

**Fire Regimes of Kipuka Forests in El Malpais National
Monument, New Mexico**

A Thesis
Presented for the Master of Science
Degree
The University of Tennessee, Knoxville

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August 2003

To the Graduate Council:

I am submitting herewith a thesis written by Daniel B. Lewis entitled “Fire Regimes of Kipuka Forests in El Malpais National Monument, New Mexico.” I have examined the final paper copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geography.

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Dedication

All of my life, I have been blessed with people in my life that care and supported me no matter the cost. My parents, Larry and Linda Lewis, raised me to believe that I could accomplish anything that I set my mind to do. Although I sometimes didn't listen, they never failed to remind me. My parents' sacrifice and dedication are the reasons that I have become the person that I am. I am the luckiest individual in the world to have been blessed with parents that always cared, and still care, about my well-being.

My wife Tonya, my daughter Kristina, and my son Christopher, have been the best things to ever happen in my life. Without my wife's sacrifice, I would not have been able to complete this thesis. She has worked full-time to support me and allow me to do what I thoroughly enjoy doing, dendrochronology. I cannot express my gratitude for her patience and sacrifice. My daughter wants to be a teacher, my son a fire fighter. I cannot think of two more honorable careers to which to aspire, and I hope that I can make them believe, just as my parents did, that they can accomplish any goal they set before themselves, no matter how unattainable it might seem.

My sister was always the studious one, making the excellent grades while I settled for second-best. I have seen her grow from someone very unsure of herself, to a graduating senior voted best undergraduate major in the Music Department at the University of Tennessee. Her success inspired me to finally care about my academic future, and stop settling for second best. Thank you Michelle.

This thesis is dedicated to all these special people, whose efforts and sacrifice have made all of this possible.

Acknowledgements

I would like to thank my advisor and mentor, Dr. Henri D. Grissino-Mayer, not only for introducing me to the science of dendrochronology, but also ensuring that I had the knowledge needed to complete this thesis. He was tireless in his help both in the field and in the laboratory. I would also like to thank Dr. Sally Horn, who for three years has charged me to continue to better myself as a scientific writer. Her confidence in my abilities and continued support instilled in me the confidence that I could overcome all of my shortcomings. I am also grateful to Dr. Kenneth Orvis, for instilling in me the importance of thinking critically and the importance of considering all possible explanations instead of just taking the easy route.

I would like to thank Bob Clark and the Joint Fire Science Program for funding this research. I would also like to thank John Lujan, Herschel Schulz, Terry Goodman, and others at the El Malpais National Monument for their kindness, logistical support, and willingness to allow me the opportunity to conduct this research.

I would like to thank the Department of Geography and the Laboratory of Tree-Ring Science for providing me the equipment and facilities to complete this thesis. Three graduate colleagues, Beth Atchley, Michael Armbrister, and David Mann, helped with field sampling at El Malpais National Monument. I would also like to thank Kevin Anchukaitis, Jake Cseke, and Georgina Wight for their insight and peer reviews of early drafts. I am also grateful to Damian Kolbay for his help with initial preparation of a number of samples.

Abstract

Currently, ecosystem processes that maintain the forests of the American Southwest are operating outside the historical range of variation that existed prior to Euro-American settlement. Areas that have been minimally disturbed by humans should be targeted for research because they contain valuable information about past ecological processes. In El Malpais National Monument, islands of older substrate material are surrounded by younger lava flows. These areas, known as kipukas, likely preserve pre-settlement forest structure and contain trees old enough to provide information on past ecological processes. The purpose of this study is to reconstruct fire history on minimally disturbed kipukas in El Malpais National Monument, New Mexico. Eight sites were sampled and 105 fire-scarred samples were collected. Increment cores were taken from living ponderosa pine (*Pinus ponderosa* Dougl. ex. Laws) trees on two kipukas to examine the age structure of the kipuka forests and to determine whether fire suppression away from the kipukas may be allowing ponderosa pines to encroach onto areas not in their local distribution in the monument. Weibull Modal Fire Intervals ranged from 2.8 years to 42.8 years. The MOI was used because it has been shown to be a superior measure of central tendency, and more effective at identifying Southwestern fire structure independent of variables such as environmental gradient and habitat type. The age structure analyses indicated large numbers of ponderosa pine seedlings as well as a large age cohort <100 years old. The combined analyses indicate that 20th century changes in fire frequency on the lava flows due to fire suppression may be indirectly affecting the forest composition on the kipukas.

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1. Introduction

The trees composing the forest rejoice and lament with its successes and failures and carry year by year something of its story in their annual rings.

