FIRE, CLIMATE, AND SOCIAL-ECOLOGICAL SYSTEMS IN THE ANCIENT SOUTHWEST: ALLUVIAL GEOARCHAEOLOGY AND APPLIED HISTORICAL ECOLOGY

by

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DEDICATION

I dedicate this dissertation to the White Mountain Apache Tribe. *A'shoog*.

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ABSTRACT

Although human land use in the industrial and post-industrial world has had demonstrable impacts on global climate, human land use may also improve or reduce the resilience of ecosystems to anthropogenic and natural climate change. This dissertation tests the hypothesis that low severity anthropogenic burning by prehistoric and protohistoric indigenous societies in the ponderosa pine forests of east-central Arizona improved the resilience of these forests to low frequency climate change. I use sedimentary charcoal, phosphorus, stable carbon isotopes, and palynology to reconstruct changes in fire regimes over the last 1000 years from seven radiocarbon dated alluvial sequences in five watersheds across a gradient of indigenous land use and occupation histories. Paleoecological evidence from occupied watersheds is consistent with small-scale, agricultural burning by Ancestral Pueblo villagers (between AD 1150-1325/1400) and anthropogenic burning by Western Apaches to promote wild pant foods (ca. AD 1550-1900) in addition to naturally frequent, low severity landscape fires. Statistical reconstructions of climate driven fire activity from tree-ring records of annual precipitation indicate that Southwestern forests were vulnerable to increased fire severity and shifts to alternative stable states between AD 1300-1650. In watersheds that were unoccupied or depopulated by AD 1325, paleoecological and sedimentological evidence is consistent with an increase in fire severity, whereas areas occupied and burned by indigenous people until AD 1400 did not yield evidence of increased fire severity. These results suggest that anthropogenic burning by small-scale societies may have improved the resilience of Southwestern forests to climate driven environmental changes.

CHAPTER 1. INTRODUCTION

Human societies have been implicated as significant agents of contemporary climate changes and, by extension, regional environmental changes. Although humans have been impacting their environments for millennia, not all impacts have been detrimental (Redman 1999). This dissertation evaluates the hypothesis that indigenous societies in the upland Southwestern United States improved the resilience of their environments by regularly burning for subsistence purposes. In an era of changing climates (Seager et al. 2007), contemporary ecosystem and fire management may benefit from an improved understanding of the consequences of traditional land use and anthropogenic burning on the response of Southwestern ecosystems to climate change. I use geoarchaeological and paleoecological methods to evaluate this hypothesis and contribute to the applied historical ecology of Southwestern forests and woodlands.

Humans, climate, and environmental change

One of the major challenges facing contemporary human societies is the apparent change in global climate conditions and its anticipated trajectories and environmental consequences. Global temperatures have been increasing in response to corresponding changes in the concentration of greenhouse gasses in the atmosphere. Human activity, particularly through the combustion of fossil fuels and the reduction of forest cover, has been implicated as the primary agent driving global climate change beyond that predicted by nonhuman contributors, such as solar forcing (Crowley 2000).

The complex relationship between human behavior and climate change is mediated by environmental change. The three-way relationship between humans, climate (global or regional patterns of weather), and environments (the generalized surroundings of humans or other organisms) is dialectical and recursive (Figure 1.1). Specifically, human activities alter global climates primarily by changing properties in their environments, such as the alteration of carbon budgets by burning fossil fuels. Alternatively, environmental change that is independent of human activity can also impact global climates by increasing or reducing carbon sequestration through increased efficiency of CO_2 fixation or its release with biomass burning in wildland fires. Environmental change, such as arroyo cutting or major biome shifts, can also impact human activity by limiting human options on the landscape (e.g., Dean et al. 1985). Finally, climate change can affect both human and environmental change by altering the seasonality and abundance of moisture and temperature in relation to growing seasons, impacting water availability for human use and plant growth as well as altering the length and regularity of fire seasons.

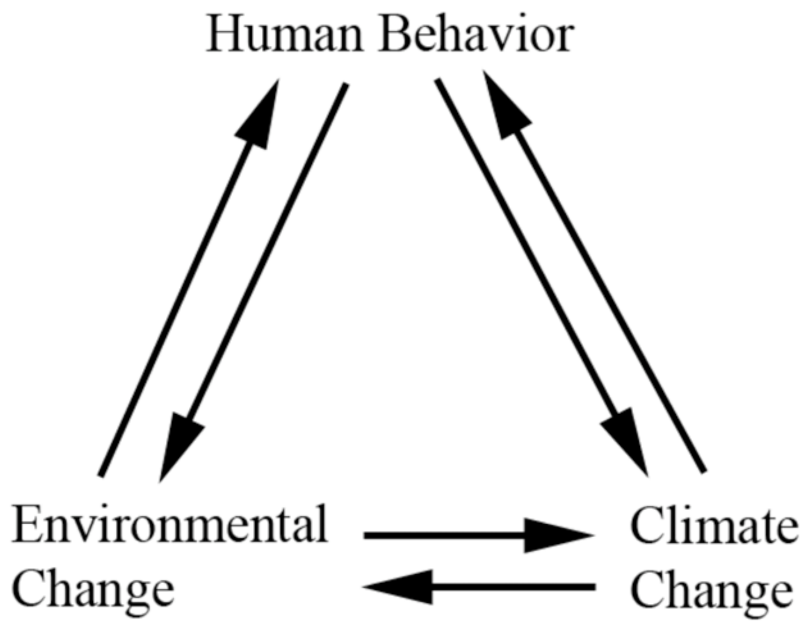


Figure 1.1 Schematic representation of the three-way, dialectical relationship between human behavior, climate, and environments.

Although a great deal of attention is given to the potential consequences of human-related global climate change on ecosystems, the greatest impact of climate change on regional environments may not be experienced as gradual changes in the range and distribution of species and ecosystems (Peterson 2008; Williams et al. 2007). Rather, climate-driven fire activity, particularly in forests and woodlands, but also in deserts (Betancourt 2008), coupled with the consequences of recent human land use history, may result in the rapid transformation of entire ecosystems. There is emerging evidence that this is already happening. The conflagrations witnessed in some Western North American environments have initiated a shift from previous metastable conditions to alternative metastable states (Savage and Mast 2005).

Changes in wildland fire activity in the American West cannot be attributed to climate alone. The condition of many Western forests, particularly in the Southwestern United States, is a consequence of more than a century of accumulating fuels and altered stand conditions (Allen et al. 2002). At the time of Euroamerican settlement in the late 19th century, middle elevation forests in Arizona were characterized by open-canopied, mixed-age stands of ponderosa pine trees (*Pinus ponderosa*) with a diverse understory of herbaceous plants (Fulé et al. 1997). Indirect fire suppression through the removal of herbaceous vegetation via grazing by domestic sheep and cattle may have begun as early as the 17th century in some parts of the Southwest (Savage and Swetnam 1990), but accelerated with the expansion of the railroads and the establishment of Indian reservations in the late 19th century (Swetnam 1990; Swetnam and Baisan 1996). In 1906, the U.S. Forest Service initiated a management plan that included the removal of all fire from U.S. forests with the intention of protecting national timber resources. As a response to lethal fires of 1910, a policy of total fire suppression was taken as the mandate for active management of American forests (Pyne 2001). After World War II, mechanized fire fighting techniques improved federal agencies' ability to quickly extinguish wildland fires throughout the forests of the American West.

Despite increasing technological options and greater financial resources available to fight fires, fire activity and severity have continuously escalated over the last 50-100 years. This has occurred in the context of increasing global temperatures, decreasing winter snow packs, and earlier springs, which have lengthened the fire season across the American West (Westerling et al. 2007). Decades of fire suppression have also contributed to elevated fuel loads and denser canopies in Western forests. In some Southwestern forests, a one-hundred-fold increase in stem density (Fulé et al. 1997) or larger (Falk 2004) has been documented. Although the direct impact of earlier springs and warmer temperatures on Southwestern forests is less clear compared to the rest of the West, it has been suggested that the current experience of increased high severity, stand replacing fires is the “new normal” for the era of global climate change (Pierce and Meyer 2008).

The “old normal”

Prior to Euroamerican settlement, open, parklike stand structures in Southwestern ponderosa pine forests were maintained by low severity surface fires every 3-10 years (Allen et al. 2002; Fulé et al. 1997). These fires consumed understory fuels, prevented fuel accumulation, and restricted canopy recruitment (the germination and growth of cohorts of young trees) by killing seedlings less than 10-15 years old. Because fire behavior is patchy, a small number of seedlings survived to produce mixed age stands of conifers in a matrix of understory plants. As a species, ponderosa pine seems to be well adapted to this type of high frequency, low severity, surface fire regime. Mature trees have thick bark, “self-prune” lower branches, reproduce and shed their entire needle cover over the course of 3-7 years, frequently producing an easily combusted fuel bed, and are capable of surviving fires in which up to 70% of their foliage is killed by high temperatures (Covington 2003). During the last glacial period, until approximately 11,000 cal BP, ponderosa pines were restricted to small refugia in the Southwest

(Betancourt 1990; Weng and Jackson 1999). Decreased seasonality during glacial periods may have reduced the length of the fire season in which surface fuels could burn. With the onset of warmer conditions, the strengthening of the summer monsoon, and perhaps the arrival of humans as an additional ignition source, ponderosa pine rapidly expanded to its current elevation range in the context of increased fire activity (Weng and Jackson 1999).

Our best evidence regarding ponderosa pine fire regimes, however, comes from the tree-ring record over the last few centuries. An extensive regional network of more than 120 fire scar study areas across Arizona, New Mexico, northern Sonora and Chihuahua, and southwestern Colorado indicates that between approximately AD 1600-1900, surface fires burned ponderosa pine landscapes frequently and with low severity (Kitzberger et al. 2007; Swetnam and Baisan 2003). Sufficient seasonality for flammable fuel conditions was probably not limiting, in that a pronounced regional drought from April through the end of June is common between the period of cyclonic winter storms and the onset of convectional summer storms associated with the North American Monsoon. Ignitions were probably not limiting either, since lightning is common during convective storms associated with the Summer Monsoon (Allen 2002). The greatest external factor apparent in regional fire variability appears to be surface fuel abundance and continuity. This is apparent in the relationship between fire scar abundance and interannual moisture. Since AD 1600, regional fire synchrony has been greater during dry years that follow 1-3 wet years (Swetnam and Baisan 2003). Hypothetically, this antecedent moisture pattern produces abundant and continuous fine fuels during wet years and cures them to burn over extensive areas during dry years, particularly after dry winters (Crimmins and Comrie 2004). These interannual moisture patterns and associated fire activity are, in part, the apparent result of hemispheric teleconnections with El Niño Southern Oscillation (ENSO), which has demonstrable impacts on winter moisture and subsequent fire activity in the Southwest (Swetnam and Betancourt 1990).

Investigators working in ponderosa pine and mixed conifer forests in the Northern and Central Rockies suggest that this pattern of frequent, low severity surface fires has not always characterized Holocene ponderosa pine forests. On the basis of radiocarbon dated debris flow events, which appear to be analogous to contemporary, high severity fire related debris flow deposits, Pierce and Meyer (Meyer and Pierce 2003; Pierce et al. 2004; Pierce and Meyer 2008) argue that periods of increased temperatures at the hemispheric scale, such as the early-middle Holocene and the so-called Medieval Warm Period (ca. AD 900-1300), created stand conditions that carried high severity crown fires. Although evidence from the Southwest is less clear (Frechette 2007; New 2007), these authors and others (Whitlock et al. 2008) suggest that the detailed fire scar records, because of their limited time depth and association with cooler hemispheric temperatures (i.e., the Little Ice Age), are no longer valid analogs for the period of contemporary global climate change.

One shortcoming of this argument, which dismisses the relevance of fire scar studies for management of contemporary forests, is that the high severity fire models lack a mechanism through which stand densities and fuel loads were altered to conditions sufficient to initiate and propagate high severity fires. For example, longer fire-free intervals would have been necessary to permit widespread canopy recruitment and the creation of ladder fuels (i.e., continuous fuels bridging understory fuels and the canopy) as well as connectivity of canopy fuels. How this could have happened during the Medieval Warm Period or during the middle Holocene has not yet been adequately explained. An additional shortcoming in these studies is that they fail to acknowledge that humans have occupied and used these landscapes throughout the Holocene. Human land use has the potential to suppress or amplify the impacts of climate change on local environments. For example, some forms of human activity that fragment fuels, such as trail establishment or road construction, livestock grazing, and village or town construction, can reduce fire frequencies at larger landscape scales and create situations in which fuels could accumulate and canopy density could increase through recruitment. These coupled human-natural ecosystems may be more vulnerable to low frequency climate change and less resilient to wholesale shifts in ecosystem structure and function (Savage and Mast 2005). This description is analogous to what has happened over the last century in the Southwest. Climate change appears to be facilitating state shifts in these forests through fire activity that occurs in landscapes of fuel and stand conditions produced by coupled human-natural ecosystem processes over the last 100 years.

Alternatively, anthropogenic burning may have made these landscapes less vulnerable to low frequency climate variability that could have impacted fire frequency and canopy recruitment. Fragmented fuels, due to changes in climate driven fuel production or human activity, are not limiting for anthropogenic burning, in which ignitions are not spatially random and can be increased in quantity, density, or seasonality to burn areas that might otherwise need continuous fuels to carry fires from fewer, stochastic ignitions, such as lightning. Coupled human-natural ecosystems with anthropogenic and natural fire regimes may have been more resilient (i.e., better able to maintain ecosystem services) to climate fluctuations in this scenario.

The anthropogenic burning controversy

The significance of anthropogenic burning in American ecosystems is a controversial subject. For centuries, Euroamericans have viewed ecosystems of the Western Hemisphere as pristine wilderness (cf., Kay 2002). Ancestors of contemporary Native American, Alaskan, and Canadian First Nation societies presumably lived in perfect harmony with their environments as Rousseauian “Noble Savages” (Ellingson 2002). During the 1960s, this image was popularized by environmental groups, who decried the obvious impacts of mainstream American society on North American environments. The image of the weeping Indian was used to communicate the tragedy that insensitive, white society was creating in the destruction of American wilderness and nature that Indians had coexisted with, without alteration, for millennia (Krech 1999).

The idea that American Indian societies had little or no impact on their environments had traction in 20th century science as well. For anthropologists through the middle of the 20th century, American Indian societies adapted to the limitations of their local climate and environment (e.g., Steward 1955). Fluctuations in climate and the natural world were limiting factors for indigenous American societies, to which they could only respond with cultural change, migration, or extinction. For natural scientists, this relationship meant that properties of landscapes at European settlement or as documented in paleoecological records were essentially free of human influence. These landscapes were idyllic wilderness equivalents to a North American Eden and paleoecological records were the simple product of natural ecological processes and climate change.

By the middle of the 20th century, however, some humanists, including anthropologists and geographers, began to question the unidirectional influence of environments on indigenous American societies (Butzer 1990; Denevan 1992; Stewart 2002). In particular, scholars such as Omer Stewart and Henry Lewis began to suggest that American Indian societies had a significant impact on their environments through the use of fire on their landscapes (Lewis 1973, 1978, 1980; Stewart 2002). Over the last 25 years, the ideas of Lewis and Stewart captured the imagination of a variety of scholars (e.g., Pyne 1994, 1998). In fact, some authors argued that carefully constructed fire histories for periods prior to Euroamerican settlement were not "natural," as they had been described, but entirely cultural (Kay 2002, 2007). In some forms of the argument, Indian groups were portrayed as beneficent land managers, in which their iconic status as stewards of the environment was maintained. In other cases, it was argued that, like many human societies before and since, American Indian groups overexploited resources and degraded landscapes (Krech 1999).

The polemic arguments associated with the rejection of the "Pristine Myth" (Denevan 1992) elicited a strong response, in which the "Humanized Myth" was disparaged (Vale 2002c). Although the explicit goal of Vale's (2002a) book and its contributed chapters was to carve out a more nuanced and less extreme middle road between the "Humanized" and "Pristine" myths (Vale 2002b), particularly with respect to fire, the general conclusion of the book dismissed the importance of Native people in most environments of the Western U.S. (Pyne 2003). Modern lightning and fire data were used to demonstrate that many Western forests (Whitlock and Knox 2002), especially in the Southwest, are not ignition limited (Allen 2002). Additionally, historical documents that attribute fires to indigenous ignitions are often ambiguous, at best. Consequently, the authors argue that indigenous anthropogenic burning can be dismissed as inconsequential in the discussion of historic fire regimes for most of the West through most of the Holocene (e.g., Allen 2002:180).

The polemic has had unfortunate consequences on the evolution of the dialog concerning American Indian societies, climate change, and fire. In the Southwest, indigenous people have lived in or used ponderosa pine forests for millennia. For example, Ancestral Pueblo peoples (also referred to as Mogollon and Anasazi) lived year-round in the ponderosa pine forests of east-central Arizona for more than 1000 years (Reid and Whittlesey 1997). These residents would have impacted fire histories in these environments simply by their presence and their daily activities in the creation and maintenance of trails, gardens, villages, fuelwood collecting, hunting, and ritual activity. More than 1000 years of observations on fire activity and behavior, communicated across generations through oral tradition, would have probably maintained a sophisticated knowledge of "natural" fires, including their frequency, seasonality, and consequences on local vegetation patterns and wildlife (Stoffle et al. 2003).

In fact, it is likely that the earliest residents of the Southwest, terminal Pleistocene Paleoindian groups, had a sophisticated knowledge of fire and its landscape uses as well. A case can be made that landscape burning was a part of the Upper Paleolithic toolkit that behaviorally modern humans took with them when they left Africa more than 50ka BP (Pyne 1998). Late Pleistocene paleoecological records from Australia have long been used to support the colonization of that continent at approximately 40-45ka BP. Charcoal influx and pollen assemblages changed dramatically at this time, which indicates major changes in fire activity and selective pressure favoring fire-adapted plant species (Bowman 1998). These records are not unique, however. Two biomass burning records that span more than three full glacial-interglacial cycles from the Sulu Sea and the equatorial West Pacific document unprecedented increases in Southeast Asian fire activity between 45-55ka BP, coincident with the earliest dated archaeological sites associated with modern humans in the area (Beaufort et al. 2003; Thevenon et al. 2004). These records cannot be interpreted without reference to the addition of modern humans to Southeast Asian ecosystems (Figure 1.2). The suggestion that modern humans used fire to alter the structure of Southeast Asian forests is further supported by isotopic work on anatomically modern human remains from the earliest deposits at Niah Cave, Borneo. Earliest residents made their livelihood, primarily from resources in closed canopy rainforest, whereas subsequent generations took advantage of resources in (probably anthropogenically created) canopy openings (Krigbaum 2007). Additionally, changes in fire activity appear to herald ancient human colonization in the Falkland Islands

(Buckland and Edwards 1998), New Zealand (McGlone and Wilmshurst 1999), and the Caribbean (Higuera-Gundy et al. 1999).

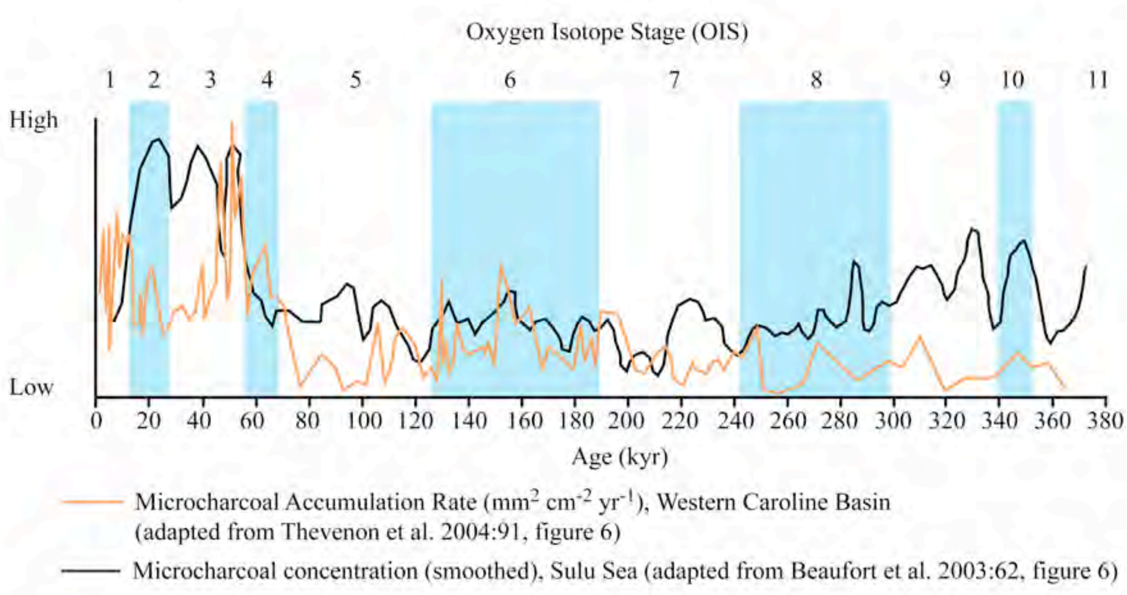


Figure 1.2 Pleistocene-aged sedimentary charcoal records from the West Equatorial Pacific (Thevenon et al. 2004) and the Sulu Sea (Beaufort et al. 2003) over four full glacial-interglacial cycles (OIS 1-10). The period of greatest change (45-55kyr) is coincident with the earliest archaeological evidence for the colonization of island Southeast Asia by modern humans (Barker et al. 2007).

Therefore, it is extremely likely that human populations colonizing the Americas had a working knowledge of fire as a tool for altering landscapes. However, the likelihood that all American Indian societies had a working knowledge of landscape burning does not support the argument that, by extension, all pre-Euroamerican fire histories were anthropogenic. This argument requires unjustified assumptions about uniformity in the human use of their landscapes and human population densities as well as the assumption that frequent fire always benefited resources of human interest. Although human mobility in the past is often underappreciated, in virtually no case was this movement random and uniform (Binford 1982). Some environments were and are invariably used more than others. Even among nomadic groups, movement is best characterized by a network of movements between nodes of more intense activity. Additionally, population density, demography, technology, and land use have all varied across time and space. The argument that all fire regimes must be driven by anthropogenic fire also assumes that natural processes cease to operate in the presence of human activity, which is insupportable. For example, the climate driven production and curing of fuels in Southwestern forests acted whether humans used the landscape or not. Lightning striking dry fuels will continue to start fires whether humans are present or not, as contemporary fire managers are well aware.

Conceptually, it is most parsimonious to consider both human and natural fire-related processes as acting together. By investigating both anthropogenic and natural fire activity in the paleoecology of Southwestern landscapes, we can more accurately assess the long-term resilience and vulnerability of these environments to external processes, such as climate change. Additionally, any variability in the frequency, seasonality, or severity of fires triggered by coupled human-natural fire regimes has implications for understanding variability in the selective mechanisms acting on other organisms living in these environments. Concepts from niche construction (Odling-Smee et al. 2003) and resilience theories (Holling and Gunderson 2002) justify the investigation of coupled human-natural ecosystems and their fire regimes over long time scales. In a niche construction and resilience theory informed applied historical ecology framework, the investigation of coupled human-natural ecosystems is necessary to better understand the range of historical variability in keystone ecological processes, such as fire.

The present study

Guided by concepts from niche construction and resilience theories, I have used archaeology and ethnohistory to inform an applied historical ecology project concerning coupled human-natural ecosystems, climate change, and fire regime variability. To this end, I have adapted sedimentary charcoal methods commonly used to analyze sediments from lakes and bogs for use on sediments from alluvial deposits in combination with geochemical and paleobotanical proxies to infer changes in fuels, fire frequency, seasonality, and severity. By reconstructing fire regime histories over a gradient of indigenous land use and occupational histories, defined by archaeological and ethnohistorical records, I examine a gradient of coupled human-natural fire regimes from more natural to more humanized. Comparisons of these records to millennial length reconstructions of climate driven fire activity improve the inferences of human influenced fire regimes superimposed on natural fire regimes. Additionally, variability in climate driven fire activity highlights periods of greater vulnerability to increased fire severity that overlap with periods of ancient human occupation. In the following pages, I will make the argument that coupled human-natural fire regimes in east-central Arizona produced ecosystems that were less vulnerable to low frequency climate change than more exclusively “natural” ecosystems.

Outline of the dissertation

I begin the discussion by articulating the theoretical concepts that form the backdrop to the present study. In Chapter 2, I discuss the relative meaning and history of the concepts of historical ecology as used by anthropologists and restoration ecologists. Concepts from the emerging literature associated with both resilience and niche construction approaches to evolutionary theory are brought to bear on the subject of applied historical ecology and coupled human-natural ecosystems. I argue that to best understand the range of historic variability for process-based restoration, the explicit addition of humans in historical ecological research is necessary to understand resilience of these environments to external change (climate or land use) as well as variation in the selective pressures on other organisms in these environments.

In Chapter 3, I introduce my study area. I have focused my attention on the Eastern Mogollon Rim Region for its ecological properties, recent fire history, and intensity of archaeological investigation, all of which make it well suited for this particular study. This region lies at the heart of the largest continuous stand of ponderosa pine forest in the United States and, in 2002, experienced the largest wildfire in Arizona's recorded history. Nearly half a million acres burned during June and July of that year in the Rodeo-Chediski fire. Intensive research by archaeologists from the University of Arizona over 65 years has contributed to a detailed understanding of local occupational and economic histories (Haury 1985; Mills, Herr and Van Keuren 1999; Reid and Whittlesey 1999). Importantly, this area witnessed spatially and temporally variable occupation by Ancestral Pueblo (sometimes called Mogollon and Anasazi) and subsequently Western Apache peoples over more than a millennium overlapping with tree-ring reconstructions of climate driven fire variability (Roos and Swetnam nd).

In Chapter 4, I discuss the ecological and geological foundations of the methods used in the study. Tree-ring based fire scar analyses provide temporally and spatially precise records of fire activity but are limited in time depth due to a "fading record" problem. Recent sedimentary charcoal based reconstructions are less precise spatially and temporally but offer the possibility of millennial length reconstructions of fire activity. These methods have been employed almost exclusively in the analysis of charcoal from lakes, ponds, bogs, and wetlands. These wet, slow aggrading depositional contexts are not common in areas occupied by indigenous people in the Southwest. I have adapted the basic methods from lacustrine sedimentary charcoal analysis to the ubiquitous, ephemeral stream contexts in the upland Southwest. Specifically, I have combined sedimentary charcoal with geochemical (phosphorus and stable carbon isotopes) and palynological proxies to investigate long-term variation in watershed scale fire regimes.

Prior to discussing the paleofire reconstructions, I discuss the field and laboratory evidence for soil and sediment stratigraphy from the sample locations. In Chapter 5, I discuss evidence from analyses for mineral grain size, carbonate and organic matter content, and soil micromorphology in relation to depositional processes and postdepositional alteration of sampled alluvial deposits. Geochronology is provided by Accelerator Mass Spectrometer (AMS) radiocarbon dating of detrital charcoal collected from these sediments. Calibrated dates were refined using Bayesian methods (Buck et al.

1991) and used to calculate age-depth profiles and average sedimentation rates for each stratigraphic sequence. The geochronological reconstructions were in turn compared to stratigraphic data to affirm their relative accuracy.

Chapter 6 details the evidence for variation in fire activity through sedimentary charcoal abundance, phosphorus content, stable carbon isotopes, and pollen assemblages. Data from AD 1600-1900 from unoccupied “control” watersheds as well as calibration pollen studies from contemporary environments (Hevly 1988; Martin 1963; Rankin 1980) and from sediments collected from deposits produced from late 20th century high severity fire events are used to interpret variations from “natural” fire regimes. Elevated biomass burning in the context of domesticated plant pollen, elevated phosphorus, but otherwise “natural” fire regime indicators is used to infer Ancestral Pueblo burn-plot agricultural activities (Sullivan 1982) superimposed on a natural fire regime. Evidence for increased herbaceous cool season plant abundance, frequent fires in fine fuels, and reduced sediment availability are used to infer Western Apache burning during the fall to promote wild seed production (cf., Kaib 1998; Kaye and Swetnam 1999; Morino 1996; Seklecki et al. 1996). Rapid sedimentation of exhumed subsoil material in conjunction with low phosphorus and low *Pinus spp.* pollen concentrations are inferred as evidence for increased fire severity in small watersheds, whereas rapid sedimentation capped with large amounts of charcoal and preserved ashes in association with eroded, unburned organic matter are used to infer high severity fire activity in larger watersheds.

In Chapter 7, I synthesize the reconstructions of human land use and fire histories in the context of climate predicted fire activity. Long occupied watersheds did not experience high severity fire activity due to coupled human-natural fire activity persisting through a decrease in the frequency of climate driven regional fire years. In contrast, watersheds abandoned prior to the decrease in climate driven activity experienced increased fire severity comparable to unoccupied watersheds. This suggests that coupled human-natural ecosystems and fire regimes were less vulnerable to long term climate change that facilitated the fuel accumulations necessary for increased fire severity on other landscapes. Subsequent occupation and burning of the Forestdale Valley landscape by Western Apaches may have further buffered this watershed from vulnerability to climate conditions conducive to increased fire severity in the late 16th century. I conclude the dissertation with suggestions of directions for future research to build on the hypotheses supported in this study.

CHAPTER 2. APPLIED HISTORICAL ECOLOGY, RESILIENCE, AND NICHE CONSTRUCTION

Historical ecology in humanist traditions

The term “historical ecology” is probably no more than 40 years old within anthropology and related disciplines (according to Don Rice, in Crumley 1998:xii). As a tradition, humanist historical ecology has developed over these four decades as a response to the deterministic explanations of the previous cultural ecology and cultural materialist paradigms (Biersack 1999). Historical ecologists conceptualize the relationship between societies and their environments as dynamic and dialectical. The actions of humans and societies affect environments, which in turn affect human societies. Although the relative importance of human or environmental agency may vary across space and through time (Crumley 1994:10), the relationship is always two-way, and “nature” and “culture” are inseparable, at least over Holocene timescales. In this view, environmental and social changes are the consequence of conflicts and tensions between human and environmental “agencies,” in what are clearly Marxist inspired explanations (although translated through the French *Annales* school of history; Crumley 1998). Reflecting this intelectual tradition, the term “historical ecology” has been used synonymously with the term “dialectical ecology” (Crumley 1994, 1998). The histories of societies and their environments have left legacies on their landscapes, which are the primary subject of historical ecological research (Balée 1998; Crumley 1987, 1994; Crumley and Marquardt 1990).

Humanist historical ecology provides concepts and units for study, such as landscapes, regions, and boundaries, which are meant to link the humanist study of human-environment relationships to natural science investigations. As envisioned by Crumley (1987, 1994) and Balée (1998), historical ecology is a research program by which anthropologists, archaeologists, historians, and geographers can investigate the consequences of human thought and action through the interdisciplinary study of landscapes and their contingent histories.

Human impacts, benign or destructive, transformative or subtle, are ubiquitous in the histories of all landscapes (Crumley 1994). The emphasis in humanist historical ecology, however, has largely been the revision of human-environmental stories to include dialectical relationships and to stress that human and environmental histories are contingent on events and processes that are both cultural and natural (Biersack 1999). The questions that guide this historical ecological research are decidedly humanist, however, in that they take human societies as their ultimate subject.

Not all anthropological and archaeological historical ecology falls entirely within this framework. The nascent field of applied zooarchaeology, for example, uses information from archaeological faunal collections to contribute to the discourse on wildlife management and conservation biology (Lyman and Cannon 2004). Such research provides long-term perspectives concerning human-environmental dialectics as well as information on pre-modern animal communities, biodiversity, and the impacts of climate change and human land use (Lyman and Cannon 2004).

Applied historical ecology in natural science traditions

Historical ecology as an applied discipline exists largely in the realm of conservation biology (the conservation of biological diversity) and restoration ecology (the study of renewing degraded ecosystems). In this context, historical ecology provides the long-term framework for interpreting the synchronic or very short-term studies that characterize most ecological research (Swetnam et al. 1999). Fundamentally, historical ecology provides the baseline data to identify degraded ecosystems or losses in biodiversity (Willis and Birks 2006). Historical ecology reconstructs reference conditions for ecosystem structures or key ecological processes. These reference conditions are often referred to as the “range of natural variability” or “historical range of variability” (Landres et al. 1999). The latter term is favored by many researchers because the concept of “nature” is both problematic and ambiguous (Egan and Howell 2001:7).

Reference conditions cannot be applied uncritically (Landres et al. 1999; White and Walker 1997). For example, reference conditions can be generated from a variety of contexts (contemporary, nondegraded but similar ecosystems; past ecosystems of the particular site to be restored; or from past ecosystems of other sites) but the most appropriate reference information will probably come from local historical ecologies rather than from more spatially distant ecosystems, where uncontrolled variables may contribute to incompatibility of historical referents (White and Walker 1997). An additional concern when interpreting historical reference conditions is the role of climate change (Millar and Woolfenden 1999). Most reference conditions describe ecosystem properties at Euroamerican settlement or during the decades in, at most, one or two centuries prior to settlement (e.g, Fulé et al. 1997). Although the timing and local consequences of global climate change of the last few thousand years were quite variable (e.g., Hughes and Diaz 1994), reference conditions that describe ecosystems during the generally cooler and wetter conditions of the so-called Little Ice Age from AD 1400-1850 may not be relevant for managing and restoring ecosystems in the current era of global warming (e.g., Millar and Woolfenden 1999). The static notion of reference conditions averaged over a short window prior to modern recording is particularly untenable in the era of global climate change (Milly et al. 2008).

Finally, Falk (2006) has argued for the importance of describing historical variation in ecosystem dynamics that maintain structure and function rather than reference conditions of structures alone. Key ecosystem processes, such as fire in Southwestern forests, regulate ecosystem structure and function (Allen et al. 2002; Falk 2006) and are particularly responsive to climate (Grissino-Mayer and Swetnam 2000; Kitzberger et al. 2007; Swetnam and Baisan 2003; Swetnam and Betancourt 1990, 1998). Only by restoring the processes that regulate ecosystem function can these environments be sustained in resilient, metastable conditions (i.e., self-sustaining dynamic regimes on the scale of multiple decades to many centuries). The sensitivity of these dynamics to long-term climate change emphasizes the importance of matching applied historical ecology to climate change research.

It is in this final context that considerations of human history are critical. For a variety of reasons, indigenous coupled human-natural ecosystems have largely been excluded as components of applied historical ecology (Crumley 1994:3). Although the controversy concerning the relative importance of indigenous American societies on pre-Euroamerican ecosystems continues to rage (Barrett et al. 2005; Denevan 1992; Krech 1999; Vale 2002c), there are theoretical justifications for explicitly incorporating ancient human societies into applied historical ecological research. I suggest that resilience theory (Holling et al. 2002; Redman 2005) and niche construction theory (Odling-Smee et al. 1996, 2003) make it imperative that coupled social-ecological systems be the subject of applied historical ecological research to understand the relationship between ecological and climate change.

Resilience theory

Two conceptualizations of the term “resilience” are frequently used in ecology. The first concept refers to the time it takes for an ecosystem to return to singular or “global” equilibrium after a perturbation; this is known as *engineering resilience* (Holling 1996). In contrast, the second concept describes the ability of an ecosystem to absorb perturbations without changing states or altering ecosystem services. This property, referred to as *ecological resilience* (Holling 1996), has gained favor among many ecologists as the abundance of alternative metastable states for given ecosystems has been documented (Beisner et al. 2003). Resilience theory provides two conceptual metaphors to describe social and ecological systems and shifts to alternative metastable states. The first, and most common metaphor applied in archaeology (e.g., Redman 2005), is the adaptive cycle (Holling and Gunderson 2002; Redman and Kinzig 2003). The adaptive cycle is a four-stage “figure eight” model of the changes in which complex adaptive systems grow, collapse, and change (Holling and Gunderson 2002; Walker et al. 2004). It is a conceptual model for how stability (or metatability, or metastable dynamic regimes) can persist in the context of change, including evolutionary change. The four stages (exploitation, conservation, release, and reorganization) serve as heuristics for describing the direction of cyclical change in an open, dynamic system (Figure 2.1). Although often described as a sequence of stages, recent statements acknowledge that not all systems experience all four phases (Walker et al. 2006). Adaptive cycles also vary in both temporal (fast vs. slow) and spatial scale (large vs. small), but are interconnected across scales within nested hierarchies or “panarchies” (Holling et al. 2002).

State shifts (e.g., shifts from forests to grasslands or locally organized villages to regional polities) may occur during the reorganization phase, although larger and slower adaptive cycles often provide “memory” to the system, keeping smaller, faster variables within existing adaptive cycles. Although state shifts are often presumed to originate in large or slow adaptive cycles, changes in small or fast adaptive cycles can ripple upwards and create a situation in which system-wide “revolt” results in widespread state shifts (Carpenter et al. 2002). Resilience, however measured, is often greatest within a social or ecological system when connectedness is low and response diversity is high (Gunderson et al. 2002). Some archaeologists have embraced resilience theory and the adaptive cycle as a conceptual metaphor for investigating long term changes in social-ecological systems, particularly the growth and collapse of civilizations (Redman 2005).

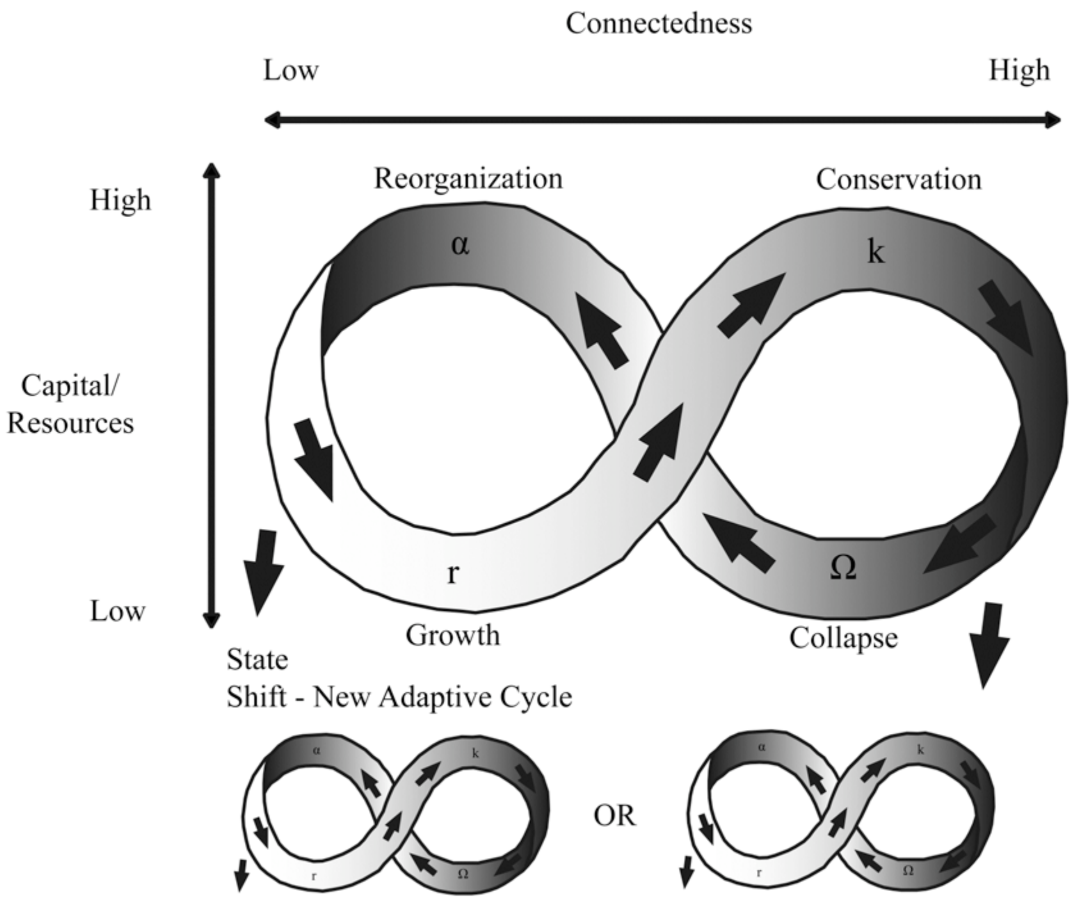


Figure 2.3 The “figure eight” metaphor of the adaptive cycle with growth (r), conservation (K), release (Ω), and reorganization (α) phases. Smaller and faster adaptive cycles are nested within larger and slower cycles in the so-called panarchy. Larger cycles can provide memory to smaller cycles when they reorganize and maintain system function through periods of change. In contrast, changes in small-scale cycles can cascade upward through the panarchy and create “revolt” changes across the system.

The second conceptual metaphor from resilience theory is the stability “landscape.” A simple two-dimensional ball and cup model of the “stability landscape” is common for discussing alternative stable states in community ecology (Beisner et al. 2003; Scheffer and Carpenter 2003; Scheffer et al. 2001). A three-dimensional stability landscape is characterized by ridges and basins across three-dimensional space defined by ecosystem parameters (Beisner et al. 2003). Alternative stable states in the ball and cup landscape metaphors are characterized by basins of attraction (metastable states) separated by unstable ridges. A “ball” can be used to indicate the current conditions of a particular real-world landscape in the parameter space of the conceptual stability landscape. The depth of the basin characterizes the resistance of ecosystems to change (i.e., the resilience of the system). The latitude or width of the basin characterizes how much of the parameter space (or the range of ecosystem dynamics) can exist while essentially maintaining similar ecosystem functions and services (Walker et al. 2004). “Balls” tend to move downslope unless upset by a “disturbance” or “surprise” change in conditions. Thresholds between alternative stable states are ridges in the parameter space. The proximity of a particular landscape to the edge of a basin (a threshold) is a measure of vulnerability to a state-shift represented by movement to an alternative attractor basin. The lower the height of the threshold, the more readily a disturbance may move the ecosystem to an alternative state.

Figure 2.2 provides an example of a ball and cup stability landscape for Southwestern ponderosa pine forests, abstracted from the research of Swetnam and Baisan (2003), Savage and Mast (2005), and Allen and colleagues (2002). Under the high frequency, low severity surface fire regime characteristic of at least two centuries prior to Euroamerican settlement, ponderosa pine forests are maintained in open canopied, parklike forests of mixed-age stands. These forests were probably very resilient to extreme climate-driven disturbance events. For example, although the year AD 1748 witnessed tremendous, regionally synchronous fire activity in most Southwestern forests, these fires occurred primarily as surface fires within ponderosa pine forests (Swetnam and Baisan 2003) and did not result in shifts to alternative metastable states. Shrubfields and meadows, present at Euroamerican settlement, may have existed as alternative metastable states as a small component of a landscape scale mosaic in the context widespread, low-density ponderosa pine forests. This situation is illustrated by Figure 2.2A.

In contrast, long fire-free intervals (>10-20 years) coupled with multiple wet years promotes the germination and recruitment of canopy species in ponderosa pine forests (Brown 2006; Brown and Wu 2005). Dense or hyperdense ponderosa pine stands are particularly vulnerable to high severity stand replacing fires during prolonged or severe droughts. Some of the dense ponderosa pine stands that burned during the severe drought of the AD 1950s have converted to shrubfields and meadows or returned to hyperdense ponderosa pine forests that have been stable over the last half century (Savage and Mast 2005). This situation is illustrated in Figure 2.2B. Longer return intervals promote increased stand density and erode ecosystem resilience, represented as a change in the topography of the stability landscape. The thresholds between alternate stable states become lowered as it requires less extreme climate events to produce disturbances sufficient to promote shifts between states.

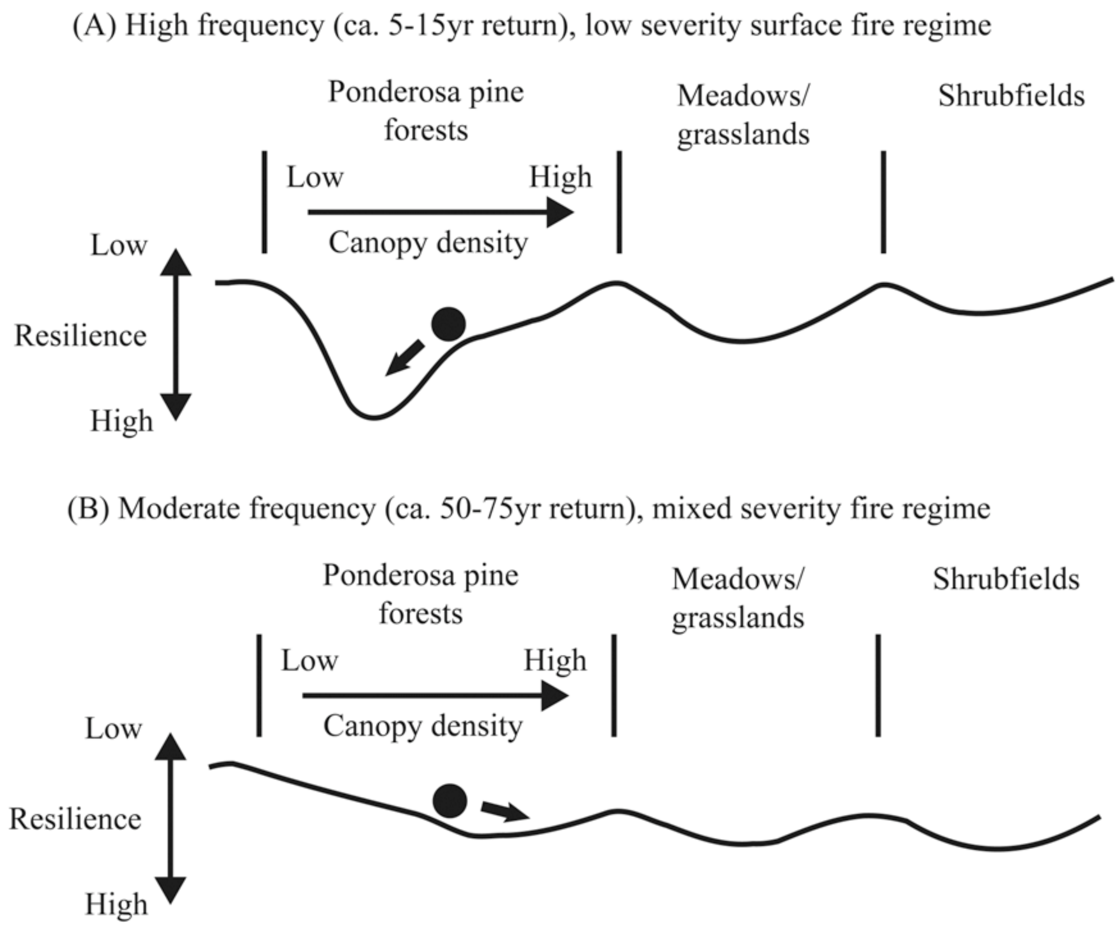


Figure 2.4 Hypothetical ball and cup stability landscapes for Southwestern ponderosa pine forests with varying fire regimes. With frequent, low severity surface fires (Figure 2.2A, top), open-canopied ponderosa pine forests are very resilient to climate changes. With longer fire-free intervals (Figure 2.2B, bottom), stand density increases and forests become more vulnerable to state shifts in the wake of climate-driven disturbances.

The key indicator of resilience in Southwestern ponderosa pine forests is probably stand density. Stand density, which is a result of recruitment patterns, is regulated by fire frequency and climate (Brown 2006; Brown and Wu 2005). Any process that might reduce fire frequency in Southwestern ponderosa pine forests potentially alters the stability landscape by increasing stand density, reducing resilience, and increasing vulnerability to state shifts. Alternatively, any process that promotes or maintains frequent fires may promote resilience by regulating stand conditions.

The importance of land use and climate change for understanding ecosystem resilience can readily be seen using the stability landscape metaphor. Both land use and climate change can affect the regime of the keystone ecosystem dynamic—fire. For example, land use related reductions in fire frequency coupled with a) climate driven recruitment followed by b) severe drought seriously altered the shape of the stability landscape for 20th century Southwestern ponderosa pine forests (Savage and Mast 2005). Decades after stand replacing fires, these environments appear to have moved into alternative metastable 1) shrublands, 2) meadows, or 3) hyperdense ponderosa pine forests that remain vulnerable to further crown fires (Savage and Mast 2005). If, as has been suggested, climate conditions drove crown fire activity in ponderosa pine forests at other times during the Holocene (Pierce et al. 2004; Pierce and Meyer 2008), climate driven reductions of surface fire frequencies are capable of generating the same alterations of the ponderosa pine forest stability landscape. Anthropogenic burning could alter the shape of the stability landscape, perhaps resisting alterations driven by climate fluctuations. Hypothetically, even if anthropogenic burning were indistinguishable from "natural" fire regimes, coupled human-natural ecosystems would be more resistant to climate driven alterations of the shape of attractor basins and thresholds between alternative metastable states. This hypothesis is testable. Information on the relative resilience of more or less intensively coupled human-natural systems (and coupled anthropogenic-natural fire regimes) would be valuable for understanding the range of historic variability in ecosystem dynamics for restoring these environments to resilient and sustainable arrangements in the face of modern climate change (Falk 2006).

Niche construction and ecosystem engineering

The fundamental premise of niche construction theory is that all organisms, through their choices and activities alter the selective pressures on themselves, their descendents, and other organisms that share their environments (Odling-Smee et al. 1996). Biologists John Odling-Smee, Keving Laland, and colleagues (Laland et al. 2000, 2001; Laland and Sterelny 2006; Odling-Smee et al. 1996, 2003) have argued for the extension of contemporary evolutionary theory to include niche construction as a previously underappreciated mechanism in evolution. Although greatest attention in the literature has been given to the argument for incorporating niche construction in formal models of biological evolution (e.g., Laland et al. 2001; Odling-Smee et al. 1996, 2003), niche construction has promise for understanding cultural evolution (Laland et al. 2000; Odling-Smee 1994) as well as for conservation biology (Boogert et al. 2006). Boogert and colleagues (2006) argue that the most successful conservation strategy has been to focus on the niche constructing activities of key ecosystem engineers (organisms whose niche construction is disproportionately important in a given ecosystem). Conservation or restoration of key ecosystem engineers or replication of their engineering behavior may be critical for successful and sustainable ecological restoration (Boogert et al. 2006).

In Southwestern ponderosa pine forests, there are at least two organisms that may qualify as key ecosystem engineers. Ponderosa pine trees are themselves niche constructors. Their thick bark and high crown scorch tolerance make them well adapted to frequent surface fires (Covington 2003). In addition, ponderosa pines create their own fuel bed by regularly (over 3-7 years) dehiscing their long, flammable needles (DeBano et al. 1998:2-3). Assuming sufficient ignitions and regular dry seasons, ponderosa pines help create the fuels for the type of fire regime that promotes resilient, sustainable ponderosa pine dominated forests.

The second species that may qualify as a key ecosystem engineer in Southwestern ponderosa pine forests is *Homo sapiens sapiens*. Throughout their history, humans have been quintessential ecosystem engineers (Laland et al. 2000; Odling-Smee 1994; Odling-Smee et al. 2003). Although population density, mobility, technologies, and economies have varied over human history (as well as across space), humans were a part of their ecosystems for millennia. Human niche construction activity would not have been equally important in all places and times and would have varied with the aforementioned variables (e.g., population density, mobility, etc.). However, the persistence of particular activities would have created sustained, altered selective pressures on other organisms in these environments. Importantly, in some times and places, human ecosystem engineering may have provided the dominant selective pressures in certain environments (e.g., in agroecosystems). For example, in ecosystems in which humans used fire out of the “natural” fire season, selective pressures on short-lived organisms (especially annual plants and invertebrates) would have been altered. Indigenous alteration of ecosystem dynamics over many generations would have had evolutionary consequences on other organisms in these environments, perhaps generating a mosaic of selective pressures across landscapes and sustaining biodiversity on a variety of scales.

Recognition of variability in ecosystem dynamics generated by human niche constructing activity, such as anthropogenic burning in frequencies or seasons different than exclusively “natural” regimes, may improve management decisions regarding variability in restoration activities or adaptive management. Additionally, if restoration of the consequences of key ecosystem engineers is important for successful ecosystem restoration, then it is imperative that managers understand where, when, and how human ecosystem engineering contributed to the stability of Holocene environments. For the purposes of this dissertation, it is not important to identify particular selective pressures created by human activity in ponderosa pine forests. Rather, niche construction theory, as it informs conservation biology and restoration ecology, emphasizes the importance of understanding the role of humans in the environmental history of the ecosystems we seek to protect, manage, or restore.

Discussion

For ecological restoration and biological conservation in the modern era of global climate change, it is important to consider the resilience of contemporary or historic ecosystems to perturbations under variable climate conditions. Resilience theory provides an analytical framework for conceptualizing resilience and vulnerability in the context of alternative metastable states (Walker et al. 2004). Specifically, the metaphor of the stability landscape with alternative states as basins separated by ridges or thresholds is useful for describing the resilience of particular environments under certain climatic and land use conditions. Alternative land use strategies may alter the topography of the stability landscape, improving or reducing the resilience of these environments to climate driven perturbations. Applied historical ecology for process-centered restoration should consider the roles that climate and land use can have on reference dynamics and the resilience of these ecosystems to surprises.

Additionally, the incorporation of niche construction into applied historical ecology necessitates consideration of coupled human-natural systems as well. Humans are among the preeminent niche constructing organisms on the planet today. Traditional land use practices may have contributed to key ecosystem dynamics, helping to maintain desirable ecosystem structures and services. Hypothetically, anthropogenic burning by indigenous peoples may have reduced the impact of long-term climate fluctuations by maintaining frequent fires. Alternatively, traditional land use that fragmented fuel continuity (e.g., pastoralism) may have reduced the resilience of these landscapes to climate change.

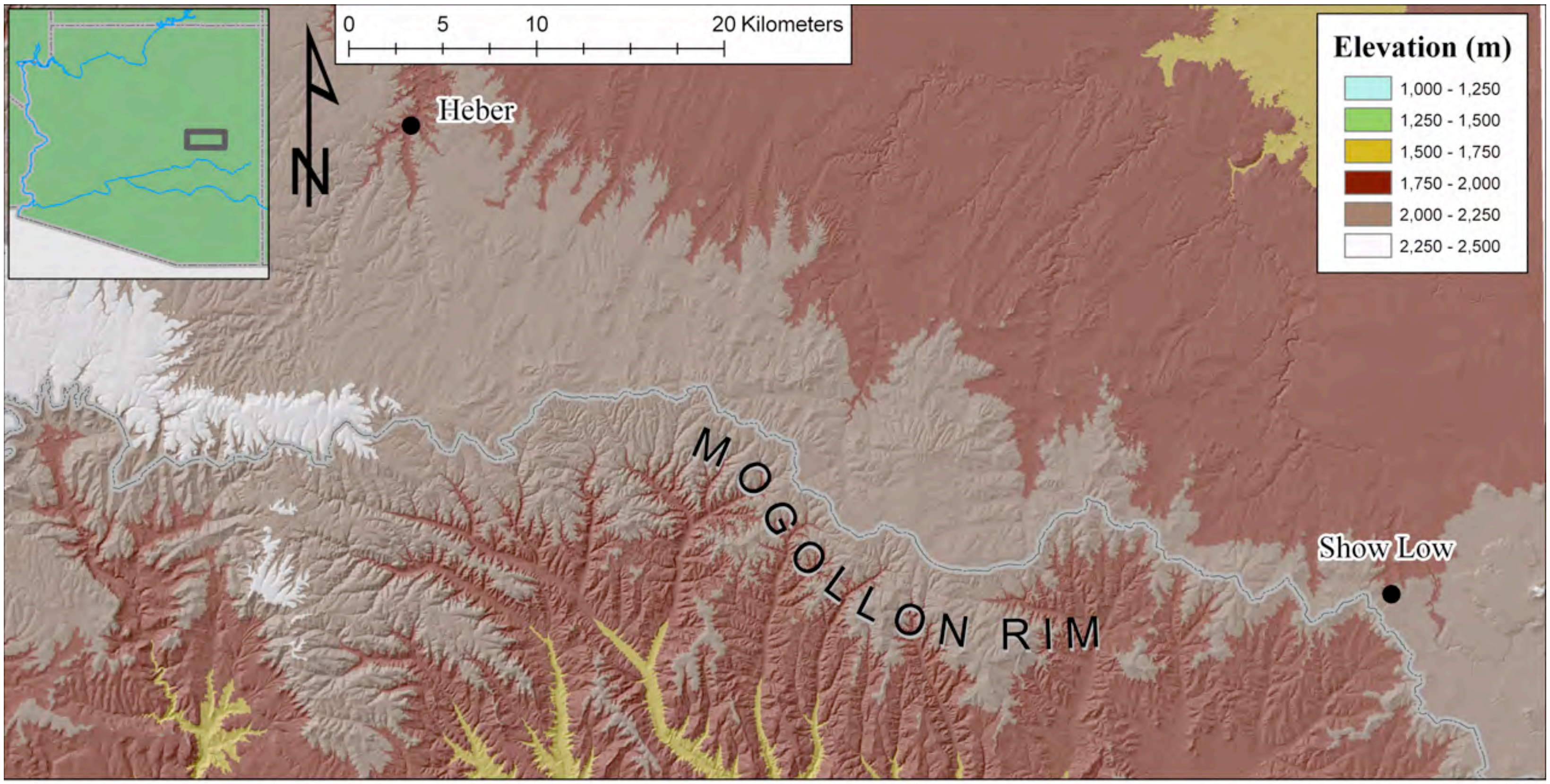
Traditional land use had variable consequences on historical ecosystems (Krech 1999; Redman 1999). For example, human niche construction probably resulted in a number of extinction events (Athens et al. 2002; Beck 1996; Grayson 1991). However, many of the consequences of indigenous land use are largely unknown. Holocene environments in the Americas were certainly coupled human-natural ecosystems, varying only in the intensity of the coupling over space and time (cf. Vale 2002c). Coupled human-natural systems in the upland Southwest have become increasingly vulnerable to climate change over the last century. Indigenous coupled human-natural ponderosa pine ecosystems may have been less vulnerable to long-term climate change, even if traditional uses of fire were indistinguishable from natural fire regimes in many of these forests (cf. Allen 2002; White 1932; 1943:314).

