interpret these to be different fires even though their dates are significantly the same.

---

**Group 7:** if 005R is related to 005Q then it is a **probable severe fire**, if it isn’t then it is a **non-severe fire** therefore it is plotted as a **possible severe fire**.

*005 R* - 125cm thick layer with common charcoal flecks concentrated in a 1cm thick continuous layer, otherwise there is v. few charcoal in the rest of the unit. This thin layer of charcoal may be a burned soil. I interpreted Grant’s Beta Analytic date to be from a position just under this unit. All of the stratigraphy from here down is difficult to follow because it is wet and separated by discontinuous lines of grungy, oxidized travertine. It is just below 005Q so it is possible that it is related to this fire. Hard to tell.

*008 E* - 31cm thick layer with common flecks of charcoal, ~10% gravel and lenses of higher concentration of gravel. It pinches downstream, and is bioturbated. This layer is difficult to interpret but it could be a thin debris flow/hyperconcentrated flow deposit.

----

**Group 8:** *009 AKQSU – Possible severe fire:* Many fine charcoal, thin layers (1/2-1cm thick), interbedded with light gray, light orange, and white calcareous sediment. All are laterally extensive. These were originally interpreted to be all one fire. The dates come from many pieces of charcoal fragments. The youngest and the oldest dates are significantly different, however they overlap with those inbetween. It is probable that
two fires are recorded within this group but it is impossible to determine where the break is between the groups.

**Group 9: Probable severe fire:**

**009VX**- Many fine charcoal, thin layers (1/2-1cm thick), interbedded with light gray, light orange, and white calcareous sediment. All are laterally extensive.

**009Z**- 7cm thick layer with v.many large fragments of charcoal. There is ~5% gravel at the tape measure and 30% gravel upstream of described section. This is a definite fire related sediment deposit and it was probably severe to get fragments in this high concentration so far down the valley.

---------------------------------------------------------------------------------------

008 interpretations- The sediment in this section may be from sediment that was removed and later refilled by the sediment I dated in the other sections and it is still intact because it is off to the side of the main channel. For that reason the interpretations of these as “severe” or “non-severe” shouldn’t depend on whether the dates show up in other sections.

G and I are from **non-severe fire**. There is no gravel associated with these thin deposits.

O- from a **possible severe fire**. It underlies a unit with 30-50% gravel with faint imbrication.

Other units that don’t match up with other sections including **007M, 005S, and UpCab1** have no gravels associated with them to suggest a severe fire. Therefore these are all non-severe.
Appendix J: Explanation of anomalous dates. Dates are in $^{14}$C yr B.P.

002I1 (727 ±34) and 002N2 (646 38): Both of these units were dated twice. The dates from 002 I2 (627 ±38) and 002 N2b (843 ±32) fit with the stratigraphy in other sections and were accordingly grouped with similar deposits.

003I (894 ±36): This date is much older than others from the same section probably due to inbuilt age.

004G (398 ±31): This unit is younger than the overlying date 004D (472 ±32). It is also younger than a date from the immediately overlying gravel that corresponds to 003K (576 ±36). 004D is younger than 003K and therefore fits with the stratigraphy. It seems reasonable to me to drop the 004G date and assign that unit the age from 003K.

005Q (647 ±32): During the radiocarbon pretreatment process humic acids were very difficult to remove from samples in this unit. It is very likely that they were not completely eliminated, resulting in a young age.

008K (1,614 ±45): The date from this unit was younger than both the overlying and underlying dated units (1,640 ±36 and 1,737 ±37).

009G (2,363 ±34): The date is older than the surrounding 5 dated deposits.