A. E. Douglass, 1922

1.1. Background

To successfully manage forests today, knowledge of the processes that maintained these ecosystems in the past is imperative. Currently, however, ecosystem processes that maintain the forests of the American Southwest are operating outside the range of variation that existed during the pre-European (<1880) settlement period (Morgan *et al.* 1994; Grissino-Mayer 1999). The overall purpose for establishing the historical range of variation is to describe the changes in ecosystem processes that occur over time (Morgan *et al.* 1994). It also assigns boundaries to ecosystem processes that occur frequently over time. Given, then, the widespread human alterations that have occurred since Euro-American settlement in the Southwest, present-day forests are likely not representative of the forests that existed prior to Euro-American settlement.

Wildfires play an important role in forest ecosystems by removing accumulated ground fuels, maintaining heterogeneity in both age and stand structure, and maintaining open, park-like conditions (Dieterich 1980; Wright and Bailey 1982). Since the early 1900s, widespread fire suppression has all but eliminated low-severity, stand maintenance fires. This has resulted in unprecedented fuel loads in most forested areas in the western U.S. (Cooper 1960; Swetnam 1990; Mutch *et al.* 1993; Covington and Moore 1994; Arno *et al.* 1995; Covington *et al.* 1997; Fulé *et al.* 1997; Veblen *et al.* 2000), and has dramatically increased the likelihood of high-severity, stand-replacement fires.

Beginning in the early 1970s, park managers came to understand that wildfires are important to the forest ecosystem, and managers are currently attempting to reintroduce fire via prescribed burning into areas where it has long been excluded (Covington *et al.* 1997; Fulé *et al.* 1997).

To better understand forest dynamics, areas that have been minimally disturbed by humans should be targeted for research because they contain vital information about past ecological processes. Such minimally disturbed areas exist primarily in isolated parts of the Pacific Northwest and in the American Southwest. In El Malpais National Monument, New Mexico, “islands” of older substrate material (usually sandstone or limestone) are surrounded by younger lava flows (Lindsey 1951). These islands, known as “kipukas,” likely preserve pre-settlement forest structure and contain trees old enough to provide insight into the ecological processes that were at work prior to Euro-American settlement.

These relict areas are also important for understanding 20th century fire regimes. Previous studies (Grissino-Mayer 1995; Grissino-Mayer and Swetnam 1997) have shown that these kipukas have unbroken fire records that extend into the late 1900s. Most other areas of the West and Southwest show abrupt fire decline occurring in the late 1800s and early 1900s (Dieterich, 1980; Baisan and Swetnam 1990; Savage and Swetnam 1990; Grissino-Mayer *et al.* 1994; Swetnam and Betancourt 1997; Brown and Sieg 1999; Brown *et al.* 2000; Veblen *et al.* 2000). Likewise, some areas inside El Malpais National Monument, including a number of kipukas, show a marked decline in fire frequency beginning *ca.* 1930 (Grissino-Mayer 1995).

Little is known about 20th century fire regimes in relation to pre-settlement fire regimes. The majority of fires that have occurred recently in the U.S. have been widespread, stand-replacing fires that are likely atypical. The relatively undisturbed kipukas may hold the key to understanding what the 20th century fire regime would have been like in this area in the absence of human-related disturbances.

1.2. Dendrochronology

This project will rely primarily on dendrochronological techniques. Dendrochronology is the science that uses tree rings dated to their exact year of formation to examine temporal and spatial patterns of environmental processes investigated for both the physical and cultural sciences (*e.g.* Kaennel and Schweingruber 1995). *Dendro* is derived from the Greek word *dendron*, meaning tree, and *chronology* is a temporal sequence of events. Andrew Ellicott Douglass (1867–1962) is widely considered the father of dendrochronology as it exists today.

Douglass (1946) formulated three major principles that are important in dendrochronological studies: (1) site selection, (2) surfacing, and (3) crossdating. Site selection and crossdating are closely related. Crossdating is made possible by the variability in the ring pattern (*i.e.*, wide and narrow rings), and this variability may be dependent on site characteristics. For example, a tree growing beside a stream, or some other water source, is never limited by the availability of water, so its ring pattern will be “complacent.” Conversely, a tree growing in a semi-arid location is limited by the amount of available moisture. In years of above average precipitation, the tree will put on more growth, and in below average years, less growth will occur, resulting in tree-ring

patterns that are “sensitive.” Therefore, researchers should carefully choose sites in which trees are limited by some environmental factor, (precipitation, temperature, humidity, or some other factor), so that the trees growing in that area will have distinct ring patterns associated with the environmental controls.