This hypothesis guides the present study. Specifically, I evaluate the hypothesis that indigenous anthropogenic burning improved or sustained the resilience of Southwestern ponderosa pine forests by maintaining frequent fires despite variability in climate conditions amenable to naturally frequent surface fires. As mentioned above, the key indicator of resilience in Southwestern ponderosa pine forests is probably stand density. However, this indicator is impossible to reliably measure over millennial timescales using contemporary methods. Consequently, I test this hypothesis by generating long-term evidence for variability in the ecosystem dynamics that regulate stand density—fire regimes. By examining paleoecological records across a gradient of land use and occupation history, I expect that less closely coupled or more “natural” landscapes will disclose evidence of high severity fires or state shifts to grasslands or shrubfields during or following periods of climate driven vulnerability. The paleoecological records from these real landscapes would be analogous to the metaphorical stability landscape described in Figure 2.2B. In contrast, I expect that more intensively coupled human-natural ecosystems that witnessed both anthropogenic and natural fires would persist in more resilient conditions analogous to Figure 2.2A. These social-ecological landscapes are expected to have evidence for frequent, low intensity surface fires that are contemporaneous with high severity fires and state shifts in the unoccupied or more “natural” landscapes. In this study, I focus on the Eastern Mogollon Rim region of east-central Arizona because of its long history of archaeological research, the extent of modern ponderosa pine forests, and the recent fire history of the area.

CHAPTER 3. STUDY AREA AND BACKGROUND

The Eastern Mogollon Rim region

The Mogollon Rim is a geological feature that marks the southern edge of the Colorado Plateau. The Rim is a fault scarp created by the uplift of the Colorado Plateau approximately 30 million years ago. The scarp is more or less pronounced topographically across the region. It is expressed as dramatic, sheer cliffs in the western reaches, from Payson to Flagstaff, Arizona, to minor topographic changes in streamflow direction in its eastern region, near Show Low, Arizona. Elevations along the Rim range from approximately 1500m to 2300m with ecozones graded by elevation (see Figure 3.1). Because of its great topographic diversity, the Mogollon Rim region includes major zones of Great Basin Grassland, Great Basin Conifer Woodland, and Petran Montane Conifer Forest biotic communities with traces of Madrean Evergreen Woodland, Interior Chaparral, Petran Montane Subalpine Conifer Forest, and Sonoran Desert communities (Brown 1994).



Source: National Elevation Dataset

Figure 3.1 Elevation of the Mogollon Rim Region. The eastern Mogollon Rim region extends from the Chevelon Canyon area (a few kilometers west of Heber) to the White Mountains (southeast of Show Low).

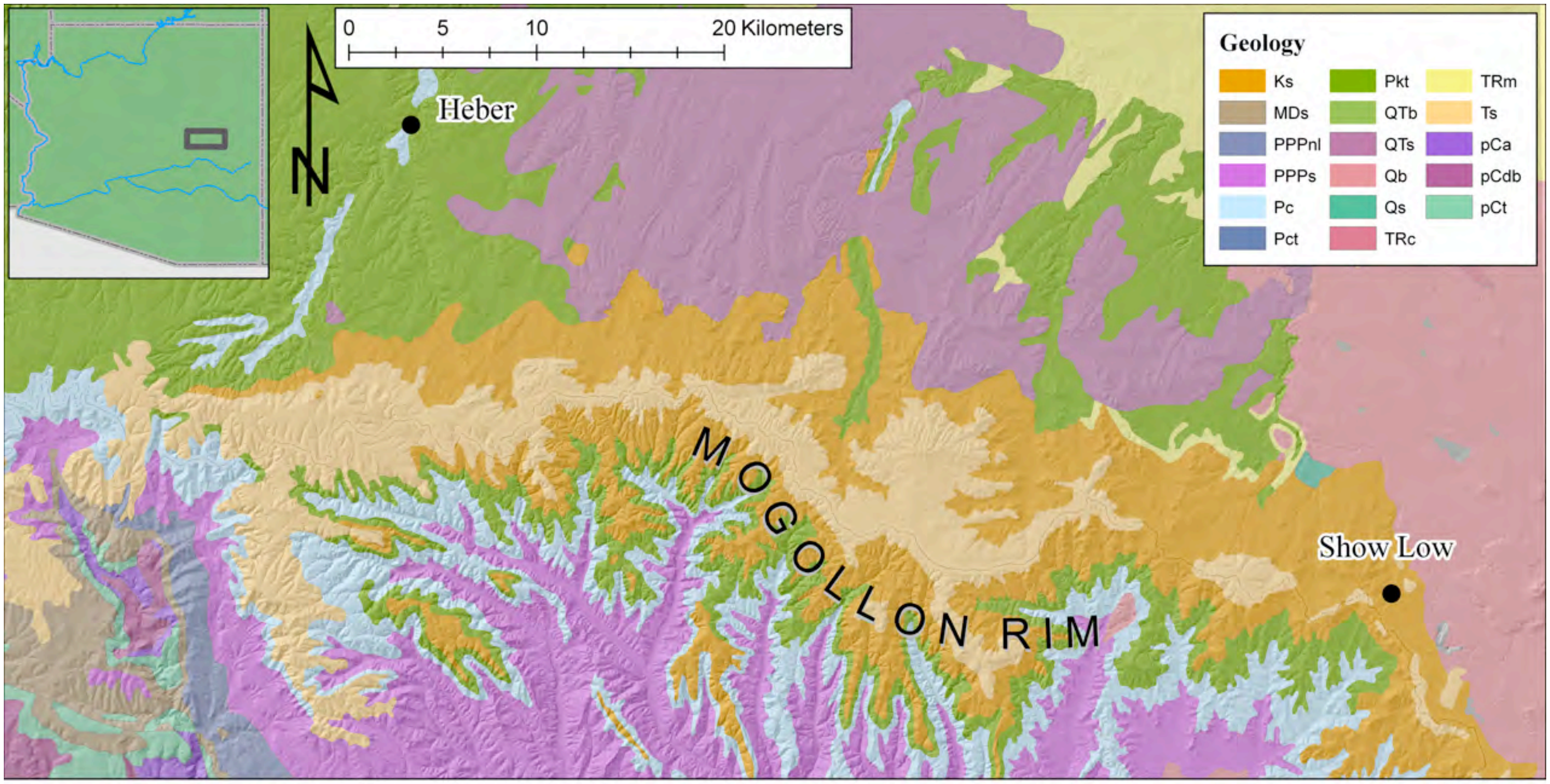
The area has great archaeological diversity as well (Cordell 1997; Reid and Whittlesey 1997). Sinagua, Cohonina, Hakataya, and Hohokam cultural traditions are all represented in the Western Mogollon Rim region. In the Mogollon Rim region east of Payson, Ancestral Pueblo (formerly Mogollon and Anasazi) occupied the area prior to Spanish *entradas*. Historically, the western part of the area was occupied by Yuman language speakers whereas the eastern region was occupied by Western Apaches (Whittlesey et al. 1997). In the present study, I focus on the Eastern Mogollon Rim region, defined on the east by the White Mountains and on the west by Chevelon Canyon.

The region is geologically diverse (see Figure 3.2). Faulting and warping associated with the uplift of the Colorado Plateau have created a heterogeneous landscape of exposed volcanic and sedimentary rocks. Above the Rim, the surface geology of the western portion of the study area is dominated by the Permian Kaibab formation limestones, sandstones and sandy dolostones (Kaldahl 1999). Moving east from Heber, Arizona, surface geology becomes increasingly dominated by undifferentiated Cretaceous sedimentary rocks, which are largely sandstones with interbedded mudstones, siltstones, and shales. Along the Rim, Tertiary “Rim Gravels” commonly drape hilltops and ridges. Near Show Low, Arizona, local geology becomes monolithically defined by Tertiary and Quaternary basalt flows. Below the Rim, drainages incise through Permian Kaibab formation and Coconino sandstones west of the Quaternary basalt flows. Older, Paleozoic marine deposits form the surficial geology as one moves westward through the White Mountain Apache reservation to the Grasshopper Plateau (Moore 1968; Triadan

1997). Precambrian granites and Paleozoic sedimentary rocks are exposed in the canyons of tributaries to the Salt River to the south.

The Eastern Mogollon Rim region is characterized by tremendous environmental diversity as well. Conifer dominated ecosystems occur at higher, more mesic elevations, whereas pinyon-juniper woodlands and desert grasslands can be found at lower elevations (Figure 3.3). Landscapes south or “below” the Mogollon Rim receive greater rainfall than comparable elevations above the Rim (Kaldahl and Dean 1999). Orographic precipitation, with both convectional summer storms and cyclonic winter storms, delivers greater rain and snowfall on the windward side (below the Rim) and creates a subtle rain shadow above the rim. At the highest elevations, in the western and extreme eastern areas, mixed conifer forests are dotted with wet meadows. Mixed conifer forests grade into Southwestern ponderosa pine forests below 2300m. Ponderosa pine dominates in almost pure stands between 1700 and 2300m. Varieties of juniper and oak occur as minor components of ponderosa pine forests. As aridity increases, ponderosa pine gives way to pinyon-juniper woodlands between 1200m and 1800m. At elevations below 1200m (1600m above the Rim), high desert grasslands predominate. As a result of historic land use, the grassland community is probably depauperate relative to its pre-Euroamerican condition (Kaldahl and Dean 1999), although “range improvement” activities have also reduced the extent of pinyon-juniper woodlands at their lower elevation ecotone (Nabhan et al. 2004). Although each of these biotic communities was used by indigenous people (and continues to be used), only the high desert grasslands, pinyon-juniper woodlands, and ponderosa pine forests were ever occupied for long periods.

The fire ecologies of desert grasslands and pinyon-juniper woodlands are very poorly understood. A great deal of variability characterizes possible pinyon-juniper fire regimes (Baker and Shinneman 2004; Barney and Frischknecht 1974; Despain and Mosley 1990; Everett and Ward 1984; Floyd et al. 2003; Pieper and Wittie 1990), much of which seems to be related to underlying geology, stand density, and understory vegetation (Romme et al. 2008). For grasslands, very little fire history information is available. On the basis of life history traits of plants and animals in these ecosystems and the historically low levels of woody vegetation, MacPherson suggests that fire return intervals of approximately 10 years were probably common in southern Arizona (MacPherson 1995). Fire scar analyses from canyons adjacent to desert grasslands also indicate 5-10 year fire return intervals for grassland ecosystems in the Southwest (Kaib 1998; Kaib et al. 1996).



Source: Arizona Geological Survey

Figure 3.2 Geology of the Eastern Mogollon Rim Region.

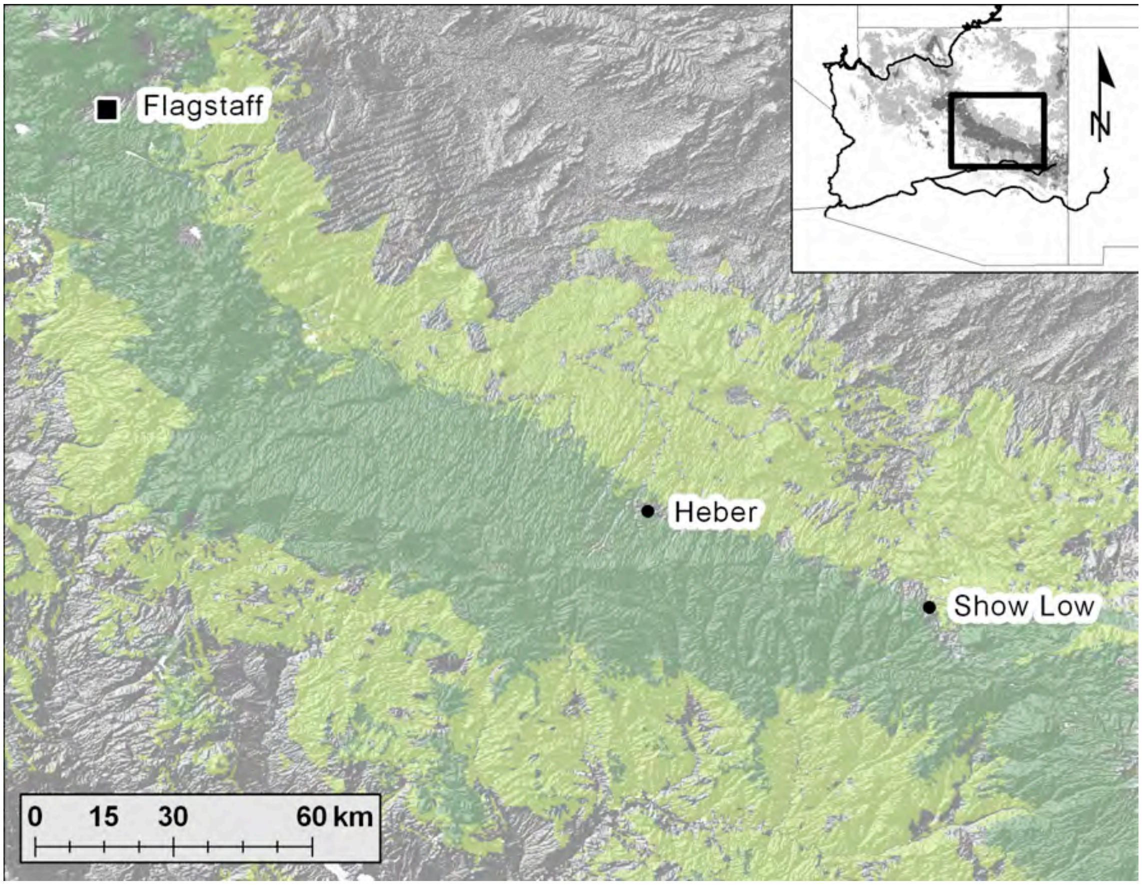


Figure 3.3 Vegetation zones of the Mogollon Rim region. Dark green areas are dominated by Petran conifer forests (largely, Southwestern ponderosa pine forests). Light green areas are Great Basin conifer woodlands (largely, pinyon-juniper or juniper woodlands).

Fire ecology and historic fire regimes for ponderosa pine forests, however, are exceptionally well studied. On the basis of more than 120 regional fire scar study localities, fire historians have reconstructed a well-replicated pattern of low severity surface fires occurring every 3-10 years in ponderosa pine forests throughout Arizona, New Mexico, northern Mexico, and southern Colorado. Such fires maintained an open canopied, mixed age stand structure in these parklike forests. Regionally synchronous fire activity in ponderosa pine forests corresponded with dry years that have followed 1-3 wet years (Crimmins and Comrie 2004; Swetnam and Baisan 2003). In semiarid ponderosa pine forests, ignition sources are not a limiting factor in fire activity. Both lightning and human ignitions are abundant in these environments (Allen 2002). Additionally, the bimodal pattern of seasonal precipitation creates an annually occurring, arid foresummer between April and July in which fires typically burn (Figure 3.4). The abundance and connectivity of surface fuels, however, appear to be a limiting factor in fire activity in these environments. Multiple wet years preceding fire years are probably important for the production of fine biomass, including herbaceous vegetation and needle litter, necessary to carry widespread fires. Continuous fine fuels are cured to burn during dry years, particularly following dry winters (Crimmins and Comrie 2004). This pattern of antecedent moisture has been observed to be statistically significant for both fire scar reconstructions (Swetnam and Baisan 2003) and for modern fire activity in middle elevation forests and woodlands (Crimmins and Comrie 2004; Westerling and Swetnam 2003).

In mixed conifer and higher elevation forests, less frequent surface fires appear to have coexisted with infrequent, stand replacing fires (Fulé et al. 2003; Margolis 2007; Margolis et al. 2008; Touchan et al. 1996). Teleconnections of El Niño Southern Oscillation, particularly as mitigated by the amplifying effects of cool phase Pacific Decadal Oscillation and a warm phase Atlantic Multidecadal Oscillation, appear to be significant drivers of fire activity in these environments (Kitzberger et al. 2007; Margolis 2007; Margolis et al. 2008). Perhaps due, in part, to the short length of the crop growing season (Kaldahl and Dean 1999), mixed conifer and spruce-fir forests were never occupied for prolonged periods by indigenous people in the Southwest.

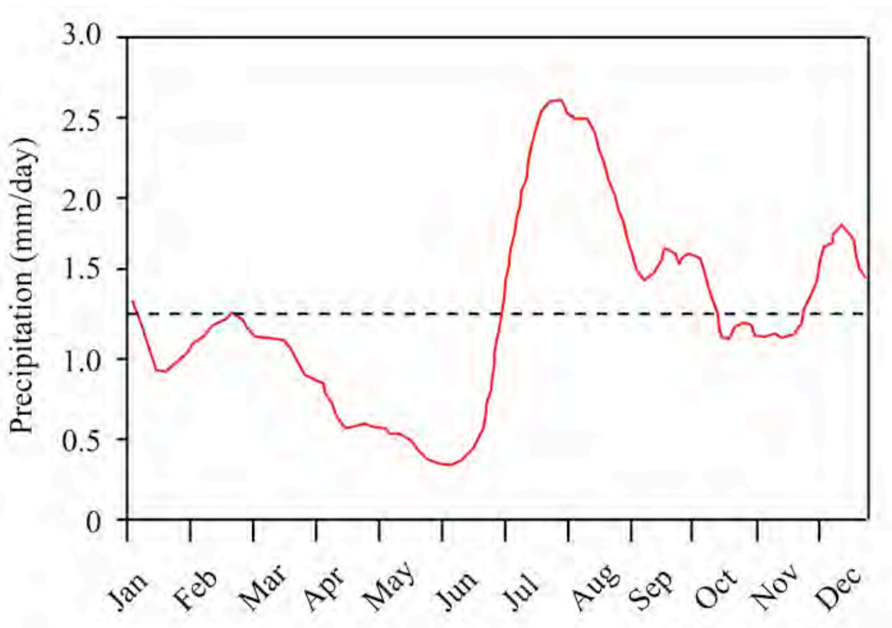


Figure 3.4 Mean daily precipitation by month for Show Low, Arizona for the years AD 1980-2004. The dashed line indicates mean daily precipitation for all recorded days.

For the purposes of this study, I define the project boundary as coincident with the distribution of ponderosa pine forests in the Eastern Mogollon Rim region. This ecological zone was the highest landscape unit regularly occupied for more than two seasons out of the year by indigenous populations and also provides the most detailed and best studied historical fire regimes. This latter component is important, in that it provides an ecological baseline for distinguishing “natural” fire regimes from human influenced fire regimes. Admittedly, prehistoric and historic peoples did not distinguish their lifestyles on the basis of ecological types defined by modern ecologists. Additionally, as noted in the following section, the locations of ecotones between these environments have shifted over time. Even over the last century, these ecotones have been dynamic, due to climate induced mortality and species migration (Swetnam and Betancourt 1998). Following a discussion of the relationship between climate change, fire, and Southwestern ponderosa pine forests since Late Pleistocene, I discuss the human history of the region across the ponderosa pine forest, pinyon-juniper woodland, and grassland transition zones, within the greater Eastern Mogollon Rim region.

Late Quaternary climate change, ponderosa pine forests, and fire

During most of the last glacial period (ca. 110,000-11,500 cal BP) in the Southwest, ponderosa pine trees were restricted to isolated refugia (Betancourt 1990). Between 11,500-9,000 cal BP, associated with increased charcoal deposition in sedimentary contexts, ponderosa pines rapidly migrated upward in elevation to their current distribution (Anderson 1993; Hasbargen 1994; Weng and Jackson 1999). A significant change in fire activity, perhaps associated with seasonality analogous to modern climates may have facilitated the rapid expansion of ponderosa pine forests (Weng and Jackson 1999).

Middle Holocene (ca. 7000-4000 cal BP) aridity has made it challenging to reconstruct ecological dynamics due to discontinuities in lacustrine records (e.g., Hasbargen 1994). However, charcoal records from alluvial fans in the Sacramento Mountains of central New Mexico suggest that landscapes that are now covered with ponderosa pine or mixed conifer forests experienced increased, high severity fire activity during the middle Holocene (Frechette 2007; New 2007). During the late Holocene

(<3500 cal BP), conditions became more mesic (generally wetter and cooler) and ponderosa pine forests returned to their modern distribution (Anderson 1993; Weng and Jackson 1999).

Fire scar records spanning the last three centuries indicate that late Holocene ponderosa pine forests experienced low severity fires during the arid foresummer (April-June) every 3-10 years, on average (Swetnam and Baisan 2003). Regionally synchronous fire years correspond to particular patterns of interannual climate. Specifically, regional fire activity was greatest during dry years that follow one to three wet years (Crimmins and Comrie 2004; Swetnam and Baisan 2003; Westerling and Swetnam 2003). Frequent fires regulated the recruitment of canopy species (Brown 2006; Brown and Wu 2005) and maintained open, parklike mixed age stands (Allen et al. 2002; Fulé et al. 1997).

Some scholars have suggested that the fire scar record of ponderosa pine fire regimes may be unrepresentative of fire regimes throughout the Holocene (e.g., Whitlock et al. 2008). It has been suggested that high severity, stand replacing fires, in particular, have been underappreciated in the history of ponderosa pine landscapes (Baker et al. 2007; Sherriff and Veblen 2008). The record of fire related debris flow events during the middle Holocene and Medieval Climate Period (ca. AD 800-1300) have led Pierce and Meyer to suggest that prolonged and severe drought may produce greater high severity fire activity in ponderosa pine and mixed conifer forests (Meyer and Pierce 2003; Pierce et al. 2004; Pierce and Meyer 2008).

To evaluate the representativeness of the period of greatest sample depth for the fire scar record (AD 1700-1900) as well as to identify long-term, low frequency variability in the interannual climate drivers of surface fire activity in ponderosa pine forests, Roos and Swetnam (nd) generated a statistical model of "natural," climate driven fire activity for Southwestern ponderosa pine forests over the last 1,418 years. We used fire scar data from 46 ponderosa pine chronologies across the margins of the southern Colorado Plateau to calibrate a multiple regression model of climate predicted fire activity using Salzer and Kipfmueller's (2005) 1,418 year and Grissino-Mayer's (1996) 2,129 year long tree-ring based reconstructions of annual precipitation for the same region. Antecedent (years t-1 and t-2) and fire year precipitation (year t) explains 39.8% of the variation in the fire scar dataset (Roos and Swetnam nd). One hundred year centered moving averages of the occurrence of peak fire years vary over the 1,418 years of the reconstruction (see Figure 3.5). In this reconstruction, unusually low frequencies of climate conditions suitable for surface fires occurred between AD 1300-1650. Prolonged wet periods during long fire free intervals would have facilitated recruitment (Brown and Wu 2005) and created ladder fuels. This reconstruction suggests that "natural" ponderosa pine forests would have been vulnerable to increased fire severity during the megadroughts of the 15^{th} and 16^{th} centuries (Stahle et al. 2007) due to 1) reductions in climate driven surface fire activity and 2) altered stand conditions resulting from prolonged wet periods during periods of reduced fire activity. The period of reduced climate driven fire activity (AD 1300-1650) is significant, in that the archaeological record also indicates that this is a period of cultural change and population movement. This multicentury period of ecological vulnerability and dynamic social changes afford an opportunity to test the hypothesis that coupled human-natural landscapes were more resilient to climate change than more “natural” landscapes.

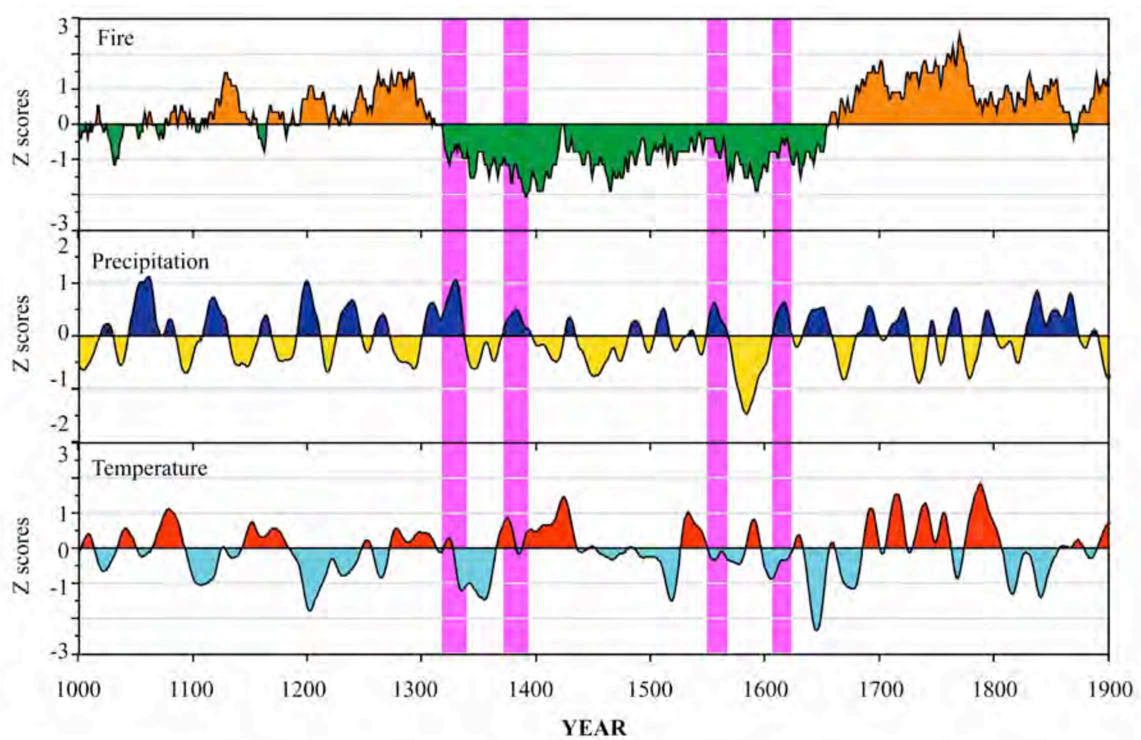


Figure 3.5 Statistical reconstruction of centennial scale variations in climate driven fire frequency and decadal scale temperature and precipitation variations between AD 1000-1900. The top graph plots the frequency of climate predicted regional fire years per century (Roos and Swetnam nd). The middle graph plots smoothed annual precipitation (Grissino-Mayer 1996; Salzer and Kipfmueller 2005). The lower graph plots smoothed annual temperature (Salzer and Kipfmueller 2005). Megadroughts during the AD 1400s and late 1500s (Stahle et al. 2007) following recruitment pulses would have been periods of heightened vulnerability to increased high severity fire activity. Purple bars indicate multi-year wet periods during reduced fire frequencies, in which conditions would have been favorable to canopy recruitment. The early AD 1600s (purple bar, above) was a period of regional ponderosa pine recruitment (Brown and Wu 2005), as predicted by this model. Data are for the southern Colorado Plateau and are plotted in standard deviation units (Z scores).

Archaeology of the Eastern Mogollon Rim region

The Eastern Mogollon Rim region has witnessed archaeological attention for more than a century. Beginning in the late 19th century, archaeologists, including Adolph Bandelier (1892) and Walter Hough (1903), recorded some of the region's large Ancestral Pueblo sites. It was not until 1929, however, in conjunction with National Geographic Society's Beam Expedition, that the ruins of the region experienced substantial excavation at the hands of archaeologists (Haury and Hargrave 1931). Both the Pinedale and Showlow ruins, near the modern towns of Pinedale and Show Low, Arizona, respectively, were tested by Emil Haury for wood and charcoal samples in an effort to bridge the gap between A. E. Douglass's modern and floating prehistoric tree-ring chronologies. The discovery of sample HH-39, from the Showlow Ruin in 1929, bridged the chronologies and, overnight, permitted the precise dating of construction events at dozens of Southwestern archaeological sites (Haury and Hargrave 1931; Nash 1999).

Later in the 1930s, Haury began his first University of Arizona Archaeological Field School in the Forestdale Valley, on the White Mountain Apache Reservation south of Show Low. From 1939-1941, Haury led a crew of students and Apache laborers in the excavation of the Bear Ruin (Haury 1985 [1940]), the Bluff Site (Haury and Sayles 1985 [1947]) and the Tla Kii Ruin (Haury 1985) in an effort to provide further evidence in support of the Mogollon Culture as a distinct entity from existing Basketmaker-Pueblo and Hohokam archaeological traditions. Haury had been at the forefront of the definition of the Mogollon Culture through his work at the Harris and Mogollon Villages in west-central New Mexico with the Gila Pueblo Foundation (Haury 1936). To continue to document Mogollon Culture in the mountains, Haury focused his attention on the pithouse components of the Forestdale Valley archaeological record.

After many years at Point of Pines on the San Carlos Apache Reservation, the University of Arizona Archaeological Field School returned to the eastern Mogollon Rim region in 1963, under the direction of Raymond Thompson. Over the course of the next 30 years, Thompson, William Longacre, and J. Jefferson Reid directed research on the late prehistoric Pueblo occupation of the Grasshopper Plateau and surrounding areas west of Cibecue, on the Fort Apache Indian Reservation (Reid and Whittlesey 1999, 2005). After the closure of the Grasshopper field school, Barbara Mills began the Silver Creek Archaeological Research Project (SCARP) to investigate Ancestral Pueblo occupations above the Mogollon Rim in the Silver Creek drainage (more or less consistent with the Eastern Mogollon Rim study area, as defined here). SCARP focused on Pueblo II, III, and IV period settlements across the study area, but primarily in present-day ponderosa pine forests (Mills 1999). From 2002-2004, SCARP conducted a collaborative project with the White Mountain Apache Tribe that combined excavations of Pueblo and Pithouse Period settlements in Apache-Sitgreaves National Forests above the Rim with archaeological survey, mapping, and damage assessment in the Forestdale Valley (Mills et al. 2008). At this time, SCARP revisited many of the sites initially recorded by Haury and his students during the original Forestdale field school in the context of systematic, full-coverage survey of the valley and its immediate surroundings (Mills et al. 2008; Seidel 2004).

More recently established research programs include the Shumway Archaeology Project (SHAP), directed by Scott Van Keuren (Van Keuren 2006a, b), and the Mogollon Rim Historical Ecology Project (MRHEP). In 2005, MRHEP was initiated as an interdisciplinary archaeological project to investigate the relationship between human societies, ecosystems, and climate change in the Mogollon Rim region throughout the Holocene (e.g., Roos et al. 2008). This dissertation reports on the results of the initial investigations of this project.

From the 1957 through 1974, Paul Martin directed fieldwork north and east of the study area near Vernon, Arizona, in the Upper Little Colorado area and surrounding the Hay Hollow Valley. Martin, with his students and colleagues (Hill 1970; Longacre 1970; Martin and Rinaldo 1960; Martin et al. 1962; Martin et al. 1963; Martin et al. 1964; Martin et al. 1975), investigated sites spanning the last several thousand years, including a fluted point Paleoindian site (Longacre and Graves 1976), Archaic Period (ca. 7000 BC-AD 100), Pithouse Period (AD 100-1000), Early and Late Ancestral Pueblo occupations (AD 1000-1390). Recently, Andrew Duff has followed up on Martin's work on the late prehistoric occupation of the Upper Little Colorado River area to the east (Duff 2002, 2004) and Julie Solometto has continued the work of the Chevelon Archaeological Research Project (CARP) to the west of the study area (Solometo 2004).

Not all of the archaeology conducted in the eastern Mogollon Rim region has been conducted in the context of academic programs. Beginning in the 1960s, salvage archaeology and cultural resources management projects have contributed to the reconstructions of regional prehistory. Excavations by the Arizona State Museum's highway salvage program, Arizona State University's contract archaeology division, and private companies have contributed evidence concerning the diversity of occupations, mobility, and economy among prehistoric communities (Dosh 1988; Hammack 1969; Reid 1982; Stafford and Rice 1979).

These investigations spanning more than 60 years provide evidence concerning variability in prehistoric occupation and land use of the eastern Mogollon Rim region. Archaeology of the region after its depopulation by Ancestral Pueblo people is exceptionally difficult due to the ephemeral nature of the archaeological remains left by mobile, Athapaskan groups (Gregory 1981). Limited archaeology from the western portion of the study area associated with the Grasshopper field school (Reid in Whittlesey et al. 1997) and with cultural resources management projects east of Payson (Herr 2008) generally corroborate ethnographic and ethnohistorical accounts of Western Apache occupations. Additionally, landscape studies of the traditional territories claimed by Hopi and Zuni Pueblos provide evidence of continued use of the study area by Western Pueblo people long after the depopulation of the area by Ancestral Pueblo people (Ferguson and Hart 1985; Zedeño 1997).

Paleoindian and Archaic Periods (ca. 11,000 BC-AD 100)

There is very little evidence for Paleoindian and Archaic Period occupation of the eastern Mogollon Rim region. Early Paleoindian (Clovis) and Late Paleoindian (Plainview) remains have been reported in the vicinity of Payson and Concho, Arizona (Huckell 1978; Wendorf and Thomas 1951), but, with the notable exception of probabilistic surface collection of a multi-component site (Longacre and Graves 1976), no systematic investigations have been conducted. Archaic sites have been excavated in the Point of Pines area of the highlands southeast of the Mogollon Rim (Haury 1957) and on the margins of large playas on the southern Colorado Plateau near Springerville (Martin and Rinaldo 1960). These sites disclosed evidence of mixed economy foragers in the greater Mogollon Rim region during the Middle and Late Archaic Periods (after 5000 cal BC).

The eastern Mogollon Rim region may have been utilized during the Paleoindian and Archaic Period, but geological formation processes could have served to limit archaeological visibility. A Late Archaic occupation has been recorded near Cibecue, Arizona, in the eastern Mogollon Rim region (Geib and Huckell 1994). The recovery of maize macrofossils among the limited cultural remains led the investigators to interpret the site as a short-term horticultural camp. Preliminary radiocarbon dating of detrital charcoal from the exposed soils and sediments from the highest alluvial terraces from watersheds investigated by MRHEP suggests that the oldest preserved deposits in the study area may be buried by more than 3m of alluvium but no older than 9000 cal BP (see dates from meadow cores in Day Wash and Willow Wash in Table 5.2).

Although not well published, the Hay Hollow site disclosed the remains of small-scale, horticultural settlement on a high terrace of Hay Hollow creek north of the study area (Fritz 1974). Radiocarbon dates are poorly reported, but Martin and Plog (1972:78) suggest that the site dates to approximately 300 BC – 300 AD. Extramural pits, probably for storage, are abundant at the site although domestic architecture is rare. Maize macrofossils recovered from the site indicate that horticulture played some role in subsistence, although occupation was probably seasonal.

Early Pithouse Period (AD 100-600)

The earliest evidence for prolonged occupation and use of the Mogollon Rim region dates after AD 100. The best known archaeological site from this period is the Bluff Site in the Forestdale Valley. Thirteen of the more than thirty pithouses were excavated by Haury and his student and Apache crew (Haury and Sayles 1985 [1947]). Architecture was diverse but definite storage features were not identified. Not all structures contained evidence of thermal features and it is possible that pithouses without such features served as storage features. Other sites of this period, including the Connie site (Rogge 1977) and Tumbleweed Canyon (Martin et al. 1962), have distinct storage pits and small, featureless structures that likely served as storage facilities.

On the basis of tree-ring dates, Mills and Herr suggest that occupation of the circum-Rim area may have been episodic (Mills and Herr 1999). The apparent lack of storage features at the Bluff Site and Hall Point, a pithouse site with an Early Pithouse Period component in Apache-Sitgreaves National Forests (Roos 2005, 2008), may indicate that perennial occupation of the ponderosa pine forests was also uncommon. The well-watered uplands near the Rim may have been ideal for horticulture, but the only two sites in these environments, the Hall Point and Bluff Sites, have not disclosed direct evidence for the consumption of domesticated plants. Although hunting was presumably important, animal bone remains are not abundant from Early Pithouse Period sites. It is unclear why bone is so poorly represented in refuse deposits from this period, although postdepositional alteration, cultural disposal practices, such as sheet-midden accumulation, and consumption by scavengers, including domestic dogs, may explain the scarcity of bone from these sites (for a general discussion of cultural and natural formation processes affecting faunal assemblages, see Schiffer 1996).

The best evidence for the consumption and storage of domesticated plants during this period occurs in lower elevation settlements near the Little Colorado River to the north. Large jacal features, which have been interpreted as granaries, are associated with Early Pithouse Period settlements around Petrified Forest National Monument (Burton 1991; Wendorf 1953). Small settlements, such as Hall Point and Tumbleweed Canyon, suggest that the basic settlement unit may have been the household. Architectural features are not very formal and, without maintenance, structures from this period were probably not occupied longer than 15-20 years (Cameron 1990; Diehl and LeBlanc 2001; Gilman 1997; Gregory and Diehl 2002). Large pithouse “villages” are likely palimpsests of multiple occupations by small groups of households.

This is also the period in which the earliest ceramics appear in the archaeological record of the region (Haury and Sayles 1985 [1947]). Crown and Wills (Crown and Wills 1995) suggest that the adoption of ceramic technology, particularly for cooking, was an important mechanism by which women coped with scheduling conflicts imposed by increased reliance on horticulture and attendant changes in the time requirements of child-rearing and food preparation. Ceramics are adopted variably across the region at this time, as predicted by Crown and Wills’s model, although not necessarily in concert with evidence for horticulture. For example, Tumbleweed Canyon disclosed evidence for maize consumption but yielded not a single sherd (Martin et al. 1962). Wills's (2001) economic autonomy model may account for the great diversity in architecture, subsistence, and use of ceramics throughout the Pithouse Period. He suggests that household autonomy in decision making, particularly in the role of female decision making, may explain this diversity.

During the Early Pithouse Period (AD 100-600), the eastern Mogollon Rim region was occupied by mobile, mixed economy hunter-collectors, who incorporated variable amounts of cultivated plants into their diets. Social units and settlements were small and household autonomy contributed to diversity in decision making regarding occupation duration, mobility, and economy.

Late Pithouse Period (AD 600-1000)

By the Late Pithouse Period (after AD 600), pithouses were elaborated and storage features, in terms of intra- and extramural storage pits and specialized storage structures, become more common (Haury 1985 [1940]). Unusually large pit structures or great kivas may have served as community structures, which were probably important for maintaining social relations among small settlements across the Mogollon Rim region. Communities and settlements may have been more substantial than in the previous period, but many of the patterns in terms of subsistence, mobility, and the size of settlement units persist from the Early Pithouse Period.

Architectural patterns and decorated ceramics from the Bear Ruin in Forestdale Valley indicate a mix of characteristics that have been attributed to classic "Anasazi" and "Mogollon" cultures. Haury (1985 [1940]) interpreted this as a "hybridization" of classical Mogollon culture with Anasazi traits. Alternatively, the mix of traits in architecture and ceramics may be the product of joint use and co-residence of households from both the southern Colorado Plateau and the Mogollon Highlands (e.g., Reid 1998).

Although ceramics and the remains of domesticated plants are a common component of the Late Pithouse Period archaeological record, many of the arguments concerning mobility, subsistence, and household economies for the Early Pithouse Period also apply to the Late Pithouse Period. Late Pithouse Period groups in the ponderosa pine forests of the eastern Mogollon Rim region were mobile, mixed economy gatherer-gardeners who lived in small groups of one to five households.

Early Pueblo Period (AD 1000-1200)

Shortly after AD 1000, populations of the study area swelled due to immigration by populations from the north and the east (Herr 2001). Regional populations reached their peak at this time, with no more than approximately 1,700 residents estimated for the greater Silver Creek drainage (Newcomb 1999). Small, multi-household settlements of both pithouses and above-ground masonry pueblos occur throughout the forests and woodlands of the study area, particularly above the Mogollon Rim (Reid 1989). Probably unroofed, masonry great kivas occurred at some Pueblo settlements and were probably focal points for dispersed communities. Even at this time, the peak of prehistoric human population densities, the social landscape was land-rich, but labor poor. Herr has made a convincing case that great kivas and their associated rituals served as foci for attracting people to settlements and increasing the labor pool (Herr 2001).

Direct evidence for the consumption of domesticated plants was more common at settlements with great kivas (Huckell 1999) than at those without (Donaldson and Stafford 1980). Horticulture may have been the most important part of the subsistence economies for social groups connected with the great kiva communities, whereas others may have continued to rely heavily upon wild plants and animals. With the exception of the Forestdale area, the pattern of great kiva communities and increased importance of horticultural products did not extend the to portion of the study area below the Rim (Reid 1989). Prior to AD 1200, mobile gatherer-gardeners continued to occupy short-lived, small pithouse settlements below the Rim.

Late Pueblo III Period (AD 1200-1275/1290)

By AD 1200, circular Great Kivas were no longer in use in the region, but diversity in architecture, settlement and mobility, and economy continued. Some settlements, such as Pottery Hill (Mills, Herr, Kaldahl et al. 1999), were occupied perennially by multiple generations and grew to sizes approaching 50 rooms. Agricultural products were common at large Pueblo III settlements, but hunting and gathering were still important components of the diet (Huckell 1999). Throughout much of this period, small game animals were much better represented than large mammals in the faunal assemblages from these sites (e.g., Zack Horner 1999). It is possible that more than 200 years of dispersed, but perennial occupation substantially reduced the ungulate population. However, by the end of the Pueblo III period, long-distance hunting of ungulates, particularly deer, appears to have increased in importance (Dean 2001).

Small, seasonally occupied settlements continue to characterize the area below the Mogollon Rim (Reid 1989; Reid et al. 1996; Reid and Whittlesey 1999). Seasonally occupied or short-term perennial settlements such as Grasshopper Spring and Chodistaas also indicate that this area continued as a landscape of joint use by different ethnic groups. For example, Grasshopper Spring Pueblo has been interpreted as a small settlement founded by households from the southern Colorado Plateau, whereas Chodistaas was occupied by people who came from a Highland Mogollon cultural tradition (Reid and Whittlesey 1999).

The end of the Pueblo III Period was dramatic. Some small Late Pueblo III settlements, such as Bryant Ranch Pueblo (Fenn et al. 2006; Mills 2007) and Chodistaas Pueblo (Zedeño 1994) were burned around AD 1290 (Tuggle and Reid 2001:93). Interpretations of these burning events differ. Some scholars attribute the conflagrations to raiding, warfare, or other intergroup conflict (e.g., LeBlanc 1999; Tuggle and Reid 2001). Alternatively, the fires may have been intentionally set by the inhabitants as part of the ritual closure of these settlements. Chodistaas, for example, seems to have been purposefully buried with refuse immediately after burning (Montgomery 1993). Settlement reorganization, immigration, and conflagrations associated with settlement abandonment during the Late Pueblo III period were coincident with local and regional droughts (Benson et al. 2007; Kaldahl and Dean 1999).

Early Pueblo IV Period (AD 1275/1290-1330)

Between AD 1275-1290, the remaining residents of the eastern Mogollon Rim region aggregated into a handful of large Pueblo villages (>100 rooms) focused on internal plazas (Kaldahl et al. 2004). Some smaller (20-100 room) settlements were occupied in areas below the Mogollon Rim, although these seem to have been a part of clustered supra-village communities at the local scale (Triadan and Zedeño 2004). Ceramic traditions, domestic and ritual architecture, and isotope studies suggest that these communities were multi-ethnic and included households from a variety of cultural traditions (e.g., Ezzo and Price 2002; Riggs 2001).

At this time, perhaps coincident with the immigration of dryland farmers from the Colorado Plateau, residents of the Mogollon Rim region became most reliant on agricultural production (Welch 1996). Wild plant foods and long distance hunting of ungulates as well as local hunting of a variety of animals (Olsen 1982; Zack Horner 1999) continued throughout this period, but the dietary importance of domesticated plants achieved its peak. Above the Rim, large villages were widely spaced (Kaldahl et al. 2004), suggesting that daily interaction between residents of these villages was unlikely or uncommon. These buffer zones may have been important for widening the sustaining area for each community. Locally, use intensity would have been at its highest associated with the greatest concentration of people on the landscape. The outlying areas were likely used, perhaps by multiple communities, but the use intensity (in terms of activities per person per unit of time per unit area) would have been much less than in the immediate vicinity of the villages.

Below the Rim, communities were larger and more widespread (Triadan and Zedeño 2004). A variety of outlying settlements appear to have been positioned to monitor movement throughout the landscape, perhaps in response to real or perceived external threats (Triadan and Zedeño 2004; Tuggle and Reid 2001). The spatial distribution of the human population across the landscape would have maintained fairly high use intensities over much of the landscape. It is worth noting that the Forestdale Valley, although below the Rim, appears to follow the Silver Creek pattern of aggregation and buffer zones rather than the dispersed village model of other areas below the Mogollon Rim (Kaldahl et al. 2004).

Late Pueblo IV Period (AD 1330-1390/1400)

By AD 1330, much of the ponderosa pine zone above the Rim was depopulated. The Bailey Ruin was no longer occupied by AD 1325/1330 (Mills 1999; Mills and Herr 1999) and the Pinedale Ruin was largely unoccupied as well (Van Keuren 2006a). After AD 1350, tree-ring dates indicate some construction continued at the original roomblocks at the Pinedale Ruin (Haury and Hargrave 1931), but the room blocks surrounding the region’s largest plaza were not completed (Van Keuren 2006a). The absence of late Pueblo IV pottery (e.g., Fourmile and Gila Polychromes), suggests that the village was largely unoccupied after AD 1330 (Haury and Hargrave 1931; Van Keuren 2006a). Construction activity peaked during this time at the Showlow Ruin (Haury and Hargrave

1931; Mills and Herr 1999) on the lower elevation ecotone of ponderosa pine forest today. Much of the remaining occupation above the Rim occurred at the large villages of Fourmile and Shumway in lower elevation ecological zones to the north (Kaldahl et al. 2004; Van Keuren 2006a, b). Inter- and intravillage diversity in ceramics and ritual architecture during this period continue to suggest that factions, perhaps tied to previous cultural traditions, divided many of these communities (Kaldahl et al. 2004; Van Keuren 2006a). The few remaining settlements above the Rim appear to have been situated in locations where perennial streams may have facilitated irrigation agriculture (Kaldahl et al. 2004; Van Keuren 2006b).

Below the Mogollon Rim, ponderosa pine forests continued to be occupied during the late Pueblo IV period. The Forestdale Valley appears to have continued to follow the trajectory shared by late Pueblo IV communities in the greater Silver Creek area (Kaldahl et al. 2004). In the Grasshopper area of the western portion of the study area, the late Pueblo IV period is characterized by dispersion away from aggregated villages (Reid 1989; Reid and Whittlesey 1999). Burials from Grasshopper Pueblo indicate that nutritional stress was common among Grasshopper residents (and, perhaps resident of the other aggregated communities, as well) coincident with the relatively new reliance upon agricultural products in the diet (Ezzo 1992; Reid et al. 1989). The shift to seasonal or perennial use of small settlements, perhaps by individual households, suggests an effort to return to prior land use strategies emphasizing residential mobility and a mix of domesticated and wild plant and animal foods (Reid 1989; Reid and Whittlesey 1999).

By AD 1390, construction activity in the region had ceased (Mills and Herr 1999). Ancestral Pueblo groups both above and below the Rim moved elsewhere. Many residents probably moved to the villages near the Zuni River in New Mexico and on the Hopi Mesas.

Tierra Despoblada (AD 1400-1550/1600)

After the area was depopulated by Ancestral Pueblo people, it continued to be used by their descendants, including the Hopi and Zuni people. The Eastern Mogollon Rim region and the White Mountains of Arizona were important parts of the larger sustaining areas and territories of members of both Hopi and Zuni communities (Ferguson and Hart 1985; Zedeño 1997). For example, Zuni people continue to claim to areas of the Upper Little Colorado and as far as the Chevelon drainage for traditional farmlands (Ferguson and Hart 1985:36-39). The uplands along the Mogollon Rim, particularly above the Rim, were important components of hunting territories and collecting areas for wild food and medicinal plants (Ferguson and Hart 1985:42-47). Additionally, the area is home to shrines for Zuni religious pilgrimages (Ferguson and Hart 1985:50-51).

By the time the Coronado expedition passed near the study area before reaching the Zuni pueblos in 1539, the region appears to have been entirely unoccupied. Importantly, the indigenous guides of Coronado's *entrada*, although well aware of people living at Hopi, Zuni, and elsewhere, made no mention to Coronado of people living in the eastern Mogollon Rim region (Forbes 1960:7-9). Undoubtedly, the area continued to be used on a short-term basis, but the use intensity (activities per person per unit of time per area) was substantially lower than it was prior to AD 1400.

Protohistoric Athapaskan Occupation (AD 1550/1600-present)

By AD 1583, the Espejo expedition west from the Rio Grande Pueblos into Arizona reported Apache-like people living along the Little Colorado River and near Mormon Lake in the Western Mogollon Rim region (Forbes 1960:59). These same groups were encountered by the Oñate expedition in 1598 (Forbes 1960:86). In AD 1626, horticultural Apaches were living in the upper Gila River area of western New Mexico (Forbes 1960:126). These dates for Apache occupation of the greater east-central Arizona and west-central New Mexico highlands is corroborated by limited archaeological evidence. Apache archaeology is notoriously difficult (Gregory 1981). The high degree of mobility and cultural penchant for recycling make identification of archaeological signatures of Apache occupation almost invisible in a landscape of obtrusive, highly visible Ancestral Pueblo remains (Seymour 2008). However, radiocarbon dated Apache occupations east of Payson (Herr 2008) and an AD 1656 pith date from a ponderosa pine tree growing within a wickiup circle at the Grasshopper Spring site (Reid in Whittlesey et al. 1997) indicate that even the western portion of traditional Western Apache territory was regularly used by the early 17th century.

Western Apaches had a regular seasonal round in which winters were spent in the lowlands of the Salt and Gila Rivers and their tributaries (Graves 1982). Winter camps were moved very regularly (e.g., every 5-10 days) to exploit agave and stored food supplies scattered throughout the winter territories. In the spring, Western Apaches would return to the highlands to plant small (ca. 1/4-1/2 acre) plots of maize, beans, and squash (Buskirk 1986). Important upland areas were reused annually as farm sites. Farm sites and their surrounding uplands were used throughout the spring, summer, and autumn as bases from which hunting and collecting of wild plant foods took place. Spring was a particularly lean time, with reliance on wild plants, particularly leafy greens, and stored foods from previous years (Buskirk 1986). Ethnographically, Western Apaches were known to have broadcast seeds of cheno-ams (*Chenopodium* spp. and *Amaranthus* spp.) around farmsite camps to ensure their abundance the following spring (Buskirk 1986). In the autumn, Western Apache groups harvested cultivated plants and wild seed plants, many of which were stored in various places both in the uplands and in locations accessible to lowland winter camps before returning to the lowlands for the winter (Buskirk 1986; Graves 1982; Griffin et al. 1971).

Most traditional Western Apache territory was below the Mogollon Rim. Traditional band territories, particularly for Cibecue and Tonto Apaches, as mapped by Goodwin (1942), often extend above the Rim, but this area seems to have been where conflicts between Apaches and Navajos were common (Basso 1998). In 1870, the Fort Apache Indian Reservation was established (Basso 1986:18). The northern border of the reservation coincides with the Mogollon Rim and the western border is more or less coincident with the western boundary of my study area. Traditional land use, however, was discouraged by the U.S. Army. Year round settlement near the Fort Apache was encouraged, as was reliance upon government issued rations.

The area of conifer forests and woodlands above the Rim was settled in the AD 1870s and 1880s by Euroamerican cattle and sheep ranchers as well as Mormon farmers. Conflicts between Euroamericans and Apaches arose briefly over a Mormon attempt to settle the Forestdale Valley, which had long been an important Western Apache farm site, in the 1880s (Jelinek 2005). Most homesteading, however, took place above the Rim, which is now a mosaic of private inholdings and land managed by the USDA Forest Service as part of the Sitgreaves National Forest. Although relationships between the U.S. Army and the Chiricahua Apache were belligerent during the late 19th century, the Fort Apache Indian Reservation was largely insulated from the violence, although the battle at Cibecue Creek was a notable exception (Welch et al. 2005).

Landscape fire in Western Pueblo societies

Relatively little is known about traditional ecological knowledge and landscape fires among Western Pueblo societies. Land use and economies at Hopi, Zuni, and Acoma have changed dramatically due to the introduction of wheat and domesticated animals by the Spaniards (e.g., Bohrer 1975; Bye 1985; Whiting 1939). Additionally, many of the classic ethnographies were done during an era in which fire ecology, as a discipline, did not exist. Later in the 20th century, questions about the use of fire in hunting and agriculture were not uncommon in the standardized surveys of the University of California Cultural Element Distribution studies (e.g., Gifford 1940). However, these questions were fairly superficial and relied heavily upon single informants to represent the activities of entire tribes. Information from these studies, however, provided the basis for much of Omer Stewart's (2002) pioneering work documenting the ubiquity of anthropogenic burning practices across native North America.

For Western Pueblo societies (Hopi, Zuni, and Acoma), however, the only reference to landscape burning in these studies was in the context of rabbit hunting (Gifford 1940). This obscures a much more sophisticated knowledge and use of fire on the landscape by Western Pueblo people. Much of this information is embedded within ritual knowledge and practice. Consequently, what little is known about traditional Western Pueblo uses of fire is probably a conservative representation.

Ethnographic information from Acoma and Zuni are especially informative. For example, landscape burning is an important component of both the ritual associated with Zuni rabbit hunting as well as the hunt itself (Stevenson 1904:90-92). For Zuni ceremonies associated with the Summer Solstice, the impersonator of the Little Fire God, Shulawitsi, "sets fire to everything in his way from Ko'thluwala'wa to Zuni" (Stevenson 1904:21). Shulawitsi also burns vegetation associated with summer pilgrimages (Stevenson 1904:158).

At Acoma, the Corn Clan was responsible for a midsummer ceremony associated with the katsina Curatca and fertility. Every five years, in late July, typically two or three weeks into the monsoon season, the Corn Clan hosts a ceremony called "Curatca Lights the Fires" (White 1932:94-96). As part of this religious practice, pairs of young men venture 10-12 miles from the Pueblo in the cardinal directions to forests, woodlands, and grassland environments on surrounding mesas and mountains. Once there, the young men light fires and return to the village, lighting fires on their way back (White 1932:94-

96). The seasonality and frequency of this ritual is provocative: it produces fires virtually identical to the "natural" fire regime of ponderosa pine forests documented through fire scar research. The oral tradition concerning the origin of the practice is provocative as well. According to Leslie White (1943:314):

> Curatca lived in the north, somewhere. He built fires on the mountains all around. Conata, Komitina, and Coma'acka (all Katsina) joined Curatca. Kaupat joined him too, as he was a great fire builder (it was Kaupat who built the fire that produced the lava beds near Grants—see White 1932:165-168; Boas 1928:76-82).
>
> When Curatca and the other katsina got close to Acoma, they met the *nawai* of the Corn Clan. "What are you doing and why?" the *nawai* asked Curatca. "This is my work," said Curatca, "I do this every 5 or 10 years. I am not doing this to burn (i.e., destroy) the world, but to heat Mother Earth to make her more fertile."
>
> Then the head of the Corn Clan said to Curatca, "I am glad to receive and welcome you. I want you to belong to the Corn Clan. I want you to be our *nawai*." So the katsina stayed with the Corn Clan at Acoma. But after a time, they went to Wenima, and the corn clan made masks to represent them. That is why the Corn Clan has the Curatca ceremony today.

This suggests an intimate knowledge of both the "natural" fire regime in upland environments by Acoma Corn Clan members as well as a sophisticated knowledge of the consequences of such fire on understory plant growth. It is not clear from the ethnographies that these surrounding uplands (e.g., forests and woodlands) over a 10-12 mile radius were used for agricultural purposes. Rather, these uplands were probably important areas for wild plant collection and hunting.

Sullivan (1982) has suggested that prehistoric horticulturalists in Southwestern forests and woodlands would likely have used fire to improve the productivity of fields and gardens. Anthropogenic burning of fields prior to spring planting would have provided an opportunity to take advantage of an "ash bed" effect, in which limiting nutrients, such as phosphorus and nitrogen, would have been increased in availability

(Covington and DeBano 1990; Covington and Sackett 1990). Pre-planting burning would also have altered the albedo of fields, potentially reducing the danger of growing season killing frosts (Sullivan 1982).