Crossdating is the single most important technique in dendrochronology (Douglass 1946). Because tree growth is primarily related to climatic factors, and trees from the same geographical area respond to similar conditions, it is possible to crossdate or match the ring pattern of a piece of wood with unknown dates to a tree with tree-ring dates that are anchored in time. Crossdating is accomplished by: (1) listing rings with characteristic features or width (Yamaguchi 1991), or (2) graphically or visually comparing the ring patterns of the undated piece of wood with the ring pattern of the dated tree (Swetnam *et. al.* 1985; Stokes and Smiley 1996).

If the tree rings from a sample cannot be successfully dated using these methods, more rigorous statistical methods exist to aid the dating process. COFECHA is a computer program that compares the ring measurements of dated or undated samples to ensure the correct temporal placement of all rings (Holmes 1983; Grissino-Mayer 2001a). The rings are first measured using a movable stage micrometer and standard measurement software such as MEDIR or Measure J2X. Each program is capable of recording ring widths to the nearest 0.001 mm, but 0.01 mm is usually accurate enough (Stokes and Smiley 1996). COFECHA then analyzes the ring pattern in segments (set at a length determined by the user) and compares that segment to the master chronology using correlation analyses (Grissino-Mayer 2001a). The master chronology used for the comparison is created from all other dated series.

It should be stressed that COFECHA, and other crossdating programs, should not be used as the sole means to crossdate samples. Rather, they are tools used to evaluate the quality of crossdating. The dendrochronologist should still determine whether a sample is successfully dated by graphical and visual inspection. Many different ecological disturbances can affect tree growth and can introduce error into the series being tested (Grissino-Mayer 2001a). For example, a dead, standing snag that falls on an adjacent, living tree may remove foliage by damaging the limbs of the living tree. This reduction of foliage will be evident in the ring series, causing growth suppression due to reduced photosynthetic activity. Disturbance-related changes in tree-ring growth might cause COFECHA to indicate inaccurate dates for the undated series. Situations such as these must be considered by the dendrochronologist to ensure that proper crossdating has been achieved.

The third technique that Douglass stressed was surfacing, a technique nearly as important as crossdating. Every sample must have a smooth, clear surface to enhance the visibility of the ring structure under standard magnification. This can be accomplished either by slicing the sample with a sharp razor blade (usually for cores only) or by sanding the sample (Stokes and Smiley 1996). When sanding, the sample is surfaced using progressively finer sanding paper until the desired quality is achieved. All of the samples in this project were sanded with a belt sander using ANSI 40-grit (500–595 μm) to ANSI 400-grit (20.6–23.6 μm) sanding belts (Orvis and Grissino-Mayer 2002). If the sample is not adequately surfaced, it will be difficult to analyze the ring series under standard magnification.

1.3. Organization of the Thesis

This thesis consists of seven chapters. In Chapter One, I introduce the background to this topic, review previous fire research conducted at the monument, state the objectives, and give justification for this research. I also examine the use of the age structure of the ponderosa forests on the kipukas to supplement the reconstruction of fire history. In Chapter Two, I discuss some of the previous research conducted on the few relict areas left in the U.S. and address the ecological importance of these relict areas. I then discuss previous research concerning tree-ring based reconstructions of fire history in the Southwest. I also include an overview of pre-settlement conditions of ponderosa pine (*Pinus ponderosa* Dougl. ex. Lawson) forests that likely existed in the Southwest. I then briefly examine the biogeography of the species and discuss its relationship to fire.

Chapter Three introduces the region surrounding El Malpais National Monument. I outline, map, and describe the major lava flows that make up the monument, including dates and descriptions of each individual flow. Next, I review the basic flora of the entire monument based on fieldwork and mapping performed by Carroll and Moraine (1992) and Bleakly (1997). A detailed description of each individual site sampled for this project follows. Chapter Four outlines the methods and techniques used in this project, including the use of FHX2 to archive and examine fire history data. Chapter Five summarizes the results. I outline the number of fire-scarred samples taken for each site, provide statistical analyses and master fire graphs for the fire history reconstruction, and include histograms for the age structure analyses.

Chapter Six discusses the major results of this research. I discuss the spatial and temporal changes that have occurred to the wildfire regimes of El Malpais National

Monument, and examine the effects of these changes on the structural characteristics of ponderosa forests on the kipukas. I also discuss the implications of this research for managing the monument. Finally, in Chapter Seven, I offer final conclusions and suggest future research that might further improve our knowledge of the fire regimes of El Malpais National Monument.