Kohler has suggested that Ancestral Pueblo agriculturalists in pinyon-juniper woodlands of southern Colorado and northern New Mexico may have used a form of swidden agriculture to achieve similar ash bed effects (Kohler 1992a, b, 2004). In this strategy, individual trees were burned to increase soil nutrients and domesticated plants were cultivated near the base of the dead tree. This strategy would have had profound impacts on pinyon and juniper populations. Reduction in the availability of these canopy species has been implicated in the abandonment of portions of the four corners region (Kohler and Mathews 1988). This strategy, albeit hypothetical for specific pinyon-juniper woodlands, would not have been effective in ponderosa pine forests because ponderosa self-prune their lower branches, making ignition of the canopy a challenge.

Additionally, there is archaeological evidence that suggests the use of landscape burning by Ancestral Pueblo and Archaic peoples to promote wild resources. The famous split-twig figurines from the Grand Canyon region were made from single, long branches of shrubs that were probably regenerated after burning (Bohrer 1983). The importance of wild plant foods from storage contexts from Ancestral Pueblo settlements near the Grand Canyon has led Sullivan (Sullivan 1992, 1996) to suggest that anthropogenic burning of grasslands, shrubfields, and pinyon-junier woodlands may have been used to promote disturbance plants. Limited paleoecological data from the Grand Canyon region support this hypothesis (McNamee 2003; Roos et al. 2008).

Landscape fire in Western Apache societies

Much more is known about traditional Western Apache uses of fire. Kaib (1998) conducted an extensive literature review concerning the ethnohistoric references to Chiricahua Apache uses of fire. In his analysis, 77% of all Spanish references to Apache burning occurred in the context of warfare (Kaib 1998). Although this analysis suggests that Apache burning for any purposes other than warfare were rare, the relative proportion of references to Apache burning must be considered in the context of Apache-Spanish relations as a whole. Apache-Spanish relationships were almost entirely in the context of conflict and warfare (Forbes 1960). The 23% of references to burning from non-warfare contexts may be significantly high, given the predominance of conflict in ethnohistoric references to Apaches.

For Western Apaches, ethnographically documented uses of landscape fire are myriad. In agriculture, fire was used to clear brush and grass from newly established agricultural fields (Buskirk 1986:61) and to maintain vegetation free irrigation ditches (Buskirk 1986:43). After harvest, husks, stalks, and shucked corn cobs were frequently burned in the fields (Buskirk 1986:77) and grasses in fallowed fields were burned because the ashes were presumed to be good for the crop (Buskirk 1986:25). Fire circles were used in rabbit hunts (Buskirk 1986:135-136) and may have been used to drive deer and antelope (Buskirk 1986:127, 131). Fire was an important part of ensuring the productivity of wild seed patches (Buskirk 1986:165-166) and for promoting wild tobacco (Buskirk 1986:97). Patches of willow and sumac were burned to ensure young shoots necessary for basketry (Buskirk 1986:166). Cheno-ams, valued for their greens, sprouts, and seeds (Buskirk 1986:191-192), flourish in post-fire environments (Barney and Frischknecht 1974; Everett and Ward 1984; Foxx 1996; West 1984; Zwolinski 1990). The habit of broadcast seeding these plants near camps may be a reservation era response to government discouragement of gathering (and perhaps, burning) practices (Buskirk 1986:199).

The White Mountain Apache folktale explaining how Apaches obtained fire is linked to both ponderosa pine forests and understory burning. According to oral tradition, Abert's squirrel, a species that is endemic to ponderosa pine forests (Snyder 1993), was the original keeper of fire. As part of an elaborate ruse, the trickster, Coyote, stole fire from Abert's squirrel an set fire to the understory plants as he ran away, passing on fire to the White Mountain Apache, who proceeded to run away, burning the understory on both sides as they went (Goodwin 1994:147-148).

Although the unambiguous identification of indigenous influence on pre-Euroamerican settlement fire regimes has been challenging (Allen 2002; Barrett et al. 2005; Swetnam and Baisan 1996), some fire scar records from southeastern Arizona (Kaib 1998; Seklecki et al. 1996), southern (Morino 1996) and central New Mexico (Kaye and Swetnam 1999) have evidence for Apache related increases in fire frequency or changes in fire seasonality. These records of Apache burning have been interpreted primarily in the context of warfare related activities (Allen 2002) based on Kaib's (1998) review. However, as mentioned above, the nature of Spanish-Apache relations may have biased the ethnohistorical documentation of Apache burning practices. For Western

Apaches, fire was an important land use tool and likely was for the historical Apache groups whose burning may be recorded in the aforementioned fire scar records. In particular, fall burning, which has been documented in the Sacramento Mountains in association with evidence of Apache use (Kaye and Swetnam 1999), is consistent with the post-harvest burning of wild seed collecting areas to promote crops of greens during the following spring as well as to sustain an adequate wild seed crop (Buskirk 1986:165-166).

Summary

The eastern Mogollon Rim study area is defined for this project as the belt of ponderosa pine forests that straddles the Mogollon Rim on the southern Colorado Plateau and the adjacent Mogollon Highlands between Heber and Show Low, Arizona. Although Paleoindian and Archaic occupations and use of the study area are poorly known, there is a rich archaeological record spanning the last two millennia. For the first 1000 years of well-known occupation and use, mobile groups of one or a few households used the area for hunting, gathering, gardening, and mineral resource procurement. Some occupations may have been seasonal, and perennial occupation may have been intermittent (Gilman 1997; Mills and Herr 1999). Landscape burning may have been used as a tool in hunting, wild-plant management, and as part of shifting horticultural strategies (Sullivan 1982). After AD 1000, populations peaked with immigration from the north and east (Newcomb 1999). Dispersed, great kiva-centered communities achieved their widest distribution above the Mogollon Rim at this time (Herr 2001). Economic strategies remained highly variable, as did settlement occupation duration. Residents of central great kiva communities appear to have relied to a greater extent on domesticated plants, whereas dispersed, mobile households continued to rely on a mix of wild and domesticated plants and wild animals (Donaldson and Stafford 1980; Huckell 1999).

Throughout the 13th century, immigration continued even as populations above the Rim began to more regularly exploit the western portion of the area below the Rim. Some settlements grew to over 50 rooms, whereas others groups remained small and seasonally mobile (Reid 1989). By AD 1280-1300, however, all remaining residents had aggregated into a handful of large villages clustered around permanent water sources. At this time, perhaps associated with immigration of dryland farmers from the Colorado Plateau, agricultural dependence reached its height (Welch 1996). By AD 1325-1340, two of these population centers in the ponderosa pine forests above the Rim were largely abandoned, leaving only the large villages of Grasshopper and Tundastusa occupied below the Rim and Showlow Pueblo, at the ecotone between the ponderosa pine forest and the pinyon-juniper woodlands above the Rim. Increased mobility, perhaps on a seasonal basis, characterized the last phase of occupation of the Grasshopper area, whereas the aggregated settlements of Tundastusa and Showlow remain aggregated until their depopulation around AD 1390-1400. Although no longer occupied by Western Pueblo peoples, the Mogollon Rim region remained important within the larger landscapes and territories of Hopi (Zedeño 1997) and Zuni (Ferguson and Hart 1985), as territories for pilgrimage, hunting, and medicinal plant collecting, and for trade routes into southern Arizona.

By the late 16th century or early 17th century, Western Apache groups and possibly Navajo groups as well, began to occupy portions of the eastern Mogollon Rim region. Navajo use may have been infrequent, but the uplands near the Mogollon Rim were important parts of the White Mountain and Cibecue bands' seasonal settlement patterns. From the spring through the fall, Western Apaches occupied farm sites in the forests and woodlands along the Rim for gardening, wild plant gathering and hunting (Basso 1986; Buskirk 1986; Goodwin 1942; Graves 1982). Some locations, such as the Forestdale Valley south of Show Low, Arizona, which were locations of frequent Ancestral Pueblo use, were also regularly used farm sites for Apaches over many generations. In 1870, with the establishment of the Fort Apache/San Carlos Indian Reservations, traditional land use was curtailed. Traditionally, Western Apaches used fire in a variety of ways, including for hunting, wild plant management, and horticulture (Buskirk 1986; Gifford 1940). Additionally, the origin story of fire in Western Apache folklore is associated with ponderosa pine forests and understory fires (Goodwin 1994:147-148).

Aggregated prehistoric settlements in the ponderosa pine forests of the study area may have affected existing fire regimes in a variety of ways. As hypothesized by archaeologists, these Western Pueblo groups may have used fire as part of hunting, wild-plant management, pest control, fireproofing areas around settlements, and diversified agricultural strategies (Bohrer 1983; Sullivan 1982, 1996; Williams 2002). All of these activities would have been superimposed on existing natural fire regimes and may have been indistinguishable from these in terms of frequency or seasonality. The Curatca katsina ceremony led by the Corn clan at Acoma illustrates how anthropogenic burning by Western Pueblo societies did not necessarily differ from reconstructed historical fire regimes in terms of frequency or seasonality (cf., Allen et al. 2002; Fulé et al. 1997; White 1932, 1943). However, some uses of fire may have occurred prior to the natural fire season (e.g., burning agricultural fields prior to planting) or after the natural fire season (e.g., post-harvest burning of wild seed collecting areas). Anthropogenic burning may have also served to increase the annual area by burning landscapes that might not have otherwise carried lightning fires (e.g., due to fuel discontinuities). In contrast to the potential impacts of densely aggregated late prehistoric Pueblo groups, protohistoric use and occupation of the Mogollon Rim area by Hopi, Zuni, Navajo, and especially Western Apache may have been important, but diffuse components of fire regimes. With the exception of regularly used Western Apache farm sites, the use intensity of the Rim region after AD 1400 would have been relatively low.

Prior to AD 1400, aspects of locally intense occupation and land use may have served to reduce natural fire frequencies. Collection of wood for fuel in domestic fires as well as the establishment of a mosaic of "fire breaks" in terms of established trails, agricultural fields, and settlements may have actually decreased the annual area burned and the effective fire frequency for some portions of the landscapes. An important example of anthropogenic impacts on fuel continuity and, by extension, fire activity is the expansion of grazing by domesticated animals and the associated reduction in fire activity through fuel reduction (Baisan and Swetnam 1997; Savage and Swetnam 1990; Swetnam and Baisan 1996). These diverse human impacts on fuels and ignitions may have negated each other as well. Increased use of fire and accidental human ignitions near settlements, trails, and agricultural fields, may have served to augment spreading surface fires ignited by lightning.

The ponderosa pine forests of the eastern Mogollon Rim region are an ideal location for pursuing the study of coupled human-natural fire regimes and the response to climate change. The area is near the center of the largest, continuous stand of ponderosa pine forest in the United States (Friederici 2003:xv). More than a century of archaeological investigation provides a rich reconstruction of ancient land use and occupational history for including spatial and temporal variability in land use intensity over the last 2,000 years. Additionally, the area is now a populous “wildland-urban” interface, in which thousands of residents live on the margins of dense ponderosa pine forest. In 2002, the largest wildfire in Arizona’s recorded history burned through nearly 500,000 acres, destroying more than 400 homes and displacing thousands of residents and visitors, including the Silver Creek Archaeological Research Project’s field school. The subject of human societies and fires in these environments is a salient one for contemporary local populations.

To explore the relationships between human societies, climate change, and fire activity in ponderosa pine forests of the eastern Mogollon Rim region, one must reconstruct variability in fire activity on spatial and temporal scales relevant to human occupational histories and long-term variation in fire-related climate. The regression model of climate-predicted fire activity presented earlier in this chapter provides the climate backdrop for inferring human contributions to fire regimes that differ from those associated with climate change. Additionally, this model highlights the periods of "megadrought" conditions in the 15th and 16th centuries when "natural" landscapes might have been vulnerable to increasing fire severity due to preceding reduced fire frequencies, canopy recruitment, and drought stress. By these periods of vulnerability in the 15th and 16th centuries, the study area was no longer perennially occupied, although it was likely used by a variety of groups. Portions of this landscape that were not occupied would likely have been more vulnerable to climate driven changes in fuels and fires. Areas below the Rim that were occupied through the 14th century decline in climate predicted fire frequencies and late 14th century recruitment may have been less vulnerable due to the addition of human burning practices. These hypotheses are evaluated with multicentury reconstructions of variability in fire activity across a gradient of land use intensity and human occupational history.

CHAPTER 4. FOUNDATIONS AND METHODS

In this chapter I articulate the geoarchaeological and ecological foundations of the study to establish the rationale for the particular methods employed. To do this, it is necessary to compare and contrast the two major methods for reconstructing fire histories with respect to the goals of the present study—to 1) identify human influences of ponderosa pine fire regimes and 2) to evaluate the resilience of ponderosa pine forests with natural and anthropogenic burning to multi-century climate change.

The two most common methods for reconstructing fire history chronologies are tree-ring based fire scar studies (Dieterich and Swetnam 1984) and sedimentology based charcoal analyses (Whitlock and Larsen 2001). Each method has advantages and disadvantages in terms of the temporal and spatial scales that are resolvable in these records. First, I discuss the differences in spatial and temporal resolution permitted by fire scar and charcoal based analyses. Following this discussion, I describe the properties of alluvial sedimentary deposits in the Southwest. Properties of discontinuous ephemeral streams, particularly in small watersheds, make them appropriate units of analysis for sedimentary fire history reconstructions. Finally, I present the field and laboratory methods employed in this study, which are informed by this discussion.

Fire history methods

Fire scars are created when a fire reaches temperatures sufficient to kill a portion of the cambium along the circumference of a tree. By removing cores or wedges from standing trees or in situ trunks, fire scars can be crossdated and cumulative, spatially explicit fire chronologies can be built (Arno and Sneck 1977). In many cases, fires can be resolved to their season of occurrence, and the sampling location is directly related to a location burned by the fire. Consequently, subdecadal (Seklecki et al. 1996), decadal, and century-scale (Grissino-Mayer and Swetnam 2000) patterns in fire events can be discerned in the reconstructed fire chronology. In the unusually long record of fire scars for Giant Sequoia, millennial scale patterns can also be discerned (Swetnam 1993).

Although fire scar chronologies are very precise spatially and temporally, this precision may be misleading. Fire scars are only capable of recording certain types of fire events. For example, fire scar chronologies rarely record stand replacing crown fires without corroborating evidence (e.g., Margolis 2007; Margolis et al. 2008). The potential for recording fire scars may be species-specific (Dieterich 1983:22) and age-dependent within species (Baker and Ehle 2001; MacDonald et al. 1991:57). For example, fires kill young trees more easily, and older, previously unscarred trees may be protected from scarring by thick protective bark.

An additional constraint is placed on the construction of fire scar chronologies by an attenuation of the record deeper in the past, sometimes referred to as the “fading record problem” (Allen et al. 2002; Clark 1988:81; Whitlock and Bartlein 2004:479). Each fire has the potential to destroy existing scarred trees, thus eliminating a portion of the record. With increasing distance into the past, senescence and mortality remove trees from the record and fewer live trees remain to record fire events further in the past. This attenuation effect places a practical limit on the temporal depth of tree-ring based fire records. For relatively long-lived tree species of the Southwest, fire scar chronologies only span the past 500 years (see Allen 2002:256), with the most reliable sample depth limited to the last 300 years (e.g., Grissino-Mayer and Swetnam 2000:215). The Giant Sequoia record from northern California is exceptional in its 2,000-3,000 year length (Swetnam 1993).

Additionally, fire scar chronologies require localized fuel accumulations sufficient to generate cambium-killing temperatures, at least for the initial scar formation event. Hypothetically, extremely high fire frequencies (annual to biennual) may not permit sufficient fuel or temperature conditions for scar formation (Lewis 1980:116), particularly if fires occur during cool seasons. As a result, it is theoretically possible that fire scars may under represent fire frequency in a given area (Baker and Ehle 2001:1206). Although Baker and Ehle (2001:1209) also assert that fires represented by fire scars may be highly localized (i.e., just around one or two trees in a stand) and overestimate fire return intervals at larger scales, high resolution comparisons of fire scars to fire atlas data (Farris et al. 2008) and experiments evaluating the representativeness of a variety of fire scar sampling designs (Van Horne and Fulé 2006) suggest that fire scars are a reliable record of past fires. Additionally, annual to biennial burning have been recorded in fire scar chronologies from the Chiricahua Mountains of Arizona, where steep slopes facilitate the rapid accumulation of fuels on the upslope side of trees and Apache cultural activities may have been important (Seklecki et al. 1996).

The analysis of charcoal in sedimentary sequences is founded on four assumptions (derived from Blackford [2000:33-34] and Whitlock and Millspaugh

[1996]): 1) sedimentary layers with an abundance of charcoal are evidence for fire events in the past, 2) most sedimentary charcoal is from primary fallout after a fire (i.e., redeposited charcoal is assumed to be relatively minor), 3) large particles are not transported long distances, and 4) charcoal fragments can be reliably extracted and quantified from sediment samples. These assumptions, however, are variably supported in experimental and calibration studies.

The quantification of large charcoal particles (generally greater than 125μm in minimum diameter) has been inferred to be a reliable indicator of local fire histories (Clark 1988; MacDonald et al. 1991; Tinner et al. 1998). Charcoal particles of this size has been reliably extracted and quantified (Assumption 4) on pollen slides (Asselin and Payette 2005), in thin sections (Clark 1988), and in sieved sediments (Whitlock and Anderson 2003). The “local” character of macroscopic particles (i.e., airborne deposition of particles greater than 125μm within 100m of the fire margin; Assumption 3) has been supported in experimental studies (Blackford 2000; Clark et al. 1998; Ohlson and Tryterud 2000). Consequently, macroscopic charcoal studies can be as spatially explicit as local hydrological and wind conditions permit. For example, macroscopic charcoal records from small hollows represent fire activity within the hydrological catchment basin (Higuera et al. 2005), whereas macroscopic charcoal records from large lakes with multiple stream inputs may better represent a homogenized record from the larger hydrological and airborne catchment.

Although the degree of secondary charcoal deposition by sheet-wash or stream action has yet to be evaluated systematically (Clark and Patterson 1997:25; Laird and

Campbell 2000:112), many investigators have suggested that erosion, sheet-flow, and saltation will move and deposit some secondary charcoal in sedimentary contexts (Clark and Patterson 1997:25, 27; Laird and Campbell 2000:120; Scott et al. 2000), particularly particles ca. 100µm in size (Clark and Patterson 1997:32, 34). Calibration studies have indicated delayed peaks due to secondary charcoal deposition that may occur as much as 12-13 years after the fire (Legleiter et al. 2003; Tinner et al. 1998; Whitlock and Millspaugh 1996), damping the chronological precision and resolution of the record. This suggests that Assumption 2 may not be valid (i.e., most sedimentary charcoal is not from primary fallout). However, the apparent correspondence between charcoal abundance and documented fires (MacDonald et al. 1991; Pitkänen et al. 1999; Whitlock et al. 2004) suggests that this assumption may not be necessary, if a lag-time is assumed or if other properties (e.g., "background charcoal") of the record are analyzed (e.g., Allen et al. 2008:128).

Because some amount of charcoal is nearly continuously deposited in Holocene sedimentary basins, methods are often used to distinguish between "background" charcoal (charcoal presumably deposited after the fire-event charcoal pulse) from "peaks" (a charcoal deposit presumably indicative of a local fire-event; Assumption 1). Locally weighted moving averages (e.g., Whitlock and Bartlein 2004) and Fourier-series filters (e.g., Clark and Patterson 1997) have been used to distinguish infrequent peaks from low frequency fluctuations in charcoal deposition. However, the scale of sediment subsampling and the sedimentation rate impact the meaning and size of the peaks and background components. The chronological interval of the resultant observations may vary between 12 and more than 180 years per peak (Mohr et al. 2000:591). If the average fire return interval is less than the length of time represented by sampling units, the resultant charcoal chronology will not be able to resolve individual fires (Whitlock and Larsen 2001:80). The complex relationship between biomass type, fire weather, fire intensity, and residence time (Whitlock and Larsen 2001:76-79) adds additional complications to the "one peak = one fire" assumption. In general, the methods that emphasize "peaks" may be more appropriate for landscapes that have only experienced infrequent (e.g., a greater than 50 year return interval) high severity fires in course fuels (Allen et al. 2008:128).

All of these issues regarding temporal precision and meaning of sedimentary charcoal records are impacted by 1) the continuity or discontinuity of the sedimentary record and 2) the methods for dating the record. Sedimentary charcoal records are potentially affected by a variety of "fading record" issues as well. Deeper in the past, stratigraphic discontinuities due to 1) hiatuses in sedimentation, 2) erosion, 3) bioturbation, or 4) weathering may reduce the likelihood that all periods are present in the record. Additionally, only varved lake sediments provide annually precise age control (Clark 1988). Other sedimentary contexts require probabilistic, radiometric dating techniques, such as radiocarbon dating. Although high-precision radiocarbon dating of non-wood tissues can provide reliable, maximum ages for sedimentary deposits (see Chapter 5), the probabilistic nature of the dating method introduces further uncertainty into the temporal precision of charcoal records.

However, this does not mean that sedimentary charcoal records are unsuitable for investigating long-term variability in high frequency fire environments. Although individual fire events may not be resolvable by this method, each fire produces charcoal that, in turn, is deposited in some sedimentary context. Consequently, low frequency variability in charcoal deposition (i.e., “background” in many studies) may be a better indicator of long-term fluctuations in high frequency fire regimes than variation in “peaks” frequency (Allen et al. 2008:128).

The amount of charcoal identified in a sedimentary deposit is a complex function of four different processes: 1) production, 2) dispersal, 3) preservation, and 4) observation methods. The aforementioned calibration and experimental studies primarily focused on the dispersal and methods of observation. There is emerging evidence that charred plant materials do not preserve equally, even over Quaternary timescales (Cohen-Ofri et al. 2006). The processes or conditions affecting variable preservation of charcoal are not yet well known.

The other complicating process in the interpretation of stratigraphic charcoal profiles is variability due to charcoal production during fires. Charcoal production is related to 1) the type and 2) amount of biomass consumed during a fire, 3) fire weather conditions, and 4) fire intensity. Variation in charcoal production due to differences in the type of fuels is particularly underappreciated. In forests with infrequent fires, background charcoal levels appear to be driven by changes in fuel amounts and fuel types (Marlon et al. 2006; Whitlock et al. 2008). In environments with frequent, low severity fires (e.g., ponderosa pine forests), fine understory plant communities are promoted by the fire regime. Due to large surface area-to-mass ratios, fine, grassy fuels dry quickly (DeBano et al. 1998:52-54) and combust efficiently, thereby producing smaller amounts of particulate byproducts (DeBano et al. 1998:27) and, probably, less macroscopic charcoal (per weight of dry biomass) than coarser fuels. Hence, fires that burn a particular landscape or patch at very high frequencies (e.g., every 2-5 years) may produce lower amounts of charcoal than a slightly longer return interval (e.g., every 10-15 years) over the same period of time, due to differences in the types of biomass consumed. To adjudicate between these alternative explanations for charcoal variability, other proxies related to fuel types, fire frequency, and fire severity would be necessary.

Comparison

Sedimentary charcoal and fire scar based chronologies provide fire history information with different temporal precision and resolution. In fuels limited environments, such as the Southwest, widespread fire events are highly dependent upon antecedent wet conditions to provide spatially continuous fuels (Swetnam 1990; Swetnam and Baisan 1996, 2003). The high-resolution spatial and temporal record provided by fire scar chronologies provide unparalleled information on fire response to the interannual climate variability that most affects fine-fuel accumulation. However, the relatively short length of Southwestern fire scar chronologies may not be well suited to the investigation of fire response to low frequency, centennial or millennial scale climate variation (cf. Grissino-Mayer and Swetnam 2000; Swetnam 1993).

Sedimentary charcoal records offer the opportunity to investigate centennial and millennial scale changes in fire-climate relationships (Whitlock and Bartlein 2004). The detailed, annual resolution fire-climate analyses from tree-ring studies are important for this investigation, however, in that they illustrate the climate-fuels relationships necessary to interpret past climate conditions from sedimentary charcoal records (e.g., Swetnam and Baisan 2003). For example, charcoal records of more frequent fires would be anticipated during periods of high frequency, strongly expressed El Niño Southern Oscillations (Swetnam and Betancourt 1990, 1998). If the type of biomass burned were to remain unchanged, a corresponding increase in the abundance of charcoal in sedimentary deposits would be expected, although "peaks" may not be discernible. The caveats mentioned above, regarding equifinality in charcoal records due to charcoal production, however, must also be considered.

Fire and alluvial systems

Most sedimentary charcoal research has been conducted on lacustrine sediments. In the arid and semiarid Southwest, lacustrine depositional contexts (lakes and ponds) are rare. Alluvial sedimentary contexts, although more complicated stratigraphically, are also more ubiquitous in these environments. Additionally, fires affect multiple properties of the alluvial sedimentary system (e.g., sedimentology, geochemistry, vegetation) that allow the construction of multiple proxy records to improve the quality of fire history inferences. As I suggest below, alluvial settings, small alluvial channel fan sequences in particular, are well suited for generating sedimentary fire history data in arid and semiarid environments.

In the American Southwest, most geoarchaeological work in alluvial settings has been conducted along "discontinuous ephemeral streams" (Bull 1997; but see also Waters 1991), characterized by alternating entrenched and aggrading reaches. Aggradation occurs on channel fans in braided distributary channels and by sheetflow deposition (Bull 1997:233, 239-241). Aggradation is common on these fans punctuated by brief episodes of channel extension and entrenchment proximately caused by oversteepening of the gradient at the distal end of the fan (Bull 1997:245). Lithostratigraphic units within channel fans often consist of upward fining units of sand and silt, although sedimentary structures and sorting are often disturbed by bioturbation (Waters 1991:142) and may be punctuated by short episodes of soil formation producing sequences of Fluvents (Bull 1997:243-244)—weakly expressed alluvial soils. Plant growth on channel fans provides an important positive feedback for aggradation and soil formation, by slowing sheetwash, which results in the release of entrained sediment, disrupting bedding due to root action, and contributing autochthonous organic matter accumulations (Bull 1997:241-242).

Channel entrenchment can occur rapidly as headcuts migrate upstream. Large flood events can extend entrenched reaches both upstream and downstream (Bull 1997:248). Entrenched channels will rapidly approach "grade" and then begin lateral erosion similar to meandering streams, although channel characteristics are more similar to braided streams (Bull 1997:248-249). Lateral erosion can flood the system with sediment triggering aggradation and channel fan formation. Small fans, also called "gully-mouth fans" (Waters 1991:141), are often 1-7 km in radius and are ideal situations for *ak-chin* style farming. Larger fans (i.e., associated with Class A drainages, below) can generate thick valley fill sequences (cf. Daniels 2003; Waters 1991:144).

Sources of sediment and responses to climate change vary by size of ephemeral drainages. Balling and Wells (1990) define three classes of ephemeral streams on the basis of watershed size. Class A streams (> 500 km^2) often drain upland areas, are slow to respond to perturbations, and have peak discharges associated with prolonged winter rains and snowmelt. Large drainages receive most of their sediment from storage in smaller drainages. Class B (20-500 km^2) and Class C (<20 km^2) drainages often have their peak discharges associated with intense summer rainstorms, receive most of their sediment from colluvial and bedrock slopes, and respond more rapidly to perturbations (Frederick 2001:58). These characteristics of ephemeral streams are important when considering the impacts of fire on sedimentary sequences in such drainage systems.

Landscape fires, regardless of "natural" or "anthropogenic" origin, can affect alluvial systems and resultant stratigraphy. Depending on the severity of fire impacts on vegetation, landscape fires can have serious and long-lasting consequences on sedimentation and erosion. Low severity and/or cool season fires often contribute little additional sediment to the alluvial system (Simanton et al. 1990). In contrast, high severity fires can contribute large amounts of sediment immediately after the fire (Inbar et al. 1998; Roering and Gerber 2005; Simanton et al. 1990:182), resulting in long-term impacts on watersheds (DeBano et al. 1998:174-177), rapid and complex geomorphic responses (Legleiter et al. 2003), and increases in runoff-related debris flows in steep watersheds (Cannon et al. 2001; Meyer and Pierce 2003; Pierce et al. 2004).

Fire-induced vegetation changes may be represented biostratigraphically in pollen assemblages (e.g., Behling et al. 2005). Additionally, alluvial sediments can provide a stratigraphic context for charcoal based fire chronologies (Whitlock and Larsen 2001). Increased stream competence resulting in better particle size-sorting (Hereford 2002:1555), reworking of sediments stored in smaller drainages, and large watershed size for Class A drainages make them unsuitable for such biostratigraphic fire reconstructions. Between brief entrenchment periods, sheetwash reaches of channel fans of Class B and C drainages aggrade regularly, have relatively small watershed size, local contributions of sediment from hillslopes, and stratified, weakly expressed soils (Bull 1997). These characteristics make Class B and C watersheds better candidates for sedimentary charcoal analysis. The small size of these watersheds does make them more sensitive to perturbations and possible complex geomorphic responses (Frederick 2001:58), but the charcoal sequences within channel fans may be a good proxy for fire regime variability.

Alluvial stratigraphic sequences may also provide contexts for geochemical investigations related to watershed scale fire regime histories. Modern investigations document changes in net phosphorus (P) concentrations in Southwestern forests and woodlands due to fire (Covington and DeBano 1990; Covington and Sackett 1990). The primary process that affects P during wildland fires is the rapid mineralization of organic P liberated in plant ash at the soil surface. In the context of Fe, Al, and Ca, PO_4 released during combustion rapidly mineralizes as Fe-, Al-, and Ca-phosphate minerals. Although

P can be lost in particulate form during combustion, temperatures greater than 774° F are necessary to volatilize P (Debano et al. 1998:117). Consequently, low intensity fires in Southwestern coniferous ecosystems often results in a net increase in available inorganic P at the soil surface (e.g., Covington and Sackett 1990). The erosion of material from the surface of upland soils can result in the accumulation of P-enriched sediment in channel fans during periods of frequent, low-intensity burning. The more frequently low intensity fires occur, the more P from plant ash is contributed to hillslope soils and alluvial basins. High severity fires, because of high combustion temperatures, may produce relatively small net amounts of P compared to low severity fires or serve to reduce available P (e.g., through volatilization) to the sedimentary basin.

Stable isotopes of soil organic carbon (SOC) have also been used successfully to evaluate disturbance frequencies (Pessenda et al. 2004) and changes in woody or herbaceous groundcover (Biggs et al. 2002). Because of frequent flooding, the sheetwash reaches of channel fans may not be suitable for woody vegetation, but inherited SOC from hillslopes (detrital SOC of Nordt 2001:428) may represent the degree of canopy density and type of understory (herbaceous vs. shrubby) maintained by different fire regimes on surrounding hillslopes. Modern ponderosa pine tissues often have stable carbon isotope rations (expressed as parts per thousand [‰] difference in ^{13}C relative to ^{12}C, or Δ^{13}C) between -23 and -25‰ (although many C3 plants have typical ratios near -27‰; Nordt 2001:422). C4 plants often have stable carbon isotope ratios of approximately -13‰ (Nordt 2001:422). Soil organic carbon pools that receive inputs from mixed C3 and C4 plant communities will yield soil organic matter carbon isotope ratios intermediate between C3 and C4 values (Nordt 2001:423). The relative abundance of C3 or C4 plants can be estimated using a mass balance equation and a measurement of the stable carbon isotope ratio of a soil or sedimentary deposit (Nordt 2001:423). Soils from pre-Euroamerican settlement ponderosa pine forests (i.e., open-canopied forests maintained by frequent spring or early summer fires) would be expected to have less negative carbon isotope ratios than modern soils from ponderosa pine forests.

Variation in the seasonality of understory fires also may affect the relative abundance of C3 and C4 herbaceous plants and, by extension, the carbon isotope pool. Fall or winter fires promote cool season grasses, which are C3, whereas spring and early summer fires promote herbaceous plants, which are often C4. Greater herbaceous understory plant production should produce even less negative (i.e., more C4 plant-like ratios) relative to "normal" ponderosa pine forest. However, because not all herbaceous weeds and grasses use the C4 photosynthetic pathway (see below), the seasonality of fires may affect the carbon isotope pool. Consequently, additional evidence (e.g., pollen assemblages) is necessary to interpret soil carbon isotope data in terms of fire frequency and seasonality.

Despite the complexities of alluvial systems (Butzer 1980), sediments and soils from alluvial settings are important contexts for identifying human land use behavior. Alluvial settings are often highly attractive to humans (Ferring 1992) and, thus, are the context for a great deal of human behavior. Additionally, more than a century of geoscientific investigation has elucidated the relationships between alluvial processes, landforms, and stratigraphy. By comparing geoarchaeological samples (i.e., geological samples from archaeological sites or archaeological landscapes) to control samples (i.e., samples from non-archaeological contexts), human behavior and its consequences may be teased from the stratigraphic record (Stein 2001:21) With respect to fire history, channel fans of small and intermediate watersheds may be ideal locations for sampling because their nearly continuous aggradation and pedogenesis provide a context for generating geochemical, sedimentological, palynological, and charcoal based proxies of past fire regimes.

Discussion

Southwestern fire scar chronologies are well suited for identifying annual, sub-decadal, and decadal scale relationships between fires, climate, and human behavior (e.g., Swetnam and Baisan 2003). However, due to the temporal limitations of Southwestern fire scar chronologies (i.e., 300-500 year maximum time depth), these records are less well suited to evaluate the relationships between fires, climate, and human behavior at multi-century to millennial time scales. Sedimentary charcoal chronologies are better suited to time depths of this scale (Whitlock and Bartlein 2004). However, the temporal sensitivity of sedimentary charcoal records produces complex relationships between charcoal concentration and fire frequency. Variation in biomass types and amounts consumed, sedimentation rates, and the precision of dating methods can contribute additional confounding variation to sedimentary fire history records.

Sedimentary charcoal analyses are often based on samples from lacustrine depositional settings (Whitlock and Anderson 2003) because of their relatively regular and constant sedimentation. In the arid and semiarid Southwest, lacustrine settings are uncommon. Alluvial deposits provide an ubiquitous alternative in which sedimentation rate may be very high (e.g., up to 3 cm yr^{-1} reported by Force 2004:601), permitting greater potential temporal resolution than in lacustrine settings. However, alluvial settings are far more dynamic in terms of sedimentation and erosion and may contribute additional variability to charcoal records based on variation in sedimentation rates, depositional energy, and postdepositional weathering (Ferring 2001). Soil stratigraphy from channel fan sequences does, however, provide opportunities for generating independent geochemical data (e.g., stable carbon isotopes and soil P) with which to corroborate and evaluate biostratigraphic data (e.g., pollen and charcoal).

Methods

To evaluate the working hypothesis that coupled anthropogenic-natural fire regimes improved the resilience of Southwestern ponderosa pine forests to multi-century and millennial scale climate change relative to more "natural" climate driven fire regimes, I use two types of synthetic analyses. First, I reconstruct fire regimes in terms of patch-specific fire frequencies, severity, fuels, and seasonality from small (Class C) ephemeral drainages across a gradient of known indigenous land use and occupation histories. These reconstructions are then compared to long-term variation in climate driven fire frequencies (see Chapter 3 and Roos and Swetnam nd) and the local cultural chronologies to identify evidence for anthropogenic burning in addition to natural fires, as driven by climate. Unoccupied watersheds, which I will assume experienced "natural" fire regimes between AD 1650-1900 (i.e., low severity surface fires every 5-10 years), provide “calibrations” of sedimentary proxies in the absence of local fire scar histories. Increased burning related to agricultural strategies (Sullivan 1982) would be expected to change the amount of biomass burned per area, per year (e.g., changes in charcoal and soil P), although changes in seasonality and plant communities, with the exception of domesticated plants, would not be expected (e.g., little to no change in carbon isotope ratios or pollen assemblages). In contrast, burning to promote wild plant resources would be expected to change the amount and type of biomass burned per area, per year, as well as plant communities and, perhaps, seasonality of fires. Changes in seasonality, however, would depend on whether burning for wild plants took place in the spring or in the fall (i.e., after harvesting wild seeds and nuts).

Second, spatial variation in reconstructed fire regimes across the gradient of land use histories (i.e., from unoccupied watersheds, occupied watersheds with early Puebloan depopulation, and watersheds with later Puebloan depopulation) are compared to each other for the periods of expected climate driven vulnerability to high severity fire activity and state shifts. If the working hypothesis is true, then unoccupied watersheds and watersheds that were depopulated prior to the climate driven reduction in surface fire frequency (i.e., Sharp Hollow, Rocky Draw, Day Wash, and Willow Wash; see below) would have evidence for high severity fires or state shifts to grasslands or shrubfields during the megadroughts of the AD 1400s or late 1500s, whereas the Forestdale Valley would not disclose such evidence because of 1) a later depopulation by Ancestral Pueblo peoples and 2) earlier use by Western Apaches. Figure 4.1 plots the location of study watersheds in relation to one another and the Mogollon Rim.

Focusing on small, ephemeral drainages in ponderosa pine forests along the Mogollon Rim, I selected five watersheds for sedimentary sampling on the basis of their archaeologically and ethnohistorically known occupation histories. Two of the five watersheds (Sharp Hollow and the East Fork of Rocky Draw), both tributaries to Black Canyon, were chosen as “control” locations because they have not disclosed archaeological evidence of prehistoric occupation and were not traditional farm sites of Western Apache groups. Two watersheds north of the Mogollon Rim were chosen because they have archaeological evidence of Ancestral Pueblo settlement. The watersheds above the Rim (Day Wash and Willow Wash) also drain the area of one of the latest occupied villages in ponderosa pine forests, the Bailey Ruin (Kaldahl et al. 2004; Mills 2007; Mills, Van Keuren et al. 1999). As mentioned in Chapter 3, the Bailey Ruin was no longer occupied after AD 1325.

I have also chosen to sample the Forestdale Valley, south of the Mogollon Rim because of its long prehistoric occupation history (Haury 1985), including one of the last occupied villages in the entire region, Tundastusa (Kaldahl et al. 2004; Mills 2007). The Forestdale Valley also has had long standing importance as a farming and wild resource collecting area for Cibecue band Western Apache peoples (Goodwin 1942; Haury 1985; Jelinek 2005).

In each watershed, drainages were surveyed for alluvial landforms suitable for sampling. Preliminary observations on stratigraphy, thickness of alluvial deposition, and ease of sampling were used to decide on localities for intensive study. Stratigraphic sequences in selected localities were exposed with narrow, manually excavated trenches to expose alluvial sediments and soils until coarse channel lag was reached. Profiles were photographed, described, drawn, and sampled. Bulk samples for soil analysis were taken opportunistically from field identified soil horizons and depositional units. Undisturbed, continuous or overlapping monoliths were cut from the exposures and supported in 40-60cm lengths of open-faced plastic down-piping (ca. 9cm wide with sample cuts ca. 8-10cm deep) and wrapped in plastic wrap for paleoecological sampling. Undisturbed soil and sediment samples were collected in plastic electrical boxes (ca. 6cm X 6cm X 9cm) for soil micromorphological analyses. Sampled localities on the Fort Apache Indian Reservation were backfilled and recontoured after sampling as part of a collaborative agreement with the White Mountain Apache Tribe.

To reconstruct fire regimes, I have focused on two characteristics of fires and their ecological impacts. To avoid reliance on single proxy records, I use multiple proxies to improve the strength of fire regime inferences. The first characteristic of importance is biomass combustion per unit time. Both sedimentary charcoal, related to the amount of biomass and the type of biomass burned within the watershed, and soil P are used to infer aspects of fire frequency in the contributing basin. Macroscopic charcoal (>250μm) was counted from continuously subsampled 2cm intervals from undisturbed monoliths using a variant of the Oregon Sieving Method (e.g., Long et al. 1998; and see Appendix A). During counting, charcoal was collected for subsequent radiocarbon dating. Mehlich II extractable soil P was measured using a colorimetric method (see Appendix A) on the <125µm fraction of bulk samples from field identified soil units.

The second focus of the paleoecological analysis was on the impact of fire frequency and seasonality on plant succession. Frequent surface fires generally promote and maintain fine, herbaceous understory plant communities. Patchy fire behavior or a reduction in fire frequencies would create a mosaic of herbaceous and woody understory plants. Higher patch-specific fire frequencies should increase the relative abundance of pollen from herbaceous taxa. Many herbaceous plants are also C4 plants (e.g., Wills 1995:229, Table 8.3), so high patch-specific fire frequencies might increase the relative contribution of C4 plants to the isotopic composition of soil organic carbon. However, if cool season herbaceous taxa are promoted by fall or winter burning, stable carbon isotopes may remain C3 dominated while pollen assemblages record an increase in herbaceous vegetation. Sediment samples from each field identified soil horizon were submitted to the University of Arizona Palynology Laboratory for processing and counting. Sediment samples for palynology were collected using an alcohol-cleaned trowel from undisturbed monoliths in the Laboratory of Traditional Technology. Decalcified sediment samples of the <125µm fraction of bulk samples from field-identified soil units were submitted to the University of Arizona Laboratory of Environmental Isotopes for measurement of stable carbon isotopes of soil organic matter.

To evaluate variability in the depositional environment and postdepositional alterations associated with bioturbation and pedogenesis, bulk samples were analyzed for grain-size, calcium carbonate content, and organic carbon content (see Appendix A for laboratory methods). Additionally, 7-9cm thick undisturbed sediment and soil samples were impregnated with epoxy from which soil thin sections were made for micromorphological analyses (Courty et al. 1989; FitzPatrick 1984; Goldberg and Macphail 2006). The following chapters discuss the field observations and analytical data on stratigraphy and chronology (Chapter 5) and paleoecology (Chapter 6).

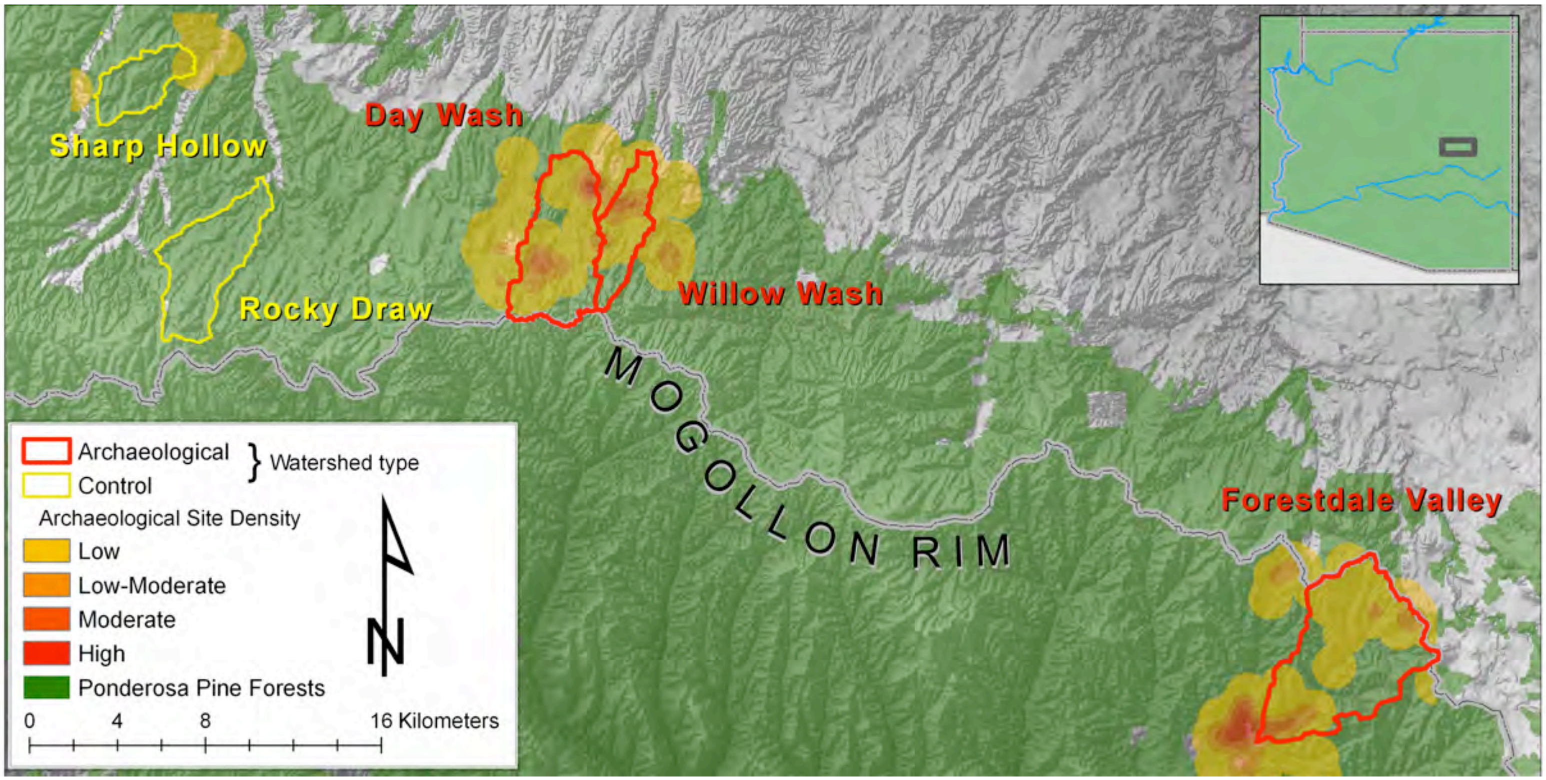


Figure 4.1 The location of the five study watersheds in relationship to the current distribution of ponderosa pine forest, the Mogollon Rim, and nearby prehistoric settlements. Archaeological site density is only shown for sites with evidence for architecture (pithouses or roomblocks) within 2km of each study watershed.

CHAPTER 5. STRATIGRAPHY AND GEOCHRONOLOGY

As discussed in the previous chapter, the analyses in the present study are rooted in alluvial geoarchaeology. In this chapter, I discuss the basic observations and data pertaining to alluvial stratigraphy, soil formation, and geochronology that form the backbone of the study. Stratigraphic control is crucial for the interpretation of the paleoecological records from these localities. Without chronological control, it would be virtually impossible to interpret the charcoal, pollen, and geochemical records in terms of climate and land use.

Numerical dating of alluvial sediments and soils is far from straightforward. A number of methods are suitable for chronometric analysis of late Quaternary alluvial deposits and soils, depending on the setting. Dendrochronology can be used (e.g., Karlstrom 1988), where *in situ* buried trees or stumps are preserved and amenable to crossdating. Luminescence is also possible in settings where quartz sand grains are abundant and stream competence is high enough (but turbulence is low enough) to permit complete resetting of internal electron traps (Anderson et al. 2003). The most common method of dating alluvial sediments and soils, however, is radiocarbon dating (Brown 1997:48). Although radiocarbon dating of humate or humin fractions of alluvial soils is common in situations where charred plant tissues are uncommon, radiocarbon dating of charcoal from alluvial contexts produces the "most reliable dates" (Brown 1997:50). However, radiocarbon dating of detrital charcoal (i.e., deposited from burning elsewhere and not burned *in situ*) at best produces *terminus post quem* or minimum ages for the associated alluvial deposit. In dynamic landscapes that have experienced natural and cultural fires at varying frequencies, the relationship between a radiocarbon dated tissue and the associated deposit may be quite complex and require additional information for adequate interpretation.

In this chapter, I build a conceptual model of the life history of detrital charred plant tissues to best understand potential sources of variation in their radiocarbon ages. Although not all of these sources of variation may be controlled, observations of the microfabric associated with coarse charcoal (>250µm) on soil thin sections as well as other sedimentary data and radiocarbon dates facilitate chronological interpretation (Dean 1978). Second, I briefly discuss the role of calibration in the interpretation of radiocarbon dates. Specifically, I discuss the use of additional stratigraphic information in the formal statistical treatment of radiocarbon dates—a method referred to as Bayesian calibration (Buck et al. 1991). Finally, I discuss soil and sediment stratigraphy from each of the seven study localities to provide a context for the interpretation of associated radiocarbon dates. In this section, I use Bayesian calibrated ages to create age-depth profiles for each locality from which to calculate sedimentation rates and to assign dates to events in the paleoecological data sets.

Life history of detrital charcoal

Radiocarbon dating of detrital charcoal from alluvial deposits is an important and commonly used tool to generate alluvial chronologies. To best date the associated alluvial deposit, it is important that the radiocarbon age closely correspond to the age of the depositional event. A number of events and processes in the life history of detrital charcoal may introduce variation into the chronological relationship between a detrital charcoal radiocarbon date and the date of a depositional event. Some of this variation is attributable to the probabilistic nature of radiocarbon dating itself. Additional variability may be contributed by time spent by a plant tissue in different life history stages (see below).

Radiocarbon dating provides a statistical estimate of the age (in radiocarbon years) that an organic tissue was last involved in metabolic processes that maintained equilibrium with carbon isotope pools in its environment. Conventionally, this can be thought of as the "radiocarbon death date," although some tissues, such as tree rings, remain part of a living organism even after "radiocarbon death." By calibrating this measurement (see below), this age can be converted to a statistical estimate of the calendar date for "radiocarbon death" of an organic tissue. It does not, however, necessarily determine the date of charring, unless the charring event resulted in the "radiocarbon death" of a previously living tissue. This highlights the first life history stage that may complicate the relationship between a detrital charcoal date and an alluvial deposit—precombustion residence time (i.e., the time between radiocarbon death and charring). For some plant tissues, such as grasses, weeds, leaves, bark, or other short-lived tissues, this time may be very short, but is still variable depending upon local climate conditions and the biological activity of decomposing organisms. Wood tissues have the longest potential residence time, since these tissues can remain part of a living (or dead) organism for years, decades or centuries after "radiocarbon death" (e.g., as inner rings of centuries old trees). Conifer needles exist in an interesting intermediate range (i.e., multi-year to decadal scale). If surface fire frequencies are high, as they are inferred to be for premodern ponderosa pine forests (Fulé et al. 1997), and needle turnover rates are high (e.g., 3-7 years for ponderosa pines), the average precombustion residence time for needles is equivalent to the average fire return interval (e.g., 5-10 years). If fire frequencies were reduced at some point in the past, needle litter can accumulate and may resist decay (Klopatek et al. 1990), resulting in an increased precombustion residence time that could approach the time since the last fire.

The next important stage to consider is the postcombustion residence time. This is the interval between combustion and subsequent transport and deposition of detrital charcoal in another context. In many post-fire environments, erosion of surface materials by wind and water is relatively rapid. However, this may also be a stepwise process in which the charred tissue is mobilized multiple times before final deposition in an alluvial setting (Scott et al. 2000). Each episode of transport, however, is an opportunity for the charcoal to be physically damaged, thereby reducing its likelihood of recovery as well. Charcoal is most vulnerable to physical damage when saturated with water (Nichols et al. 2000); this suggests that repeated fluvial transport would likely reduce charcoal below the size range sufficient for radiocarbon dating (e.g., less than 1mg minimum size for Accelorator Mass Spectrometer measurements).

Finally, previously deposited charcoal can, after a variable amount of time residing in a sedimentary deposit or soil, be exhumed by subsequent erosion. Depending on the transport distance, this exhumed charcoal may not survive long, as noted above.

However, charcoal exhumed within a mineral matrix as a soil clast or vertically within a bioturbated profile may not be subjected to the same physical degradation as repeatedly transported charcoal that is unprotected by a veneer of sediment.

Assuming that much older charcoal exhumed from previous deposits can be recognized as anomalous on the basis of other information, the two unknowns in the relationship between a detrital charcoal radiocarbon date and the date of an alluvial deposit are the pre- and postcombustion residence times. For short-lived tissues (e.g., needles), the precombustion residence time in ponderosa pine landscapes is probably relatively short due to decay or short fire return intervals. In contrast, for wood on these landscapes, the precombustion residence time could range from relatively short intervals to more than a century (Gavin 2001). The frequent fires on the landscape mean that it is likely that internal rings from a recently dead tree may be combusted and added to the surface charcoal pool for mobilization before it is fully decayed. Additionally, charred wood tissues (wood xylem, in particular) are stronger and less resistant to physical weathering than charred short-lived tissues, thus improving their chances of recovery. The timing of the natural fire season during the months prior to the summer Monsoon means that postcombustion residence times were probably short, although charcoal on the surface may have been mobilized over a period of several years.

Based on the foregoing discussion, detrital charcoal is likely to have an older radiocarbon age than its associated alluvial deposit from between a few hours or days (e.g., recent growth structures killed by a fire and mobilized by a subsequent rainstorm during the same season) to as much as centuries (e.g., inner rings from a dead tree). By focusing on short-lived tissues (e.g., needles, meristematic tissue, bark), the precombustion and postcombustion residence times can be reduced to annual or decadal scales, although never perfectly known. In landscapes with frequent surface fires and relatively rapid aggradation in alluvial settings, radiocarbon dates from short lived tissues are likely to date sometime shortly before the formation of its associated alluvial deposit. Reworked or exhumed and redeposited charcoal, however, would need to be identified on the basis of corroborative information (e.g., sediment and soil morphology, other radiocarbon dates, biostratigraphy).

Calibrating radiocarbon ages

If radiocarbon (the unstable carbon isotope, ^{14}C) was produced at an invariant rate in the upper atmosphere, radiocarbon years would provide a reasonable approximation for the calendar or solar year. However, production of ^{14}C in the upper atmosphere has varied throughout the radiocarbon timescale necessitating calibration of radiocarbon measurements to secular variation in ^{14}C production. A record of ^{14}C production over more than 12,400 calendar years has been created from measurements of independently dated tree-rings which makes it possible to convert a radiocarbon measurement and its associated statistical uncertainty into a probability distribution and range of calendar years (Reimer et al. 2004). Strictly speaking, the calibrated radiocarbon ages are no longer “independent,” in that the calibrated ages depend on both the calibration curve and the radiocarbon measurement (*sensu* Dean 1978), although these calibrated dates are independent of their archaeological or geological recovery context. This method, however, assumes that we only know two things about the sample and the world—its estimate of radiocarbon age and the calibration curve. In reality, archaeologists often have a great deal more information regarding a sample, including its stratigraphic relationship to other samples or other dated events. It is possible to use this information in conjunction with the radiocarbon age and calibration curve. This approach is called Bayesian calibration, which uses Monte Carlo statistical methods to generate probabilities of the age of an event given its radiocarbon age, a calibration curve, and other information, such as the stratigraphic relationship between samples (Buck et al. 1991). This method is particularly valuable when the distributions of calibrated radiocarbon dates overlap.

This approach assumes that the stratigraphic relationship and superpositioning of samples is indicative of the relative relationships of the radiocarbon death date of the samples. As noted above, this may not necessarily be true, due to variability in pre- and postcombustion residence times as well as possible reworking and bioturbation of samples. For radiocarbon-dated short-lived tissues in landscapes of frequent surface fires, these assumptions may be valid. For unstratified soils, however, the assumption of superpositioning of samples on the basis of relative depth may not be valid due to post-depositional bioturbation (e.g., Carcaillet 2001).

Stratigraphy and geochronology of sample localities

As noted in Chapter 4, the present study focuses on seven localities from five watersheds along the Mogollon Rim. Two of these watersheds lack archaeological or ethnohistorical evidence for intensive indigenous occupation and use (Rocky Draw and Sharp Hollow), whereas the other three watersheds (Day Wash, Willow Wash, and Forestdale Valley) have evidence for variable indigenous use and occupational histories. One locality for each watershed north of the Mogollon Rim was analyzed in detail, whereas three chronologically overlapping stratigraphic localities were analyzed from the Forestdale Valley. One hundred forty-four bulk samples were analyzed for grain-size, organic carbon and carbonate content. Fifty-three soil thin sections were surveyed for evidence of primary bedding structures, in situ and reworked slaking crusts, post-depositional features related to soil formation, bioturbation, and subsequent inundation by flooding. Table 5.1 summarizes sample sizes for each watershed for these analyses, which are described with field observations below.

Table 5.1 Characteristics of sample localities for unoccupied (Sharp Hollow and Rocky Draw) and prehistorically occupied watersheds (Day Wash, Willow Wash, and Forestdale Valley).

Locality	Thickness of exposure (m)	No. bulk samples	No. thin sections	No. radiocarbon dates
Sharp Hollow 1	1.60	9	8	8
Rocky Draw 7	0.93	5	5	5
Day Wash 14	2.55	31	14	10
Willow Wash 4	2.50	20	-	7
Forestdale Valley				
Locality 10	3.40	23	13	10
Locality 6	3.83	30	13	9
Locality 20	3.05	26	-	7
Total		144	53	56

Fifty-seven samples of detrital charcoal were submitted to the University of Arizona Accelerator Mass Spectrometer (AMS) Facility for radiocarbon measurements (Table 5.2). More than 90% of these samples were on nonwood tissues, thus reducing the possibility of “old wood” problems (Schiffer 1986) or in-built ages (Gavin 2001). The number of samples from each locality ranges from 5 to 10, with the fewest samples coming from the shallow profile of Rocky Draw 7 (Table 5.3). In the following sections, I discuss field observations, laboratory data, and observations from soil thin sections pertaining to the soil and sediment stratigraphy at each study locality. These observations inform the interpretation of radiocarbon dates, the construction of Bayesian calibration algorithms, and the construction of age-depth models for subsequent analyses.

Watersheds above the Mogollon Rim

Two watersheds north of the Mogollon Rim were selected for sampling as “control” watersheds. Sharp Hollow and Rocky Draw (Figure 5.1), which are both tributaries of Black Canyon, south of Heber, Arizona, were selected because they lacked evidence for prolonged prehistoric occupation (i.e., no evidence for architecture) despite intensive archaeological survey. As defined for geoarchaeological survey, both watersheds are Class C drainages in Balling and Wells (1990) scheme (i.e., smaller than 20km^2; see Table 5.3 for topographic characteristics of all sample watersheds). The basins above the sampled localities, Sharp Hollow #1 and Rocky Draw #7, are even smaller (less than 4 km^2).

Table 5.2. Radiocarbon data for all sampled localities discussed in the text.

Locality/Sample no.	Depth (cm)	δ ^{13}C (‰)	Material	Radiocarbon age (^{14}C BP)	2 σ Calibrated dates*	95% CI Bayesian dates*
Rocky Draw 7						
AA71723	23-25	-26.0	UNWC (stem)**	151±40	1908-1953 1795-1891 1666-1784	1791-1896 1734-1785
AA74345	35-37	-22.5	UNWC	355±33	1538-1635 1453-1530	1542-1640 1462-1528
AA74346	45-47	-23.4	*Pinus* cone scale	202±33	1920-1952 1728-1811 1644-1692	1730-1787 1641-1692 1529-1542
AA77082	67-69	-22.5	UNWC (bark scale?)	4,166±60	2581-2612 BC 2617-2891 BC	N/A
AA74347	75-77	-23.6	UNWC	4,292±36	2877-2945 BC 2947-3012 BC	N/A
Sharp Hollow 1						
AA74349	16-18	-23.7	UNWC (stem)	179±59	1904-1953 1644-1894	1718-1894 1667-1699
AA71722	18-20	-25.1	UNWC (meristem)	360±69	1433-1656	N/A
AA71721	46-48	-23.0	UNWC	316±61	1783-1796 1447-1667	1735-1799 1567-1680
AA71720	68-70	-22.7	UNWC (meristem)	250±34	1937-1951 1762-1802 1619-1681 1520-1592	1629-1669 1514-1596
AA74350	86-88	-24.7	UNWC (meristem)	257±77	1916-1952 1833-1879 1722-1817 1452-1699	1619-1649 1450-1603
AA74351	116-118	-25.0	UNWC	1766±33	138-380	N/A
AA74352	146-148	-22.5	UNWC	2153±33	358-60 BC	N/A
AA71719	154-156	-24.8	*Pinus* needle	553±88	1269-1498	1273-1441
Day Wash 14						
AA74348	44-46	-23.7	UNWC	364±59	1443-1643	1763-1804 1583-1669
AA77079	46-48	-23.3	*Pinus* needle	262±75	1917-1952 1835-1877 1725-1814 1451-1697	1721-1804 1561-1698
AA71718	62-64	-24.6	UNWC	370±33	1551-1634 1544-1547 1447-1529	1540-1640 1506-1528
AA71717	104-106	-25.7	*Pinus* needle	580±110	1590-1624 1575-1583 1218-1521	N/A

Table 5.2. Radiocarbon data for all sampled localities discussed in the text (continued).

Locality/Sample no.	Depth (cm)	δ ^{13}C (‰)	Material	Radiocarbon age (^{14}C BP)	2 σ Calibrated dates*	95% CI Bayesian dates*
Day Wash 14 (continued)						
AA77080	142-144	-26.2	UNWC (meristem)	540±35	1387-1439 1312-1358	N/A
AA71716	150-152	-23.1	*Pinus* needle	605±89	1251-1452	1479-1610
AA71715	180-182	-24.2	UNWC (meristem)	397±70	1419-1644	1404-1534
AA77081	210-212	-24.2	*Pinus* needle	599±88	1252-1455	1268-1447
AA71714	216-218	-24.5	UNWC (meristem)	342±51	1452-1644	1438-1539
AA71713	226-228	-24.5	UNWC (meristem)	397±39	1555-1632 1434-1526	1434-1517
Willow Wash 4						
AA74787	52-54	-24.3	*Pinus* needle	690±110	1150-1442 1124-1137 1049-1084	N/A
AA74788	82-84	-19.2	UNWC	424±69	1405-1642	1736-1811 1626-1685
AA74789	102-104	-23.2	UNWC	246±90	1911-1953 1831-1888 1718-1827 1460-1708	1618-1784
AA74790	122-124	-23.5	*Pinus* needle	530±120	1265-1641	1568-1668
AA74791	132-134	-21.8	*Pinus* needle	398±97	1779-1799 1388-1670 1313-1357	1544-1647
AA74792	142-144	-24.0	*Pinus* needle	328±57	1449-1657	1519-1620
AA74793	194-196	-25.4	UNWC	243±55	1918-1952 1852-1868 1726-1813 1482-1695	1485-1572
Forestdale Valley 10						
AA74344	32-34	-23.8	UNWC (stem)	371±34	1544-1634 1446-1529	1551-1646 1488-1525
AA68647	56-62	-20.6	*Pinus* xylem	755±36	1216-1290	N/A
AA68648	114-122	-24.5	*Pinus* needle	615±34	1292-1403	1348-1415
AA71707	124-126	-12.8	UNWC	518±64	1292-1483	1418-1486
AA68649	156-162	-23.7	UNWC (twig)	439±34	1601-1615 1414-1500	1326-1441
AA71706	182-184	-12.3	UNWC	619±38	1289-1404	1292-1366
AA68650	208-210	-21.8	*Pinus* xylem	1,580±140	128-688	N/A

Table 5.2. Radiocarbon data for all sampled localities discussed in the text (continued).

Locality/Sample no.	Depth (cm)	δ ^{13}C (‰)	Material	Radiocarbon age (^{14}C BP)	2 σ Calibrated dates*	95% CI Bayesian dates*
Forestdale Valley 10 (continued)						
AA68651	246-250	-23.8	UNWC	672±35	1347-1392 1271-1323	1266-1311
AA71705	274-276	-24.7	Pinus needle	1,120±120	1064-1155 668-1059	1056-1257
AA71704	302-304	-26.5	Pinus needle	800±97	1024-1316	964-1144
Forestdale Valley 6						
AA71712	46-48	-21.8	UNWC	212±54	1909-1953 1716-1891 1629-1711 1522-1573	1632-1816
AA68652	72-79	-24.3	UNWC (twig)	390±33	1558-1631 1440-1524	1555-1640
AA71711	86-88	-24.4	Pinus needle	723±84	1154-1413	N/A
AA68653	140-145	-22.6	Pinus xylem	355±38	1536-1635 1453-1533	1453-1582
AA71710	174-176	-24.9	Pinus needle	629±95	1218-1447	1391-1504
AA71709	236-238	-24.6	UNWC (meristem)	477±69	1558-1631 1384-1524 1304-1365	1378-1458 1332-1356
AA71708	298-300	-24.7	UNWC (meristem)	777±65	1361-1386 1150-1309 1123-1138 1048-1086	1339-1395 1303-1324
AA68654	340-342	-24.2	Pinus xylem	535±57	1377-1449 1298-1372	1286-1356
AA68655	365-373	-22.5	Pinus xylem	973±59	972-1211	966-1176
Forestdale Valley 20						
AA74355	30-32	-22.5	UNWC (Bark scale?)	169±82	1631-1955 1524-1558	1748-1898
AA74356	40-42	-24.2	Pinus needle	257±98	1911-1953 1832-1887 1718-1827 1450-1708	1716-1876
AA74357	80-82	-21.9	UNWC	195±32	1919-1952 1727-1812 1646-1694	1729-1772 1644-1695
AA74358	120-122	-25.7	Pinus needle	442±77	1391-1642 1321-1348	1568-1660

Table 5.2. Radiocarbon data for all sampled localities discussed in the text (continued).

Locality/Sample no.	Depth (cm)	δ ^{13}C (‰)	Material	Radiocarbon age (^{14}C BP)	2 σ Calibrated dates*	95% CI Bayesian dates*
Forestdale Valley 20 (continued)						
AA74359	130-132	-23.8	UNWC	258±33	1940-1951 1776-1800 1765-1772 1618-1677 1516-1596	1515-1600
AA74796	180-182	-24.8	Pinus needle	200±89	1616-1954 1512-1601	1444-1548
AA74797	280-282	-24.1	UNWC (needle?)	453±56	1557-1632 1394-1525 1326-1343	1393-1495 1321-1348
Miscelaneous dates						
Willow Wash 1						
AA64420			Pinus needle	334±35	1460-1650	
Willow Wash Meadow Core						
AA78632	126-127	-24.7	Wood charcoal	7,260±310	6773-5533 BC	
AA78633	320-330	-23.5	Wood charcoal (angiosperm)	8,988±98	8350-7789 BC 8394-8370 BC 8427-8402 BC	
Day Wash Meadow Core						
AA78631	165	-24.3	Wood charcoal	8,386±98	7589-7180 BC	
AA78630	259	-24.8	Wood charcoal	8,810±30	8170-8115 BC 8086-8082 BC 8056-8046 BC 7989-7746 BC	
Forestdale Valley 8						
AA74353	16-18	-23.7	UNWC	2,472±34	466-415 BC 674-483 BC 764-679 BC	
AA78634	116-118	-21.8	Wood charcoal	4,040±110	2887-2291 BC	
AA74354	166-168	-24.0	UNWC	4,298±72	2818-2663 BC 3104-2834 BC 3264-3241 BC	
AA78635	226-228	-23.6	UNWC (bark scale)	4,370±230	3640-2460 BC	

* All calibrated dates are in cal AD unless otherwise noted.
** UNWC abbreviates “Unidentified nonwood charcoal.” When possible, tissue types are indicated in parentheses.

Table 5.3. Topographic characteristics for control (Sharp Hollow and Rocky Draw) and prehistorically occupied watersheds (Day Wash, Willow Wash, and Forestdale Valley).

	Sharp Hollow	Rocky Draw	Day Wash	Willow Wash	Forestdale Valley
Watershed size (km^2)	9.12	18.63	23.64	10.38	38.29
Maximum elevation (m)	2158.0	2327.1	2203.7	2212.4	2104.7
Minimum elevation (m)	1999.2	2034.9	1994.7	1986.9	1823.6
Elevation range (m)	158.8	292.2	209	225.5	281.2
Average elevation (m)	2091.3	2143.4	2085.5	2063.9	1966.5
Maximum slope (degrees)	26.5	25.7	35.1	26.1	37.4
Minimum slope (degrees)	0	0	0	0	0
Average slope (degrees)	6.5	4.4	5.2	5.1	8.6

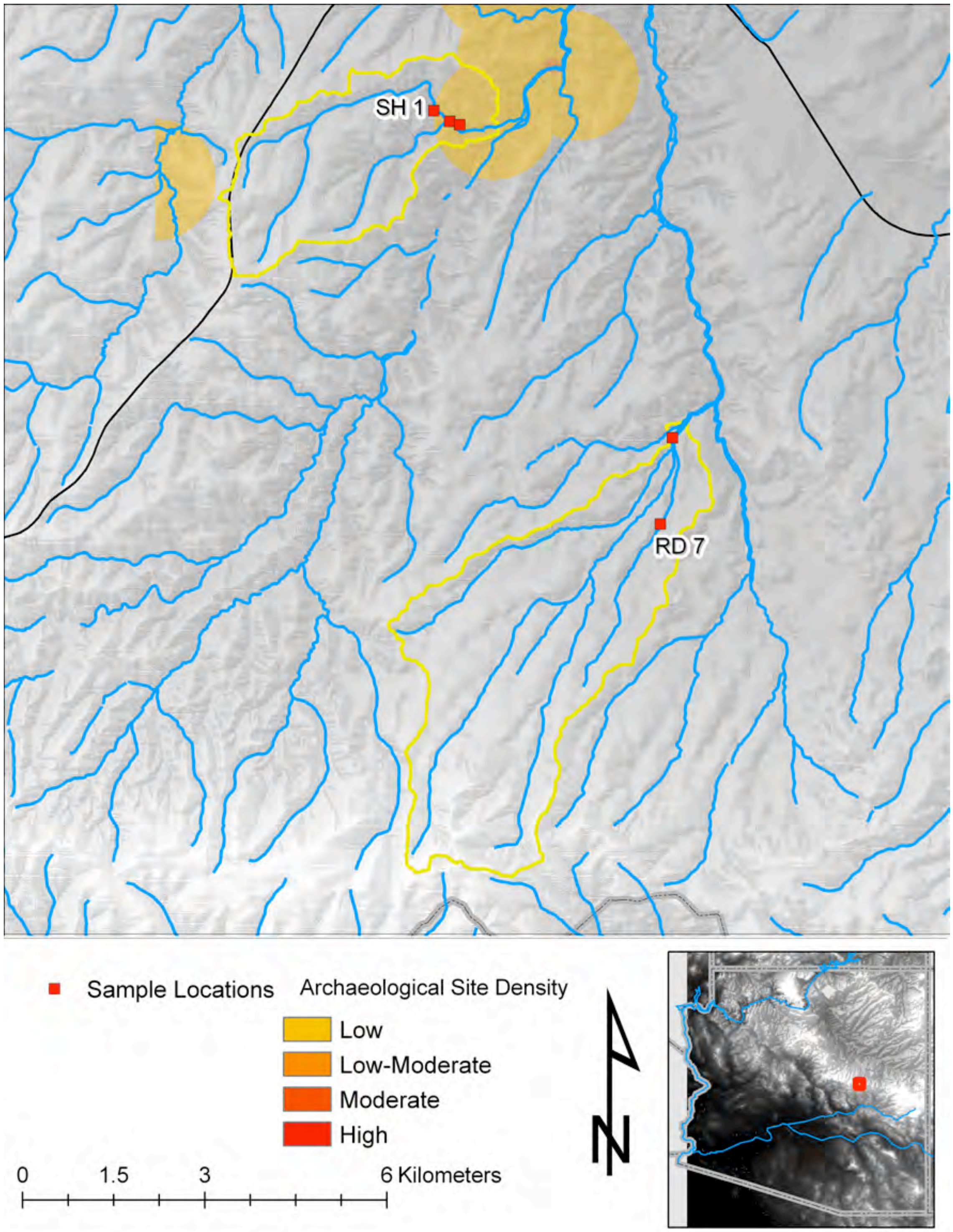


Figure 5.1 Archaeological site densities in the vicinity of Sharp Hollow and Rocky Draw study watersheds. One prehistoric settlement is located less than 2km from the watershed boundary of Sharp Hollow, which accounts for the "Low" density within the study area.

Two watersheds adjacent to the Bailey Ruin (above the Rim) were sampled as "archaeological" watersheds. The area around Day Wash and Willow Wash was intensively occupied prehistorically (Figure 5.2), with excavation documenting Early Pithouse Period occupations (Roos 2008) through Pueblo IV occupation (Mills 1998, 1999). However, the Bailey Ruin was no longer occupied perennially after AD 1325 (Kaldahl et al. 2004; Mills 1998; Mills, Van Keuren et al. 1999). These watersheds may have been part of the traditional territory of the Cibecue Band Apache during the Historic Period (Goodwin 1942), but no archaeological evidence of Apache use has yet been reported in the area (see Chapter 3). Both Day Wash and Willow Wash predominantly drain undifferentiated Cretaceous sedimentary rocks, which include interbedded sandstones, mudstones, and shales (Figure 5.3). Tertiary "rim gravels" drape some hilltops and ridgetops in these drainages, particularly near the Mogollon Rim. As defined for geoarchaeological survey, the watershed of Day Wash is more than twice the size of Willow Wash (Table 5.3). Above the sample localities, however, both drainages are Class C (i.e., $<20km^2$) in Balling and Wells (1990) scheme.

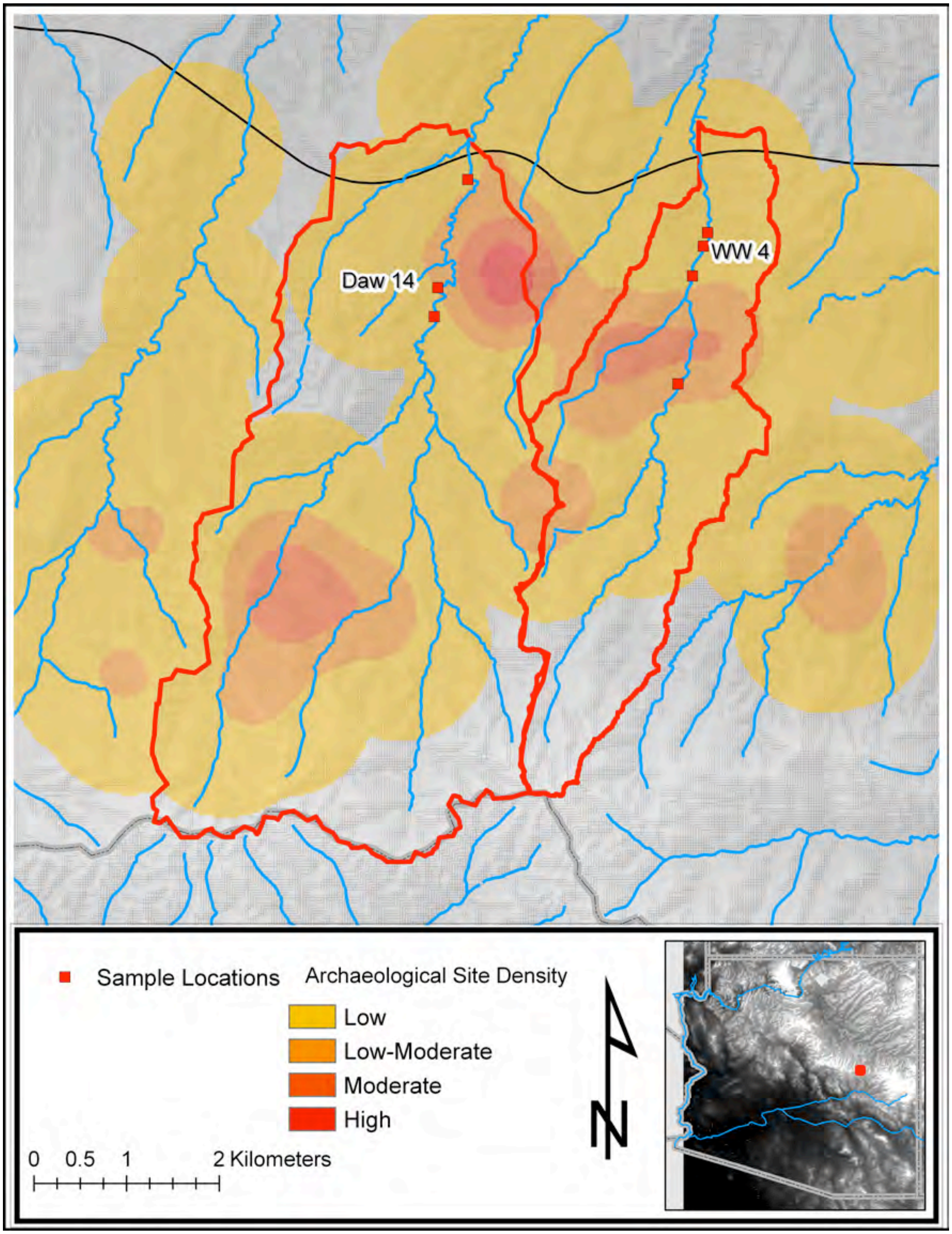


Figure 5.2 Archaeological site densities in the vicinity of Day Wash and Willow Wash study watersheds.

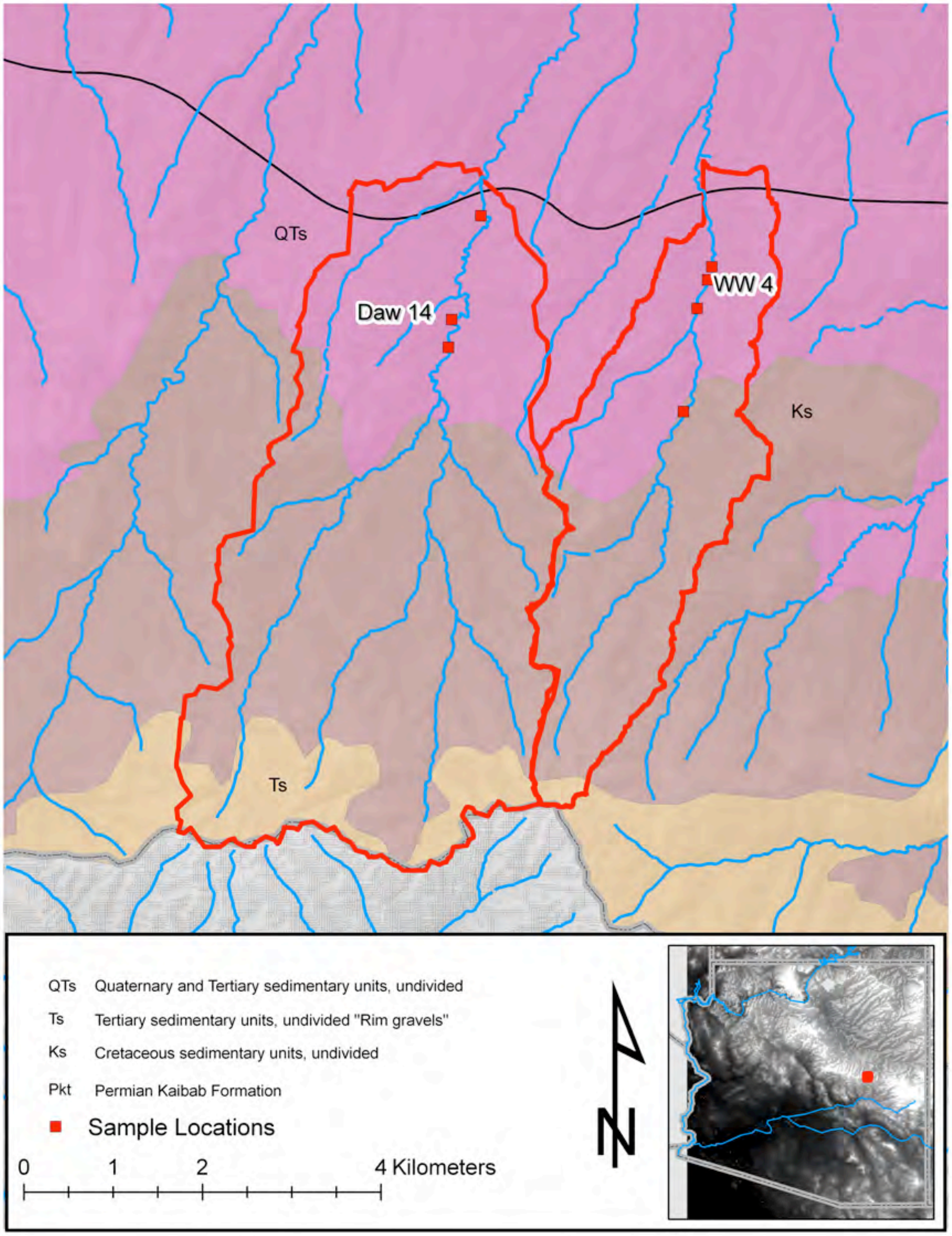


Figure 5.3 Surface geology of the area surrounding the Day Wash and Willow Wash study watersheds. Most of the area contributing sediment to the sample localities (Day Wash 14 and Willow Wash 4) is characterized by undivided Cretaceous sedimentary rocks, which include intercalated sandstones, mudstones, and shales.

Sharp Hollow 1

Geologically, Sharp Hollow is unique among the study area watersheds because it exclusively drains sediments and soils derived from the Permian Kaibab formation (Figure 5.4**)**. In May, 2005, a two-person crew surveyed likely areas of accumulated valley bottom alluvium (as predicted by digital elevation model-derived slope maps) in the Sharp Hollow drainage from its confluence with Black Canyon. The valley floor is covered with herbaceous plants, whereas the surrounding hillslopes currently support ponderosa pine forest (Figure 5.5). We manually exposed sediments at three locations in alluvial fan sediments, each of which disclosed a sequence of three thick, buried A horizons covered with a thin (ca. 10-15cm thick) veneer of young sediments in which current vegetation is growing (an AC horizon). Texturally, all sediments were very similar, although A horizons could be distinguished by changes in color and consistence (i.e., firmness) in the field. We defined these sediments as a single lithological unit (Unit I) of sandy alluvial fan sediments overlying limestone cobbles and gravels. Three buried soils (Ab1, Ab2, and Ab3) below the weakly expressed surface horizon were defined in the field.

Nine bulk samples were analyzed for grain-size, carbonate, and organic matter content from Sharp Hollow 1 (Figure 5.6). Eight soil thin sections were analyzed for evidence for depositional structures and post-depositional alterations. The thickness of the buried A horizons, in conjunction with soil thin section observations of near surface bioturbation throughout each horizon, suggests that each buried soil cumulized (i.e., grew in thickness by accretional deposition of alluvial sediment and penecontemporaneous soil formation). Carbonate features are less well preserved towards the top of the profile but appear to be coincident with evidence of earthworm activity in the form of round granules filling chamber voids (Figure 5.7). Organic matter stained, dusty clay coatings are ubiquitous in thin section, indicating that the fan surface was regularly inundated by floodwaters. Overall, the bulk and thin-section data indicate that each of the three buried soils formed under similar conditions and over similar periods of time. Each of the buried soils appears to have been an overthickened A horizon created by regular inputs of alluvial sediment reworked by biological activity and soil formation. Buffering of soil environments by carbonates may have created favorable conditions for earthworm activity in the past. The absence of earthworm evidence from the currently forming soil may indicate that these environmental soil conditions are absent at Sharp Hollow #1 today (upper 40cm of the profile).

Eight, nonwood samples of detrital charcoal collected from sediments from Sharp Hollow 1 (SH 1) were submitted for AMS radiocarbon dating (see Table 5.2). Six of the eight dates have two-sigma calibrated age ranges that span approximately cal AD 1300-1950. Two dates from the lowest unit at SH 1 predate all other samples by more than 1000 years. These dates are stratigraphically above a 13^{th} or 14^{th} century date from near the base of the oldest buried soil at SH 1, suggesting that these are likely reworked from exhumed, older soils upstream. However, no clearly reworked soil aggregates were observed in thin section. Macroscopic charcoal concentrations are relatively low throughout Ab3 (see Chapter 6 for full charcoal results) and some of this charcoal is well rounded, which indicates reworking. As stated above, there is no evidence from soil morphology, thin sections, or bulk data to support the hypothesis that the older dates for SH 1 date the deposition of their associated sediments. On the basis of the majority of the soil, sedimentary and other radiocarbon evidence, these dates appear to be too old because, in all likelihood, the material was exhumed from older soils upstream and redeposited.

The six remaining radiocarbon dates overlap at two standard deviations. The stratigraphic relationships of these radiocarbon dates were used in the algorithm to further constrain the age of the samples using Bayesian methods. AA71722 could not be accommodated in Bayesian calibration without violating the statistical assumptions of the model, so it too was removed from the final calibrations. Finally, it was assumed that the current, entrenched channel of Sharp Hollow was formed by AD 1910, when other channels were known to have been incised in the region (Haury 1985 [1940]:144). The five calibrated dates suggest that each buried soil may represent the accumulation and syndepositional soil formation over approximately 100-200 years each from the 14th century through the early 20th century. Minimum and maximum ages from the 95% confidence interval of Bayesian calibrated age ranges for these six dates were used to generate a second order polynomial function (r^2=0.74; p=0.0044) to model the age-depth relationship for subsequent analyses (Figure 5.8). This age-depth model implies relatively steady accumulation between the mid 14th century and the end of the 19th century. Although truly continuous accumulation does not characterize the SH 1 stratigraphic sequence, the evidence for cumulization throughout its formation history does not indicate major changes in deposition or stability, which is consistent with the stratigraphic scenario described above. Inferred sedimentation rates (see Figure 5.6) are also consistent with the deposition and soil formation history described above. With the exception of initial formation of parent material for Ab3, the inferred average sedimentation rates are well below the 0.5cm per year threshold reported by Daniels (2003) as the difference between the relative importance of deposition or pedogenesis in the valley fill of the Western United States. Sedimentation rates below this threshold (i.e., less than 0.5cm yr^{-1}) result in deposits displaying predominantly pedogenic characteristics, whereas sedimentation rates above this threshold (i.e., greater than 0.5cm yr^{-1}) result in deposits displaying predominantly depositional characteristics.

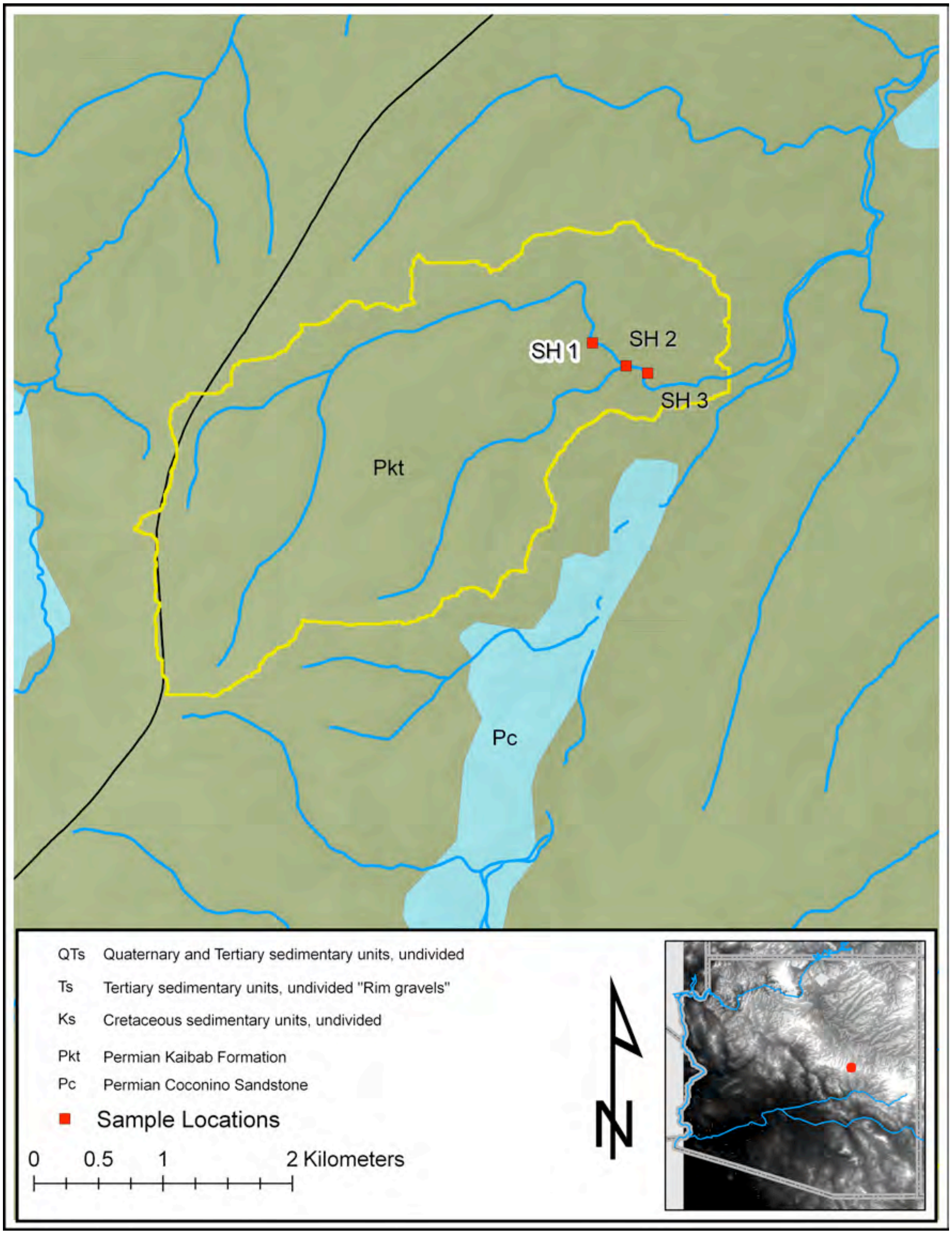


Figure 5.4 Surface geology of the area surrounding the Sharp Hollow study watershed. All of the area contributing sediment to the sample locality (SH 1) is Kaibab formation limestones, sandstones, and sandy dolostones.

Figure 5.5 View downstream (east) from sampling locality Sharp Hollow 1 (lower right).

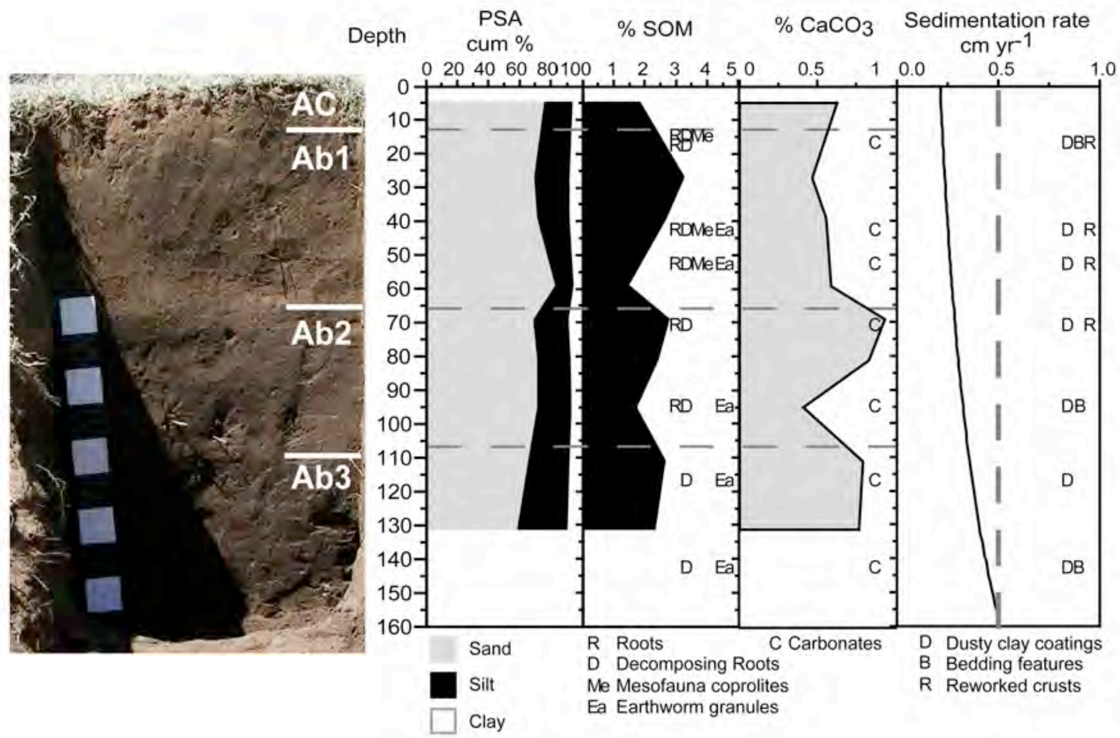


Figure 5.6 Bulk and micromorphological data for Sharp Hollow 1. Grain size (left) is represented in cumulative percent of sand (gray), silt (black) and clay (white). Soil organic matter (SOM; middle left) is represented as percent estimated from Walkley-Black measurements of organic carbon. Calcium carbonate content (middle right) is expressed as percent measured with the Chittick apparatus (see Appendix). Horizontal dashed lines indicate the uppermost elevation of field identified soil units. Letters indicate the presence of features on soil thin sections. Average sedimentation rate is estimated from the polynomial age-depth function. The vertical dashed line marks 0.5 cm yr^{-1}, below which pedogenic processes dominate (Daniels 2003).

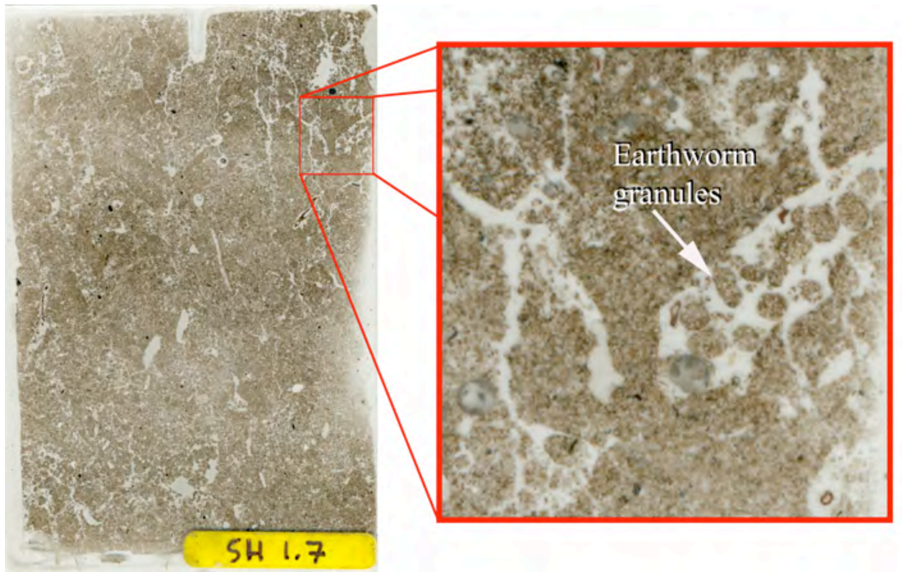


Figure 5.7 Scan of soil thin section from 113-122cm depth at Sharp Hollow 1 illustrating earthworm granules in a coarse chamber void. Thin section (at left) is 5cm wide.

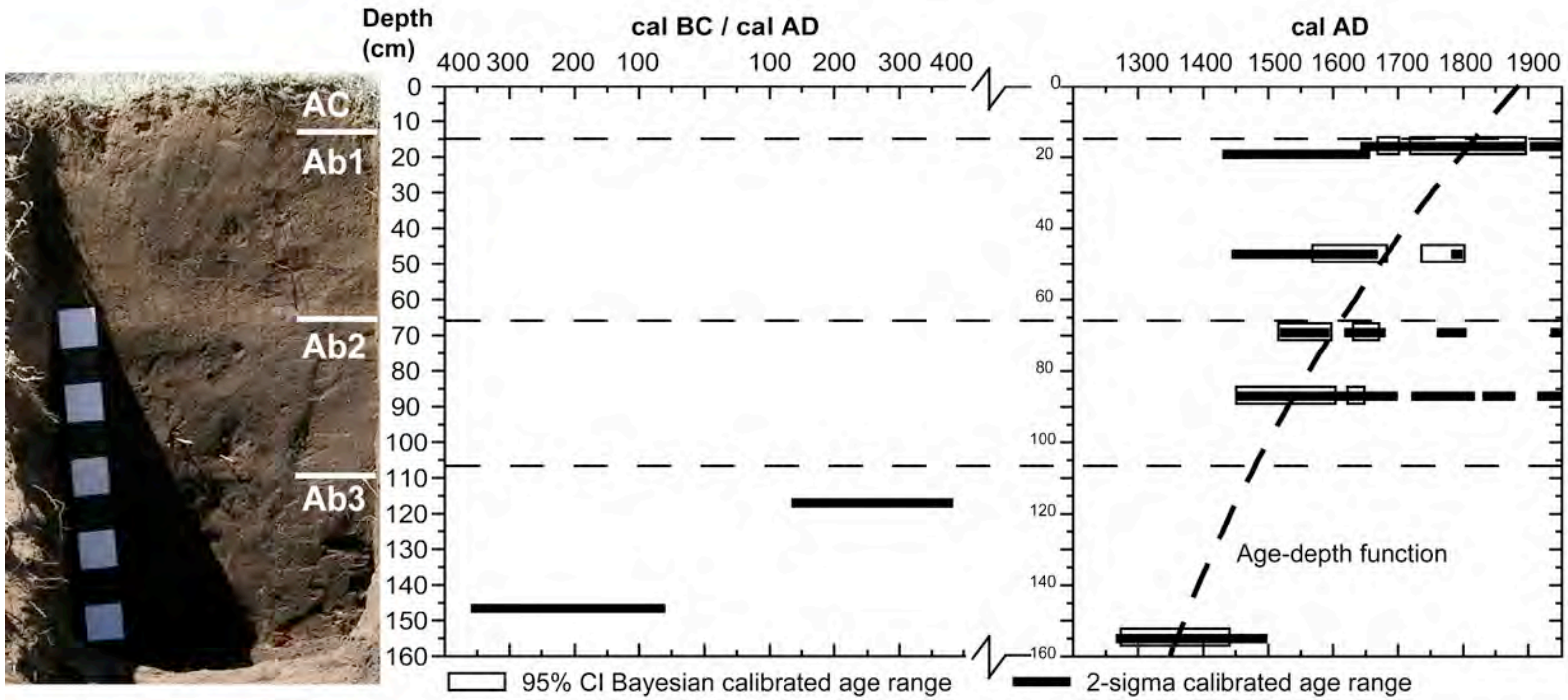


Figure 5.8 Radiocarbon ages, age-depth function, and soil stratigraphy from Sharp Hollow 1. Both traditional (95.4% CI) and Bayesian calibrations (95% CI) are indicated by solid and open bars, respectively.

Rocky Draw 7

Geologically, Rocky Draw is also quite different from all other watersheds surveyed. As the name implies, the main drainages of this watershed are “rocky” (Figure 5.9). In the main and west forks of the Rocky Draw drainage, Tertiary gravels and cobbles have limited the stream morphology to very broad, cobbly, braided channels with shallow, coarse textured terraces (Figure 5.10). The east fork of Rocky Draw is the smallest of the contributing tributary drainages but disclosed a single, fine-grained alluvial geomorphic surface (Figure 5.11). Two different manual exposures of this valley bottom alluvial fan disclosed a single, thick A horizon with a moderately expressed Bw horizon identified on the basis of changes in color and consistence. This soil was formed in a single sedimentary unit of sandy alluvium overlying cobble and gravel channel lag. The A horizon was exceptionally thick for soils in these environments (>50cm), which is indicative of cumulization of the A horizon through additional sedimentary inputs as plant growth; and bioturbation contributed to the formation of the A horizon. Five bulk samples and five soil thin sections were analyzed from Rocky Draw 7 (Figure 5.10). The slight increase in soil organic matter at 65 cm from the surface (30cm above coarse channel lag at the bottom of the deposit) may indicate an original soil surface that has been welded into the cumulized soil above it (Figure 5.12). Superpositioning of clay coats from inundation support this interpretation as well. Limpid clay coats, probably produced by the downward fining of suspended sediment infiltrated into the sandy soil during flooding, is superimposed on dusty clay coatings (from near-surface inundation) on thin sections at the base of the profile (Goldberg and Macphail 2006:358). Overall, the bulk and micromorphological data suggest that the sediments at Rocky Draw 7 accumulated rapidly in their initial formation (e.g., the first 30cm), followed by slow accumulation and syndepositional soil formation.

Five, nonwood charcoal samples collected from sediment samples from Rocky Draw 7 (RD 7) were submitted for AMS radiocarbon dating. Three of the dates from the single, cumulic soil indicate accumulation since at least the 16th century AD (Table 5.2, Figure 5.13). The two dates from the Bw horizon, however, are both more than 4000 years old. These dates are anomalously old when considered in the context of the overall soil morphology and the young dates from the A horizon. In the two thin sections from the Bw horizon, coarse fraction charcoal (i.e., charcoal that could be collected for dating) only occurs within well-rounded, rubified (i.e., reddened) soil aggregates (Figure 5.14). These aggregates likely were exhumed and eroded from Middle Holocene age soils upstream. Coarse charcoal is infrequent in the earliest sediments deposited at RD 7 (see Chapter 6). In fact, the initial accumulation of sediment was fairly high energy and rapid (see above). The ages greater than 4000 cal BP appear to be unrelated to the age of deposition of the alluvial channel fan at RD 7 but are indicative of subsoil erosion upstream prior to the initial accumulation of the valley-bottom fan. On the basis of the three dates from the single, overthickened A horizon, this geomorphic feature probably began accumulating sometime prior to AD 1600. Interestingly, the exhumed, older charcoal deposited at RD 7 is probably generally synchronous with the evidence for the deposition of exhumed, older charcoal at SH 1.

Although there is evidence for mixing within these deposits, the stratigraphic relationships between the dates were assumed to be valid for the purposes of Bayesian calibration. As stated above, this assumption may not be valid in this case, but for consistency and to constrain the radiocarbon ages for the purposes of constructing an age-depth model, this assumption was used. Bayesian calibration likewise suggests an initial accumulation of sediments at RD 7 during or prior to the 16th century AD.

The minimum and maximum ages from the 95% confidence interval of Bayesian calibrated age ranges for these three dates were used to generate a second order polynomial function to model the age-depth relationship for subsequent analyses (r^2=0.56; p=0.124). This function (Figure 5.13) implies accumulation beginning in the mid 15th century with sedimentation rates decreasing above 50cm in depth, which is consistent with the geoarchaeological observations. Overall, the radiocarbon based chronology suggests that RD 7 accumulated approximately 30cm fairly rapidly in the 15th and early 16th centuries AD with continued deposition and syndepositional pedogenesis from the 16th century through the early 20th century when the current channel of the east fork of Rocky Draw entrenched. Although the assumptions necessary for Bayesian calibration may not be supportable for this locality, the resultant age-depth profile is consistent with the accepted (i.e., not reworked) radiocarbon ages and soil information, even if the stratigraphic relationships of the charcoal samples are not in chronological order due to postdepositional mixing.

The inferred sedimentation rate (Figure 5.12) is consistent with the predominance of bioturbation and soil formation with the addition of sedimentary inputs. Only the initial formation of the alluvial parent material is above the 0.5 cm per year threshold for the preservation of bedding structures reported by Daniels (2003).

Figure 5.9 William Reitze in the center of broad, cobble and boulder paved channel of Rocky Draw (view upstream).

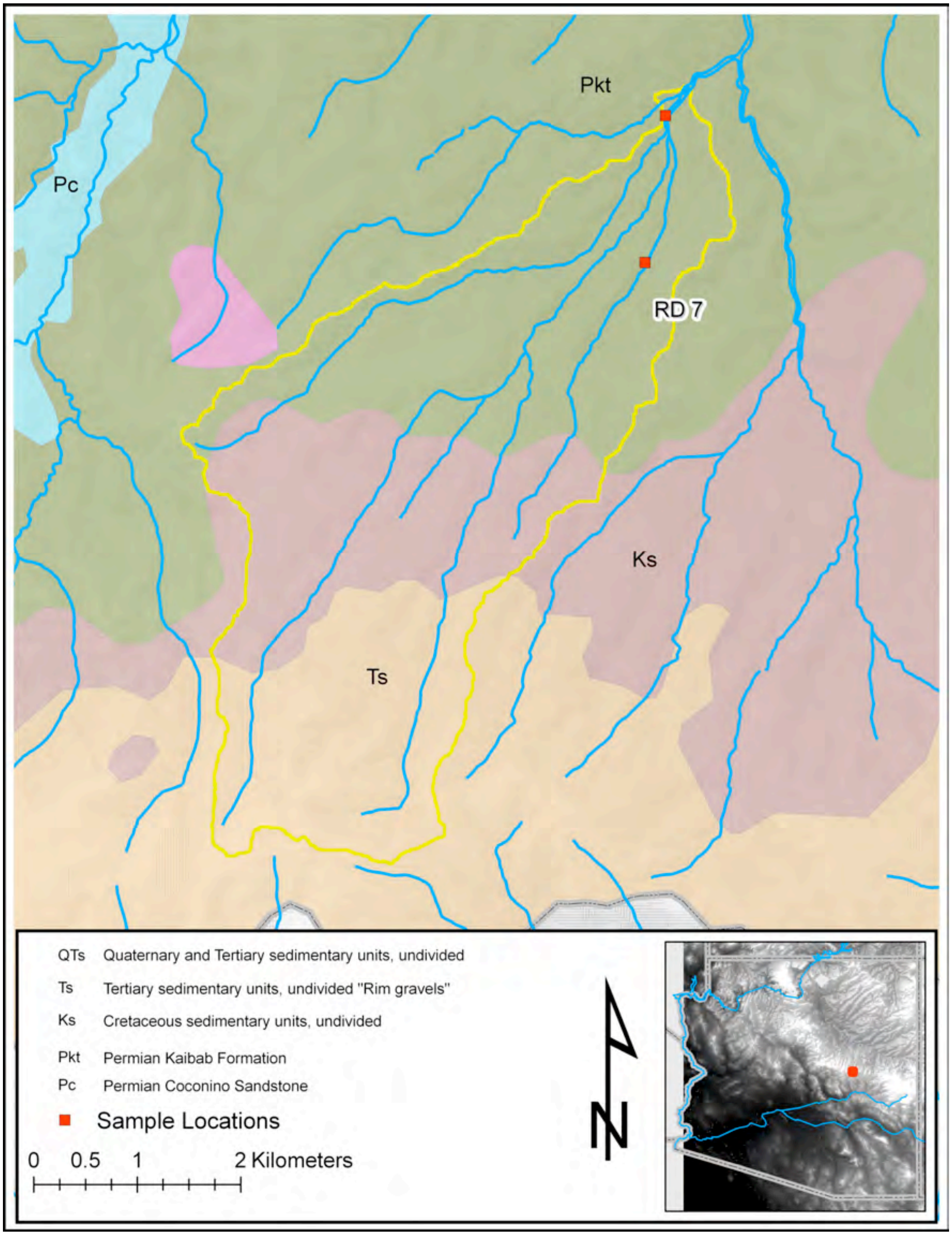


Figure 5.10 Surface geology of the area surrounding the Rocky Draw study watershed. The area contributing sediment to the sample locality (RD 7) includes undifferentiated Cretaceous sedimentary rocks and Kaibab Formation deposits.

Figure 5.11 View of the area surrounding Rocky Draw locality 7 (in center, view downstream). This 20-30m wide valley bottom fan extends approximately 500m further upstream behind the photographer. This area was burned with high severity during the 2002 Rodeo-Chediski fire.

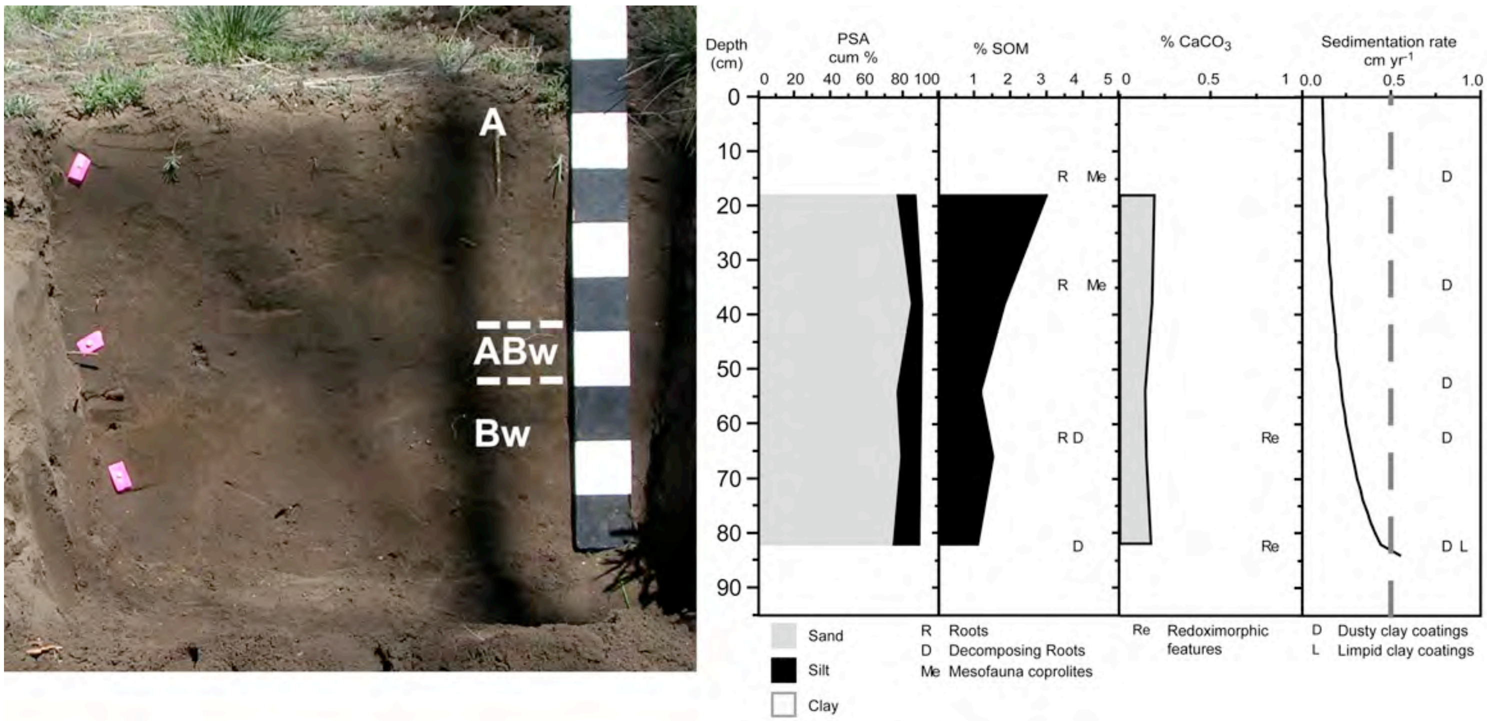


Figure 5.12 Bulk and micromorphological data for Rocky Draw 7. See Figure 5.6 for description of the axes. The limpid clay coatings (from later, deeper inundation) are superposed onto dusty clay coatings (from earlier, shallower inundation) suggesting cumulization of the profile.

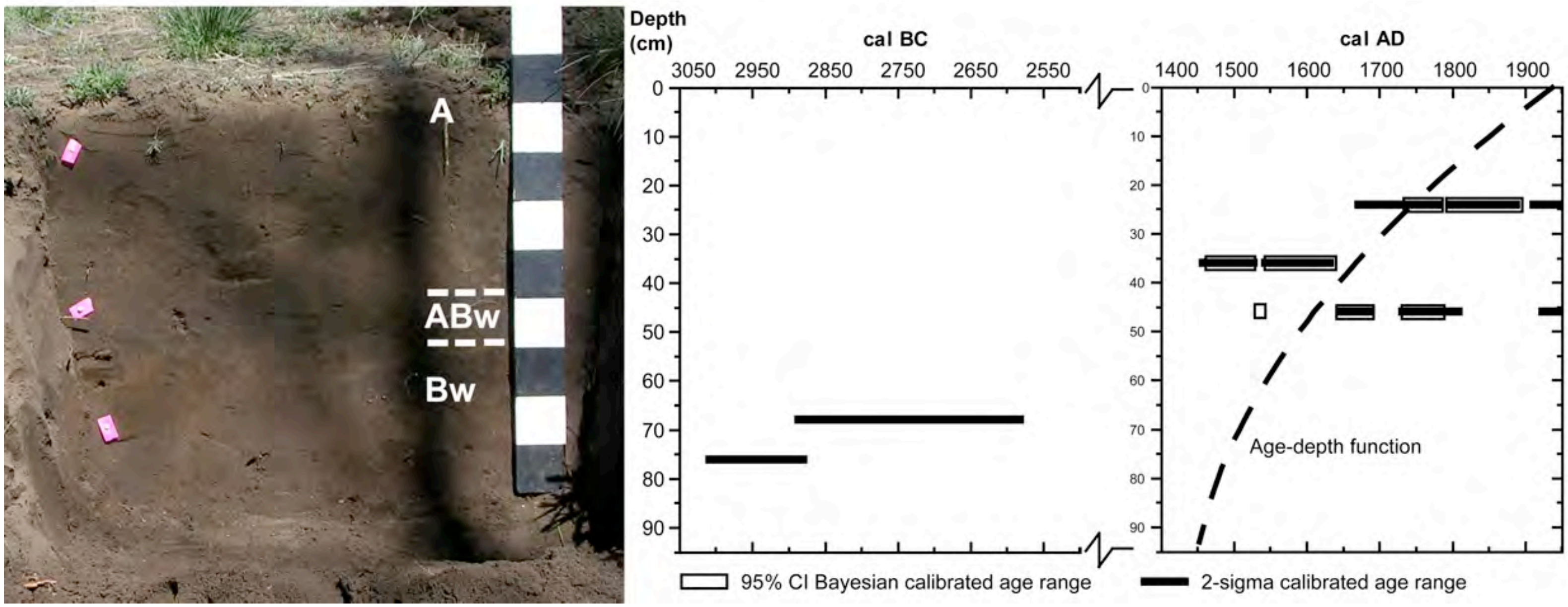


Figure 5.13 Radiocarbon ages, age-depth function, and soil profile from Rocky Draw 7. Both traditional (95.4% CI) and Bayesian calibrations (95% CI) are indicated by solid and open bars, respectively.