1.4. Fire history in El Malpais National Monument

1.4.1. Background

The first large-scale reconstruction of fire history in El Malpais National Monument was accomplished by Grissino-Mayer (1995), who also analyzed past climate in the monument, creating a 2,129-year record of precipitation. Grissino-Mayer found three major discontinuities in the fire record over the last 300 years. The first of these was a long hiatus of fire events beginning *ca.* 1790. One possible hypothesis for this discontinuity is the introduction of widespread livestock grazing. This hiatus, however, also appears in the fire records of the kipukas, where grazing likely did not occur, indicating that some other variable must be controlling the absence of fires. Although livestock grazing occurred in the monument, it is unlikely that large-scale grazing occurred because of the rugged, inaccessible terrain and the lack of a viable, long-term water source (Grissino-Mayer 1995). It is possible that Mesita Blanca, one of the kipukas included in the study, could have been grazed, thus reducing fire frequency, but this hiatus also shows up on Hidden Kipuka, a relatively inaccessible kipuka, indicating that some other factor must be responsible for causing this hiatus in fires.

A second hypothesis for this long fire-free period concerns the probable effects of climate change in the region. Climatic reconstructions from El Malpais National Monument indicate a shift in precipitation from below-average precipitation levels to above-average precipitation levels *ca.* 1790 (Grissino-Mayer 1995, 1996; Grissino-Mayer and Swetnam 2000). Numerous southwestern fire chronologies do show evidence of this fire-free period, although the duration of the period tends to vary spatially. For example, this fire hiatus occurred between 1820 and 1840 in the Gila Wilderness sites of southwestern New Mexico (Swetnam 1983, 1990; Swetnam and Dieterich 1985). It appeared from 1819–1838 in the Pinaleño Mountains of southeastern Arizona (Grissino-Mayer *et al.* 1994), and from 1800–1851 in Chiricahua National Monument (Swetnam *et al.* 1989).

The second major discontinuity in the El Malpais record occurred *ca.* 1880 with the introduction of livestock grazing by Euro-American settlers (Grissino-Mayer 1995). Widespread livestock grazing occurred in the monument itself, and fire records from the lava flow areas did indicate a reduction in fire occurrence beginning *ca.* 1880. Although the number of fire events diminished in the malpais in the late 1800s, fires did not abruptly cease in the area, as was the case in the nearby Chuska Mountains (Savage and Swetnam 1990).

The third major discontinuity in the fire records of the malpais area occurred *ca.* 1940. This discontinuity is a direct result of more effective widespread fire suppression efforts in the Southwest (Grissino-Mayer 1995). During this period, fire suppression methods became much more advanced, especially with the introduction of aircrafts as tools for fighting fires. Though some areas of the monument, primarily the isolated

kipukas, were not directly affected by fire suppression efforts, the inability of fire to spread may still have affected fire occurrences on these isolated areas. One hypothesis proffered by Grissino-Mayer (1995) that will be addressed by this study is how this fire suppression away from the minimally disturbed kipukas has affected fire frequency on the kipukas. I hypothesize that prior fire suppression in certain areas of the monument may have allowed ponderosa pine forests to encroach onto areas of the kipukas where they formerly did not exist by reducing fire occurrences on the kipukas themselves.

Fire occurrences abruptly ceased in the late 1930s on most of the lava flow areas sampled by Grissino-Mayer (1995). The next major fire in the malpais region occurred in 1976. Although many of the kipukas sampled by Grissino-Mayer are still actively recording fires throughout this period, the frequency begins to decline. If these kipukas truly are examples of relict vegetation, it is imperative that we understand how management techniques over the last 60–70 years have affected these ecologically important sites.

1.4.2. Justification

Grissino-Mayer (1995) indicated that widespread human disturbances (such as livestock grazing and fire suppression) have drastically altered the natural fire regimes in the monument. These alterations are also evident in most areas of the western United States. In recent years, high-severity, widespread fires have garnered considerable media attention, not only in the western United States, but also in the southeastern United States where a total of 203,522 hectares burned in 2002 (as of 12/2002, Southern Area Coordination Center 2002). The summer of 2002 was also one of the worst fire years

that the U.S. has seen in recent decades, with nearly 2.9 million hectares burning that year alone (National Interagency Fire Center 2002). This is nearly double the previous ten-year average (National Interagency Fire Center 2002). It has become more evident that widespread fire suppression has dramatically changed the natural fire regime in most forested areas in the United States. The lack of fire has allowed the build-up of heavy surface fuel loads and increased the likelihood of high-severity, crown-replacing fires. To help minimize the possibility of such catastrophic events, the agencies in charge of developing fire management guidelines must have knowledge of the local pre-settlement (*i.e.*, <1880) fire regime. This study will provide that information to the managers of El Malpais National Monument.