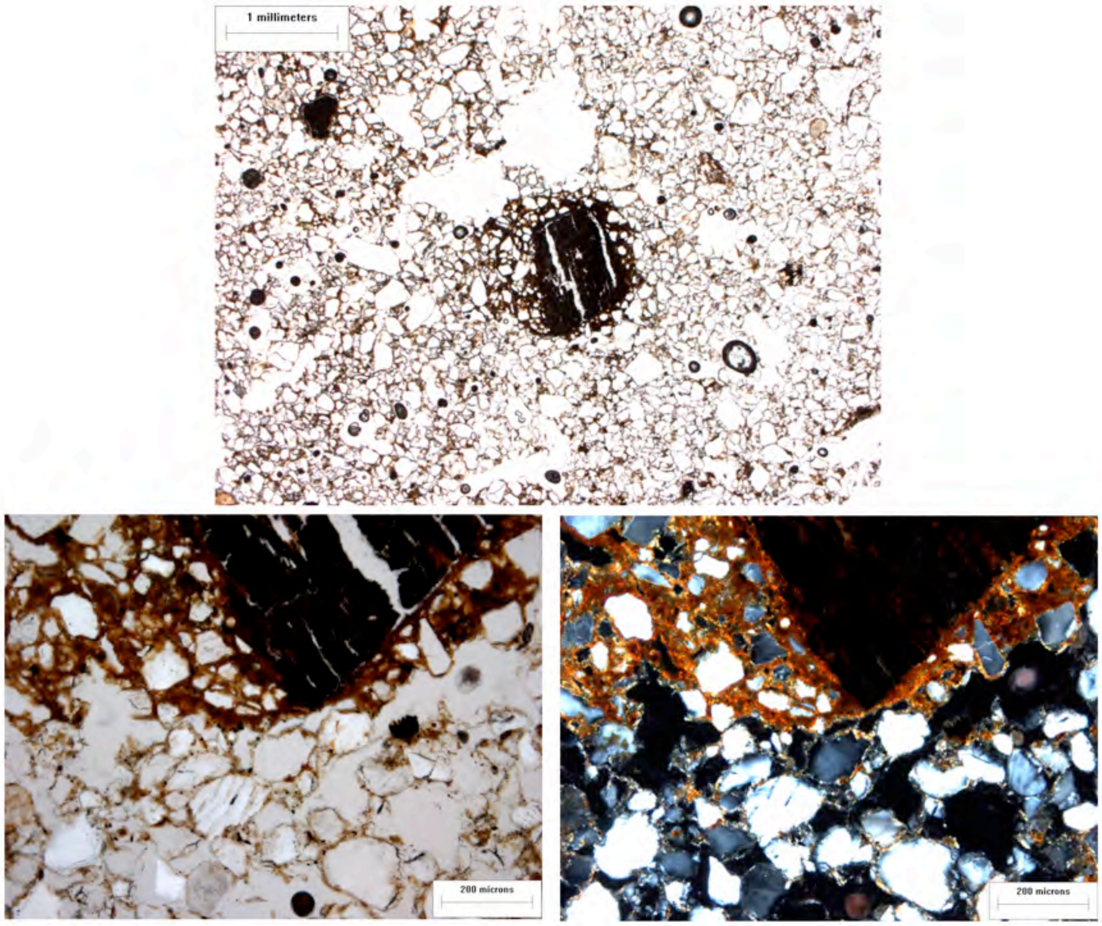


Figure 5.14 Photomicrographs of charcoal in reworked soil aggregates from Rocky Draw 7 in plane polarized light (PPL, top and lower left) and crossed polarized light (XPL, lower right). The soil matrix surrounding the charcoal is heavily reddened in contrast with the orange and yellow dusty clay coats and bridges elsewhere in this horizon.

Day Wash 14

In Day Wash, young terraces are inset in meander scars, which made it difficult to laterally trace these geomorphic surfaces very far within the drainage. Day Wash Locality 14 was chosen for further investigation because subtle stratigraphy of weakly developed soils was identified in the upper 1m of the deposits during survey. Upon manual exposure, two distinct sedimentary units were identified in the field. Unit I (Figure 5.15) was defined as a sequence of massive, fine-grained deposits with intercalated charcoal beds. This unit was deposited on a coarse channel lag of cobbles and gravels approximately 30 cm below the grade of the current channel. Bioturbation clearly disturbed the uppermost charcoal bed, and this upper portion of Unit I was inferred to have been a weakly expressed soil (Ab11). Unit II, as defined in the field, consisted of weakly separated soils in graded, sandy alluvium (Ab1 through Ab10). The surface soil was weakly expressed but had a 2 cm-thick O horizon of undecomposed and partially decomposed pine duff. Vegetation on the Day Wash 14 surface is almost exclusively young ponderosa pine (<60 years old; Figure 5.16). Although much of the Day Wash watershed burned, the immediate vicinity of Day Wash 14 was not burned at high severity during the Rodeo-Chediski fire in 2002.

Thirty-one bulk samples were analyzed for grain-size, carbonate, and organic matter content and 14 thin sections were surveyed for depositional structures and post-depositional alterations (Figure 5.15). Although some evidence of bioturbation was observed on thin sections from Unit I (including rare channel voids and decayed root tissues), the dominant features were depositional, indicative of alluvial, colluvial, and eolian inputs of sediment. Bulk data indicate that these deposits included both sandy and fine-grained facies. High levels of oxidizable organic matter, coincident with high concentrations of charcoal (see Chapter 6), are probably from detrital, unburned organic matter deposited in association with the charcoal. Unit II is characterized by three 40-60cm thick upward coarsening units with moderate levels of carbonates and organic matter. Carbonates are largely pedogenic and occur in the form of hypocoats (see Appendix A for definitions of micromorphology terms) on empty channel voids or in association with decayed roots but never in association with living roots. The source of the carbonates is probably atmospheric dust, although redeposited ash may also be a contributor. In Ab9, a preserved slaking crust contains relatively well-preserved carbonate ashes (Figure 5.17). Similar to Sharp Hollow 1, evidence of earthworm activity is limited to buried soils with evidence of carbonate accumulation and is not present in recent buried soils or the modern soil. Most carbonate features have evidence of etching, suggesting that current soil-forming environments may not be conducive to carbonate accumulation or preservation (i.e., carbonate features that previously formed are now being removed by leaching). In Unit II, the relative abundance of depositional structures decreases towards the top of the unit. Remnants of bedding are less well preserved in Ab2, Ab3, and Ab4, and bioturbation from soil fauna and plants is more common, indicating lower rates of sedimentation relative to stability and soil formation.

To summarize, sediments within Unit I at Day Wash 14 accumulated rapidly as alluvium, colluvial mudflows, the collapse of nearby stream banks, and eolian sands, capped with beds of charcoal and unburned plant tissues that subsequently decomposed.

Preserved depositional structures are common throughout Unit II as well, although preservation decreases towards the top, indicating reduced sedimentation rates relative to syndepositional alteration. Evidence of near surface bioturbation and plant growth in the form of channel voids, chambers, earthworm granules, and decayed plant roots indicates that Units I and II formed over some time, with opportunities for plant and animal activity to take place on stabilized surfaces. Bioturbation and soil formation increased in relative importance towards the top of the deposit (A, Ab1, and Ab2, in particular), which suggests that average sedimentation rates had decreased to the point that pedogenic processes dominated (Daniels 2003).

Ten nonwood samples from deposits at Day Wash 14 (DaW 14) were submitted for AMS radiocarbon dating (Table 5.2). The massive, fine-grained deposits of Unit I, capped with charcoal beds, suggest very rapid accumulation after a fairly large fire (see also Chapter 6). Charcoal dates from throughout this profile support this interpretation and point to a period in the 15th century as a likely time when this fire occurred. In fact, it is statistically possible that most of the dated charcoal recovered from throughout this section had been remobilized from this initial 15th century fire. However, it is also possible that subsequent charcoal samples were from more recent fires that only overlap with the earlier radiocarbon dates due to normal statistical uncertainties. The latter scenario is most likely, given the likelihood that fragile, nonwood charcoal would be unlikely to survive on the surface for centuries and that the micromorphological data indicate syndepositional bioturbation and soil formation throughout the accumulation history.

The stratigraphic relationships of eight of the ten radiocarbon ages were used to build a Bayesian algorithm for calibration. Two dates (AA71717 and AA77080) were omitted because they could not be accommodated in the Bayesian calibration function without violating the statistical assumptions. In the final algorithm, samples from the rapidly accumulated Unit I at the base of the profile were assumed to be contemporaneous whereas stratigraphic superposition was assumed to be valid for all dates above these samples (Figure 5.18). These Bayesian calibrated age ranges are consistent with the stratigraphic data indicating relatively rapid accumulation with some bioturbation and very weak soil formation cumulizing the profile in the upper 1.8m.

Minimum and maximum ages from the 95% confidence interval of Bayesian calibrated age ranges for these eight dates were used to generate a third order polynomial function (r^2=0.68; p=0.0009) to model the age-depth relationship for subsequent analyses (see Figure 5.18). This age-depth model implies very rapid accumulation during the 15th century (ca. 1m of accumulation) followed by relatively slow accumulation (the remaining 1.4m) over the next 300 years until historic downcutting in the early 20th century. It is difficult to gauge the differences in sedimentation rate and soil formation in the upper 1.5m, but the elevated soil organic matter in Ab1 and Ab2 suggests that there was greater relative stability and decreased sedimentation, which is consistent with the age-depth model and the inferred average sedimentation rate (see Figure 5.15). Inferred sedimentation rates are well above Daniels' (2003) 0.5 cm per year threshold, which is also consistent with the micomorphological observations.

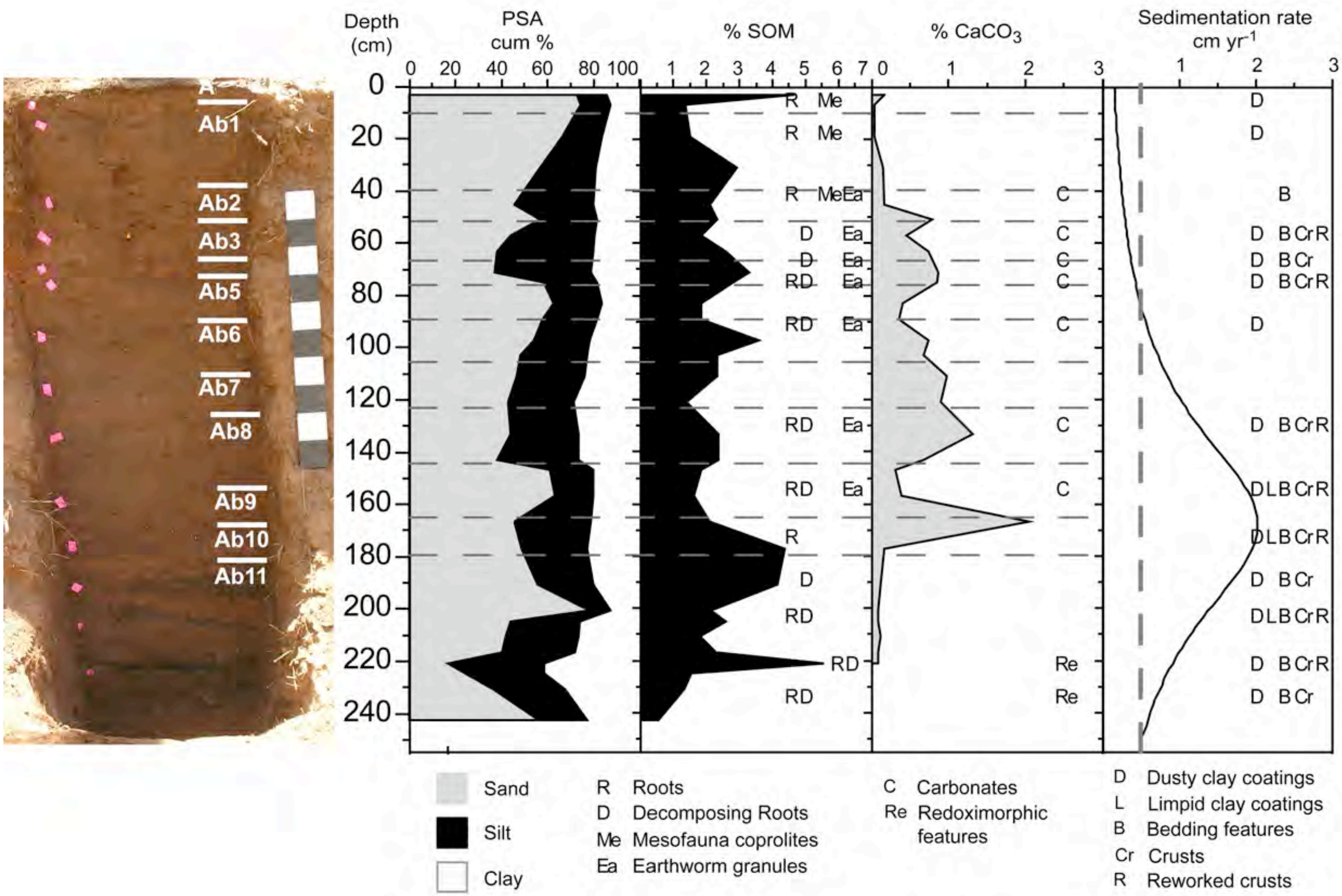


Figure 5.15 Bulk and micromorphological data for Day Wash 14. See Figure 5.6 for description of the axes.

Figure 5.16 View downstream (to the northeast) of the environment surrounding Day Wash locality 14 (in lower right). The immediate vicinity burned at low and moderate severity during the Rodeo-Chediski fire in

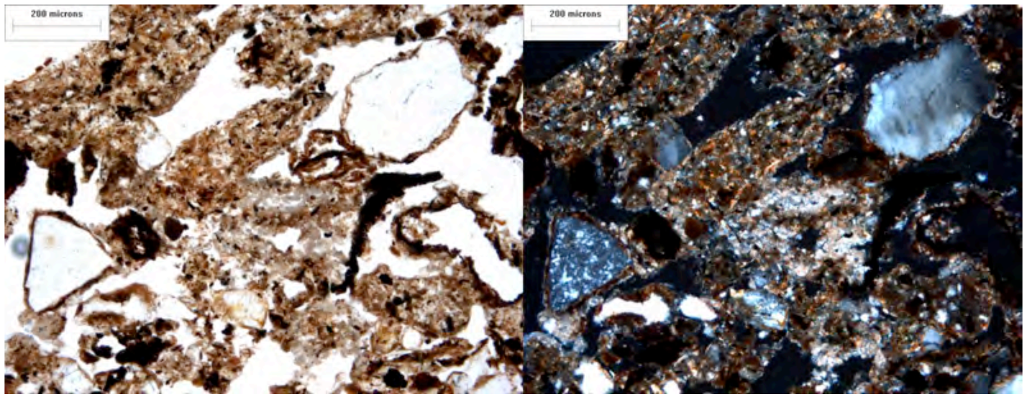


Figure 5.17 Photomicrographs of preserved ashes (rhombs of micritic calcite) from Day Wash locality 14 (center of field in each) in PPL (left) and XPL (right).

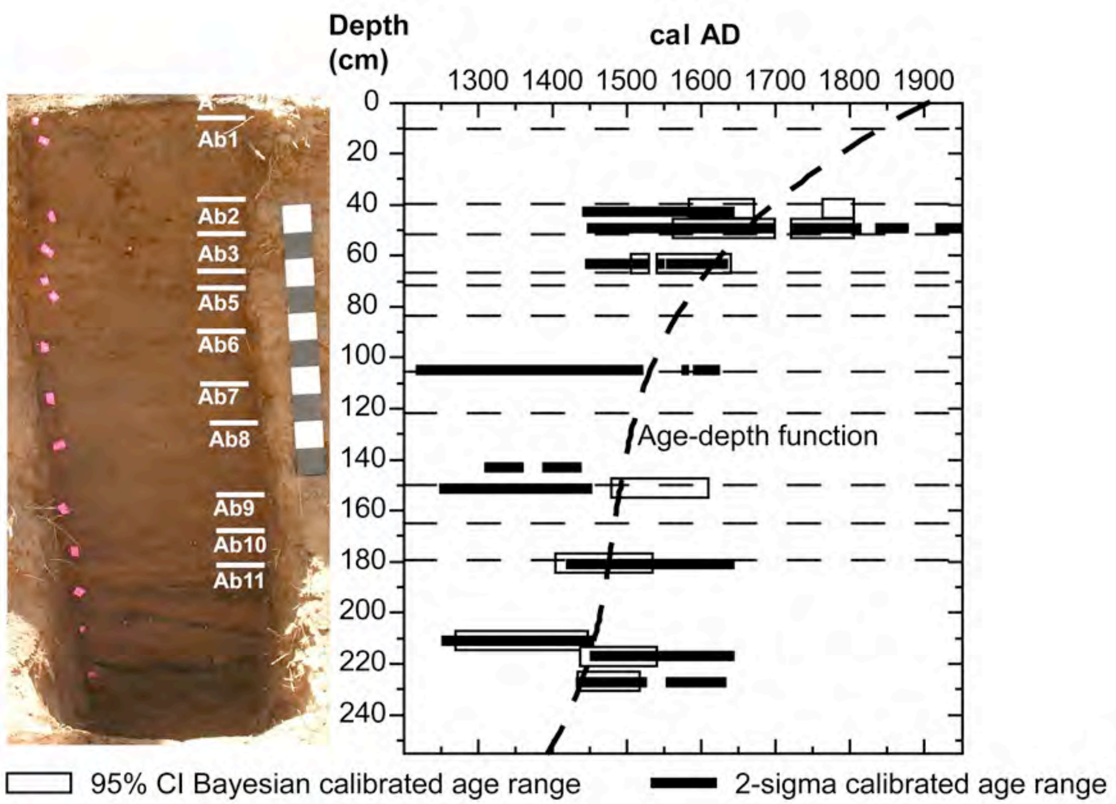


Figure 5.18 Radiocarbon ages, age-depth function, and soil stratigraphy from Day Wash 14. Both traditional (95.4% CI) and Bayesian calibrations (95% CI) are indicated by solid and open bars, respectively.

Willow Wash 4

During geoarchaeological survey of Willow Wash in 2004 and 2005, a traceable alluvial channel fan was located about 1km downstream from Hall Point. Initial sampling of Locality 1 was done during the 2004 Silver Creek Archaeological Field School (Figure 5.3). Three lithological units were defined in the field on the basis of texture, color, and bedding (Figure 5.19). Thirty-four bulk samples were analyzed for grain size, carbonate, and organic matter content from Willow Wash 1. Ten soil thin sections were prepared from these deposits, but have not yet been analyzed. In 2005, Locality 4 was manually exposed and sampled. Two lithological units were identified in the field (Figure 5.20), which appeared to be distal fan facies of deposits discerned upstream at Willow Wash 1. Twenty bulk samples were analyzed from Willow Wash 4; Eleven soil thin sections were also made but have not yet been analyzed. The results from Willow Wash 1 and 4 are, as yet, preliminary.

Unit I at Willow Wash 1 was poorly sorted, dark gray alluvium with no field-observable bedding structures (Figure 5.19). A dark horizon with a gradual lower boundary caps Unit I and was probably a buried A horizon. Unit I was buried by fine-grained overbank and intercalated, bioturbated silt and sand beds (Unit II). Unit III is friable, sandy sediment with welded, weakly expressed A horizons above a discontinuous gravel lens, marking a disconformity at the top of Unit II. One charred *Pinus* sp. needle, which was collected from a lens of oxidized sediment at the contact between Units I and II, yielded a date of cal AD 1460-1650 (see Table 5.2). This lens may be an archaeological feature or the location of coarse woody debris that burned during a landscape fire. No artifacts were found during manual exposure of sediments at Willow Wash 1, but current evidence does not allow for adjudication between these two alternative interpretations.

Unit I at Willow Wash 4 was described as massive, dark gray-brown, cumulic loamy soil (Figure 5.20). Unit II was described as a sequence of weakly separated buried A horizons formed in upward-fining sheetwash units. Curiously, carbonate accumulation is greatest near the top of Ab1 and A, which suggests that carbonate wicking rather than leaching is common at this locality. Micromorphological analyses may clarify this situation. At first, I thought that Units I and II were comparable at both localities; however, radiocarbon dating at Willow Wash 4 indicates that Units I and II at this locality may be chronologically comparable to Unit II or Units II and III at Willow Wash 1.

Seven samples of nonwood detrital charcoal from alluvial deposits at Willow Wash 4 (WW 4) were submitted for AMS radiocarbon dating. The dates indicate that the seven weakly separated soils at Willow Wash 4 accumulated sometime since the 14th or 15th century AD, which is in keeping with the bulk data and field observations of the soils. Six of the seven radiocarbon dates were used in Bayesian calibration based on superpositioning, which further constrained the ages to the 15th century or later. Bayesian calibrated ages would make Willow Wash 4 entirely contemporaneous with Day Wash 14 and, possibly, Rocky Draw 7 and Sharp Hollow 1 (see Discussion below).

Minimum and maximum ages from the 95% confidence interval of Bayesian calibrated age ranges for these six dates were used to generate a third order polynomial function (r^2=0.70; p=0.0024) to model the age-depth relationship for subsequent analyses (Figure 5.21). This age-depth model implies more or less consistent accumulation and pedogenesis throughout the 500-year sequence, which is consistent with the cumulized profile.

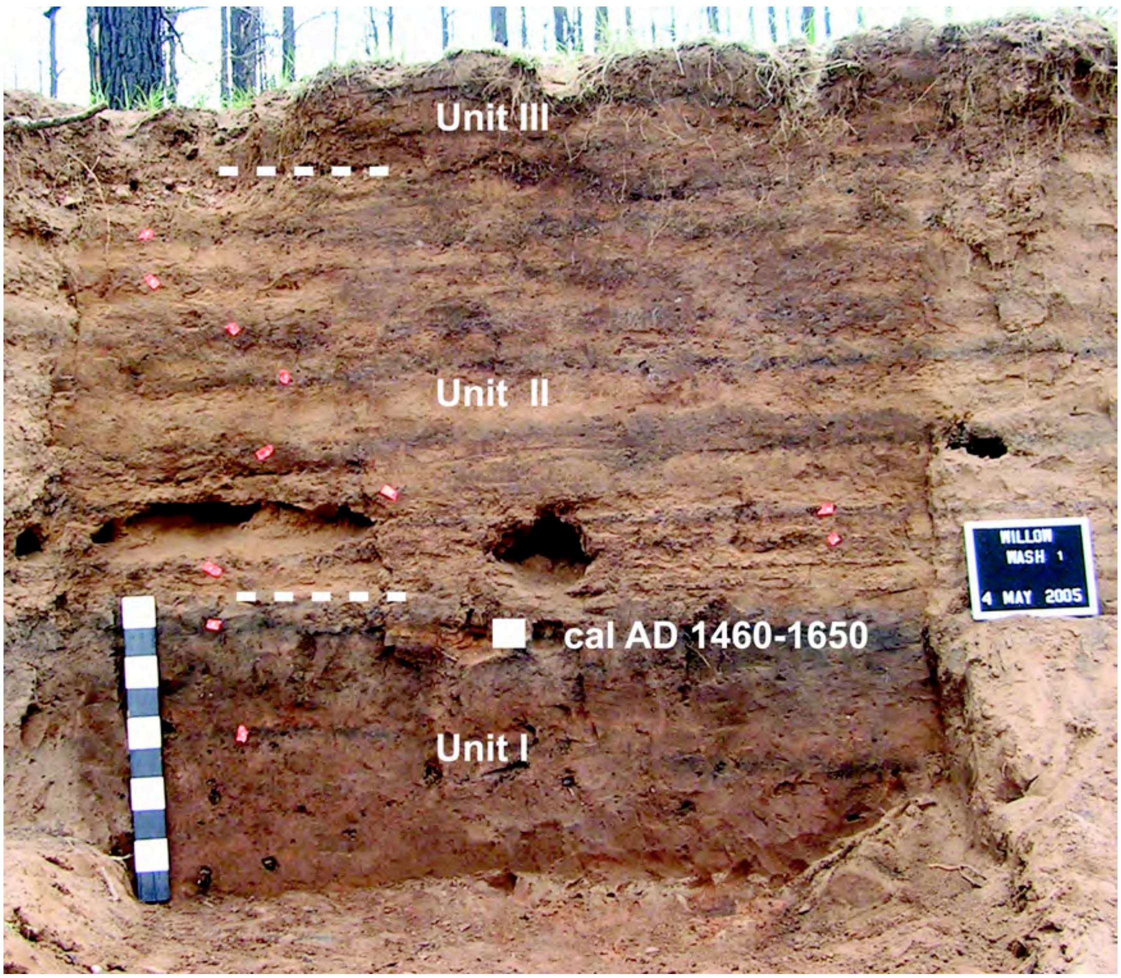


Figure 5.19 Lithological units at Willow Wash Locality 1. An AMS dated charred *Pinus* sp. needle collected from the orange lens at the contact between Units I and II dates to cal AD 1460-1650 at two standard deviations.

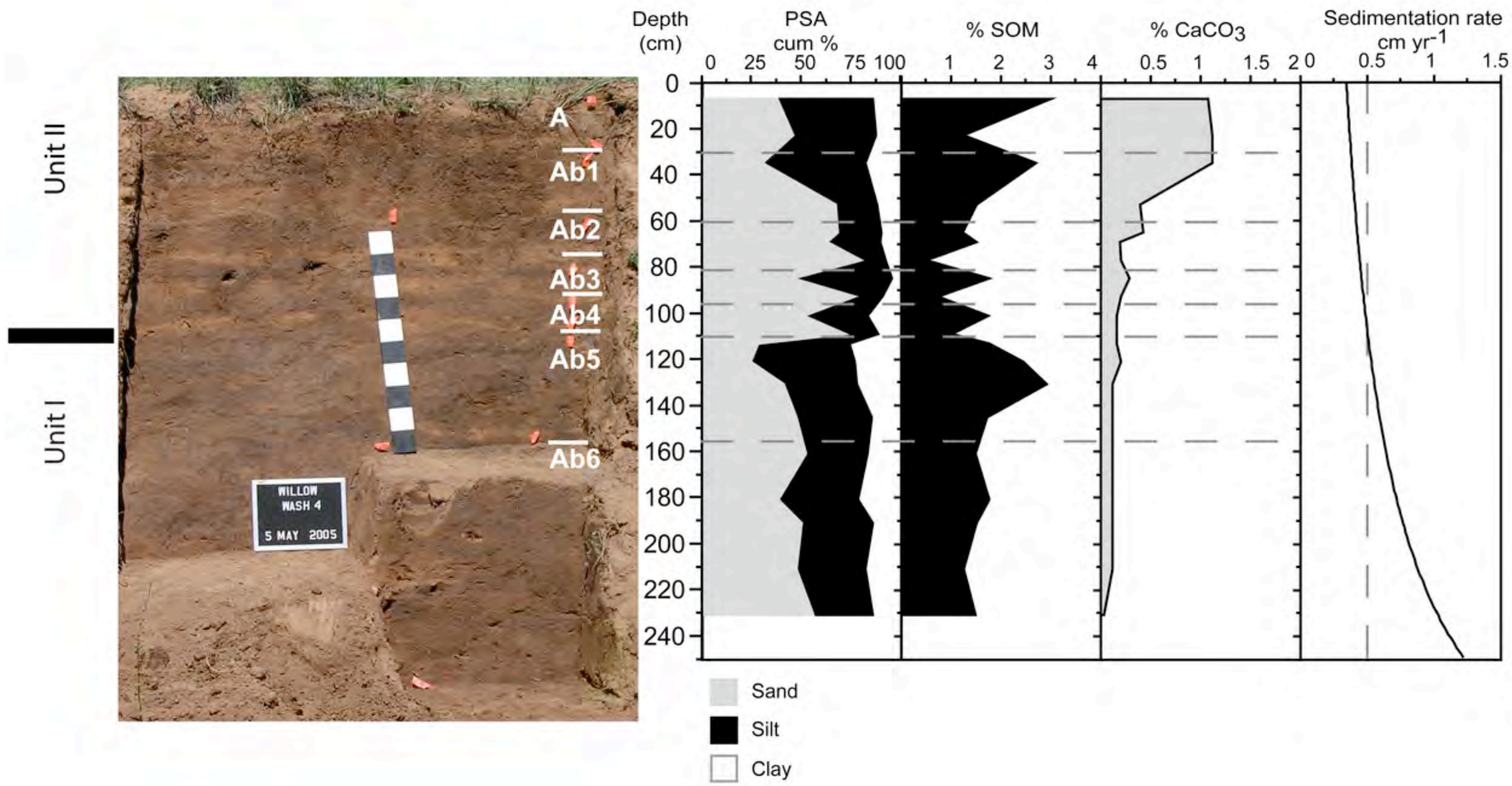


Figure 5.20 Bulk data for Willow Wash 4. See Figure 5.6 for description of the axes.

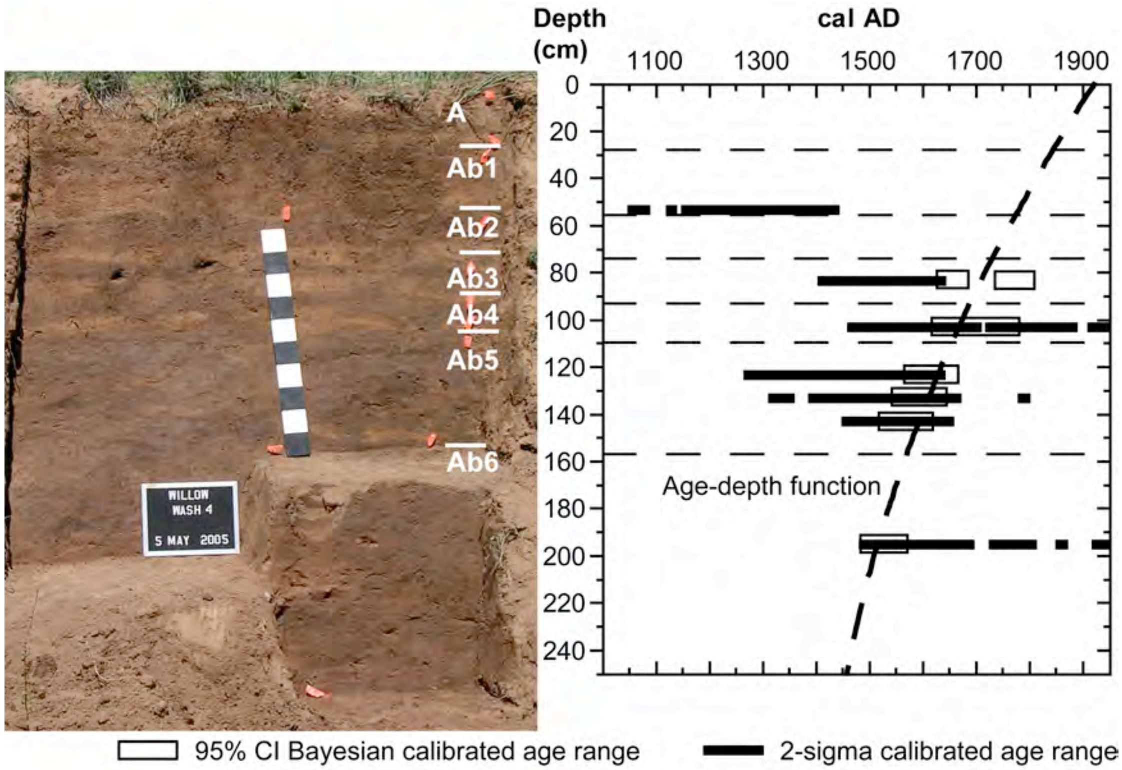


Figure 5.21 Radiocarbon ages, age-depth function, and soil stratigraphy from Willow Wash 4. Both traditional (95.4% CI) and Bayesian calibrations (95% CI) are indicated by solid and open bars, respectively.

The Forestdale Valley

The Forestdale Valley is the only sampled watershed below the Mogollon Rim. The surficial geology of the upper Forestdale Valley is largely Permian Coconino sandstone with Kaibab formation and Cretaceous sedimentary rocks present in the upper reaches of drainages (Figure 5.22). Emil Haury (1985) directed fieldwork in the Forestdale Valley in 1939-1941 (see also Chapter 3), which documented a long prehistoric occupation from the Early Pithouse Period Hilltop Phase (ca. AD 200-400) through the Late Pueblo IV Canyon Creek Phase (ca. AD 1325-1390; revised chronology from Mills and Herr 1999). From 2002-2004, Barbara Mills directed pedestrian survey of the Forestdale Valley, overlapping Haury's field school study area as part of the Silver Creek Archaeological Research Project (SCARP; Mills et al. 2008). Materials collected during this survey support the long, but episodic (Mills and Herr 1999) occupation of the Forestdale area from at least AD 200-1390 (Jauss 2004; Seidel 2004) (other SCARP references from field school). SCARP also conducted damage assessment and surface collection on the large ruin of Tundastusa, which yielded ceramic evidence of later Pueblo IV period occupation (e.g., Kinishba, Fourmile, Showlow, and Kechipauan polychrome ceramics;) (Arrighetti 2004; Shenendoah 2003), postdating the depopulation of Bailey Ruin at the end of the Early Pueblo IV period at AD 1325/1330 (Kaldahl et al. 2004; Mills 2007).

From July 10-13, 1939, Ernst Antevs, a geologist at the University of Arizona, visited Haury's Forestdale Valley field school and conducted limited geoarchaeological investigations of the Holocene alluvial sequence of the upper Forestdale Creek watershed (Antevs 1939; Haury 1985 [1940]:143-144). Antevs identified at least three distinct, inset alluvial terraces in the vicinity of the Bear Ruin (Haury 1985 [1940]:144) and Tla Kii Ruin (Haury 1985:17-19) Downstream from Tla Kii, past a fence demarcating cattle paddocks, Antevs (1939) noted the absence of inset terraces. Although Antevs recorded coarse stratigraphic observations from a few exposed cutbanks, his identification of distinct terraces was based primarily on topographic variation. On the basis of archaeology on the three geomorphic surfaces, Haury (1985 [1940]:144) generated the following chronological inferences for the three terraces: Terrace I is older than AD 600, and stabilized prior to occupation of the Bear Ruin ca. AD 600-800; Terrace II is after

AD 600 but before AD 1100, with no evidence of Bear Ruin occupation but stabilized before the construction of the great kiva at Tla Kii in ca. AD 1100; and Terrace III is after AD 1150 until historic downcutting in 1910 and fills the erosion scar in the great kiva at Tla Kii. The disconformity between Terrace II and III was thought to have been an erosional episode during the Great Drought from AD 1276-1299.

In July and August of 2005, a two-person crew surveyed cutbanks in the same area as Antevs' fieldwork in 1939. We also surveyed farther upstream and downstream for suitable exposures. Using Haury's published terrace maps (1985 [1940]:145), we chose to sample locations mapped as Terrace I and Terrace II upstream from the Bear Ruin. A third, unmapped locality (approximately 1km upstream from these localities) of relatively young, stratified soils was sampled with the expectation that these sediments were coeval with Terrace III. Mapped Terrace III-age deposits were too closely associated with archaeological remains to sample, as per the collaborative agreement with the White Mountain Apache Tribe's Heritage Program. Stratigraphy at a "Terrace I" locality (Forestdale Locality 8) was similar to that described by Antevs (1939). Radiocarbon dates on detrital charcoal (see Table 5.2) suggest that Terrace I formed during the Late-Middle Holocene, from approximately 3500-500 cal BC. Analyses of sediments from Locality 8 are still underway and are not reported here.

Sediments at Locality 10 (upstream, presumed to be Terrace III) and Locality 6 (near Bear Ruin, mapped as Terrace II) were manually exposed with narrow trenches. Both localities, however, contained similar stratigraphic sequences and yielded similar radiocarbon dates (see Table 5.2, and below), indicating their approximate contemporaneity. At Forestdale 10, Unit I was defined as a160cm thick set of upward fining units above coarse channel lag (Figure 5.23). Each coarse-scale upward fining unit was capped with a weakly expressed soil (Ab7-Ab11). Decomposed root tissues and carbonate hypocoats on channel voids are common, although carbonates are only present in trace amounts. Bedding structures are often preserved on soil thin sections from Ab7-Ab10, and the presence of both dusty and limpid clay coatings and bridges on sand grains indicate that inundation and sediment accumulation were common and relatively rapid. Unit II was defined as approximately 50cm of relatively massive, fine-grained deposits. Traces of carbonate filaments as well as gradual boundaries between horizons were observed in the field and used to infer three partially welded alluvial soils (Ab4, Ab5, Ab6) in this unit. Carbonate hypocoats and an increase in bulk carbonate concentration were noted for this unit, as was evidence for earthworm activity (Figure 5.23). The uppermost lithological unit, Unit III, was identified in the field as cumulized, sandy, alluvial soils. Carbonates and earthworm granules were absent from the uppermost three welded soils (A, Ab1, Ab2).

A similar stratigraphic sequence was observed at Forestdale 6 (Figure 5.24). In the field, Unit I was divided into two units (Unit Ia and Unit Ib). Unit Ia consisted of thin upward fining units capped with weakly expressed, organic-rich soils. The irregularity of the stratigraphy in this Unit was indicative of deformation while saturated, which could also be observed in thin section. Unit Ib was an 80cm thick deposit of intercalated beds of sands, muds, and laminated beds of sands and silts capped with a weakly expressed soil (Ab7). Zones of iron accumulation are common in thin sections from Unit I, which indicates that Unit I was seasonally saturated with groundwater. Superpositioning of carbonate hypocoats over iron concentrations in Ab7 suggests that this period of groundwater saturation preceded the period of carbonate accumulation. Unit II (Ab4, Ab5, Ab6) was represented by weakly separated, fine-grained soils with carbonate accumulation and earthworm activity. Unit III was defined as cumulized, sandy alluvial soils without carbonates or earthworm activity in thin section (A, Ab1, Ab2, Ab3).

The similarities in the stratigraphic sequence, soil morphology, and micromorphology between Forestdale Localities 10 and 6 suggests that they probably are coeval. In 2006, a two-person crew revisited the upper Forestdale Valley to identify whether these localities were equivalent to Antevs' Terrace II or Terrace I. Near the Tla Kii Ruin, we relocated a profile described by Antevs (1939), which included the filled paleochannel that had eroded portions of the Tla Kii great kiva (Haury 1985:51). The Terrace II aged sediments cut by the paleochannel differed from the "Terrace II" stratigraphy recorded at Forestdale 6, 10 and the Terrace I stratigraphy at Locality 8 (Figure 5.25). Similarly, the channel fill observed near Tla Kii had only five weekly expressed buried soils in a paleochannel more than 1m above the current channel (Figure 5.26). A similar sequence of five, very weakly expressed buried soils above relatively unaltered channel fill was sampled (Forestdale #20) southwest of the Bear Ruin for comparison with localities 6 and 10.

Two lithological units were defined at Forestdale 20 (Figure 5.27). Unit I was characterized by largely undisturbed crossbedded sands with intercalated muds and rounded mud clasts. Unit I was capped by a massive, fine-grained alluvial soil. Unit II was characterized as sets of weakly altered, sandy channel fill sediments capped with finer grained soils (A, Ab1, Ab2, Ab3, Ab4). Welded fine-grained soils marked as Ab4 are relatively rich in carbonates, similar to Ab4 from both Forestdale 6 and 10. Similarity in the depositional environment inferred from grain-size distributions, the weak expression of the buried soils, and the similar sequence of carbonates[1] may indicate contemporaneity of field-identified soils A, Ab1, Ab2, Ab3, and Ab4.

Lithological and soil evidence suggests at least partial contemporaneity among soil stratigraphic units mapped at Forestdale Valley 6 (FDV 6), 10 (FDV 10), and 20 (FDV 20). Consequently, the 26 radiocarbon dates from these three localities may best be used in concert to date soil strata across the localities. First, each watershed is considered independently and then the aggregate radiocarbon data with respect to soil chronology are discussed for valley-wide accumulation and soil formation history for the upper watershed of the Forestdale Valley.

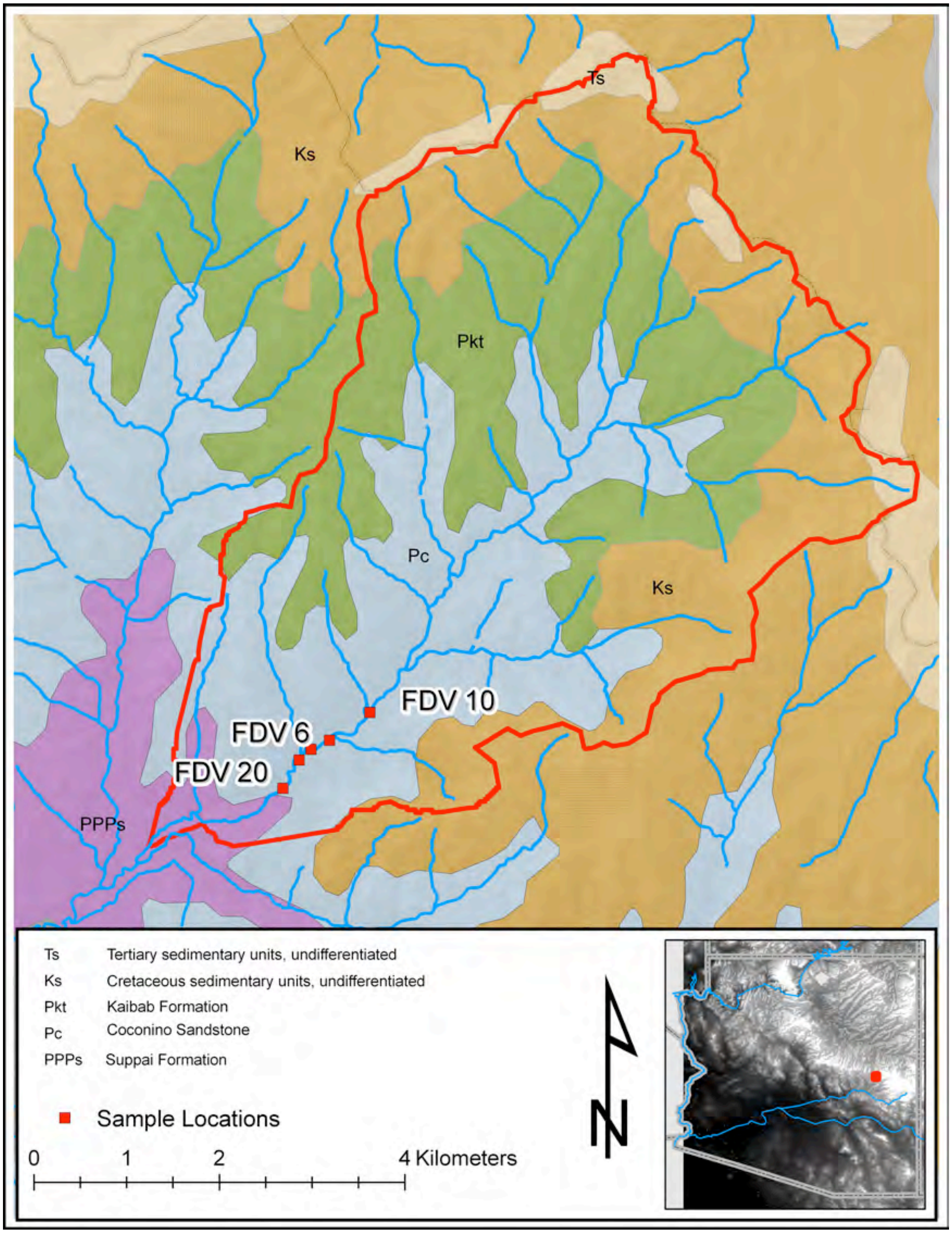


Figure 5.22 Surface geology of the area surrounding the upper Forestdale Valley study watershed.

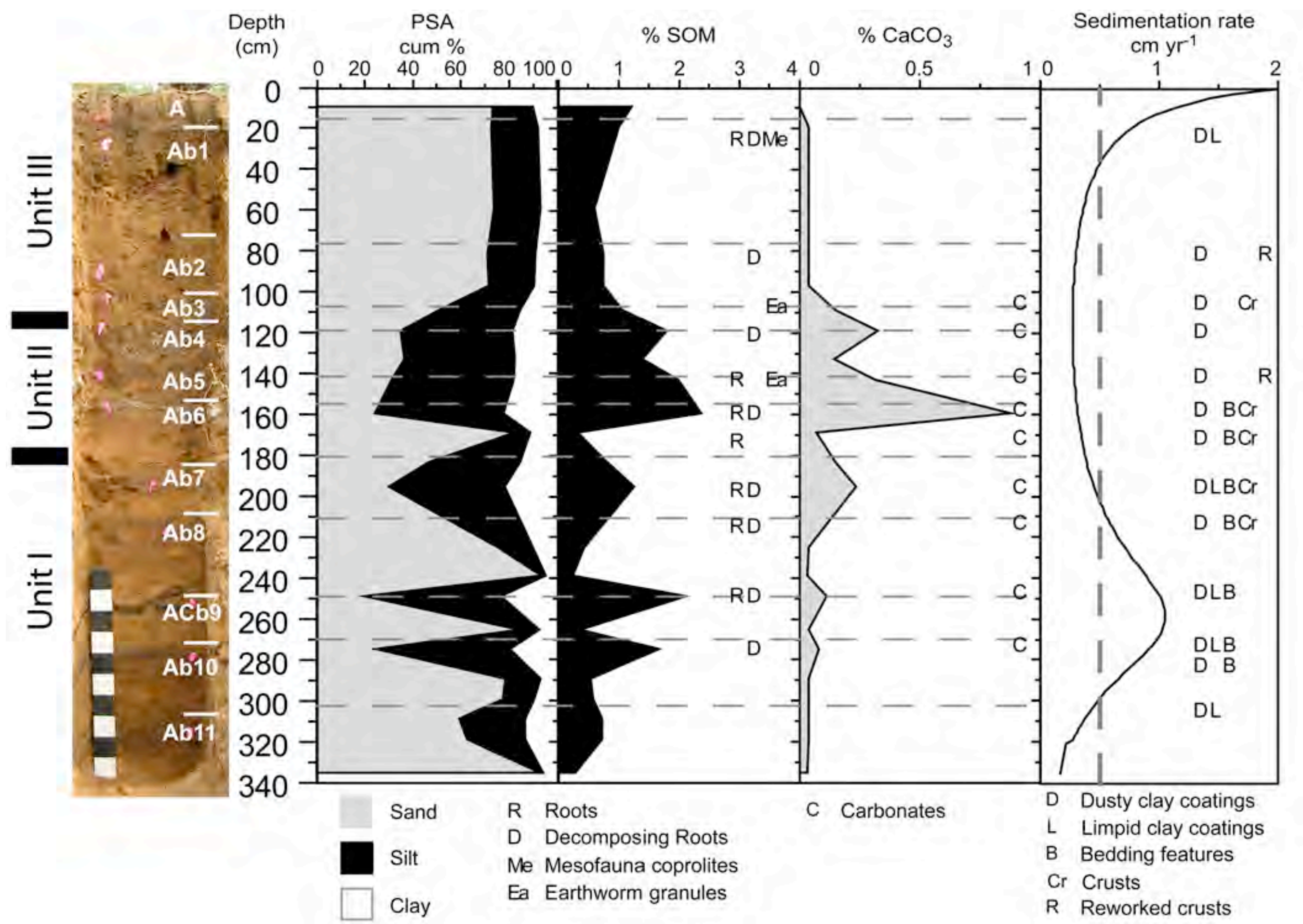


Figure 5.23 Bulk and micromorphological data for Forestdale Valley 10. See Figure 5.6 for description of the axes. Sedimentation rates calculated from polynomial age-depth derived from estimated soil dates (see Table 5.4).

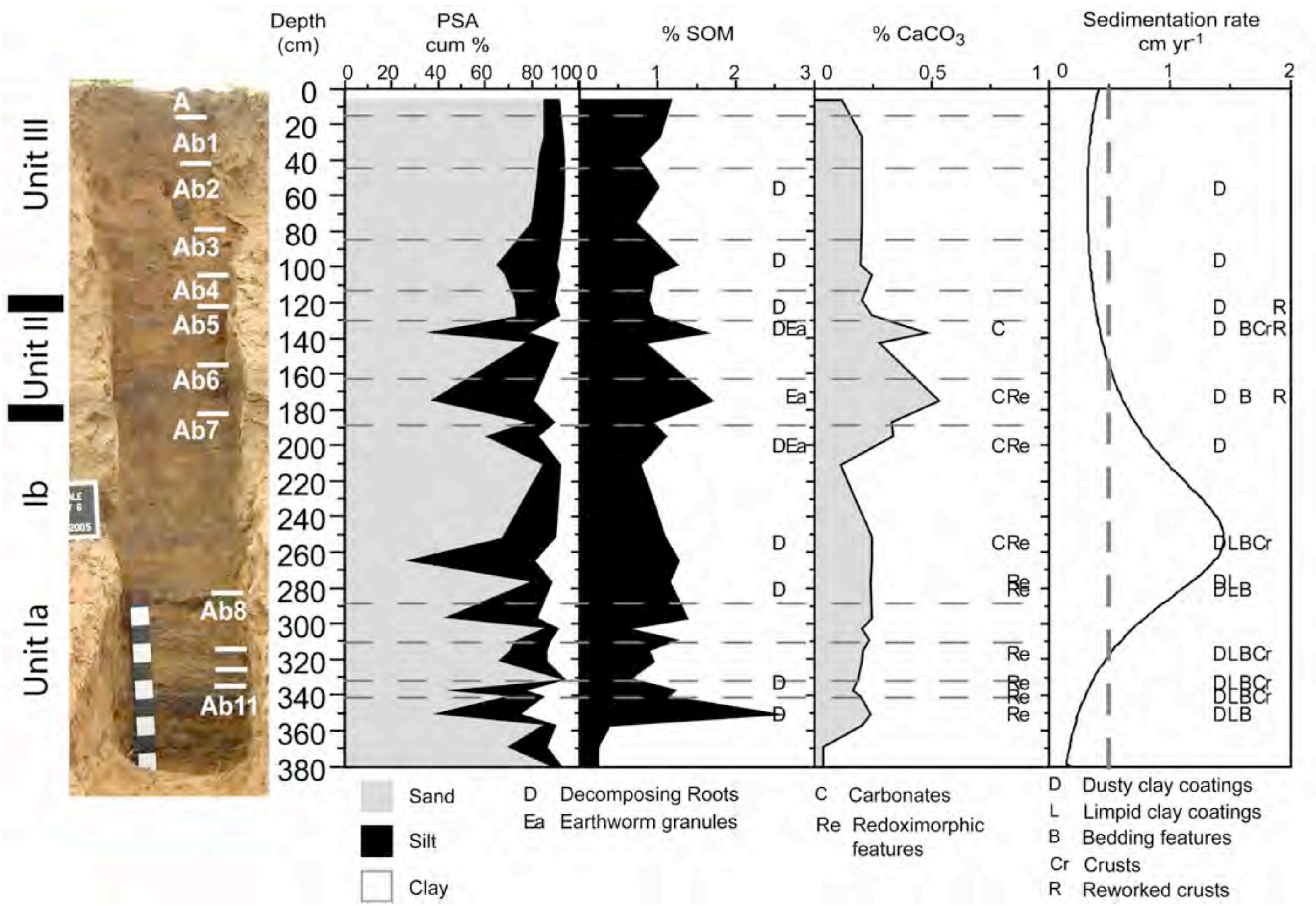


Figure 5.24 Bulk and micromorphological data for Forestdale Valley 6. See Figure 5.6 for description of the axes. Sedimentation rates calculated from polynomial age-depth derived from estimated soil dates (see Table 5.4).

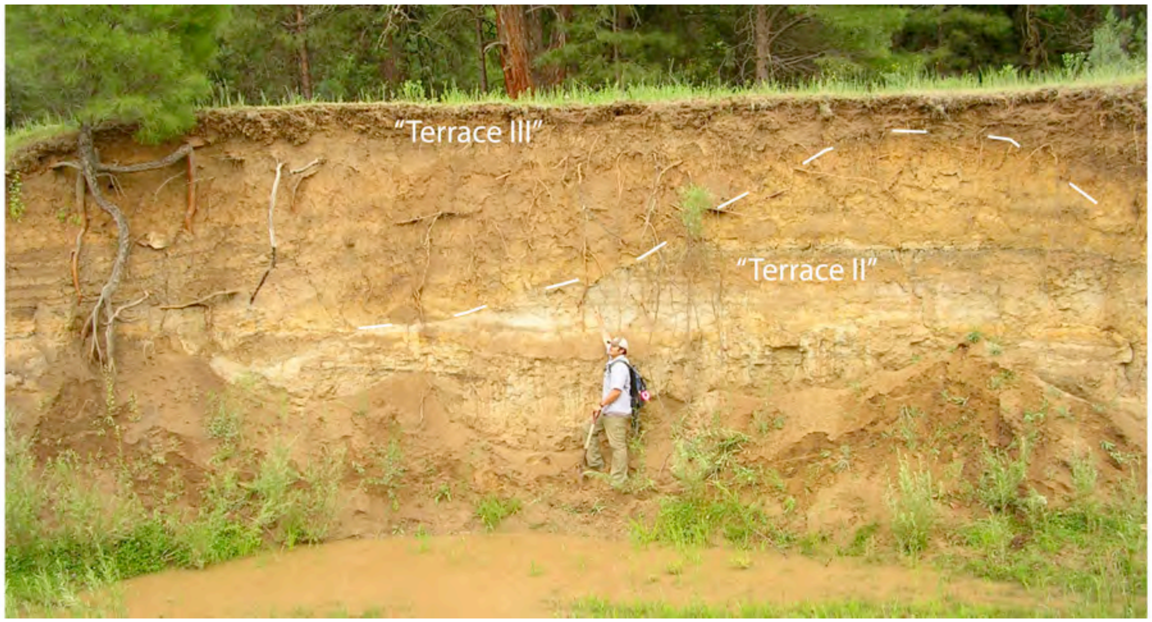


Figure 5.25 Nick Laluk pointing at the disconformity between Terrace II (lower unit) and Terrace III (upper unit and channel fill on the left) as recorded by Antevs near the Tlaa Kii ruin (Antevs 1939; Haury 1985).

Figure 5.26 Detail of stratified, weakly expressed soils in Terrace III aged channel fill above a slump block of Terrace II sediment in the paleochannel.

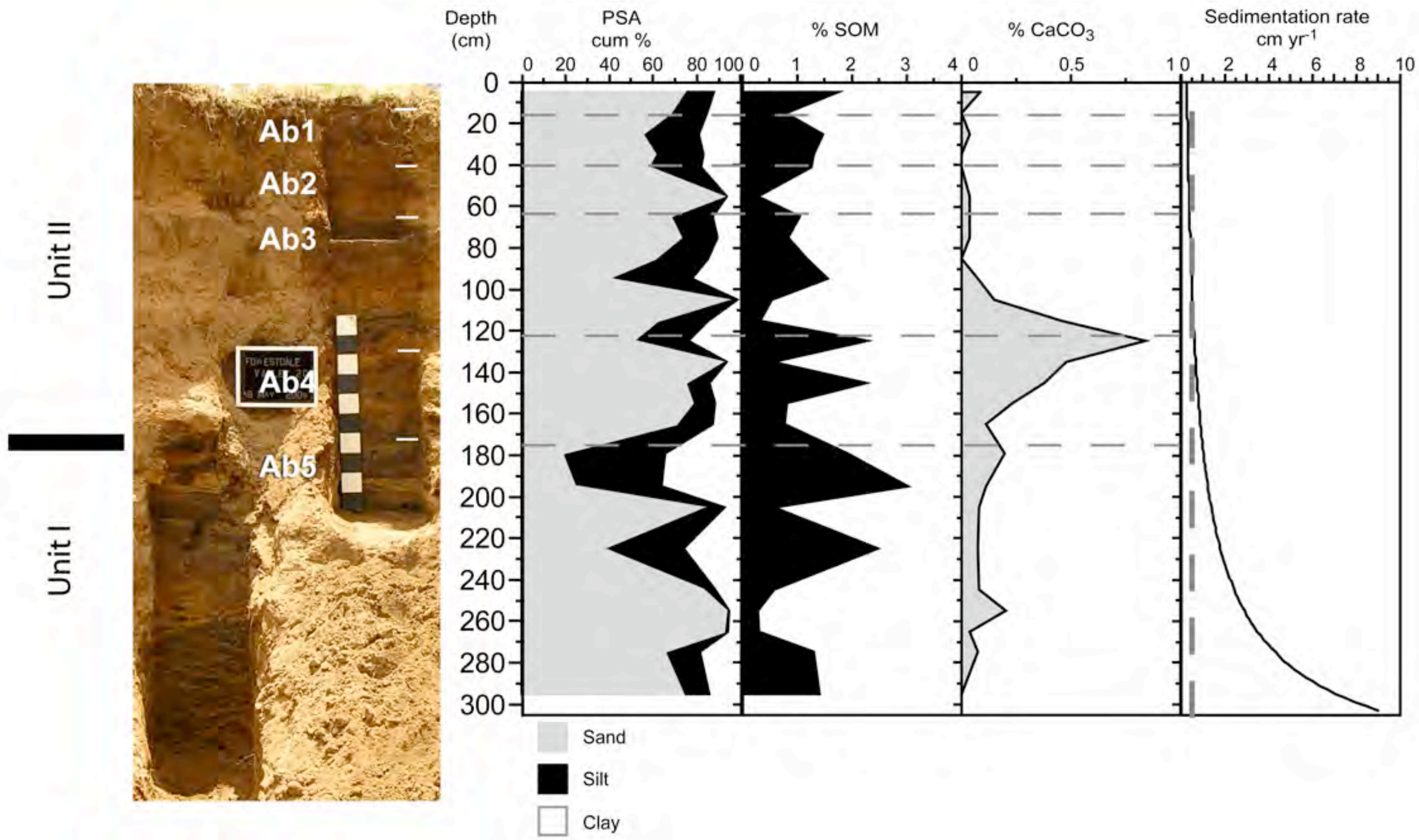


Figure 5.27 Bulk data for Forestdale Valley 20. See Figure 5.6 for description of the axes. Sedimentation rates calculated from polynomial age-depth derived from estimated soil dates (see Table 5.4).

Forestdale Valley 6

Nine charcoal samples from sediments collected at FDV 6 were submitted for AMS radiocarbon dating. Although three of the nine samples were *Pinus* sp. wood (Table 5.2), all ages are stratigraphically consistent with the others. The consistency in the dates indicates that old wood or inbuilt age effects probably do not affect the wood charcoal radiocarbon dates. On the basis of calibrated age ranges, it appears that FDV 6 began accumulating slowly as early as the 10th century AD, in channel bottom cienega muds and soils, a condition that may have lasted for centuries (Figure 5.28). Relatively undisturbed beds of alluvium from approximately 200-280cm below the surface indicate very rapid deposition without near surface bioturbation or pedogenesis. These deposits date to sometime in the 14th or 15th centuries. Lithology and micromorphology indicate that after this rapid accumulation, soil formation was generally cumulic in a slowly aggrading floodplain and ultimately an aggrading fan until approximately 1910, when historic entrenchment began (Haury 1985 [1940]).

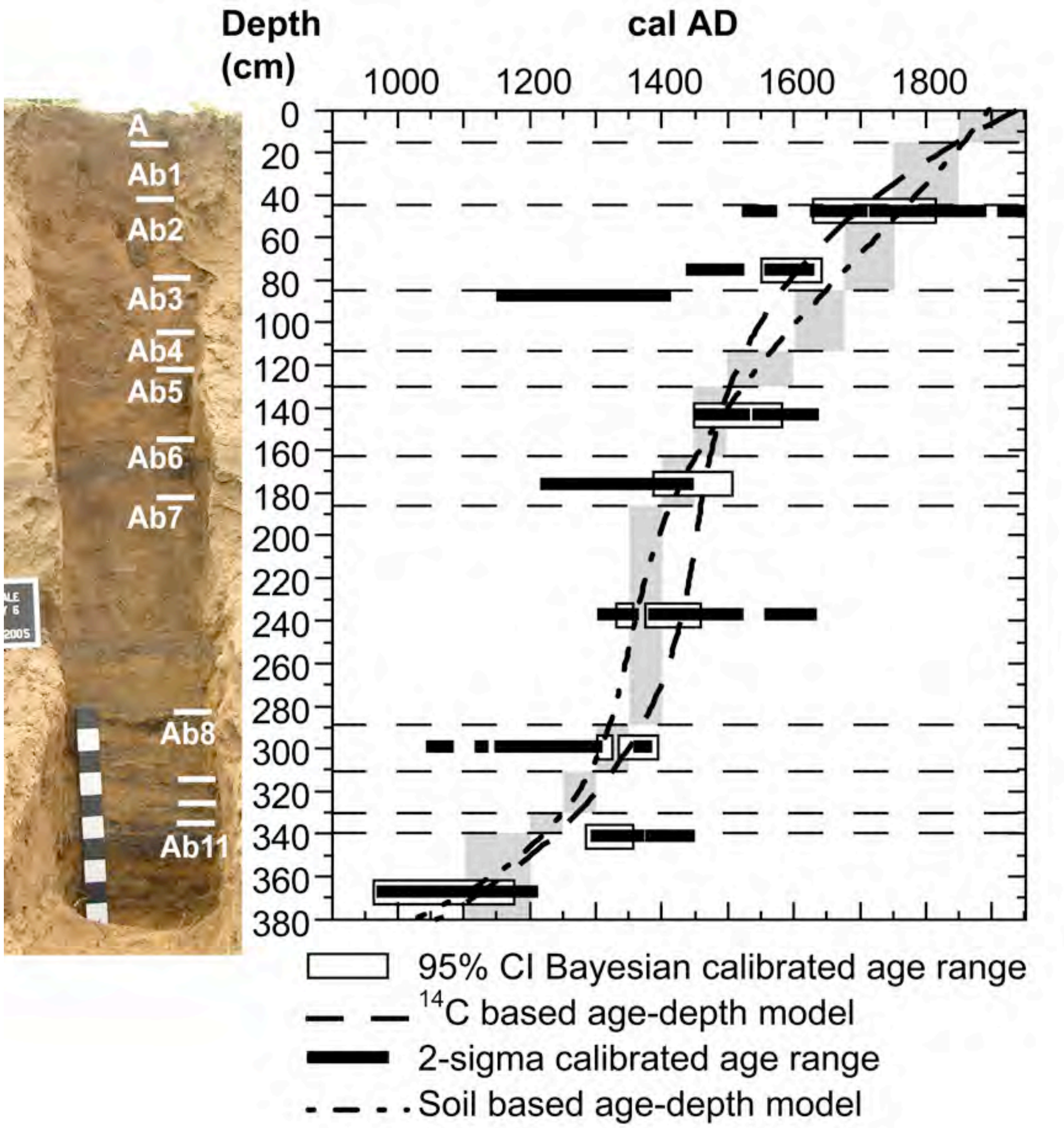


Figure 5.28 Radiocarbon ages, age-depth functions, and soil stratigraphy from Forestdale Valley 6. Both traditional (95.4% CI) and Bayesian calibrations (95% CI) are indicated by solid and open bars, respectively. Vertical gray zones indicate inferred soil ages (see Table 5.4) used for the soil age based age-depth model.

Forestdale Valley 10

Ten charcoal samples from deposits at FDV 10, including eight nonwood samples, were submitted for AMS radiocarbon dating (Table 5.2). Unlike the wood charcoal samples from FDV 6, both wood samples at FDV 10 appear to be to old relative to dates above and below them in the stratigraphic sequence. Sample AA68647, which dates to within the period of sediment accumulation but too old for its stratigraphic position, may simply be locally reworked. Sample AA68650, however, predates all other radiocarbon ages by at least 500 years (Figure 5.29) and is likely an "old wood" or "inbuilt age" date (Gavin 2001; Schiffer 1986). The remaining eight radiocarbon ages with their stratigraphic relationships were used for Bayesian calibration. Interestingly, samples from buried soils Ab4 and Ab6 appreciably predate their stratigraphic equivalents from FDV 6 (see Table 5.4 and compare Figures 5.28 and 5.29). It is possible that these soils are not contemporaneous, although this seems unlikely, given the similarities in lithology, stratigraphy, and postdepositional pedofeatures. Rather, these dates are probably *terminus post quem* in the strictest sense and only constrain the earliest possible dates for the deposits. The dates from below Ab6 at FDV 10 are consistent with those from FDV 6, and the soils and lithology support the interpretation that the two sequences are largely contemporary between approximately AD 1050/1100-1910.

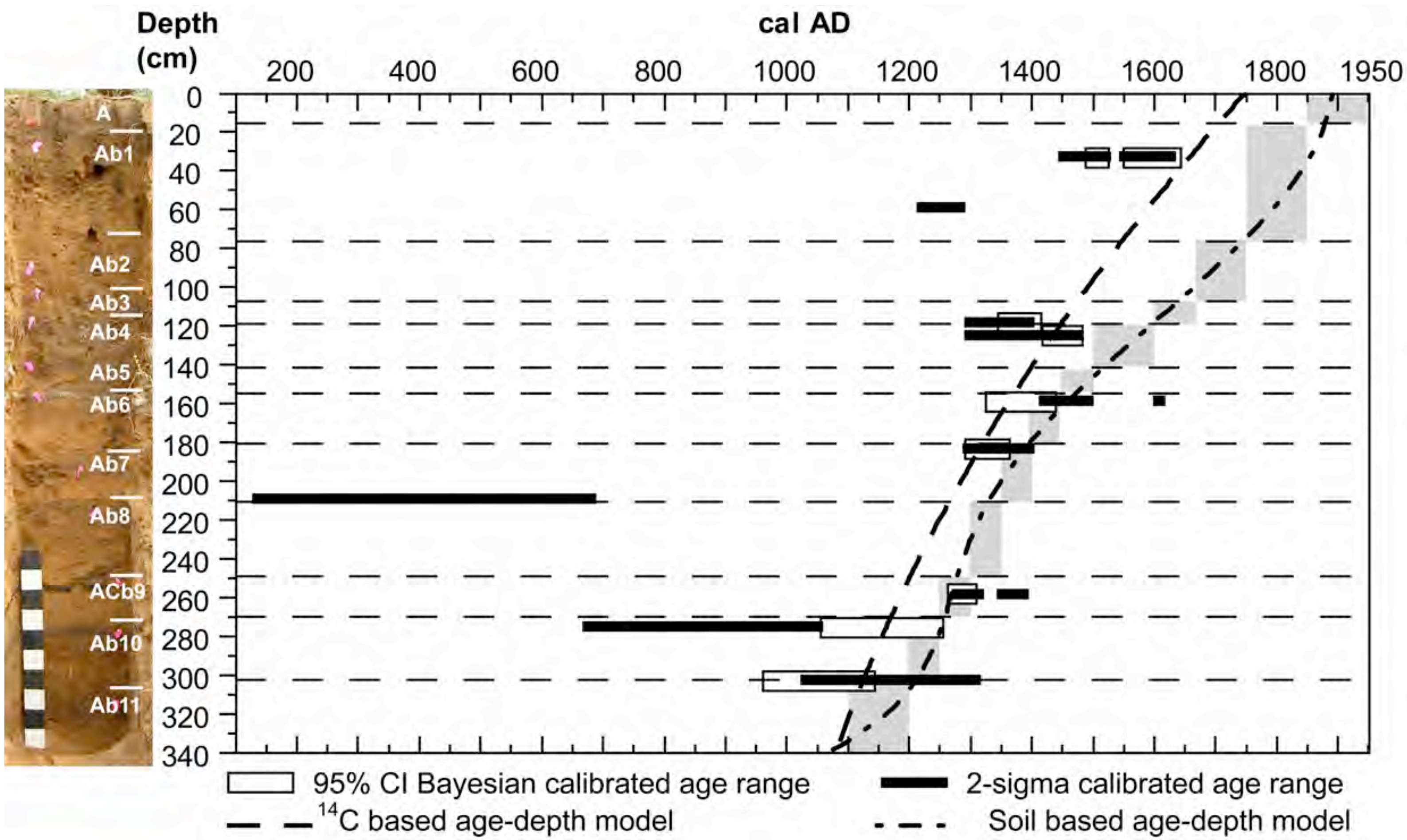


Figure 5.29 Radiocarbon ages, age-depth functions, and soil stratigraphy from Forestdale Valley 10. Both traditional (95.4% CI) and Bayesian calibrations (95% CI) are indicated by solid and open bars, respectively. Vertical gray zones indicate inferred soil ages (see Table 5.4) used for the soil age based age-depth model.

Forestdale Valley 20

Seven nonwood charcoal samples from deposits at Forestdale Valley 20 were submitted for AMS radiocarbon dating. Lithology and soils data as well as calibrated radiocarbon dates (Table 5.2) indicate that FDV 20 is younger than FDV 10 and FDV 6. The calibrated radiocarbon dates indicate that accumulation may have begun as early as the 15th century. Accumulation was initially rapid, producing the crosslaminated sands and muds in Unit I, followed by slower channel fan accumulation in upward fining units with some syndepositional soil formation until historic channel entrenchment in AD 1910. All seven dates were used with their stratigraphic relationships to generate a Bayesian calibration algorithm (Figure 5.30).

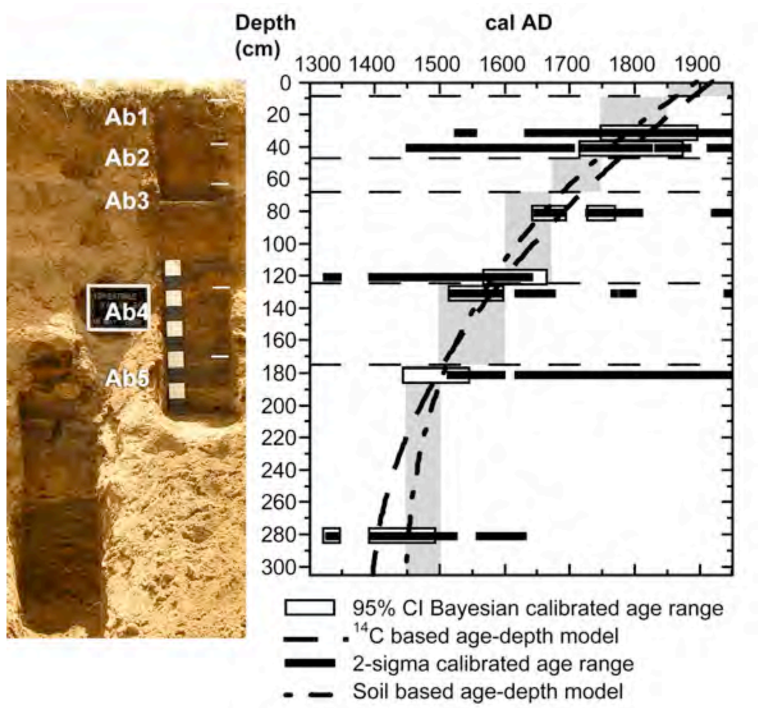


Figure 5.30 Radiocarbon ages, age-depth functions, and soil stratigraphy from Forestdale Valley 20. Both traditional (95.4% CI) and Bayesian calibrations (95% CI) are indicated by solid and open bars, respectively. Vertical gray zones indicate inferred soil ages (see Table 5.4) used for the soil age based age-depth model.

Dating the Forestdale Valley Soil Stratigraphic Sequence

Comparison Bayesian calibrated charcoal dates that were derived from all three localities independently indicates that the 95% confidence intervals for overlapping dates and dated adjacent soils represent more or less continuous sedimentation and syndepositional soil formation at FDV 6 and 10 since the 11th or 12th centuries AD. Lower sedimentation rates and soil formation characterize floodplain deposits in soils Ab4, Ab5, and Ab6 at both FDV 6 and 10, which appear to be contemporaneous with the accumulation of channel fill at the base and early soil formation at FDV 20. This suggests that the channel of Forestdale Creek may have entrenched briefly during the early 15th century prior to the accumulation of the channel fill at FDV 20 and contemporaneous with floodplain accumulation and soil formation (Ab6) at FDV 6 and 10. Using date ranges from each of the three sequences, I assigned dates to each soil stratigraphic unit (Table 5.4). The minimum and maximum ages for these soils were then assigned to the respective minimum and maximum depths of the soil unit for each locality. Using these ages, I fit 3rd (FDV 10; r^2=0.98; p<0.0001; and FDV 20; r^2=0.99; p=0.0008) and 5th order polynomial functions (FDV 6; r^2=0.99; p<0.0001) to these soil ages to generate age-depth profiles for each locality (Figures 5.28, 5.29, 5.30).

These dates, coupled with stratigraphic relationships, indicate that FDV 10 and FDV 6 accumulated slowly in channel bottom fans during the 12th and 13th centuries. Sedimentation rates elevated during the 14th century with rapid accumulation at FDV 6 due to upland erosion in the late 14th century. Such rapid accumulation may have changed internal stream gradients and resulted in channel readjustments, as described for discontinuous ephemeral streams in general by Bull (1997:245). These readjustments included a brief episode of entrenchment prior to resumed accumulation in the late 15th century. Sedimentation shifted at FDV 6 and 10 to sandy fan sediment in cumulized soil setting until entrenchment in 1910.

Table 5.4. Dates for buried soils for three localities, Forestdale Valley 6 (FDV 6), 10 (FDV 10), and 20 (FDV 20), in Forestdale Valley since AD 1000. All dates are 95% confidence intervals (CI) from Bayesian calibration in years cal AD. Dates in parentheses indicate traditional two sigma calibrated ages for samples interpreted as "old wood" or "reworked" and, therefore not included in the Bayesian calibration function. All dates are interpreted as "maximum ages." The buried soils postdate the radiocarbon measurement by an unknown amount of time.

Soil	FDV 6	FDV 10	FDV 20	Estimated calendar dates
A				**1850-1910/ Present**
Ab1		1551-1646	1748-1898	**1750-1850**
		1488-1525		
ACb1		(1216-1290)	1716-1876	
Ab2	1632-1816			**1675-1750**
ACb2	1555-1640			
Ab3	(1154-1413)		1729-1772	**1600-1675**
			1644-1695	
ACb3		1348-1415	1568-1660	
Ab4		1418-1486	1515-1600	**1500-1600**
Ab5	1453-1582		1444-1548	**1450-1500**
Cb5			1393-1495	
			1321-1348	
Ab6	1391-1504	1326-1441		**1400-1450**
Ab7		1292-1366		**1350-1400**
Cb7	1378-1458			
	1332-1356			
Ab8	1339-1395	(128-688)		**1300-1350**
	1303-1324			
Ab9		1266-1311		**1250-1300**
Ab10		1056-1257		**1200-1250**
Ab11	1286-1356	964-1144		**1100-1200**
Cb11	966-1176			

Discussion

On the basis of 45 Bayesian calibrated ages from the seven study localities from five watersheds, a picture of erosion and sedimentation along the Mogollon Rim since AD 1000 emerges. Below the Mogollon Rim, Forestdale Creek was entrenched prior to AD 1100. Accumulation began shortly thereafter in low energy, channel bottom fans until upland erosion increased in the late 14th century resulting in rapid accumulation at FDV 6. In the early 15th century, Forestdale Creek briefly entrenched, possibly due to internal gradient changes. It appears that this period of entrenchment eroded the great kiva at Tla Kii. Forestdale Creek resumed accumulation and soil formation after cal AD 1500. In AD 1910, Forestdale Creek entrenched again to its current level.

Above the Rim, Willow Wash, Day Wash, and Sharp Hollow were all entrenched prior to cal AD 1350. Since no other valley bottom fans were found in the east fork of Rocky Draw, the landform sampled at RD 7 appears to have been singular in the Late Holocene history of the watershed. I cannot say with confidence, therefore, that Rocky Draw was also entrenched prior to cal AD 1350. Regardless, all four watersheds began aggrading in the 14th or 15th century. In Rocky Draw, Day Wash, and Sharp Hollow, sedimentation was initially quite rapid or included exhumed material and colluvium. Sedimentation slowed at Rocky Draw and Day Wash after cal AD 1600-1700. All watersheds probably entrenched again around AD 1900.

It is important to note that even if the assumptions necessary for the use of Bayesian calibration are not fully met due to variable residence time of charcoal on the landscape or postdepositional mixing, the same chronological story could be constructed.

Calibrated radiocarbon dates treated in aggregate for each locality indicate that the basic chronological story would remain the same, particularly if the charcoal dates are treated as true *terminus post quem* dates (Figure 5.31). The meaning of the generally synchronous accumulation at FDV 20, WW 4, DaW 14, SH 1, and RD 7 (ca. 1400/1500-1900) can't be fully understood in terms of climate and land use without the data presented in Chapter 6. However, the synchronous nature of accumulation suggests a similar cause. In Day Wash, the initial accumulation is associated with geological evidence for a large landscape altering fire (see also Chapter 6). Paleoecological data may provide evidence on the possible role of unusually large fires in the other watersheds. Land use is an unlikely alternative explanation, since the occupation histories are different for Forestdale Valley (AD 1000-1390), Day Wash and Willow Wash (AD 1000-1330), and Rocky Draw and Sharp Hollow (no perennial occupation). An alternate climatic driver for entrenchment, perhaps due to extended droughts in the late 14^{th} and early 15^{th} century, remains possible but does not explain the onset of accumulation during the dry 15^{th} century. Entrenchment followed by accumulation from the 15^{th} through 19^{th} centuries has been observed regionally and attributed to a variety of conflicting climatic factors (Hereford 2002). In the next chapter, I detail the paleoecological records from each sample locality to construct the cut and fill story from each watershed and to reconstruct changes in watershed-scale fire regimes over their accumulation history.

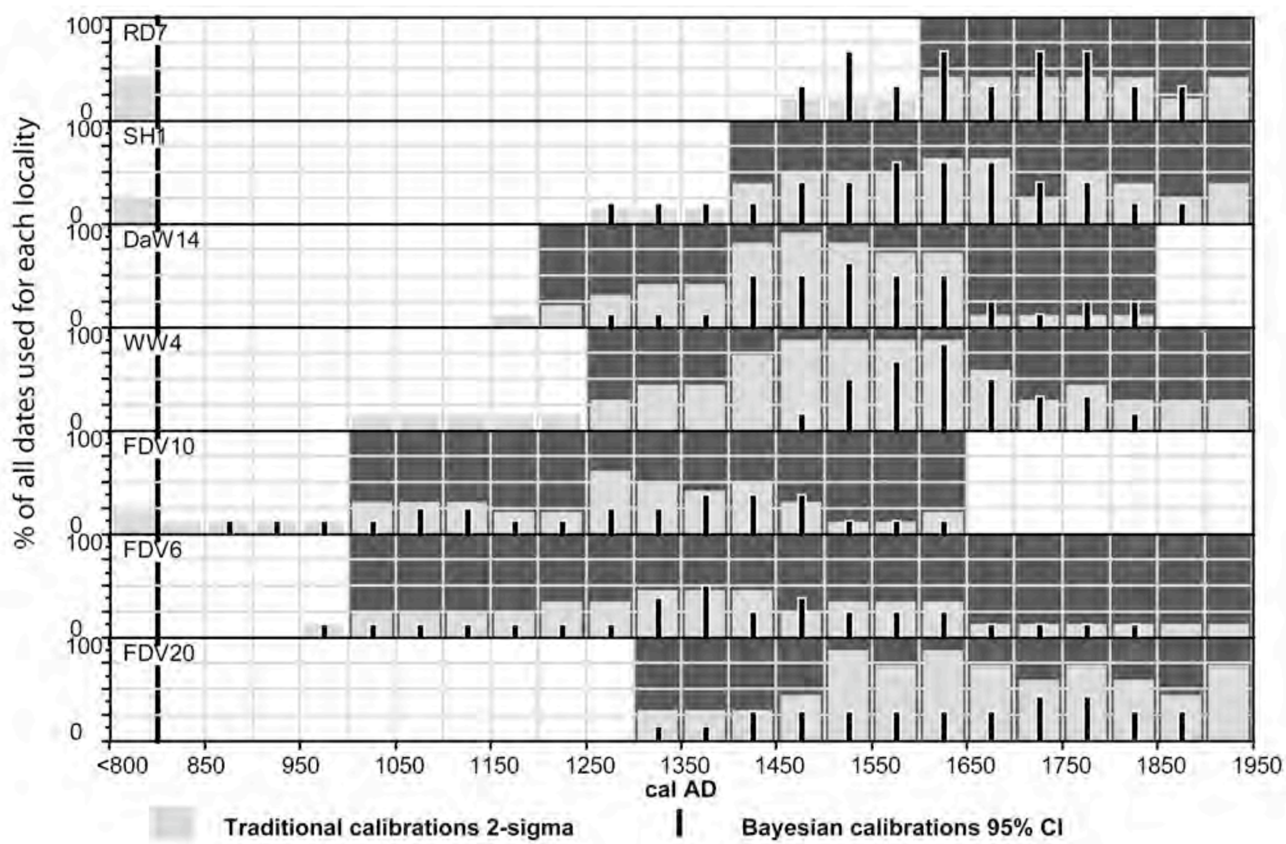


Figure 5.31. Histogram (50 year bin width) of 2σ calibrated radiocarbon ages in aggregate for each sample locality. The y axis for each locality is the percentage of all radiocarbon dates that fall within each 50 year bin. Dark gray background zones indicate the period beginning with at least two dated samples to the end of the date range. The bin on the far left is for all dates prior to cal AD 800.

Notes

[1] In all three Forestdale localities (6, 10, 20), carbonate content first peaks between 120-130cm below the surface, which may also indicate a leaching front with typical depth of 120-130cm for the wetting front removing carbonates from the upper sediments. However, the co-occurrence of earthworm activity and carbonates in these soils, the etching of all carbonates and their reprecipitation as acicular crystals observed in thin-section and in the field suggest that the carbonates are associated with some older soil environment.

CHAPTER 6. PALEOECOLOGY

As described in Chapter 4, I use macroscopic sedimentary charcoal (>250μm), stable carbon isotopes of soil organic matter, soil phosphorus content, and stratigraphic palynology to infer changes in fire regimes and local ecology maintained by those fire regimes. Macroscopic charcoal is complexly related to charcoal production (amount and type of biomass burning), dispersal, preservation, and technique of quantification. By focusing on coarse, sieved charcoal (>250μm) from small watersheds (<40km^2), variation in charcoal dispersal and quantification are held relatively constant. At the time scales represented by the study localities (ca. AD 1100-1910), variable charcoal preservation is probably not an issue (Cohen-Ofri et al. 2006). Preliminary differential thermal and thermogravimetric analyses (DTA/TGA) of charcoal collected from Forestdale Valley localities 6 and 10 indicate that some charcoal from these sequences may be better preserved than others (Cohen-Ofri and Weiner 2007). Alternatively, the combustion temperature of charcoal produced during these periods (ca. AD 1200-1400) may have been lower than earlier or later periods (Cohen-Ofri and Weiner 2007). The latter interpretation is favored here because charcoal concentrations are quite high from these strata, which suggests that differential preservation has not affected the charcoal data (see below). Samples for sedimentary charcoal analyses were collected continuously from 2cm depths in undisturbed soil monoliths (see Table 6.1 for sample sizes).

Table 6.1 The number of samples analyzed for charcoal, phosphorus, stable carbon isotope analyses, and palynology for each locality.

Locality	Sedimentary Charcoal	Soil P	$\delta^{13}C$	Pollen	^{14}C Dates
Rocky Draw 7	35	5	5	8	5
Sharp Hollow 1	75	9	9	10	8
Day Wash 14	124	16	16	15	10
Willow Wash 4	18*	0*	0*	13	7
Forestdale Valley 10	161	15	15	12	10
Forestdale Valley 6	179	25	25	15	9
Forestdale Valley 20	154	0*	18	11	7
Total N=	746	70	88	84	56

* Analyses are not yet complete.

Samples for stable carbon isotopes and soil phosphorus were taken from bulk samples that yielded soil organic matter (SOM) measurements greater than 0.6%. These data are not stratigraphically continuous but represent each of the field-identified soil horizons as well as organic-rich sedimentary units. Pollen samples were collected from undisturbed monoliths using a clean trowel in the Laboratory of Traditional Technology at the University of Arizona. Stork's bill (*Erodium cicutarium*, an introduced European forb) was observed flowering in the study area during fieldwork. It is possible that stork's bill pollen was introduced as a contaminant during collection of monoliths from prehistoric sediments (see below). Pollen samples were taken opportunistically from finer-grained facies, when possible.

To facilitate the interpretation of paleoecological proxies in terms of vegetation communities and fire severity, a number of sediment samples were collected from channel fan deposits that postdate the 2002 Rodeo-Chediski Fire and the 1974 Day Burn, both of which burned at moderate to high severity upstream from the sample collection localities. Analyses for the total suite of paleoecological proxies (charcoal, phosphorus, and carbon isotopes) have not yet been completed for these samples. However, the bulk soil analyses, micromorphology, and palynology of these samples are informative concerning the sedimentary and palynological indicators of high severity, stand replacing fires in the study area. Benchmark work by Martin (1963), Hevly (1988), and Rankin (1980) provide analogues for pollen assemblages from canopy ponderosa pine forests and meadow settings within these forests. All palynological analyses for the present study were done by Owen K. Davis in the University of Arizona Paleoecology Lab (Davis 2007), although the interpretations from the original report have been modified to incorporate chronometric and paleoecological data that had not been available to Davis at the time.

Palynology of ponderosa pine communities and high severity fires

Martin (1963), Hevly (1988), and Rankin (1980) all reported on the relative abundances of *Pinus* spp. (pine), *Quercus* spp. (oak), Cupressaceae (largely juniper), Chenopodiaceae-Amarathaceae (cheno-ams, including goosefoot and pigweed), Compositae (sunflower family), and Graminae (grasses) for ponderosa pine forests in east-central Arizona (Table 6.2). Martin used data from the vicinity of the Point of Pines archaeological field school on the San Carlos Apache reservation (Martin 1963:16-18). Samples from modern cattle stock tanks, cienega soils, and a spring between 1820-1880m in elevation from "Pine Parkland" yielded relatively low pine pollen, relatively high *Quercus*, cheno-am, compositae, and grass pollen, and moderate juniper pollen abundances. Arboreal taxa, especially pine pollen, may be underrepresented in this data set based on the sampling of disturbed grazing areas (Hevly 1988:113). Surface pollen from "Yellow Pine Parkland (Canopy)" (Hevly 1988:101) on the southern Colorado Plateau had much higher abundances of pine pollen and moderate levels of oak, juniper, undifferentiated compositae, grasses, and cheno-ams. For "Yellow Pine Parkland (Meadow)," pine abundances were lower, whereas compositae, cheno-ams, and grasses were similar to Martin's elevated values for grazing land near Point of Pines (Hevly 1988:101).

Rankin's study area, Corduroy Creek, lies immediately south and east of the Forestdale Valley study localities (Rankin 1980) and may be the most relevant to the present study because of the virtually identical nature of her ecological units and my study localities. In a variety of ponderosa pine forest settings with oak, juniper, or Douglas-fir (*Pseudotsuga menziesii*) as occasional secondary canopy species, Rankin (1980:348-349) reports pine, oak, juniper, compositae, and cheno-am pollen abundances similar to those reported by Hevly (1988) for canopy ponderosa pine settings. Low-spine compositae (probably *Ambrosia*) was the dominant or sole type of compositae pollen reported for samples collected from forest settings. For meadow settings, pine, juniper, oak, cheno-ams, and grass pollen abundances were comparable to those reported by Martin (1963) and Hevly (1988) for meadow settings in ponderosa pine forests. In contrast to the other studies, sunflower-type pollen (compositae pollen) was much more abundant in the Corduroy Creek meadow samples. Similar to the other studies, but in contrast to all forest-type samples, low-spine compositae (*Ambrosia*) only makes up a portion (18-50%) of the overall assemblage of sunflower-type pollen.

In contrast to these studies, the pollen from postfire sediments collected in 2005 from geomorphic surfaces produced after the Day Burn (1974) and the Rodeo-Chediski Fires (2002) yielded pollen assemblages almost entirely dominated by *Pinus* species (see Table 6.2). Overall pollen concentrations are exceptionally high for these postfire samples (Davis 2007). The deposition of large amounts of unburned organic matter in association with charcoal in these postfire deposits may account for the elevated pollen concentrations. Charcoal-rich deposits at Day Wash Locality 16 (a very young, small fan and point-bar sequence that probably accumulated after the 1974 Day Burn; Figure 6.1) are also exceptionally rich in oxidizable soil organic matter (up to 10.6%). Although SOM has not been measured from Rocky Draw 158 (a near surface sample collected from a small channel bottom fan in the middle fork of Rocky Draw, which burned heavily in 2002; Figure 6.2), unburned plant tissues are clearly included in bedded charcoal deposits on soil thin section (Figure 6.3). Importantly, the lowest sedimentary unit at Day Wash 16 was not sampled for pollen. The lowest unit may have been the first package of sediments to accumulate after the Day Burn and may have a different pollen signature. For example, local pollen production after a high severity fire would be expected to be quite low due to fire-related mortality. Disturbance taxa might be expected to have disproportionate significance in such a low-concentration, immediate postfire pollen assemblage.

Table 6.2 Abundance of selected pollen taxa from modern ponderosa pine forest and meadow environments. Day Wash 16 and Rocky Draw 158 are samples collected from sediments deposited after modern high severity fire events.

Study	No. of Samples	*Pinus* range (mean) %	*Quercus* range (mean) %	Juniperus/ Cupressaceae range (mean) %	Chen-ams range (mean) %	All composites range (mean) %	Low-spine compositae or *Ambrosia* range (mean) %	*Graminae* range (mean) %
Martin (1963)								
Meadow (?)	6	12-53	4-19	0-6	5-30	14-52	?	6-20
		(29)	(7.7)	(1.9)	(13)	(28.8)		(13.3)
Hevly (1988)								
Canopy	2	65-80	7-8	5-10	10	8-10	4-5	4-8
Meadow	3	40-55	2-6	5-12	10-20	15-20	1-5	15
Rankin (1980)								
Canopy	36	38-89	0-12	0-50	1-9	4-16	3-13	0-4
		(74)	(3.4)	(8.6)	(3.8)	(7.9)	(6.4)	(0.8)
Meadow	5	21-58	0-7	2-9	4-13	19-61	6-31	3-15
		(41.6)	(4.5)	(6.7)	(8.7)	(46.5)	(18.5)	(8.6)
Day Wash 16								
Post-Day Burn	4	82-90	0.3-1.3	0.3-1.3	0.3-2.3	4-9	3.3-5.3	0.7-1.3
(1974)		(85.9)	(0.7)	(0.6)	(1.4)	(6.6)	(4.7)	(1.1)
Rocky Draw 158								
Post-Rodeo-	1	93.4	0.3	0	2	2.4	1	1.3
Chediski (2002)								

Figure 6.1 Cleaned profile of Day Wash 16. Wet-deformed crossbedded charcoal and organic-rich sands lie unconformably above charcoal and organic-rich horizontal channel fan beds that postdate the 1974 Day Burn.

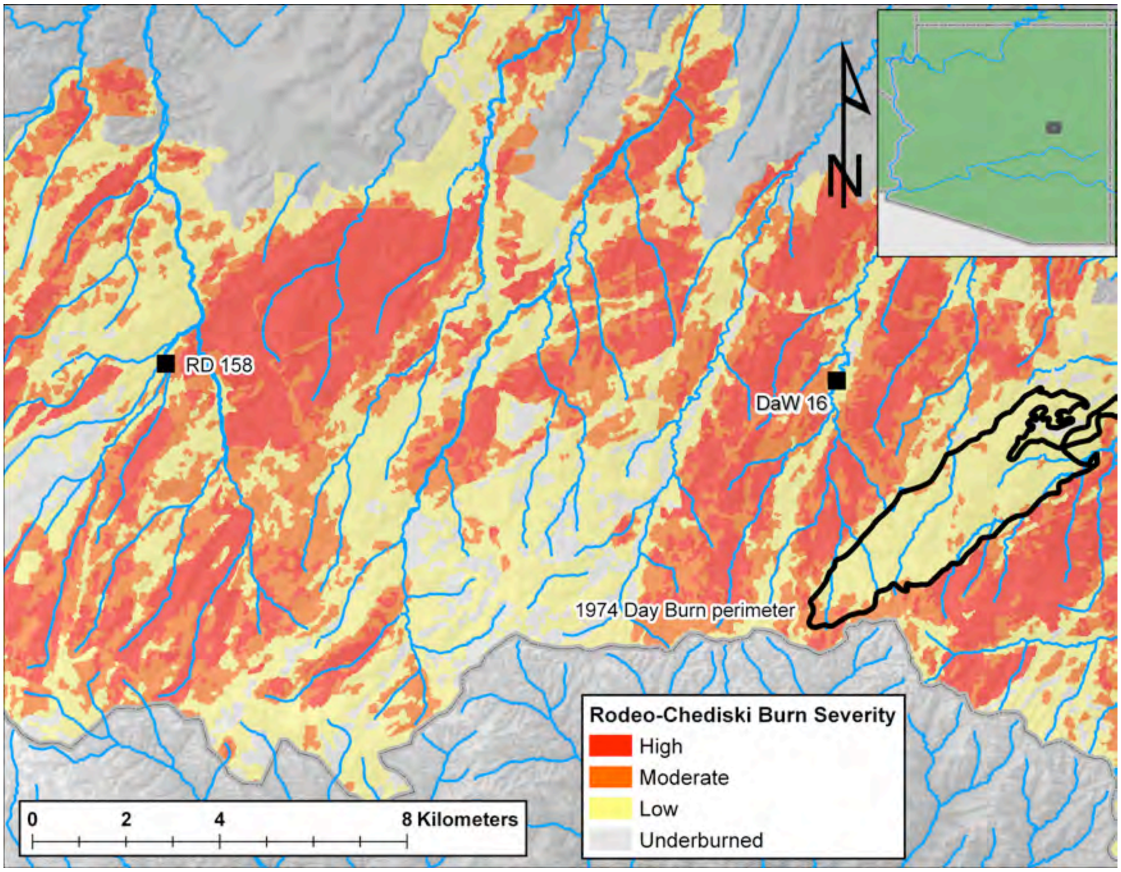


Figure 6.2 Day Wash 16 and Rocky Draw 158 modern analog samples in relation to the 1974 Day Burn perimeter and burn severity from the 2002 Rodeo-Chediski Fire.

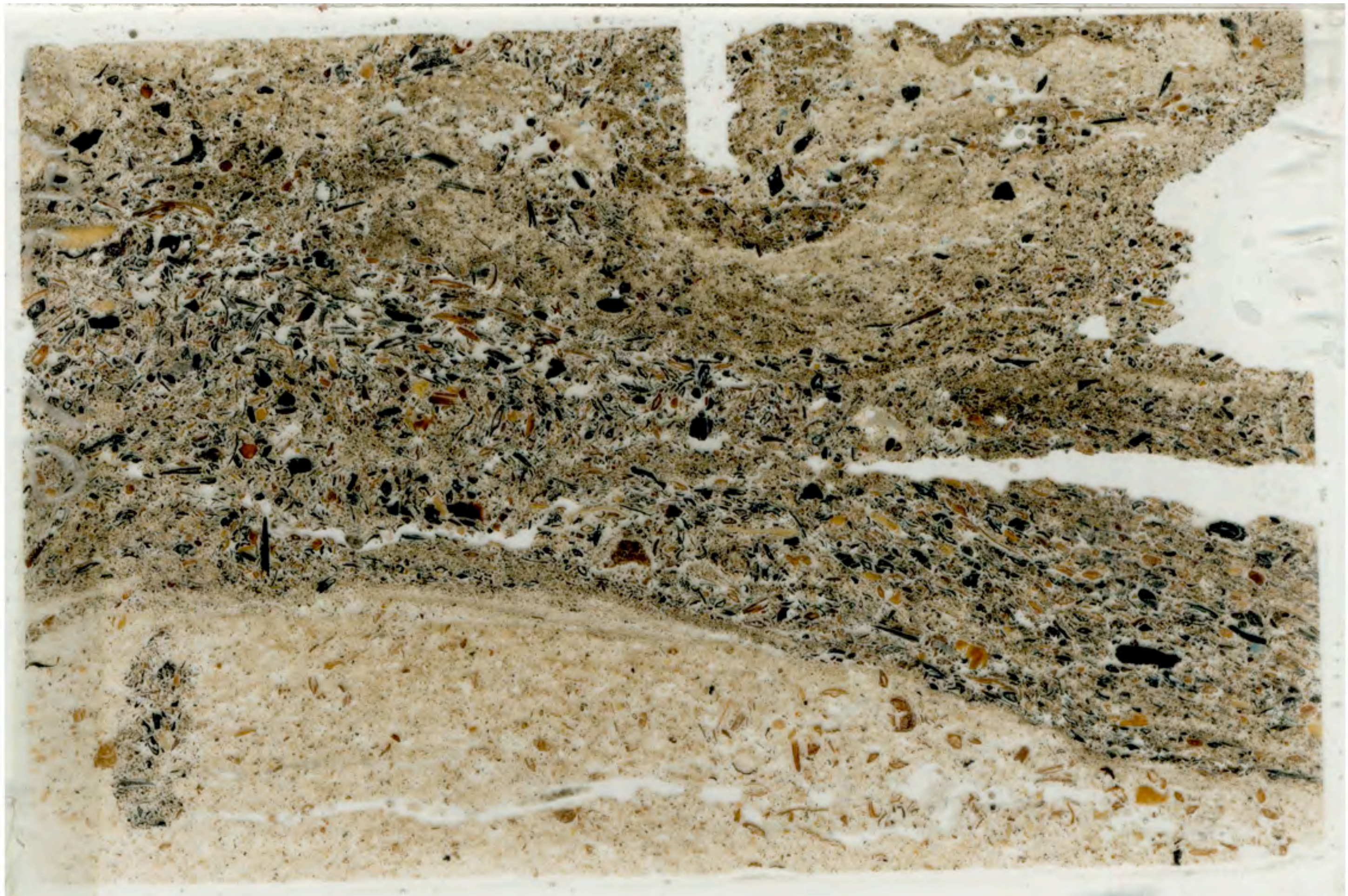


Figure 6.3 Scan of bedded charcoal and unburned organic matter from a thin section collected at Rocky Draw 158. Width of image is approximately 75mm. Lower unit is composed of bedded sands and unburned plant tissues.

From these studies, we may infer that canopy-dominated ponderosa pine forests should have a pollen signature that includes relatively high pine pollen abundances (60-80%), little representation of juniper and oak pollen (0-5%), grasses (ca. 5%), cheno-ams (5-10%), and composites (5-15%). In the compositae assemblage, more than 50% should be low-spine or *Ambrosia* pollen. In contrast, open meadow or meadow-like settings should have reduced pine pollen representation (30-60%), with higher representation of cheno-ams (>10%), grasses (>5-10%), and composites (>20%). Other or “high-spine” composites should make up the majority (>50%) of the sunflower-type assemblage. In both environmental units, however, human activity or other frequent disturbances, such as fires, may elevate the local production of pollen by cheno-ams, composites, and grasses (Hevly 1988:113).

Theoretically, low pollen concentration and an assemblage dominated by disturbance taxa would be expected from sediments or soils that immediately postdate a high severity fire. However, as charcoal, unburned plant tissues, and eroded organic matter begin accumulating in alluvial deposits after a high severity fire, pollen concentrations and pine pollen abundance would be expected to be very high. Other information, including radiocarbon dates, inferred sedimentation rates, sedimentology and micromorphology, and macroscopic charcoal stratigraphy would be necessary to adequately interpret the pollen stratigraphy.

Peaks in macroscopic charcoal concentrations are not necessarily expected to identify individual fire events (Chapter 4). Under surface fire regimes described by fire scar studies with “natural” fire frequencies (e.g., every 5-10 years), consistent sedimentation rates greater than 1cm per year would be necessary to distinguish individual fires in sedimentary records. In lieu of such an unlikely situation, and considering the *average* sedimentation rates defined in Chapter 5, the charcoal concentrations from sediments dated to AD 1650-1900 from Rocky Draw and Sharp Hollow (the "control" watersheds) are used to define charcoal concentration values for "natural" fire regimes. Variation in charcoal concentrations above or below the "natural" levels should represent variation in biomass burning (type, amount, frequency) different from or in addition to natural fire regimes.

Localities above the Mogollon Rim

Study watersheds above the Mogollon Rim were selected based on the presence or absence of evidence for prehistoric occupation. As presented in Chapter 5, all sedimentary sequences sampled for this study above the Rim postdate the period of prehistoric occupation. Unless prehistoric human activity in the vicinity of Day Wash and Willow Wash had consequences on stand composition and fuels for more than a century after the depopulation of the Bailey Ruin (ca. AD 1325), the paleoecology of these watersheds should yield evidence of similar, climate-driven ecological processes as "control" watersheds (Rocky Draw and Sharp Hollow). Western Apaches (as well as Hopi, Zuni, Navajo and Yavapai groups) probably used these areas during the protohistoric and historic periods (after AD 1450). This use intensity, however, would have been dramatically less than the prehistoric occupation. Additionally, these areas were probably less regularly used than Apache farm sites below the Rim, such as the

Forestdale Valley. All four of these localities are expected to be more sensitive to climate fluctuations and internal ecological processes than human land use. All dates used in the following sections have been derived from the polynomial age-depth functions described in Chapter 5.

Sharp Hollow 1

Figure 6.4 plots stratigraphic variation in sedimentary charcoal, stable carbon isotopes, and phosphorus content in relevant data from bulk samples. Phosphorus content was unusually high for the study area (all >10ppm). Unfortunately, this abundance probably does not have paleoecological significance. Analysis of soil thin sections from SH 1 indicated that sand-sized phosphate minerals (collophane) were present as part of the parent material in the sand fraction of limestone pebbles as well as the sandy parent material of the fan itself (Figure 6.5).

Coarse charcoal concentrations were generally low throughout Ab2 and Ab3 (below 75cm or before AD 1580). Between 15-75cm (ca. AD 1580-1820), charcoal concentrations were relatively high compared to the local mean and displayed only minor variability (Figure 6.4). Charcoal concentrations declined precipitously in the young, AC horizon that postdates AD 1820 and may date as late as AD 1900. Adjusting charcoal concentration with the average sedimentation rate to create a charcoal accumulation rate or CHAR (pieces of charcoal cm^{-2} yr^{-1}) did not change the shape of the profile, although overall numbers decreased.

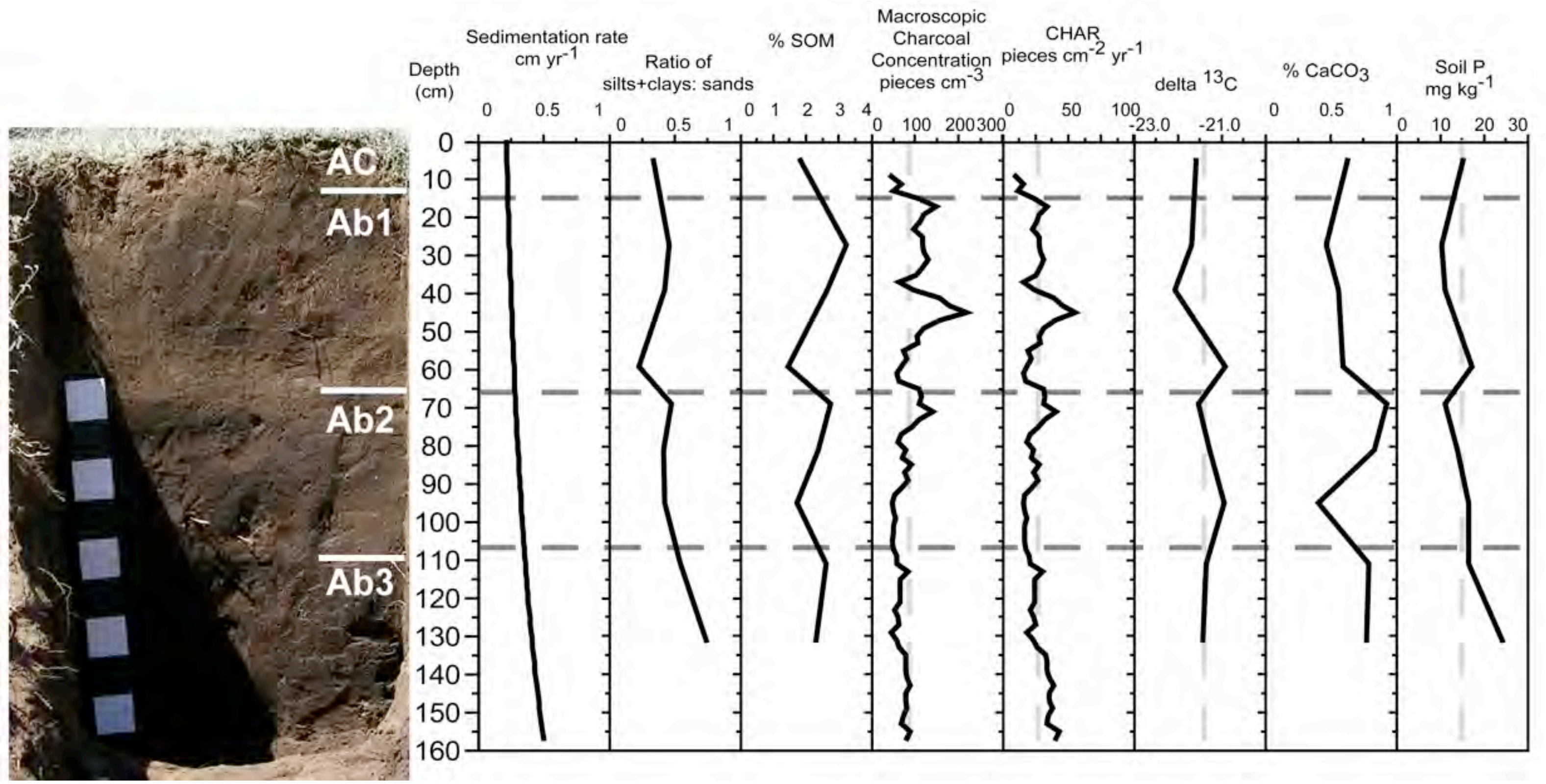


Figure 6.4 Macroscopic charcoal, stable carbon isotope ratios, and soil phosphorous content in relation to sedimentation rate, grain size (ratio of silts and clays to sand), soil organic matter and carbonate content from Sharp Hollow 1. Horizontal dashed lines demarcate soil horizons. Vertical dashed bars indicate the locality mean value for charcoal, delta ^{13}C, and phosphorus content.

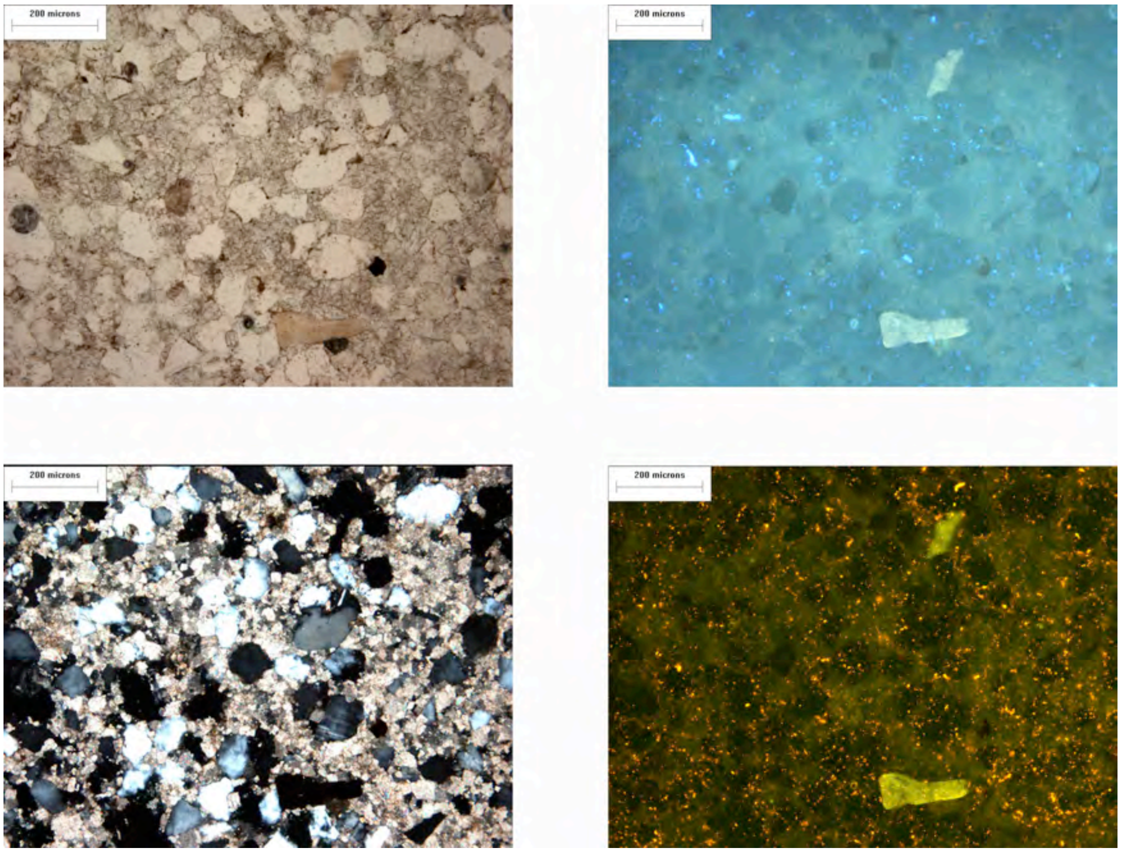


Figure 6.5 Photomicrographs of collophane (fluorescent, isotropic, gray-brown mineral in bottom and top center) as part of the sand fraction of a limestone pebble from Sharp Hollow 1. Collophane, a phosphate mineral, is present as part of the parent material at Sharp Hollow 1 and obscures phosphate contributions from plant ash and biomass burning. Upper left image was taken in plane polarized light (PPL); lower left was in cross polarized light (XPL); the upper right image was in blue light fluorescence; and the lower right was with UV fluorescence.

There was very little variation in stable carbon isotope ratios throughout the section. Overall delta ^{13}C values were generally heavier (i.e., less negative) than in other study localities (see below), but remained only 1-2‰ heavier than isotope ratios derived from C3 plant tissues radiocarbon dated for this study (e.g., *Pinus* needles in Table 5.2). Regardless, contributions of C4 plants may have been greater in Sharp Hollow throughout the sequence when compared to the other study localities. Locally, isotope ratios were less negative (Figure 6.4) prior to AD 1650, representing greater C4 plant input during this period of soil formation and sediment accumulation.

Although pollen concentrations and counts are generally low (ca. 1000 grains cm^{-3}), pollen preservation is fairly good (Figure 6.6). Pine pollen abundance was relatively low in Ab3 (between ca. AD 1390-1480) and was associated with elevated levels of *Ambrosia*, *Artemisia*, other composites, grasses, and cheno-ams and exceptionally high concentrations of pollen-slide charcoal. *Sporormiella*, a fungus that grows on herbivore dung (Davis 1987), was also present during this period. Stork's bill was present as well, but is probably a contaminant, as it was observed in the area when the locality was excavated and sampled and its presence is inconsistent with the radiocarbon dating. Throughout the rest of the sequence, pine pollen was relatively abundant (52-75%), pollen-slide charcoal declined, *sporormiella* occurred episodically, and nonarboreal assemblages changed very little. The overall pollen assemblage after ca. AD 1525 was consistent with a typical ponderosa pine forest setting (Table 6.2).

Relatively low macroscopic charcoal concentrations, high microscopic charcoal concentrations (pollen-slide charcoal), elevated abundance of disturbance plants, and elevated contributions of C4 plants to the carbon isotope pool may indicate elevated, low severity fire frequencies prior to AD 1500. A conversion of understory fuels to increase the fine, herbaceous component would reduce macroscopic charcoal and elevate the representation of these plants in local pollen assemblages. Early season (spring or summer) burning would promote warm-season (C4) herbaceous plants. However, two of the radiocarbon dates from this part of the sequence indicated substantial erosion of older subsoil material upslope from SH 1 (Chapter 5). An alternative explanation for this sequence is that the material dated to the 15th century accumulated in the wake of a high severity fire (or fires) that resulted in a prolonged reduction in canopy cover. Postfire erosion would account for the reworked charcoal dates as well as the low charcoal concentrations (i.e., most fire-related charcoal was transported downstream by greater stream energy). On the basis of interannual moisture patterns (Chapter 3; Roos and Swetnam nd), the 14th and 15th centuries were probably periods of *reduced* fire frequency. Unless the area was burned regularly by indigenous people during the late 14th and 15th centuries, for which there is no evidence of use or occupation, elevated fire frequencies are difficult to explain. On this basis, it is more likely that the 15th century material includes evidence for increased fire *severity* followed by surface fire activity in herbaceous succession communities before ponderosa pine forest reestablished.

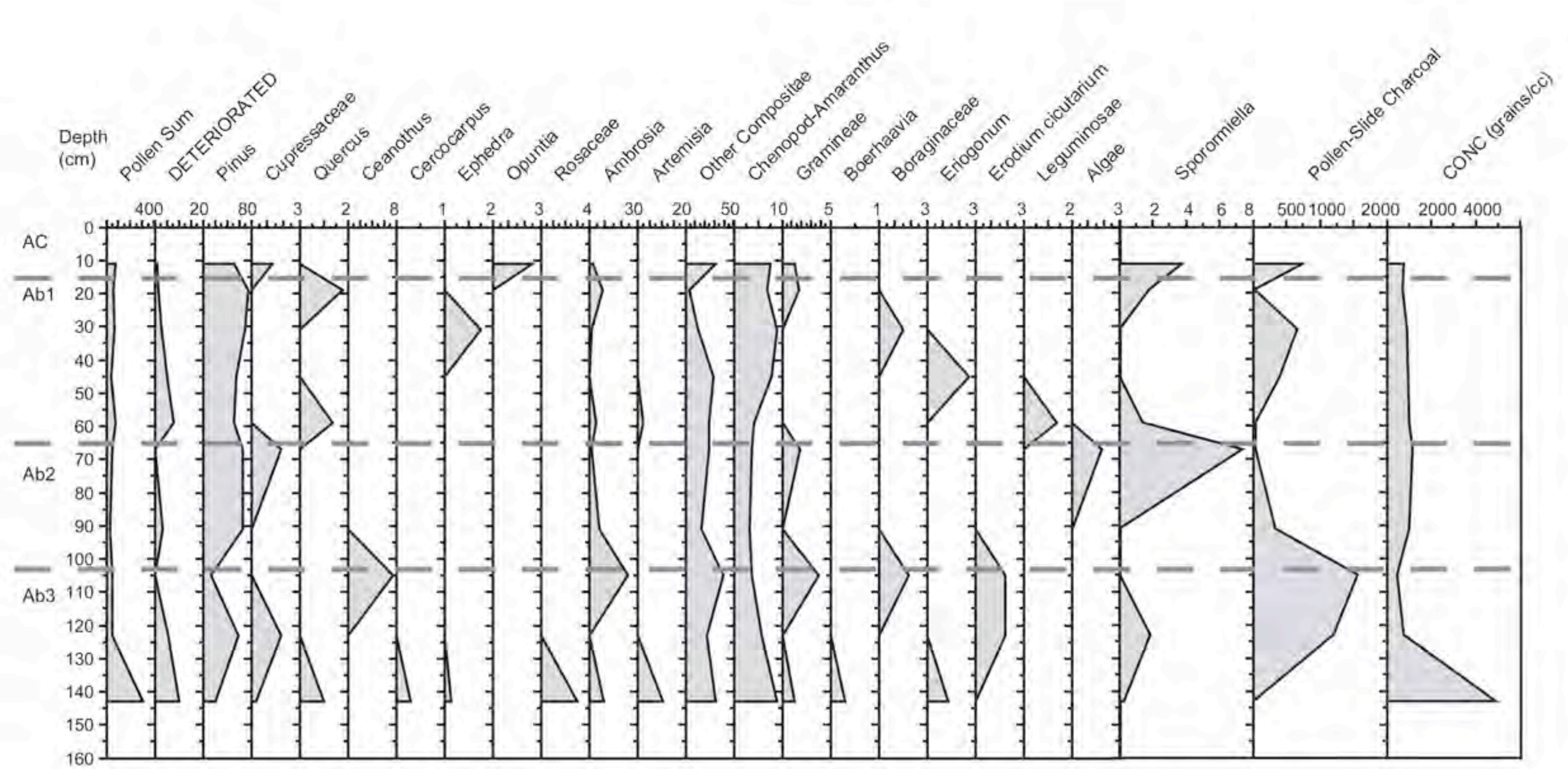


Figure 6.6 Percentages of selected pollen taxa, palynomorphs, and pollen-slide charcoal from Sharp Hollow 1. Horizontal dashed lines mark soil horizon boundaries.

Rocky Draw 7

Below 50cm at Rocky Draw 7(before ca. AD 1580; Figure 6.7), macroscopic charcoal concentration was very low. Adjusted for sedimentation rate, stratigraphic CHAR exhibited a similar pattern, although CHAR at 70-75cm was above the local mean. Micromorphology and radiocarbon data suggest that much of this charcoal was redeposited from older subsoils farther upstream (Chapter 5). Stable carbon isotope ratios were slightly heavier below 50cm, although actual values were more than 1‰ lighter (i.e., more C3 contributing to isotope pools) than at Sharp Hollow 1. Initial phosphorus concentrations were very low (<1ppm) at 80cm (ca. AD 1475) and moderate above this (3-5ppm). Above 50cm (after ca. AD 1580), macroscopic charcoal concentrations were similar to comparable aged sediments from Sharp Hollow 1 (i.e., 100-200 cm^{-3}). Additionally, isotope ratios became more negative at RD 7 and sediments of comparable age at SH 1 (after AD 1580).

Below 50cm, pollen concentrations were exceptionally low, whereas microscopic charcoal was relatively abundant and pine pollen was entirely absent (Figure 6.8). Despite the low pollen concentrations, pollen preservation appears to be quite good. Pollen samples between 60-80cm (ca. AD 1475-1550) were dominated by *Ambrosia*, other composites, cheno-ams, and grasses. From 60cm and above (after ca. AD 1550), pine pollen increased between 32-59% with additional contributions from *Picea* (spruce), oak, and *Pseudotsuga* (Douglas-fir). *Sporormiella* and *Salix* (willow) were consistently present after AD 1600, which indicates the presence of herbivores as well as riparian vegetation during the historic period. Overall, the pollen assemblage after AD 1550 was consistent with a very open ponderosa pine forest or small forest meadow, whereas the pre-1550 assemblage is "completely consistent with what might be expected from mid-Holocene deforested vegetation" (Davis 2007). The soil morphology and micromorphology, however, is inconsistent with a mid-Holocene age (Chapter 5) but the "deforested vegetation" inference appears valid.

Overall, the sequence from Rocky Draw 7 is very similar to the Sharp Hollow 1 sequence. The reworked, Middle Holocene charcoal in soil aggregates within the deposits between 60-95cm further supports the inference of unusual postfire erosion of upland soils. Stratigraphic evidence of 1) low macroscopic charcoal concentrations, 2) low pine pollen concentrations, 3) high microscopic charcoal concentrations, and 4) unusual amounts of postfire upland erosion prior to AD 1500/1550 is consistent with the working hypothesis that early accumulation in the "control" watersheds followed a high severity fire or fires.

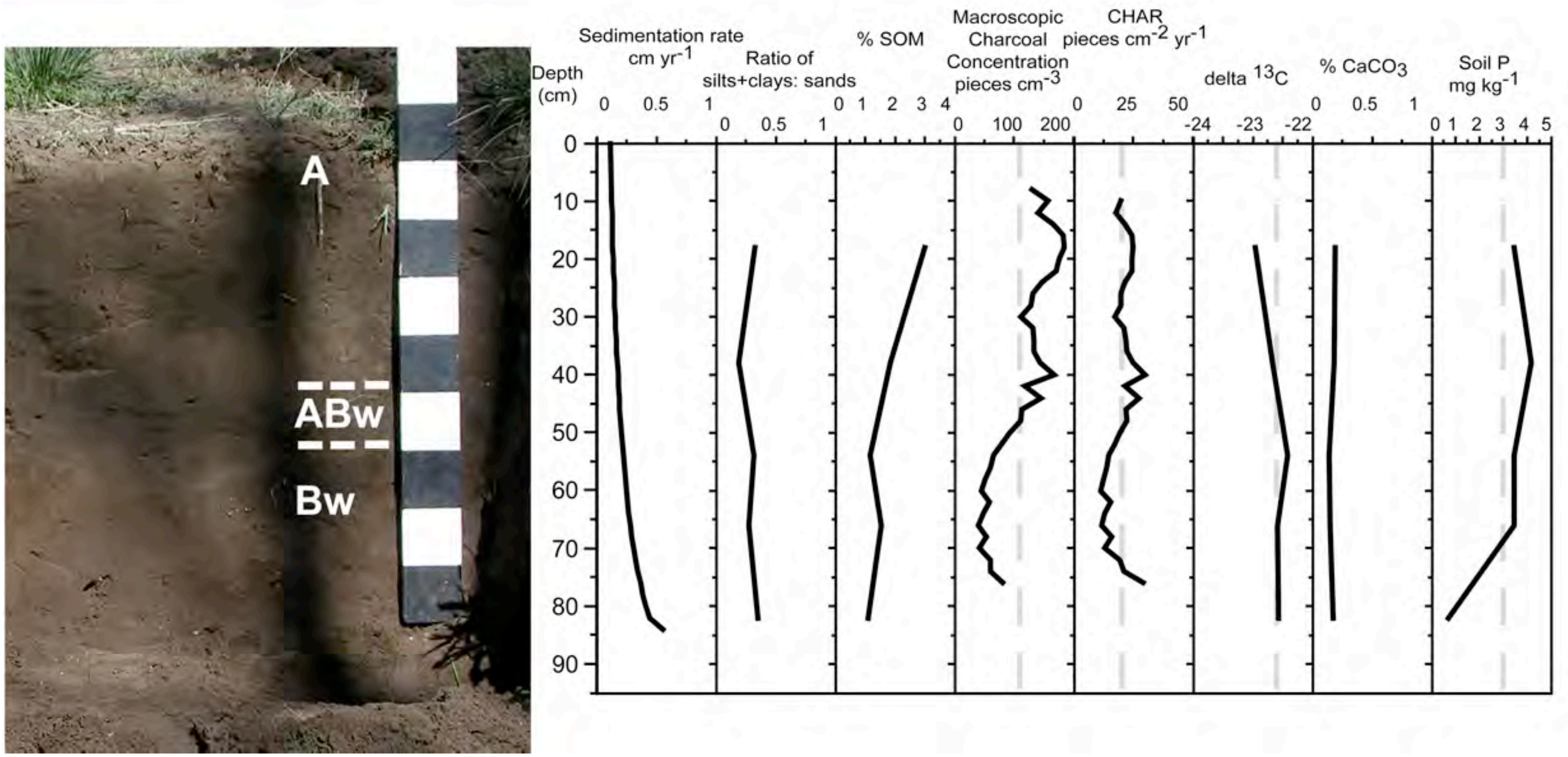


Figure 6.7 Macroscopic charcoal, stable carbon isotope ratios, and soil phosphorous content in relation to sedimentation rate, grain size (ratio of silts and clays to sand), soil organic matter and carbonate content from Rocky Draw 7. Vertical dashed bars indicate the locality mean value for charcoal, delta ^{13}C, and phosphorus content.

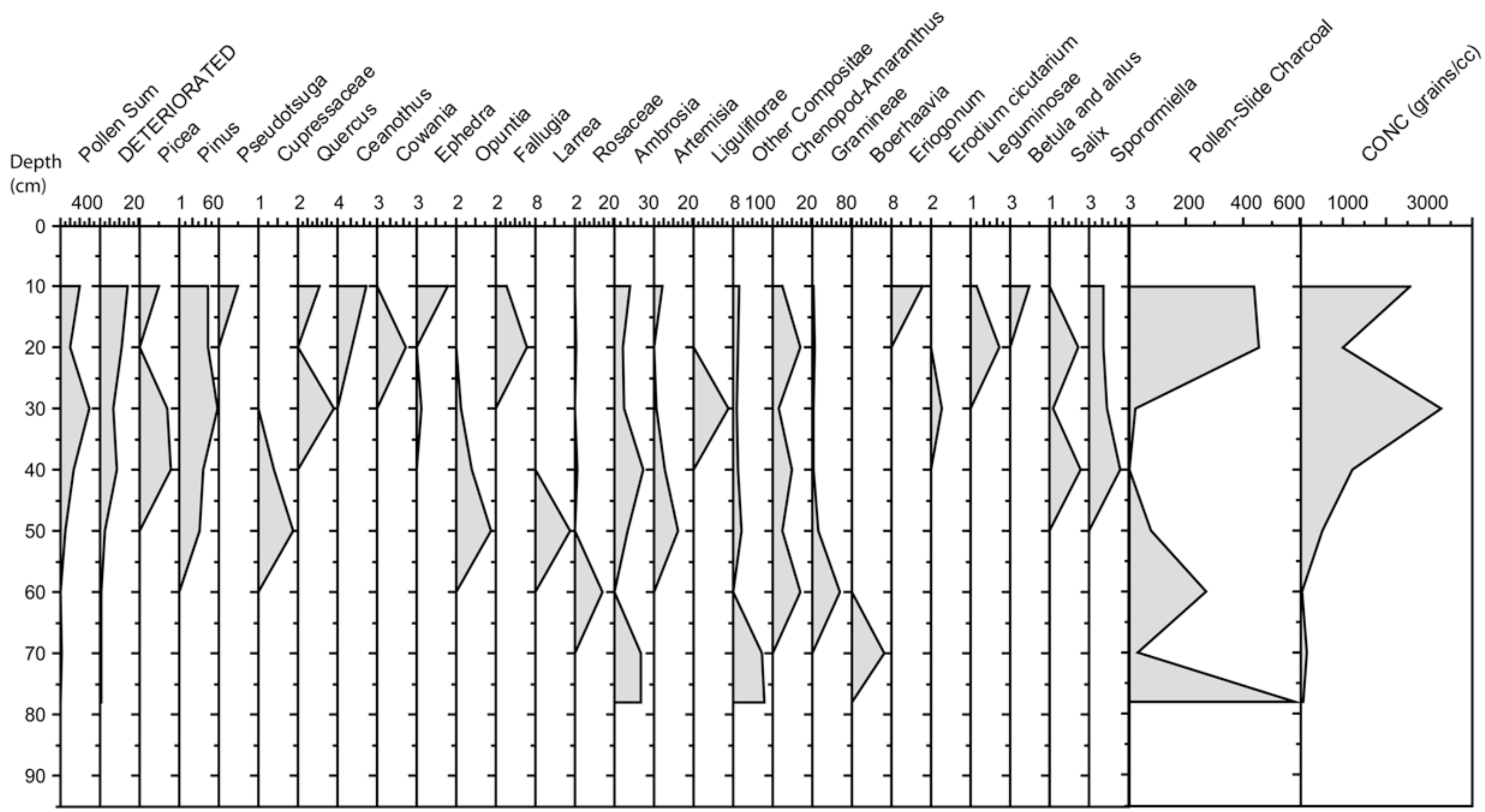


Figure 6.8 Percentages of selected pollen taxa, palynomorphs, and pollen-slide charcoal from Rocky Draw 7.

Day Wash 14

In Chapter 5, I suggested that Unit I at Day Wash 14, which was characterized by massive, heterogeneous sedimentary deposits capped with charcoal beds, was evidence of major postfire erosion. Exceptionally high macroscopic charcoal concentrations between 170-220cm support this inference (Figure 6.9). Interestingly, charcoal concentrations were not highest in fine-grained sedimentary deposits. This suggests that variation in settling velocity did not generate the major variation in charcoal concentration here. Soil organic matter is exceptionally high in Unit I above 220cm as well. Since there is little micromorphological evidence that this organic matter is autochthonous (i.e., due to *in situ* plant production), these elevated SOM values were probably from detrital, unburned organic tissues and organic-rich sediments. Unit I pollen concentrations (2470 grains cm^{-3}) and pine pollen abundances (91.3%) also peaked at 220cm (Figure 6.10) coincident with a peak in SOM. This pattern is consistent with the pattern observed in modern postfire sediments (see above). Additionally, pollen-slide charcoal was exceptionally abundant throughout Unit I and pine pollen abundance was exceptionally low (11.1%) at 240cm, which may have been associated with the immediate postfire plant communities. According to the age-depth model presented in Chapter 5, all of these sediments date between ca. AD 1420-1480. Riparian taxa (algae and *Typha latifolia* or cattail) at 240cm suggest that initial accumulation of postfire sediment may have been facilitated by riparian vegetation within the incised channel of Day Wash. Just above Unit I, between 150-180cm (ca. AD 1480-1490), *sporormiella* occurs at moderate levels, which is consistent with an increase in herbaceous forage in postfire environments of the Day Wash 14 area.

Macroscopic charcoal concentrations remained moderately high between 50-170cm (ca. AD 1480-1650) in association with elevated carbonates (some of which are ash derived), pollen concentrations, and moderate phosphorus concentrations. Pine pollen was consistently high (64-72%) throughout this portion of Unit II. *Artemisia*, *Ambrosia*, other composites, and cheno-ams were consistent contributors to understory taxa during this period as well. This pattern is consistent with frequent fires in mixed surface fuels of a ponderosa pine forest. In Ab1 and Ab2 (15-50cm or ca. AD 1650-1820), macroscopic charcoal and pine pollen concentrations declined, phosphorus concentrations increased to very high levels (10-25ppm), as cheno-ams, other composites, and grass pollen increased in abundance. This pattern is consistent with increased frequencies of low severity fires promoting herbaceous understory plant taxa. In the surface soil, carbon isotope ratios, which had been stable throughout the sequence, decrease by more than 1.5‰. Other fire-related proxies (pine pollen, phosphorus, macroscopic and microscopic charcoal) all degraded in the surface A horizon as well, probably representing the consequences of historic fire suppression.

The entire sequence from Day Wash 14 is suggestive of landscape-altering, high severity fire activity in the 15th century, followed by the relatively rapid return of ponderosa pine forest. During the 16th and early 17th century, regular fires produced moderate amounts of phosphorus and moderate to high amounts of charcoal in the context of high pine pollen abundance and C3-dominated isotope ratios. Between ca. AD

1650-1820, phosphorus, charcoal, and pollen assemblages suggest an increase in low severity fire frequency. Although Western Apaches (or other indigenous groups) may have used this area during this time, the archaeological evidence is limited (Chapter 3). These proxies are similar to those from contemporary samples in the Forestdale Valley, where Western Apache use is clearest (see below), but cannot be distinguished at this point from the climate-predicted increase in fire frequency suggested by Roos and Swetnam (nd; see also Chapter 3).

Conversion of the Day Wash 14 macroscopic charcoal data set to CHAR illustrates the potential problems of using CHAR data from complexly accumulated alluvial deposits (Figure 6.9). The shape of the overall charcoal stratigraphy does not change, but the absolute CHAR values throughout the sequence are substantially higher than those from sediments of comparable age at Sharp Hollow 1 or Rocky Draw 7. None of the other data sets, however, support the CHAR-based suggestion that greater biomass burning occurred between AD 1500-1650 in Day Wash than in the "control" watersheds. Rather, the Day Wash data set highlights the sensitivity of CHAR to sedimentation rate estimates, which can only be imperfectly known due to the complexity of radiocarbon dating of detrital charcoal, alluvial sedimentation, and soil formation.

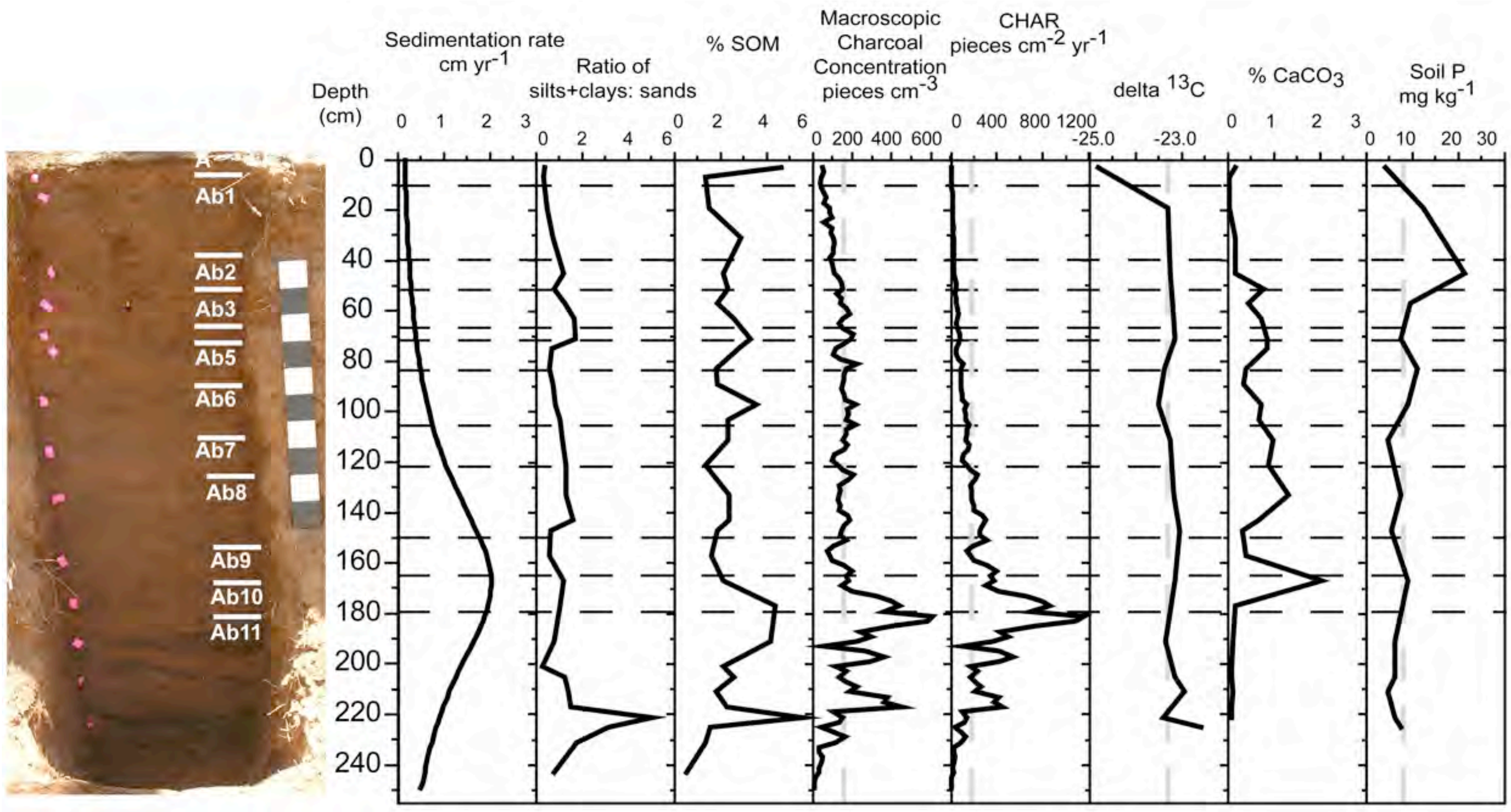


Figure 6.9 Macroscopic charcoal, stable carbon isotope ratios, and soil phosphorous content in relation to sedimentation rate, grain size (ratio of silts and clays to sand), soil organic matter and carbonate content from Day Wash 14. Horizontal dashed lines demarcate soil horizons. Vertical dashed bars indicate the locality mean value for charcoal, delta ^{13}C, and phosphorus content.

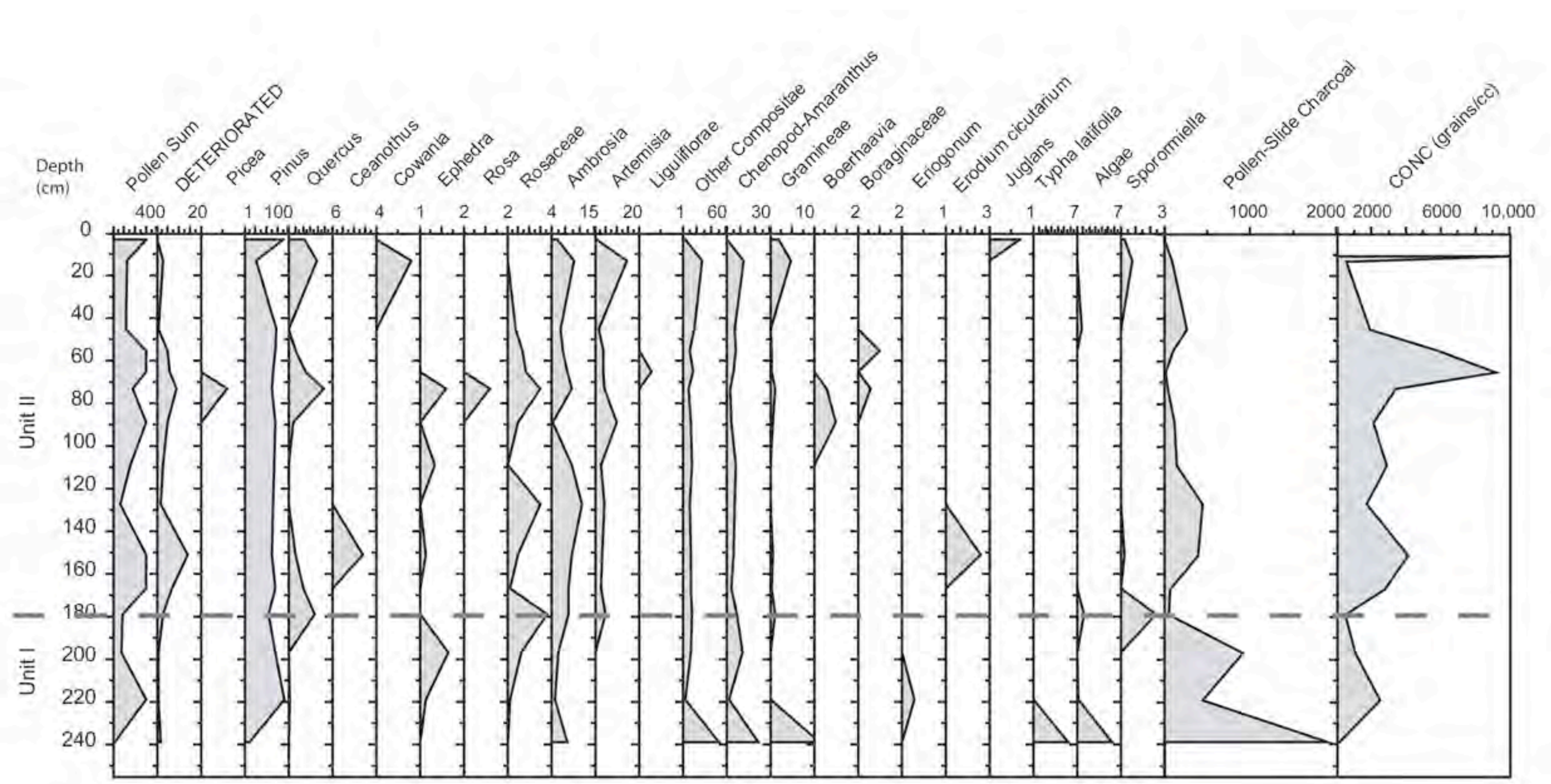


Figure 6.10 Percentages of selected pollen taxa, palynomorphs, and pollen-slide charcoal from Day Wash 14. The horizontal dashed line demarcates the boundary between Unit I and Unit II.

Willow Wash 4

Macroscopic charcoal, phosphorus, and isotope data have not been generated for the stratigraphic sequence at Willow Wash 4. Pollen data, however, contribute to the local vegetation history of the Day and Willow Wash area (Figure 6.11). Overall pollen concentration was moderate and pollen was well preserved. At 195cm (ca. AD 1515), pine pollen concentrations were exceptionally low (18%) while other composites and cheno-ams were at their highest level in the record. Overall microscopic charcoal values were quite low throughout the sequence, but were at their highest level at this time as well. Throughout the rest of the sequence, pollen assemblages are consistent with a very open ponderosa pine forest or forest meadow. Additional contributors to arboreal pollen assemblages were oak, juniper, spruce, fir (*Abies*), and box elder (*Acer negundo*). The latter three taxa as well as *sporormiella* spores were only episodically present. Riparian indicators (algae, cattail, and willow) were all present between 140-195cm (ca. AD 1515-1600).

Altogether, the pollen profile from Willow Wash 4 is "similar to that from Sharp Hollow 1 and Rocky Draw 7" (Davis 2007). Interestingly, pollen from domesticated beans (*Phaseolus* spp.) was recovered from 73cm (ca. AD 1725), which indicates indigenous cultivation of the Willow Wash 4 area in the 18th century. The contemporaneity of this evidence of indigenous land use with the period of elevated fire frequency in the adjacent Day Wash watershed may support the hypothesis that some component of the AD 1650-1820 paleoecological record from DaW 14 was anthropogenic. Additionally, the similarity of the WW 4 pollen record before AD 1550 to Sharp Hollow, Rocky Draw, and Day Wash also suggests that Willow Wash burned at higher severity during the 15th or early 16th century.

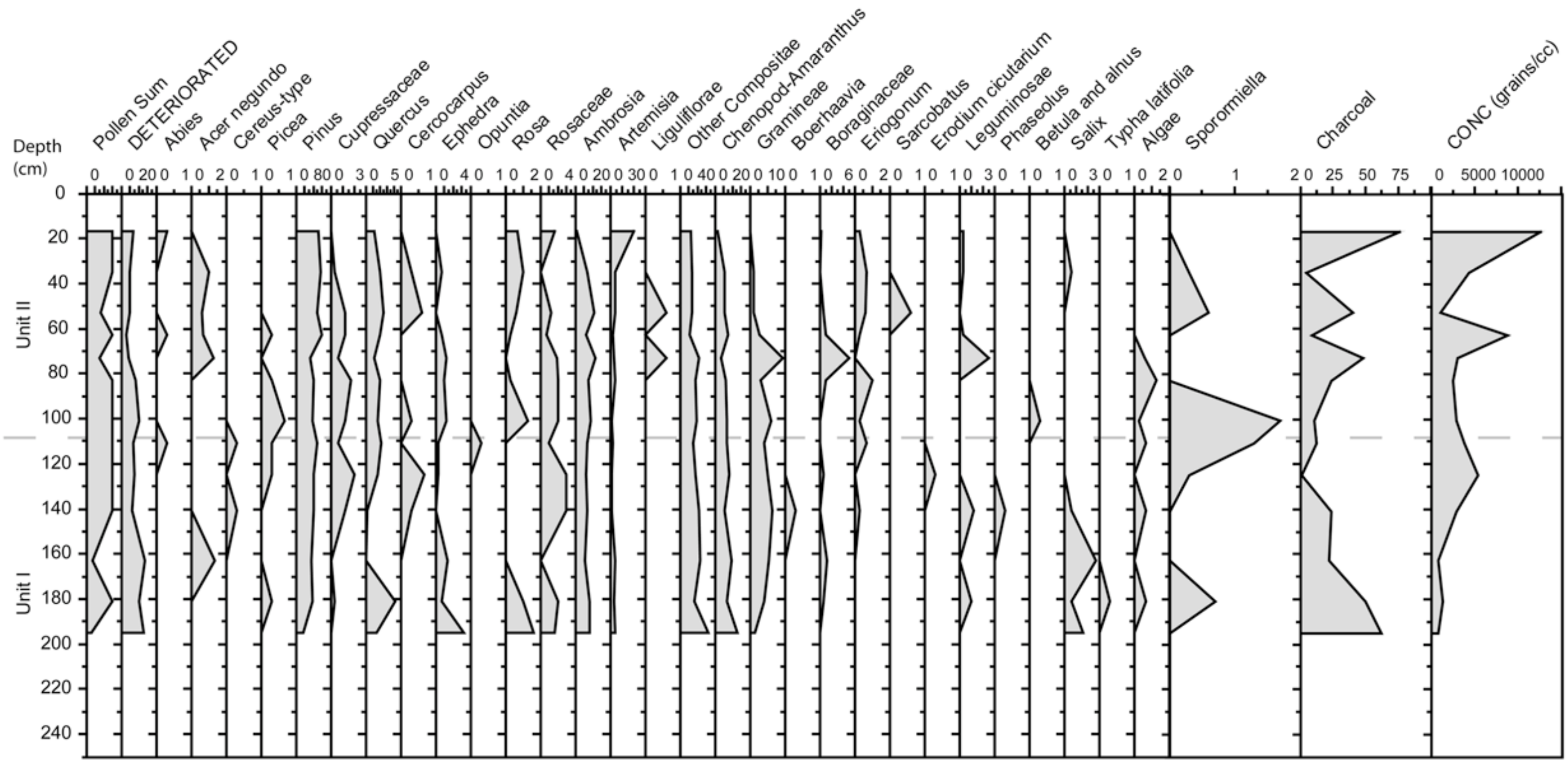


Figure 6.11 Percentages of selected pollen taxa, palynomorphs, and pollen-slide charcoal from Willow Wash 4. The horizontal dashed line demarcates the boundary between Unit I and Unit II.

Forestdale Valley localities

The three, chronologically overlapping sequences from the upper watershed of the Forestdale Valley display similar stratigraphy (Chapter 5) but are located in slightly different ecological settings. Locality 6 and 20 are at the upstream end of the current valley-bottom meadow environment. Some young pines are now growing on older terrace surfaces in this environment. In contrast, Locality 10 is in a more restricted valley-bottom setting in much closer proximity to dense, ponderosa pine forest. The differences in local environments should affect the pollen record from each locality. Because each locality should have mineralogically identical parent material, phosphorus values from FDV 6 and 10 (20 has not yet been analyzed for phosphorus) should be comparable.

Forestdale Valley 6

Macroscopic charcoal concentrations (Figure 6.12) were highest between 230-345cm (ca. AD 1200-1370) and, as mentioned above, DTA/TGA analyses suggest that combustion temperatures may have been lower (Cohen-Ofri and Weiner 2007). Below 125cm (before AD 1540), phosphorus concentrations were generally below the locality mean with the exception of a sample at 280cm (ca. AD 1330). Carbon isotope ratios varied little throughout the sequence with values between -23 to -23.5‰ below 50cm (before ca. AD 1750). In contrast to the "control" watersheds, isotope ratios became slightly less negative (i.e., more C4 plant contributions) between AD 1750-1850. Above 130cm (after AD 1550), phosphorus concentrations were relatively high but macroscopic charcoal concentrations declined in the context of largely sandy sediments. The variability in charcoal and phosphorus may be linked to similar landscape processes affecting the grain-size variability, but do not appear to be affected by changes in settling velocity. Below 130cm, charcoal, grain size, and phosphorus varied but not in concert. Some of the consistently high charcoal concentrations and low phosphorus concentrations came from sandy facies between 190-250cm. Charcoal accumulation rates (CHAR) highlight the large amount of charcoal entering the system while sedimentation rates were high between AD 1250-1400.

In general, pollen concentrations were low to moderate and preservation was good. With the exception of two samples between 340-345cm (ca. AD 1220-1250), pollen assemblages from FDV 6 were consistent with a meadow environment surrounded by ponderosa pine forest (Figure 6.13). At the lowest depths, assemblages were more consistent with ponderosa pine forest, which may indicate that the upstream portion of the valley-bottom meadow originated during the late prehistoric occupation. Between 190-290cm (ca. AD 1320-1410), oak pollen declined dramatically and juniper pollen disappeared entirely. The reduction of these arboreal taxa may have been due to harvesting of these species for fuel or architectural wood during the period of greatest aggregation in the valley. Riparian taxa are absent below 190cm (before AD 1410) and *sporormiella* only occurs at trace levels at 260cm (ca. AD 1340) and 345cm (ca. AD 1220), which suggest that riparian environments were limited and local herbivore use of the area was limited and infrequent.

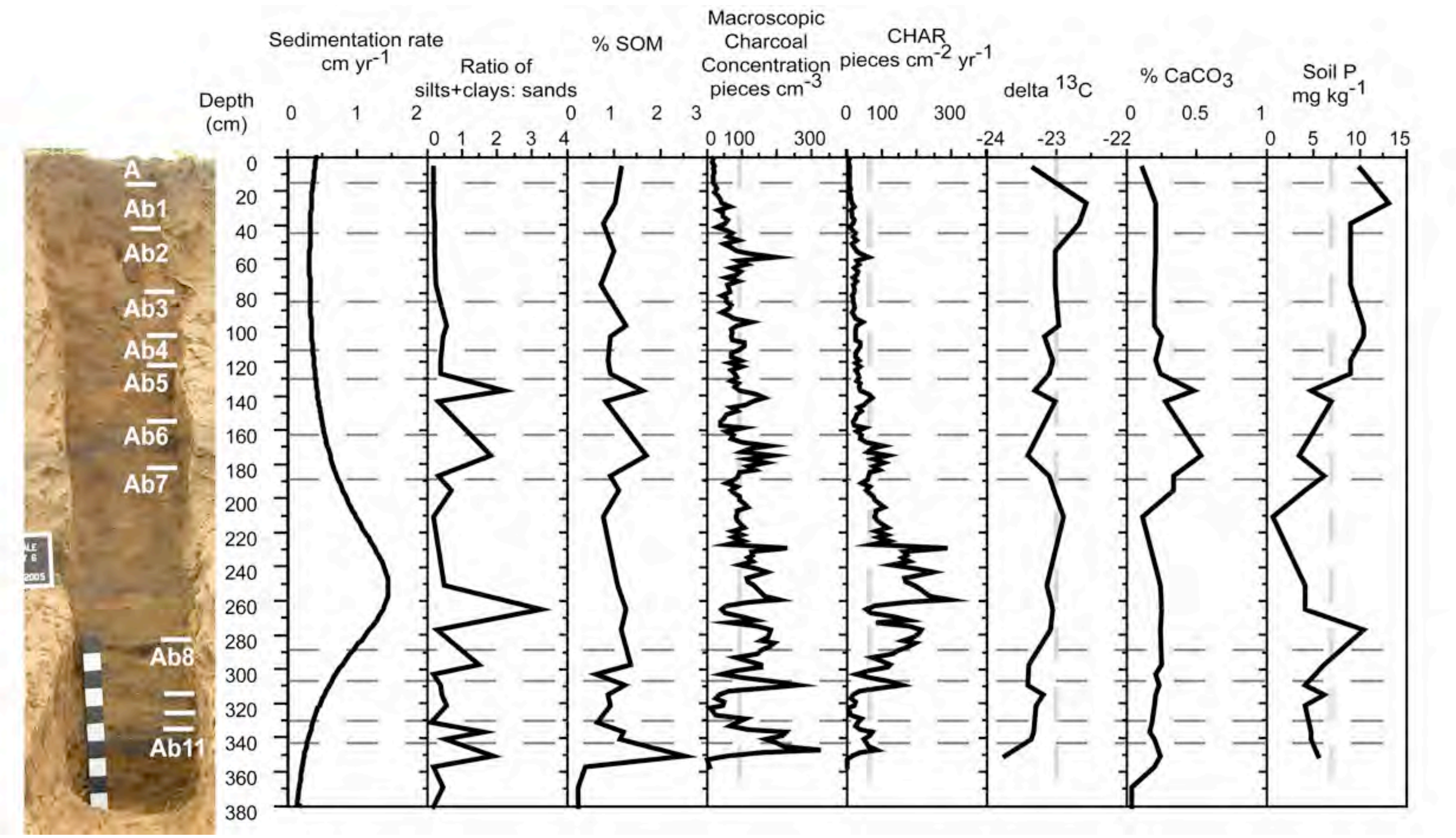


Figure 6.12 Macroscopic charcoal, stable carbon isotope ratios, and soil phosphorous content in relation to sedimentation rate, grain size (ratio of silts and clays to sand), soil organic matter and carbonate content from Forestdale Valley 6. Horizontal dashed lines demarcate soil horizons. Vertical dashed bars indicate the locality mean value for charcoal, delta ^{13}C, and phosphorus content.

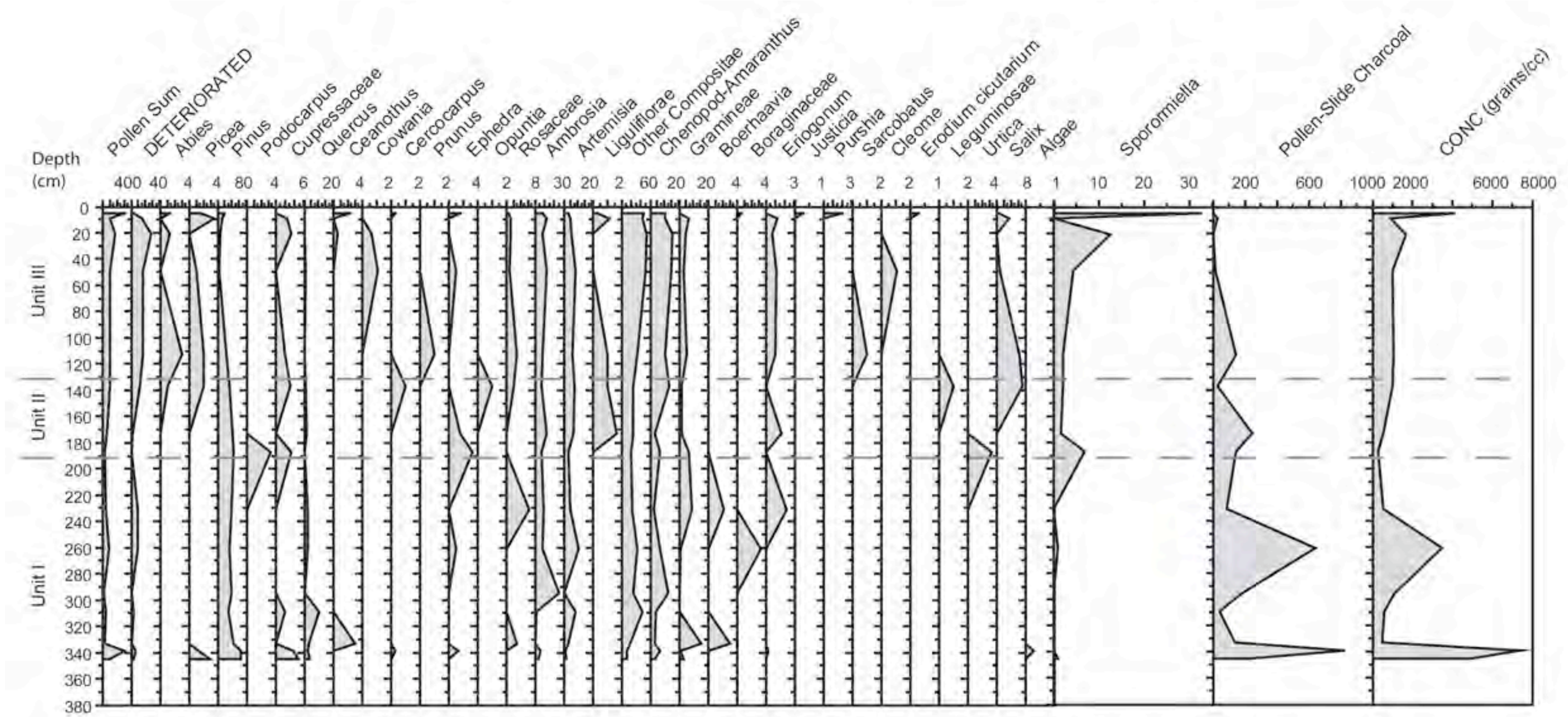


Figure 6.13 Percentages of selected pollen taxa, palynomorphs, and pollen-slide charcoal from Forestdale Valley 6. The horizontal dashed lines demarcate the boundaries between Unit I, Unit II, and Unit III.

In the postabandonment floodplain deposits of Unit II (ca. AD 1400-1530), juniper and oak pollen rebounded in association with riparian taxa (nettles [*Urtica*] and willow) and abundant *sporormiella* spores. Spruce and fir pollen appeared as a component of this record as well. Overall, however, the pollen assemblage continued to resemble a meadow within ponderosa pine forest. Charcoal concentrations from these deposits were similar to those from the "control" watersheds under "natural" fire regimes (ca. 100-150 pieces cm^{-3}), which suggests that after the prehistoric depopulation of the area, natural fire regimes persisted.

In Unit III (ca. AD 1530-1910), pollen assemblages changed in concert with decreases in macroscopic charcoal and increases in phosphorus. Pine pollen decreased to exceptionally low levels in conjunction with very high cheno-am, grass, and compositae pollen abundances. Willow pollen was episodically present, indicative of some riparian environments. *Sporormiella* spores increased towards the top of this unit, which suggests substantial numbers of herbivores grazing in the fire-maintained meadow environment. Pollen, charcoal, isotope, and phosphorus records degraded in the surface A horizon, associated with the highest levels of *sporormiella*, which probably represents cattle grazing and fire suppression during the reservation era.

Overall, changes in the Locality 6 paleoecological records are consistent with the major periods of occupation, abandonment, and reoccupation of the Forestdale Valley. Between AD 1200-1400, heightened levels of biomass burning (charcoal) occurred in an otherwise typical ponderosa pine meadow environment. High human population densities may have suppressed populations of herbivores due to hunting pressure, and other human activities may have impacted local oak and juniper populations as well. Elevated levels of biomass burning (but at lower temperatures) are consistent with preplanting burning of agricultural fields as part of a shifting, burn-plot agricultural strategy (Sullivan 1982) superimposed on natural fire regimes.

After abandonment ca. AD 1400, oak, juniper, and herbivore populations rebounded but natural fire regimes persisted. By the middle of the 16th century, synchronous changes in phosphorus, macroscopic charcoal, and disturbance pollen taxa indicated elevated fire frequencies, which promoted increased production of herbaceous plants and a decrease in woody fuels. The decrease in sediment yield and the largely sandy character of these deposits coupled with only minor contributions from C4 plants to the carbon isotope pool may indicate that many of these fires occurred after the natural fire season. Fall burning would disproportionately promote cool-season (C3) herbaceous plants and probably increase intercept of monsoon rainfall during the following summer by decreasing the proportion of bare ground exposed. Increased intercept would have reduced rainsplash energy and may have restricted monsoon-related sediment mobilization to the more readily eroded sand-sized fraction of sediments and soils on surrounding hillslopes (Figure 6.14). Fall burning would be consistent with postharvest burning of wild seed collecting areas to promote spring greens and greater productivity in the following year (Buskirk 1986:165; Gifford 1940). Additionally, a shift to late season burning has been identified in fire scar studies of Apache burning elsewhere in the Southwest (Kaye and Swetnam 1999; Morino 1996).

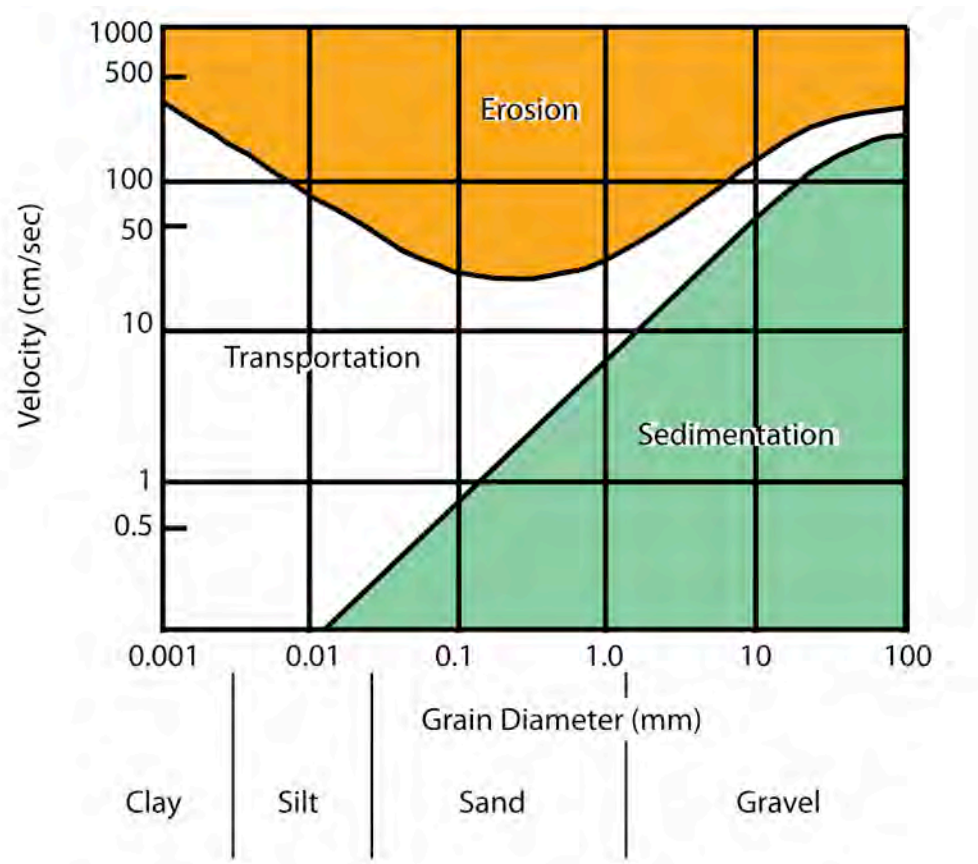


Figure 6.14 Hjulstrom diagram of the streamflow energy required to erode, transport, and deposit sediments of different grain size. The sand fraction requires the least energy to mobilize (adapted from Waters 1992:121, Figure 3.4).

Forestdale Valley 10

Macroscopic charcoal concentrations were moderate to very high below 180cm (before ca. AD 1400) with highest concentrations occasionally coinciding with upward-fining units (Figure 6.15). Coincident with the period of high charcoal concentrations, phosphorus concentrations were also elevated in Unit I. With the exception of a sample at 335cm (ca. AD 1100), stable carbon isotope ratios from Unit I were lighter than -23‰, indicative of relatively little C4 plant contribution to organic carbon pools. In the finer facies of Unit II, charcoal concentrations were moderate (similar to "control" watersheds), phosphorus values were low, and isotope ratios were largely unchanged. In Unit III (by 115cm, or ca. AD 1610), charcoal concentrations declined, phosphorus amounts increased, and carbon isotopes became slightly heavier (i.e., more C4 plant inputs) in the context of largely sandy facies. Charcoal, phosphorus, and isotope records all degrade in the surface A horizon, consistent with the modern removal of fire from these landscapes.

Similar to FDV 6, pollen concentrations from Locality 10 were moderate and pollen was well preserved (Figure 6.16). Pollen assemblages from Unit I and II were generally consistent with those from ponderosa pine forest settings, as would be expected from the current vegetation surrounding the locality. *Zea* pollen from 305cm (ca. AD 1205) indicates that the locality was used for cultivating domesticates during the prehistoric occupation of the valley. Pollen-slide charcoal and grasses were relatively abundant in Unit I (prior to AD 1400). With the exception of a reduction in microscopic charcoal and grass pollen, the pollen assemblage from Unit II below 130cm (before ca. AD 1560) was virtually identical to the assemblage from Unit I. The only peak in *sporormiella* at 157cm (ca. AD 1460) indicates a rebound in local herbivore populations after prehistoric depopulation.

At the top of Unit II and throughout Unit III (after ca. AD 1560), other composites, *Ambrosia*, cheno-ams, and grasses increased in abundance in association with a decrease in pine pollen abundance and increased microscopic charcoal concentrations. Overall pine pollen abundances were higher than those from contemporary samples at FDV 6, as would be expected from the differences in local ecological communities. Although the Unit III pollen assemblage could be interpreted as evidence of the establishment of a meadow community after AD 1560, the pollen assemblage coupled with the macroscopic charcoal, isotope, and phosphorus data suggest the creation of a more open canopied pine forest with fire-promoted increases in herbaceous understory plants. The minor change in isotope values and the change in grain-size at FDV 10 support the interpretation of a synchronous increase in fall burning at both FDV 6 and FDV 10. Consistent with historical accounts, Unit III pollen assemblages also contained evidence of riparian communities in the form of algae, willow, and walnut (*Juglans*) pollen.

Overall, the records from Localities 6 and 10 are remarkably similar. Both records document elevated levels of charcoal deposition (and perhaps lower temperatures of combustion) in the context of upward-fining channel fan or channel margin deposits between AD 1200-1400. Phosphorus values were greater upstream but soil carbon pools were largely dominated by organic matter derived from C3 plants. The charcoal data suggest that more burning took place during the prehistoric occupation than “natural” fires alone. Reduced combustion temperatures (Cohen-Ofri and Weiner 2007) and elevated charcoal concentrations coupled with direct pollen evidence of horticulture support the hypothesis that elevated biomass burning was anthropogenic and that at least some of this burning was related to early spring burning of agricultural fields prior to planting (Sullivan 1982).

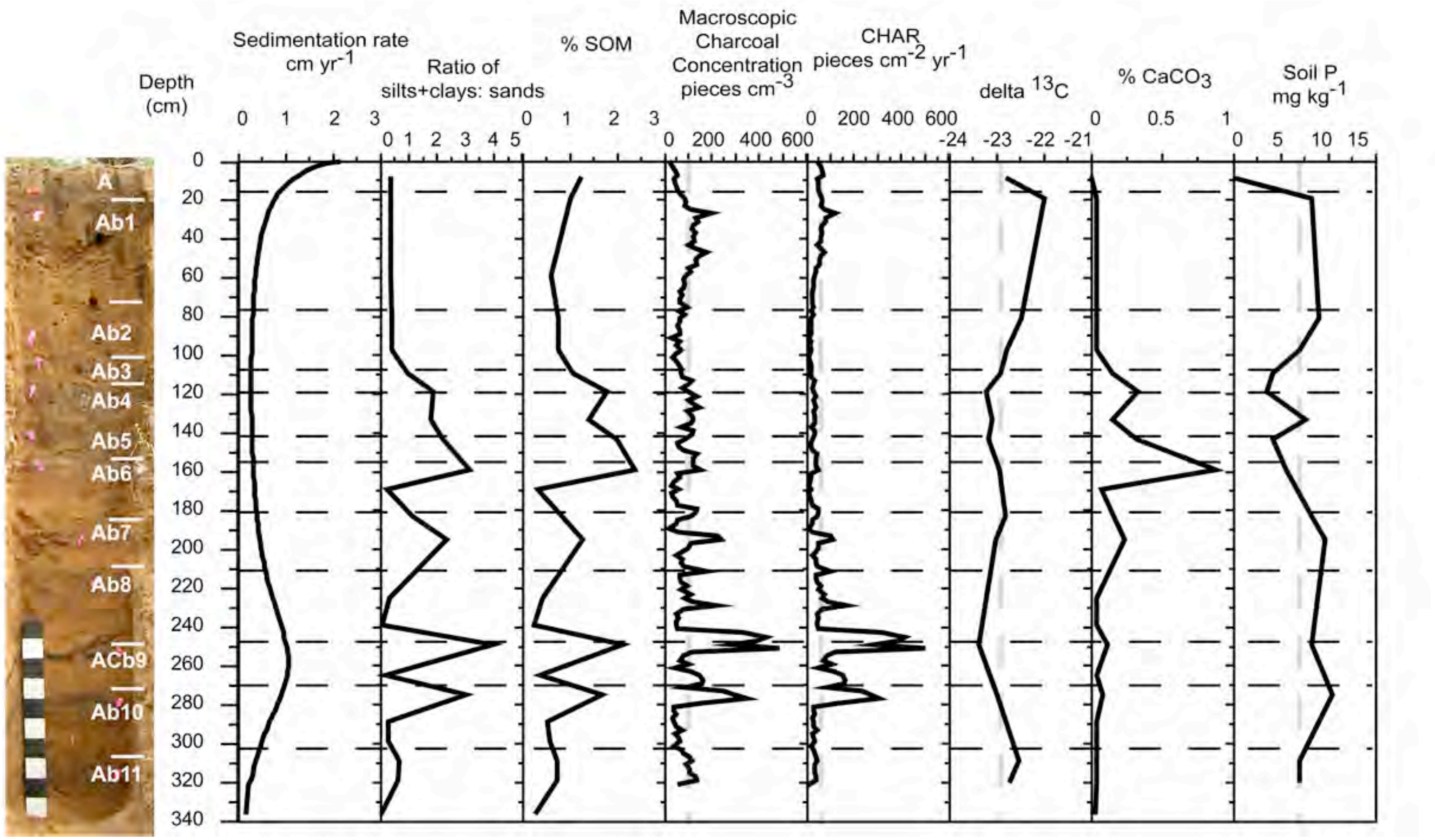


Figure 6.15 Macroscopic charcoal, stable carbon isotope ratios, and soil phosphorous content in relation to sedimentation rate, grain size (ratio of silts and clays to sand), soil organic matter and carbonate content from Forestdale Valley 10. Horizontal dashed lines demarcate soil horizons. Vertical dashed bars indicate the locality mean value for charcoal, delta ^{13}C, and phosphorus content.

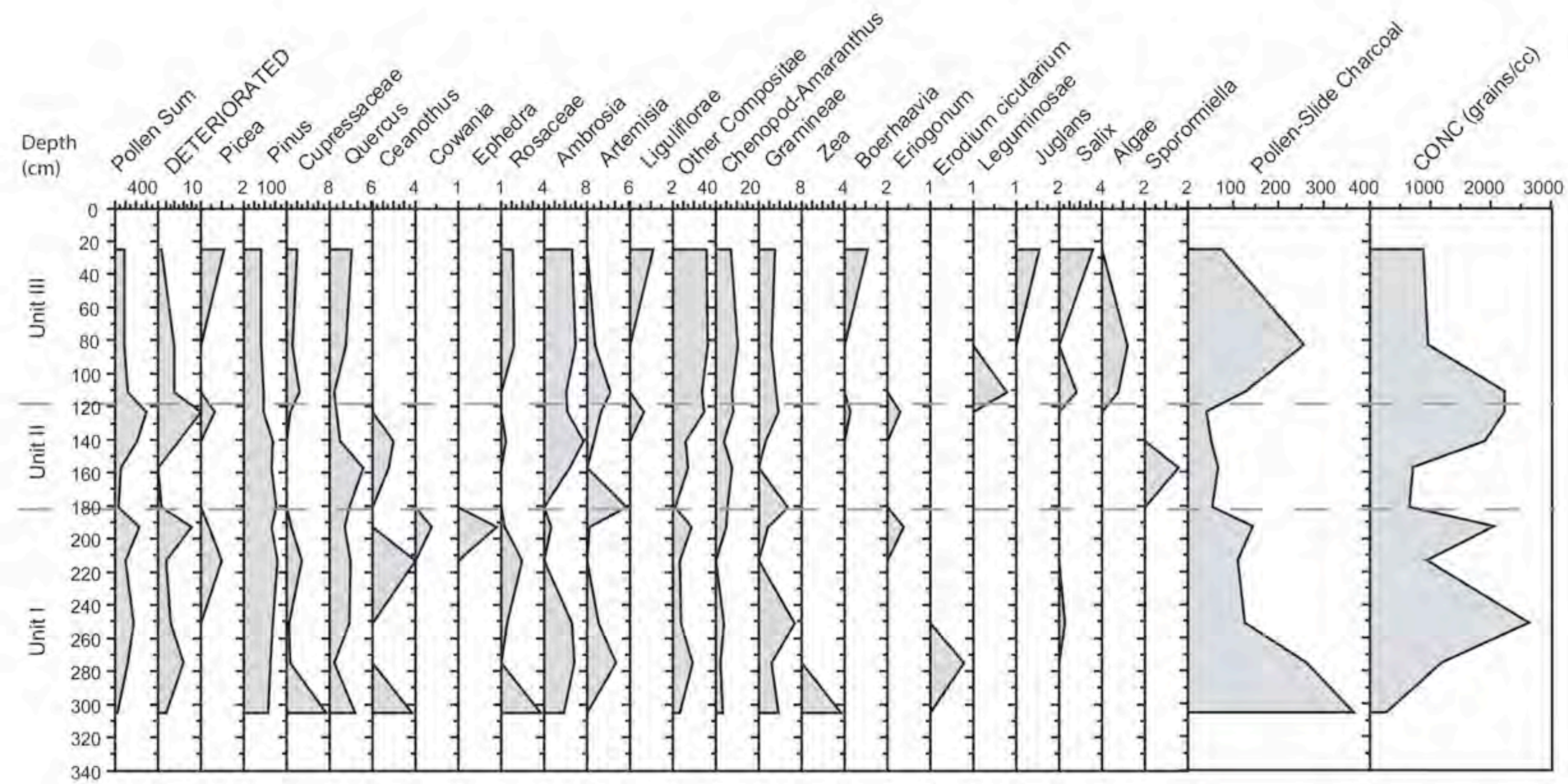


Figure 6.16 Percentages of selected pollen taxa, palynomorphs, and pollen-slide charcoal from Forestdale Valley 10. The horizontal dashed lines demarcate the boundaries between Unit I, Unit II, and Unit III.

After depopulation of the valley between AD 1390-1400, local herbivore populations and juniper and oak populations near the larger settlements rebounded from prehistoric hunting and collection pressures. Riparian vegetation began to appear near FDV 6, although Forestdale Creek had entrenched less than 200m downstream (Chapter 5). Charcoal concentrations in floodplain deposits of this age were similar to those from “control” watersheds, which suggest that “natural” fire regimes persisted after depopulation. By the middle of the 16^{th} century, both localities recorded increases in fire frequency that promoted herbaceous plant communities above previous levels and changed surface fuel characteristics. Relatively minor changes in isotope ratios coupled with changes in grain size and evidence for increased fire frequency support a tentative hypothesis of increased fall burning in addition to late spring and summer “natural” fires. Both the timing and the character of these fire regime changes are consistent with Western Apache settlement of the Forestdale Valley in the late 16^{th} century, the ethnohistoric practice of postharvest burning of wild seed collecting areas (Buskirk 1986; Gifford 1940), and a similar increase in fall burning reported from fire scar studies in areas of Apache occupation elsewhere in the Southwest (Morino 1996).

Forestdale Valley 20

Locality 20 is chronologically contemporaneous with a portion of Units II and III from Localities 6 and 10 (Chapter 5). Macroscopic charcoal concentrations were very low in the cross-bedded deposits below 220cm (before ca. AD 1475). Concentrations were highest between 140-220cm (ca. 1475-1550), but were generally comparable to those from the “control” watersheds. Above 140cm (after AD 1550) charcoal concentrations decreased slightly within largely sandy sediments. Virtually no charcoal was recovered from surface sediments (Figure 6.17). Stable carbon isotopes varied little between -23‰ and -23.7‰ throughout the sequence.

Pollen was well preserved, but concentrations were generally low to moderate (Figure 6.18). With the exception of a sample from 217cm (ca. AD 1480) pine pollen abundance was typical for meadow settings (i.e., between 30-52%). Above 93cm (after ca. AD 1630), composites, cheno-ams, grasses, and *sporormiella* increased in abundance. Riparian vegetation is only indicated in the uppermost buried soil (after ca. AD 1750). Although the record from Locality 20 is not as clear as those from Localities 6 and 10, the shifts in charcoal, *sporormiella*, herbaceous pollen abundance, isotopes, and grain-size data all echo the protohistoric impacts of Western Apache burning in addition to natural fires by the 17th century.

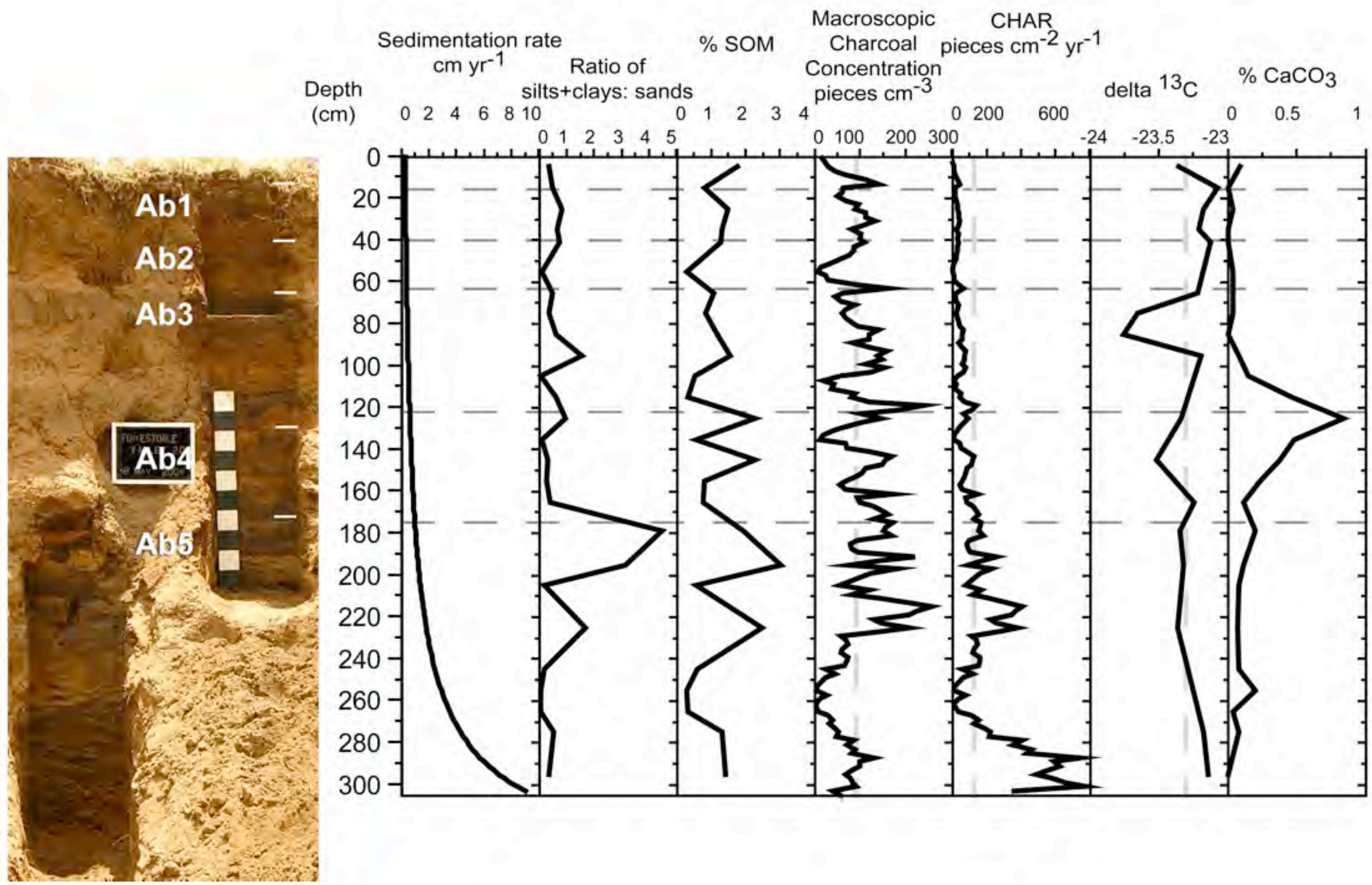


Figure 6.17 Macroscopic charcoal, stable carbon isotope ratios, and soil phosphorous content in relation to sedimentation rate, grain size (ratio of silts and clays to sand), soil organic matter and carbonate content from Forestdale Valley 20. Horizontal dashed lines demarcate soil horizons. Vertical dashed bars indicate the locality mean value for charcoal and delta ^{13}C.

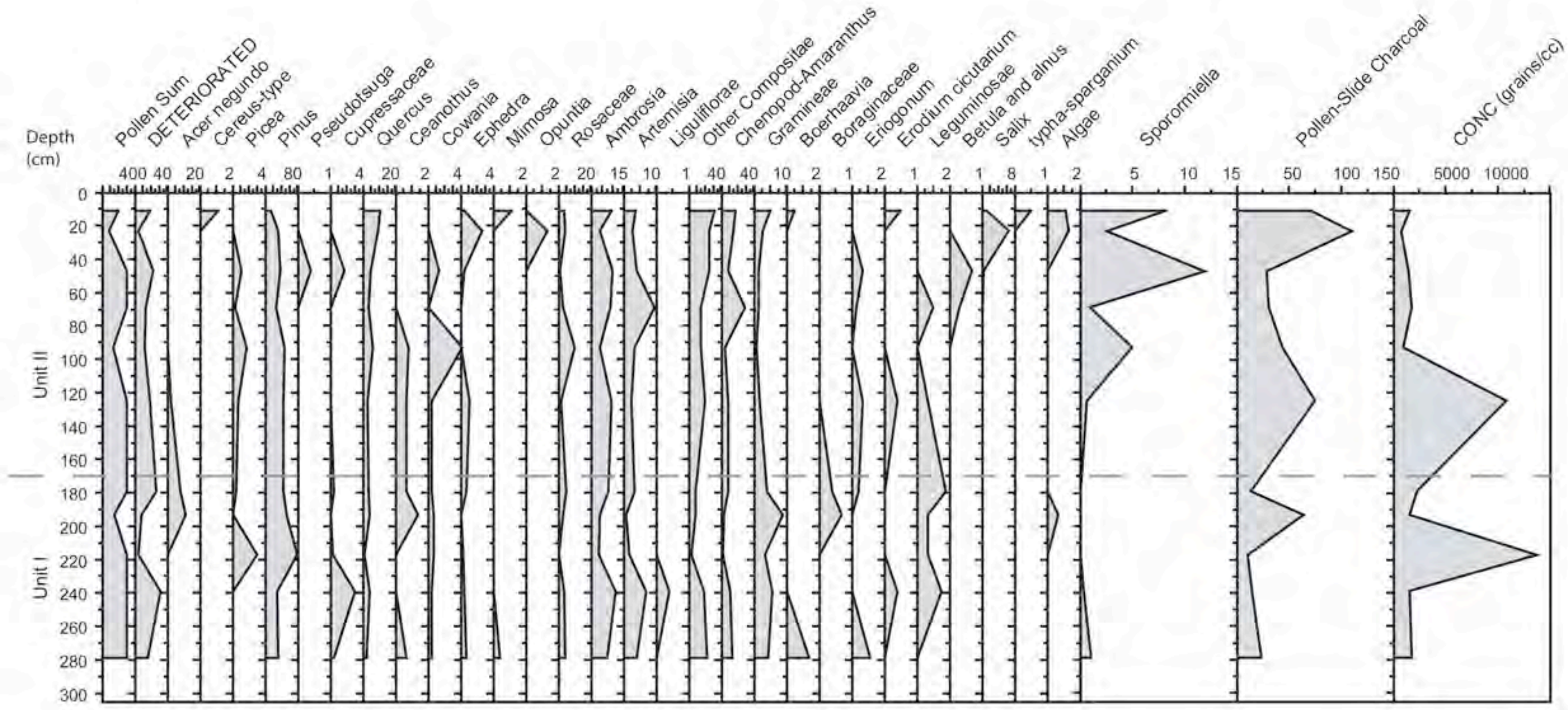


Figure 6.18 Percentages of selected pollen taxa, palynomorphs, and pollen-slide charcoal from Forestdale Valley 20. The horizontal dashed lines demarcates the boundaries between Unit I and Unit II.

Summary

Despite variability in channel morphology, watershed size, and occupation history, all four watersheds above the Mogollon Rim record evidence of altered fire activity during the late 15th or early 16th centuries. At Day Wash 14, where the stratigraphic sequence of charcoal, pollen, sedimentology, and chronometry was clearest, there was evidence for a landscape altering, high severity fire or fires during the middle or late 15th century. At Willow Wash 4, Rocky Draw 7, and Sharp Hollow 1, charcoal, pollen, and evidence for extreme erosion were also suggestive of high severity fire activity in the late 15th or early 16th centuries. The 15th century megadrought was one of the periods highlighted by Roos and Swetnam (nd; see also Chapter 3) when antecedent climate conditions may have facilitated fuel accumulation and canopy recruitment necessary for crown fires to carry in ponderosa pine forests. These records seem to corroborate the argument that, in the absence of other mechanisms for burning, low frequency variability in interannual moisture patterns that facilitate widespread fires may produce ponderosa forests vulnerable to high severity, stand replacing fires during prolonged droughts.

From the 16th through the 19th centuries, the paleoecological records from these three watersheds were consistent with “natural” high frequency, low severity fire regimes within ponderosa pine forests. *Phaseolus* pollen from 18th century sediments at Willow Wash 4 may corroborate elevated burning of the Day Wash and Willow Wash areas by indigenous groups in the protohistoric period. Where samples were analyzed, charcoal decreased, carbon isotope ratios became dramatically lighter (i.e., more C3), pine pollen became more abundant, and phosphorus values declined precipitously in surface sediments. This pattern is consistent with the anomalous removal of fire from ponderosa pine landscapes since the late 19th century.

In the Forestdale Valley, Localities 6 and 10 recorded charcoal evidence for anthropogenic burning in addition to natural fires during the prehistoric agricultural occupation between ca. AD 1200-1400. During the 15th and early 16th centuries, the area was unoccupied and charcoal, pollen, phosphorus, and isotope ratios were all consistent with "natural" fire regimes. By the late 16th century, these localities recorded increased burning that promoted herbaceous understory vegetation and may have occurred outside of the natural fire season. Grain-size and isotope data from these localities are consistent with postmonsoon burning that promoted cool-season herbaceous plants and reduced sediment mobility during the following year's intense summer rains. The timing of this shift in fire regimes and the inference of fall burning is consistent with the ethnohistoric practice of postharvest burning of seed collecting areas by Western Apaches, who probably used the Forestdale Valley regularly after moving into the area between AD 1550-1600. Stratigraphic evidence from Forestdale Locality 20 corroborates the records from Localities 6 and 10. At these localities, charcoal, phosphorus, pollen, and isotopes also record the late 19th century removal of fire from the Forestdale landscape.

CHAPTER 7. SYNTHESIS AND CONCLUSIONS

Despite emerging interest in multidisciplinary historical ecology among anthropologists and archaeologists, the ecological impacts of prehistoric human societies and traditional land use are rarely considered in applied historical ecological research. The legacy of the "noble savage" has persisted, albeit largely implicitly, in the investigation of pre-Euroamerican "natural" ecosystems for restoration and conservation. Science-based conservation utilizes historical ecological information to describe the range of "natural" variability (Landres et al. 1999; Swetnam et al. 1999), the resilience of alternative stable states (Gunderson et al. 2002), and the importance of key ecosystem engineers (Willis and Birks 2006) for restoring the structure, function, and services of degraded environments. Humanist historical ecologists necessarily recognize that social and "natural" systems can only be separated arbitrarily. From this perspective, landscape history is written by both human and natural events and processes in dialectical interplay (Crumley 1994). Humans are also preeminent niche constructors (Odling-Smee 1994; Odling-Smee et al. 2003) and have, throughout the Holocene, exerted new selective pressures on themselves and on other organisms in their environments through their activities and choices. In some cases, this activity has reduced the resilience of coupled social-ecological systems that ultimately transformed into alternative stable states resulting in the collapse of services and particular social organizations (Redman 1999, 2005).

However, assuming the ubiquity of human impacts on landscape history is just as misleading as assuming that traditional or indigenous societies had no impact on the ecological histories of the Americas. Human impacts were time and space specific and varied with mobility, land use strategies, technologies, and population densities. As responsible scientists, we benefit from 1) recognizing that indigenous societies may have impacted their environments in variable ways, at variable times and places; and 2) acknowledging that it is incumbent on historical ecologists to investigate the “where, when, and how” questions necessary to learn from past human experiences with American ecosystems and climate change.

Adaptive management strategies emphasize the process of learning from alternative management scenarios (Holling 1978). Archaeological historical ecology offers the opportunity to learn from millennia of landscape management activities. Such long-term perspectives allow the resilience of particular arrangements of coupled human-natural systems to be evaluated in the context of low and high frequency climate changes. Archaeologically informed applied historical ecology provides methods not only for inferring the historical ranges of variation for ecosystem structures and dynamics but for evaluating the resilience of different couplings of human land use, climate, and ecosystem processes.

For Southwestern ponderosa pine forests, it has become imperative that we understand the relationship of various coupled human-natural systems to long-term climate change. High severity fires have become more frequent, costly, and larger over the last half century coincident with increasing global temperatures (Westerling et al.

2007). Additionally, people are increasingly moving into vulnerable, Southwestern forests, thus expanding the widland-urban interface. Frequent, long and severe droughts in the Southwest are predicted outcomes of global climate change (Seager et al. 2007). High frequencies of long and severe droughts are implicated in increased fire severity from paleoecological and geomorphic records from Northern ponderosa pine forests (Meyer and Pierce 2003; Pierce et al. 2004; Pierce and Meyer 2008; Whitlock et al. 2008). Some scholars have suggested that these records indicate that 1) cool and wet conditions of the so-called “Little Ice Age” (ca. AD 1400-1900) obscured the role of high severity fire in ponderosa pine forests in fire scar records; and 2) that global climate change towards conditions outside of the “Little Ice Age” defined historical range of variation (HRV) means that the fire scar inferred fire regimes and HRV are no longer relevant for managing Southwestern forests (Sherriff and Veblen 2008; Whitlock et al. 2008).

This perspective, however, remains a hypothesis in need of testing. If climate is the primary driver of long-term changes in fire severity, what caused the changes in ecosystem properties (fuel accumulation, canopy density) that resulted in such a state shift? Drought may increase the vulnerability of hyperdense forests to stand replacing fires, but drought alone cannot explain changes in fuel structure and canopy density necessary for high severity fires to propagate (cf. Brown 2006; Brown and Wu 2005). Roos and Swetnam (nd; Chapter 3) hypothesize that low frequency change in interannual moisture patterns that are closely associated with surface fires during the historic period may promote the accumulation of fuels and allow accelerated canopy recruitment. By reducing the frequency of widespread surface fires, parts of the landscape could become vulnerable to crown fires. This model is similar to what happened in much of the Southwest in the late 19th and early 20th century. Widespread grazing by sheep and cattle reduced fire frequencies and facilitated fuel accumulation and regional pine recruitment during the exceptionally wet 1910s. Severe drought in the 1950s allowed crown fires to carry through altered stand conditions. Many of these areas have apparently shifted to alternative stable states (Savage and Mast 2005).

The role of land use is obvious in the modern scenario. Livestock grazing, and subsequent fire suppression by government agencies, reduced fire frequencies and altered the resilience of ponderosa pine forests. To use the "stability landscape" metaphor presented in Chapter 2, the major land use changes that accompanied Euroamerican settlement of the upland Southwest altered the shape of the basins and ridges separating alternative stable states for these environments. Indigenous land use, likewise, may have made these landscapes more or less resilient to climate change, but probably in different ways. For example, by applying surface fire in traditional land use, indigenous societies could have counteracted climate driven changes in fire frequencies in the past and prevented fuel accumulation by increasing ignition frequencies in areas where surface fuels had become discontinuous. Anthropogenic burning by indigenous Southwestern societies may have replicated "natural" fires in terms of frequency and seasonality (White 1932:94-96), may have occurred more frequently (Kaib 1998; Seklecki et al. 1996), or outside of the typical fire season (Kaye and Swetnam 1999; Morino 1996). Although anthropogenic burning by American Indian societies in the Southwest remains controversial (cf. Allen 2002), evidence from ethnography (Buskirk 1986; White 1932, 1943) and archaeology (Adams 2004; Sullivan 1982, 1996) suggests that modern and ancient Pueblo and Apache societies had a sophisticated knowledge of landscape fire and its uses on the landscape for ritual and economic purposes. Therefore, it is unnecessary to question whether Southwestern societies used fire on their landscapes. Rather, it is more meaningful to pursue when, where, and how traditional anthropogenic burning affected the ecological history of Southwestern landscapes. What were the long-term consequences of traditional burning? How did natural and anthropogenic fire regimes interact during periods of climatic stability or climate change?

The purpose of this dissertation has been to 1) evaluate the evidence for anthropogenic burning in relation to "natural" fire regimes and 2) evaluate the hypothesis that more closely coupled human-natural systems associated with traditional land use and anthropogenic burning were more resilient to long-term climate change that made less closely coupled environments vulnerable to high severity fires. To pursue these goals, I used spatially and temporally explicit analyses to identify where and when human impacts may have been most significant. I used a multiproxy approach to reconstruct fire regime history from alluvial sediments in five watersheds across a gradient of indigenous land use and occupation over the last 1000 years in the eastern Mogollon Rim region. Two unoccupied watersheds (Sharp Hollow and Rocky Draw) served as "controls" for sedimentary charcoal accumulation under "natural" fire regimes from AD 1650-1900. Two watersheds north of the Rim (Day Wash and Willow Wash) were occupied perennially by Ancestral Pueblo agriculturalists until AD 1325 (Mills 1998). Day Wash and Willow Wash were also on the northern edge of Cibecue Band Apache traditional territory during the historic period. South of the Mogollon Rim, the Forestdale Valley was occupied until AD 1390-1400 (Haury 1985; Mills and Herr 1999), and was also settled and regularly used by Western Apache groups (Goodwin 1942; Haury 1985), perhaps as early as the 17th century (Whittlesey et al. 1997:198).

Geoarchaeological evidence for anthropogenic burning

The best evidence concerning anthropogenic burning comes from the Forestdale Valley, where human-natural ecosystems were most closely coupled. The prehistoric occupation of the Forestdale area was longer than the archaeological study units above the Rim (Day Wash and Willow Wash) and the valley continues to be an important farm site for Western Apaches. Additionally, the stratigraphic sequences from Forestdale Localities 6 and 10 (FDV 6 and FDV 10) are the only sequences to overlap with the prehistoric occupation of the region.

Figure 7.1 plots sedimentary charcoal (macroscopic and pollen-slide charcoal), phosphorous, stable carbon isotopes, pine pollen, and pollen of herbaceous plants (all composites, cheno-ams, grasses, and herbs) as cumulative Z scores (standard deviation units around the mean). Z scores were calculated for macroscopic charcoal using the mean and standard deviation for “natural” fire regime periods from the control watersheds. Pollen data (including pollen-slide charcoal) were converted to Z scores using locality-specific means and standard deviations. Isotope ratios and phosphorus Z scores were calculated using values for all profiles from the watershed. These last two decisions were made because 1) pollen data are sensitive to local plant abundances (e.g., meadow vs. forest settings) as well as landscape pollen rain; and 2) because surfaces represented by weakly expressed soils were probably short lived, the phosphorus content and isotope ratios of organic matter are probably detrital and, therefore, largely represent basin-wide inputs and are standardized to reflect basin-wide variation.

During the Pueblo III and Pueblo IV period occupations of the Forestdale Valley (ca. AD 1200-1400), both FDV 6 and FDV 10 recorded unusually large (but variable) amounts of biomass burning, relative to “natural” fire regimes (Figure 7.1). At FDV 10, high phosphorous concentrations and maize pollen accompany the high charcoal concentrations. Downstream, at FDV 6, phosphorous concentrations are only high in the early 14th century (prior to massive upland erosion, see Chapter 5). At both localities, stable carbon isotope ratios vary little from the watershed mean (with a notable exception, ca. AD 1100-1200, at FDV 10) and pollen assemblages are typical for forest (upstream at FDV 10) and meadow (FDV 6) settings. This pattern is consistent with the burn-plot hypothesis. Sullivan (1982) suggested that Mogollon horticulturalists (Ancestral Pueblo, as used in this dissertation) may have taken advantage of the ash-bed effect of increased nutrient availability (Covington and Sackett 1990) by purposefully burning off vegetation and understory fuels of agricultural fields. The increase in biomass burning (elevated charcoal and phosphorous) associated with evidence of the cultivation of domesticates (*Zea* pollen) without evidence of increased abundance of wild herbaceous plant taxa is consistent with this hypothesis. Essentially, more fuels were burned per year than under natural fire regimes alone, but the areas burned by people were planted with specific plants (cultigens) rather than succeeding into postfire communities of wild herbaceous plants. This anthropogenic burning may have differed little in terms of seasonality (spring, prior to planting) and frequency (ash-bed effects typically last no more than 3-5 years) from the natural fire regime.

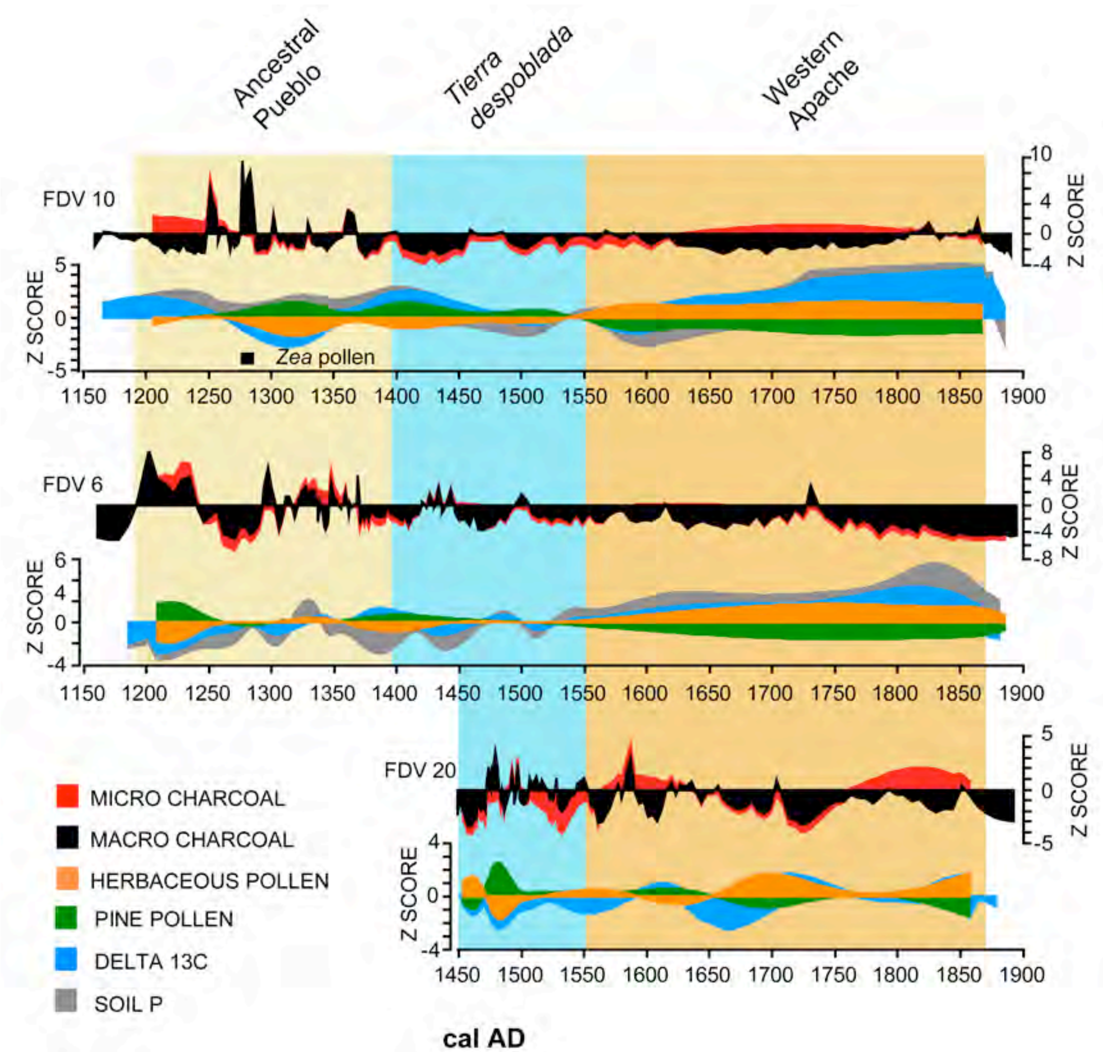


Figure 7.1 Charcoal, pollen, isotope, and phosphorus anomalies from the Forestdale Valley presented in cumulative Z scores (standard deviation units). Major periods of occupation and depopulation are highlighted. Consistent with burn-plot agriculture, elevated charcoal and phosphorus during the Ancestral Pueblo occupation is associated with pollen of domesticated plants and "natural" plant communities. *Tierra despoblada* paleoecological proxies are similar to the AD 1650-1900 "natural" fire regimes in control watersheds (Figure 7.2). During the Western Apache occupation, decreased macroscopic charcoal, increased phosphorus, microscopic charcoal, and herbaceous plant pollen are consistent with very high fire frequencies from natural fires and anthropogenic burning to increase productivity of wild seed harvesting areas.

It is probable that landscape burning was used for other purposes as well. Sullivan (1996) has suggested that Ancestral Pueblo communities in other parts of the southern Colorado Plateau used fire to improve wild plant productivity. The pollen data do not support this for the late prehistoric occupation of the Forestdale Valley. Pollen assemblages were virtually identical during the prehistoric occupation (ca. AD 1200-1400) and abandonment (AD 1400-1550) periods.

Ethnographies from modern Western Pueblo groups (probable descendants of prehistoric Ancestral Pueblo societies in eastern Arizona and western New Mexico) suggest other hypotheses for possible uses of landscape burning. Similar to ethnographic uses of fire by the Corn Clan at Acoma (White 1932, 1943), Forestdale residents may have used landscape fire within a 15-20km radius of the valley as part of communal rituals. Such burning may not have been part of agricultural strategies, but would have kept fuel loads low and promoted forage for deer and elk. The virtual absence of the herbivore dung fungus, *sporormiella*, in prehistoric deposits in the Forestdale Valley is suggestive; perhaps the high human population density of the Forestdale area suppressed local large game populations through overhunting, thus reducing *sporormiella* production. *Sporormiella* spiked at FDV 6, 10, and 20 during the early abandonment period (AD 1400s, see Chapter 6), indicating that herbivore populations rebounded in the valley once its human residents moved away. Despite local hunting pressures, large game appears to have become an even more important component of late Pueblo III and Pueblo IV diets (Dean 2001). Regular burning at a distance from the pueblo, akin to that described in the "Curatca lights the fires" ceremony at Acoma (White 1932, 1943), may have promoted forage for wild game to sustain regular longer-distance hunting forays. Although the archaeofaunal assemblage is consistent with this hypothesis, it cannot be evaluated with current geoarchaeological evidence.

Overall, the paleoecological and geoarchaeological evidence from the Forestdale Valley is consistent with burn-plot agricultural uses of fire by Ancestral Pueblo residents until depopulation between AD 1390-1400. An alternative interpretaton of the multiproxy record between AD 1100/1200-1400 may be that less frequent but larger or more severe fires occurred during this period, producing higher, but irregular charcoal concentrations and elevated sedimentation rates. Hypothetically, prehistoric trails and fuelwood collecting effects on surface fuel connectivity or the effects of Medieval Climate Period droughts on fire severity may have produced less frequent, more severe fires. Additionally, several late Pueblo III period settlements located in the ponderosa pine forest (Chodistaas, Grasshopper Spring Pueblo, AZ P:14:197 [ASM], and Bryant Ranch) were catastrophically burned in the late 13th century (Mills 2007; Tuggle and Reid 2001; Zedeño 1994). However, these conflagrations have been interpreted as anthropogenic, either as part of social conflict (LeBlanc 1999; Tuggle and Reid 2001) or as part of ritual decommissioning of these settlements (e.g., Montgomery 1993). Additionally, the fire severity interpretation of the prehistoric Forestdale Valley record is inconsistent with pollen assemblages (analogous to frequent surface fire assemblages with the addition of domesticates) and phosphorus data (indicative of net increases in phosphorus from more frequent ash inputs from low severity fires).

As would be expected, fire regimes during the *tierra despoblada* period—between the prehistoric depopulation of Forestdale Valley (AD 1400) and the colonization of the area by Western Apaches (ca. AD 1550-1600)—were virtually identical to "natural" fire regimes prior to Euroamerican settlement (compare the *Tierra despoblada* period from Figure 7.1 and the "natural fire regimes" from Sharp Hollow and Rocky Draw in Figure 7.2). Charcoal concentrations varied little around the mean values for control watersheds and pollen assemblages were unchanged from prehistoric assemblages. Phosphorus values declined at FDV 10 and FDV 6, consistent with the reduction in biomass burning after burn-plot cultivation ceased.

In the middle or late 16th century, nearly all proxies from all three localities in the Forestdale Valley recorded an increase in low severity, surface fire frequency that was sustained until historic stream downcutting (ca. AD 1910). These sequences record a reduction in coarse charcoal and increases in fine charcoal, herbaceous pollen taxa, and phosphorus. These coincident changes are consistent with fire return intervals frequent enough to promote and maintain herbaceous understory plants (and fuels). Carbon isotope ratios became slightly more negative, which could indicate small increases in C4 (warm-season grasses and weeds) plant production. The increase in C4 plant production does not appear to have been of comparable magnitude to the increase in herbaceous plants, which may indicate that the increase in fire activity promoted cool-season grasses more than warm-season taxa. Fire activity after the monsoon during the fall could explain this pattern. The change in sediment availability recorded at the Forestdale localities during this time is consistent with fall burning as well. Although hypothetical, increased intercept of monsoon rainfall by dense, understory vegetation promoted by fall burning during the previous year may explain the changes in sediment availability during the protohistoric occupation of the Forestdale Valley. Additionally, fall burning has been documented in fire scar studies elsewhere in Apacheria (Kaye and Swetnam 1999; Morino 1996).

The protohistoric period paleoecological record from the Forestdale Valley is inconsistent with expectations of a cooler and wetter Little Ice Age. For example, although increased fire frequencies might promote C4 plants (if the seasonality of burning were appropriate), C3 grasses would be expected to *increase* relative to C4 plants during cooler conditions. Carbon isotope changes from the control watersheds (Sharp Hollow and Rocky Draw; see Figure 7.2), however, are consistent with the expectation of cooler conditions promoting C3 grasses at the expense of C4 grasses, which further emphasizes the unexpected nature of the isotopic changes in the Forestdale Valley.

Western Apaches traditionally used fire as part of horticultural practices (Buskirk 1986:25, 43, 61, 77), in hunting (Buskirk 1986:127, 131, 135-136), and to promote wild plants (Buskirk 1986:97, 165-166). As an important farming area, the Forestdale Valley would have been used from the spring through the fall for planting gardens, wild plant harvesting, and hunting (Graves 1982; Pool 1985). The greens of cheno-ams and cool-season herbaceous plants were particularly important during the spring when other wild resources were scarce (Buskirk 1986:191-192). Fall burning of wild seed collecting areas during the previous fall (Buskirk 1986:165-166), associated with broadcast seeding of cheno-ams (Buskirk 1986:199) would have been economically important for prereservation Apache subsistence. An increase in fall burning is associated with Apache land use from fire scar studies (Kaye and Swetnam 1999; Morino 1996). The stratigraphic evidence from Forestdale suggests that ethnographically known Apache burning practices to promote wild plants modified local ecosystems soon after first colonization of the area. Although Zuni and Hopi people claim portions of the Mogollon Rim as traditional territories (Ferguson and Hart 1985; Zedeño 1997), the consistency of the paleoecological pattern from Forestdale suggests that most of the anthropogenic burning activity inferred from the paleoecological record was associated with Western Apache land use.

Stratigraphic evidence from Day Wash, above the Mogollon Rim, for the period between AD 1650-1850 is similar to that for the Western Apache burning pattern from Forestdale (Figure 7.2). Day Wash is not currently part of the Fort Apache Indian Reservation, but is included in maps of Western Apache traditional territories (Goodwin 1942:4, Map 1). Pollen of domesticated beans from contemporaneous deposits in the adjacent Willow Wash watershed support the hypothesis that at least some component of the historic period fire record at Day Wash was anthropogenic. The evidence for increased fire frequency at Day Wash, however, is coincident with a predicted increase in climate conditions suitable for widespread fires in the middle AD 1600s (Roos and Swetnam nd; see Figure 3.5). Episodic use by Western Apaches (or other indigenous groups) coupled with climatic conditions favorable to spreading fires may have combined to increase fire frequency in this area after AD 1650.

Altogether, there is stratigraphic evidence to support specific anthropogenic burning hypotheses for periods of Ancestral Pueblo and Western Apache occupation of the study area. Ancestral Pueblo burning, primarily for burn-plot cultivation, appears to have differed little in terms of seasonality and frequency of fires relative to the natural fire regime. After depopulation of the Forestdale area in AD 1400, natural fire regimes resumed. Beginning shortly after immigration into east-central Arizona in the 16th century, it is likely that frequent Western Apache fall burning to promote wild plants augmented natural fires.

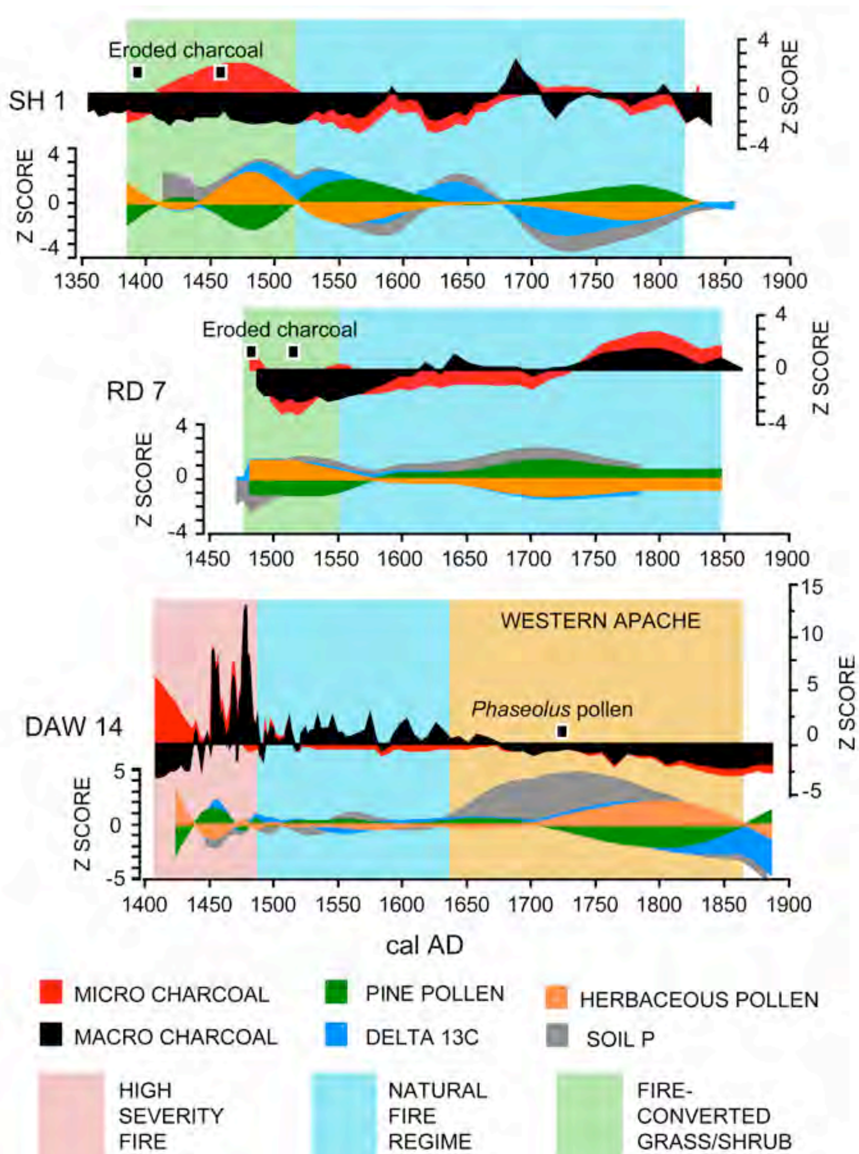


Figure 7.2 Charcoal, pollen, isotope, and phosphorus anomalies from three localities above the Mogollon Rim presented in Z scores (standard deviation units). Evidence for high severity fires or fire converted alternative stable states during the 15th and early 16th centuries was predicted by the interannual fire-climate model presented in Chapter 3 (Figure 3.5; Roos and Swetnam nd). Unoccupied, “control” watersheds (Sharp Hollow 1—SH 1; Rocky Draw 7—RD 7) record “natural” surface fire regimes after AD 1500/1550 (as inferred from regional fire scar analyses; Swetnam and Baisan 2003). After AD 1650, decreased macroscopic charcoal, increased phosphorus, microscopic charcoal, and herbaceous plant pollen at Day Wash 14 (DaW 14) are consistent with very high fire frequencies from natural fires and anthropogenic burning to increase productivity of wild seed harvesting areas by Western Apaches (Figure 7.1).

Resilience of coupled human-natural ecosystems and fire regimes

In the model of climate-driven fire activity presented in Chapter 3 (Roos and Swetnam nd), the 14th, 15th, and 16th centuries were identified as periods of below normal fire frequencies for woodlands and forests on the southern Colorado Plateau and adjacent areas. With reduced fire frequencies, multiyear wet and warm periods in the late 14th century would have been ideal for conifer recruitment (Brown and Wu 2005). Megadroughts during the 15th and 16th centuries would have been periods of elevated vulnerability to high severity fire activity *if climate were the only driver of fire activity*. However, indigenous occupants of ponderosa pine forests of east-central Arizona probably augmented natural fire regimes with anthropogenic burning. Over short time scales, this burning may not have been ecologically significant. For example, burn-plot agriculture in the Forestdale Valley does not appear to have reduced canopy density or have altered understory plant communities. The intensity of coupled human-natural fire activity, however, was probably limited to the vicinity of major human occupation (ca. 10-15km from residential sites) or along travel routes. The control watersheds were never occupied and the archaeological watersheds above the Rim were depopulated by AD 1325. Unless prehistoric land use of these watersheds had elevated fuel loads, these landscapes probably experienced the same climate driven reductions in fire frequencies and increases in canopy density similar to those of the "control" watersheds.

At Day Wash, unprecedented high charcoal concentrations (both macroscopic and pollen-slide) associated with pollen signatures of high severity fire activity dates to the 15th century. In the smaller control watersheds, evidence for unusual erosion and deforested vegetation date to the 15th and early 16th centuries (Figure 7.2). In contrast, prehistoric agricultural burning kept fire on Forestdale landscapes during the 14th century decline in natural fire frequencies. During the 15th and 16th century abandonment period, Forestdale Valley fire regimes appear to have been analogous to historical "natural" fire regimes. This suggests that more closely coupled human-natural systems associated with both natural and anthropogenic burning were less vulnerable to the long-term climate changes that resulted in high severity fires in less intensively coupled (unoccupied) landscapes. Interestingly, forest cover at Day Wash appears to have recovered relatively quickly, whereas the control watersheds appear to have been dominated by herbaceous and shrubby vegetation for up to a century after stand replacing fires.

Although these results should still be considered preliminary and suggestive rather than conclusive, it appears that anthropogenic burning associated with traditional land use improved the resilience of these landscapes to climate-driven fluctuations in fuel accumulation and fire severity. A larger sample of late-occupied ponderosa pine forest watersheds would be necessary to raise confidence in this hypothesis. However, it is probably significant that the Forestdale Valley did not experience increased fire severity during the late 16th century megadrought either, perhaps due to increased surface fire activity associated with Apache land use.

The results of this dissertation have important implications for contemporary management discussions. Some researchers suggest that the increased size and severity of Western fires may be due to climate change rather than the last century of land use, at least for ponderosa pine and mixed conifer forests from the Northern and Central Rockies

(Meyer and Pierce 2003; Pierce and Meyer 2008; Sherriff and Veblen 2008). By extension, they would maintain that the ecological reference conditions from the so-called "Little Ice Age" are no longer relevant to managing forests during the era of global warming. The present study casts appreciable doubt on this claim, at least for the Southwest. The ancient high severity fires above the Mogollon Rim probably occurred during the early centuries of the Little Ice Age (i.e., the AD 1400s and 1500s). It would appear that climate and land use are capable of amplifying or suppressing each other's impacts. The results of this dissertation suggest that, in the context of indigenous burning, low frequency climate change impacts may be suppressed. Although Southwestern ponderosa pine forests are vulnerable to high severity fires during droughts today, forest thinning coupled with natural and anthropogenic burning should be able to sustain open-canopied parklike forests and reduce the risk for high severity fires (Finney et al. 2005; Pollet and Omi 2002; Strom and Fulé 2007). This dissertation provides a long-term perspective that supports this view. Even in the context of variable climate conditions analogous to the range of variation over the last 1,400 years (Roos and Swetnam nd), frequent anthropogenic and natural surface fires are capable of reducing the risk for high severity, stand replacing fire, and sustaining "natural" ponderosa pine forests.

Considerations for future research

This study concludes that closely coupled human-natural systems and fire regimes in Southwestern ponderosa pine forests were more resilient to climate change than exclusively natural fire regimes. Confidence in this conclusion could be raised with a larger sample of study areas. Additionally, this hypothesis could be evaluated in ponderosa pine forests with different occupational and land use histories. For example, human impacts on landscape-level fire activity may be scale-dependent. Land use activities associated with higher population densities (i.e., more villages, fuelwood collecting, trail use, agricultural fields) may have reduced spatial continuity of surface fuels to the degree that some ponderosa pine forests became more vulnerable to droughts and ecosystem state shifts than areas with low population densities analogous to the Eastern Mogollon Rim region.

Confidence in the interpretation of alluvial proxies could be improved with systematic calibration studies. Sediments from recent, stand replacing fires have been helpful in this study, but the combination of fire scar analysis with alluvial sedimentary fire histories would improve interpretations of variation in low severity fire regimes. The use of alluvial sedimentary charcoal analysis is not yet common (McNamee 2003; Roos et al. 2008). Comparative studies with fire atlas or fire scar data, as have been done for lacustrine sedimentary charcoal analyses (Allen et al. 2008; Tinner et al. 1998; Whitlock and Millspaugh 1996; Whitlock et al. 2004), would be beneficial.

With improved interpretive reliability, alluvial fire histories could be developed further into the past in Southwestern ponderosa pine forests and adjacent ecosystems. Fire histories of pinyon-juniper woodlands have proven particularly difficult to reconstruct (e.g., Floyd et al. 2003; Romme et al. 2008). Small watersheds in pinyon-juniper woodlands, which were a favored habitat for prehistoric Southwesterners (Dean et al. 1985), may yet prove to be valuable sources of sedimentary fire history data.

Overall, this kind of research on fire histories, humans, and climate change has great promise. Multiproxy sedimentary analyses from alluvial deposits may extend Southwestern fire histories further into the past. By explicitly incorporating spatial and temporal variability in traditional land use into these applied historical ecology studies, one can learn more about the long-term dynamics of these systems than simply describing the range of historic variability. As we head into a future of uncertain climate change, it becomes increasingly important that we learn from the millennia of experiences that American Indian societies have had with Southwestern environments and climate change. By pursuing multidisciplinary research that does not arbitrarily remove indigenous people and their history from their environments, we will expand the learning window for adaptive management from a few years or decades to millennia.

APPENDIX A. LABORATORY METHODS

Laboratory analysis for 1) grain size distributions (Janitsky 1986b), 2) calcium carbonate (Machette 1986), and 3) organic carbon content (Janitsky 1986a) followed published protocols that have been adapted for use in the University of Arizona Geoarchaeology Laboratory. Sediment samples for 4) stable carbon isotope analyses were pretreated according to an unpublished protocol used in the University of Arizona Geoarchaeology Laboratory. Sediment samples analyzed for 5) phosphorus content were processed using a modified version of the protocols developed by Manuel Palacios-Fest (nd) at Statistical Research, Inc. Sediment samples for 6) macroscopic charcoal analyses were processed using an adaptation of the protocols described by Whitlock and Anderson (2003) and Rhodes (1998). Analyses of 7) soil thin sections were done using the reference material provided in Stoops (Stoops 2003), Bullock et al. (1985) Courty et al. (1989), and Goldberg and Macphail (2006) with the assistance of Paul Goldberg, Richard Macphail, Susan Mentzer and Francesco Berna. Appended to the brief description of laboratory methods for analyses 1-7 (above) is a list of the properties and associated interpretations for micromorphological observations presented in the Figures 5.6, 5.12, 5.15, 5.23, and 5.24.

Grain size analysis

1. Subsample approximately 25g of ground sediment (<2mm fraction).
2. Decalcify with approximately 2000ml of 0.5N HCl for 12-24 hours at 60° C in a hot bath.
    i. Decant.
3. Digest organic matter with 10ml of reagent grade (29-32%) H_2O_2 at room temperature for 12-24 hours at room temperature.
    i. Add to 60° C hot bath for 1-2 hours.
    ii. Decant.
4. Add 25ml of 10% Na-pyrophosphate (dispersant).
    i. Disaggregate with a malt mixer.
    ii. Wet screen through 63µm mesh with 1000ml of deionized water into graduated cylinder.
5. Dry sand fraction (>63µm) and measure weights of sand fraction by dry sieving.
6. Pipette silt and clay (<63µm) and clay (< 4µm) using settling velocity estimates.
    i. Weigh dried fractions and adjust for the weight of the dispersant.

Calcium carbonate using the Chittick apparatus

1. Subsample approximately 1-10g (based on effervescence estimate of carbonate content) of ground sediment (<2mm fraction).
    i. Place sample in round bottomed flask.
2. Attach flask to Chittick apparatus.
3. Slowly mix in 10ml of 3N HCl to the sample for 60 seconds.
4. Measure the volume of displaced CO_2.
5. Calculate the percentage of $CaCO_3$ in the sample based on the weight of the sample and displaced CO_2, adjusted for atmospheric pressure and temperature.

Organic carbon and soil organic matter

1. Subsample approximately 0.25g of ground sediment (<2mm fraction).
2. Add 10ml of potassium dichromate and 20ml sulfuric acid, allow to react for 30 minutes.
3. Add 150ml of deionized water and 4 drops of feroin indicator.
4. Titrate and mix in ferrous sulfate until the feroin indicator reacts.
5. Calculate the amount of oxidizable carbon using measures of 1) the strength of the normality of the ferrous sulfate, 2) the weight of the sample, and 3) the amount of ferrous sulfate needed to complete the oxidation.
6. Calculate soil organic matter by multiplying oxidizable carbon by 1.724.

Pretreatment of soil samples for stable carbon isotope measurement

1. Subsample 5ml of ground sample (<125μm) fraction.
2. Add 2ml of deionized water and 2ml of 3N HCl to the sample.
3. Place samples in 60° C hot bath for 2 hours.
4. Top off samples with deionized water, centrifuge and decant until sample is at approximately pH 5.
5. Dry and grind.
6. All stable isotope measurements were made at the University of Arizona Laboratory of Environmental Isotopes by Chris Eastoe.

Soil phosphorous analysis

1. Subsample 2g of ground sample (<125µm) fraction.
2. Add 25ml of diluted (1:6) Mehlich 2 extractant, gently shake for 10 minutes.
3. Filter sample and solution to remove sediment.
4. Mix 1ml of sample solution, add 99ml deionized water.
5. Mix 10ml of diluted sample solution with one Phosver3 reagent pillow in 10ml glass colorimeter sample cell.
6. Measure PO_4 of diluted sample using a Hach Portable Colorimeter, adjusted to measurements of blanks (deionized water with Phosver3 only).
7. Calculate PO_4 concentration for original sample (adjusted for dilution and sample weight; multiply by 212.5, a value derived by M. Palacios-Fest).
8. Calculate P concentration based on the atomic weights of oxygen and phosphorus; multiply by 0.326).

Sedimentary charcoal analysis

1. Subsample 5cm^3 of dry, loose sediment.
2. Add 100ml deionized water.
3. Add 25ml of diluted (3.5%) H_2O_2 to digest and lighten the color of unburned plant materials (Rhodes 1998).
    i. Allow to react at room temperature for 12-24 hours.
4. Add 25ml of 10% Na-hexametaphosphate to diflocculate the sample.
    i. Soak at room temperature for 4-8 hours.
5. Wet screen sediment through 250μm mesh.
6. Wash into gridded petri dish and allow to dry.
7. Count black plant tissues using a binocular microscope at 5-25X magnification.
8. Collect large plant tissues for radiocarbon dating.
9. Calculate charcoal concentrations (pieces cm^{-3}).

Soil micromorphology

a. Observations of soil thin sections were made using:

   i. Flatbed scanners (Arpin et al. 2002),

   ii. Microfiche reader (Goldberg and Macphail 2006),

   iii. Stereomicroscope with transmitted and reflected plane polarized light (PPL) and cross polarized light (XPL),

   iv. Petrographic microscope with transmitted and reflected PPL, XPL, and blue-light and UV fluorescence.

List of features recorded during survey of soil thin sections

1. Roots (R)—recently living roots, identifiable by high-order interference colors of cellulose in cell walls. These are probably from very recent, near surface plant activity (i.e., within the rooting zone).
2. Decomposing roots (D)—decomposing roots were identified based on their similar morphology and context to living roots (i.e., in channel voids) but lack of cellulose. Decomposed roots often contain evidence of consumption by soil microfauna (excrement features). These features may be from recent, near surface plant activity (i.e., within the rooting zone) or from plant growth in the past, perhaps associated with a now buried surface.
3. Mesofauna coporlites (Me)—identified as a jumble of plant tissues (often containing cellulose) between 1-4mm in maximum diameter. In most places, these were encountered as part of the groundmass and not within

voids. This was interpreted to mean that the coprolite was once on the surface and was subsequently buried by further sedimentation.

4. Earthworm granules (Ea)—identified as uniform sized, spherical aggregates of the groundmass (matrix of the sediment) within channel voids. These are evidence of earthworm activity (Stoops 2002).
5. Carbonates (C)—high-order interferene colors of micritic, microsparitic, and sparitic calcite. Most often was observed as hypocoatings on voids (coatings that impregnate the groundmass around a void). In some cases, carbonate features showed signs of etching and dissolution (incomplete, fragmentary hypocoats), particularly higher within profiles. In some cases when etching was observed, fine acicular (needlelike) crystals of calcite were also observed. These so-called lublinite crystals are indicative of reprecipitation of dissolved carbonates.
6. Dusty clay coatings (D)—fine grained grain (or void) coaings and bridges between grains (or aggregates) that lack the sharp extinction lines of well sorted, very fine clays and often have silt sized punctuations (charcoal or organic matter). In the context of the study localities, these coatings probably form via inundation (flooding) and percolation of suspended material through open pore space. Coarser material would be expected to settle out higher in the profile leaving finer material to settle out lower in the profile, producing limpid clay coats (L).

7. Limpid clay coatings (L)—fine grained grain (or void) coatings and bridges between grains (or aggregates) that have sharp extinction lines and clean, translucent appearance. My be indicative of downprofile sorting of periodically inundated contexts (see dusty clay coatings, above) or of *in situ* weathering of minerals to produce clays that are translocated downprofile as part of natural weathering and soil formation (i.e., lessivage). The latter situation is highly unlikely in semiarid climates over very short time frames, as represented by the sampling contexts.
8. Bedding features (B)—sedimentary features including graded beds/laminations (beds/laminations that become finer or coarser with depth), horizontal, or crossbedding/lamination. If any indications of major depositional features were observed, they were recorded. The lack of depositional features would be expected with a prolonged hiatus in sedimentation, bioturbation, and soil formation.
9. Reworked crusts (R)—thin, graded beds of silt and clay sized material that are often convex from drying while exposed on the surface. These features are also indicative of flooding and sedimentation.
10. Crusts (Cr)—*in situ* slaking crusts (see reworked crusts, above).
11. Redoximorphic features (Re)—indications of iron mobilization and accumulation (i.e., depletion zones and/or concretions) were recorded as redoximorphic features. These features are indicative of groundwater

fluctuations and periodic, perhaps seasonal, saturation and subsequent drying.

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