Although much research has been accomplished on the fire history of the malpais area, only a small portion was conducted on the kipukas. Only two of the many malpais kipukas have been sampled, Mesita Blanca and Hidden Kipuka (Grissino-Mayer 1995; Grissino-Mayer and Swetnam 1997). This project will re-examine those kipukas, and include three other kipukas not previously sampled. The Hoya de Cibola lava flow, which surrounds all but one of the kipukas included in this study, will also be examined to analyze the influence of this lava flow and its broken topography on the fire regimes of the kipukas. A more precise mapping of fire-scarred samples is also needed to more accurately depict the spatial patterns of past wildfires. The malpais kipukas could (1) increase our knowledge of 20th century fire occurrences; (2) further quantify effects of human disturbances on Southwestern fire regimes; and (3) resolve which factors may have impacted fire regimes in such isolated areas.

1.4.3. Objectives

The following primary objectives were addressed in this study for the reconstruction of fire history on the minimally disturbed kipukas.

- Samples of ponderosa pine, piñon (*Pinus edulis* Engelm.), and Rocky Mountain juniper (*Juniperus scopulorum* Sarg.) with multiple fire scars were collected from five malpais kipukas to develop fire chronologies as far back temporally as possible.
- To study the effects the Hoya de Cibola lava flow may have had on fire spread to the kipukas, I collected fire-scarred ponderosa pine samples to develop fire chronologies from three adjacent lava flow sites.
- I analyzed the spatial and temporal changes that have occurred in these fire regimes and will offer possible explanations for these changes.
- Analysis of the seasonality of past wildfires in the malpais region will be presented and discussed in terms of the changes in fire seasonality that have occurred.
- I will present precise maps of fire-scarred sample locations to foster more efficient study the spatial aspect of wildfires.
- This study also analyzes how the 20th century fire regime differs from that of the pre-settlement fire regime, and offers suggestions to those managing the monument to aid in the development of fire management policy.

1.5. Age Structure as a Supplement to the Fire History Reconstruction

1.5.1. Background

Fire suppression efforts away from the kipukas may be indirectly reducing the frequency of fire occurrences on the kipukas, thus allowing ponderosa pines to encroach onto areas of the kipukas outside of the tree's pre-settlement, local distribution.

Historically, ponderosa pines dominated the periphery of the kipukas, and were also found intermixed with piñon and juniper (primarily alligator juniper (*Juniperus deppeana* Steud.), one-seed juniper (*Juniperus monosperma* (Engelm.) Sarg.), and Rocky Mountain juniper) on the central ridges of the kipukas. This is evident from visual examination of the ages of the ponderosa pines on the adjacent lava flows and the central ridges of the kipukas. Grasses and small shrubs dominated the lower slopes of the kipukas.

Recently, though, ponderosa pines have begun to encroach onto the lower slopes of the kipukas. Numerous even-aged stands of younger ponderosa pines can now be seen growing on the lower kipuka slopes. The most likely cause for this encroachment is a reduction of fire occurrences on the surrounding lava flows. Although the kipukas themselves have not been directly affected by widespread fire suppression due to their inaccessibility and remoteness, they may have been indirectly affected. Based on fire reconstructions by Grissino-Mayer (1995), widespread fires that occurred on the lava flows are synchronous with widespread fires on the kipukas. This indicates that the majority of the fires occurring on the kipukas are carried to them from the adjacent lava flows. Changes in fire frequency on the adjacent lava flows will ultimately cause changes to the fire regimes of the isolated kipukas. The reduction of fire frequency on

the kipukas may be allowing ponderosa pines to establish and mature on areas formerly out of their pre-settlement, local distribution in the monument.

1.5.2. Justification

In a fire history and age structure analysis conducted on Mount Graham in southeastern Arizona, Grissino-Mayer *et al.* (1994) stated that the analysis of age structure along with the local fire history reconstruction may offer valuable insights concerning the ability of forests to recover following a disturbance. By conducting a systematic sampling of ponderosa pines growing on the kipukas, the age structure of the trees on different parts of the kipukas can be determined. My working hypothesis states that large numbers of trees less than *ca.* 100 years old will be found on the lower slopes of the kipukas, along with large numbers of seedlings. Any structural changes in forest composition will be more evident on the lower slopes due to the proximity of the established ponderosa pine forests on the adjacent lava flows. If the hypothesis is true, changes in fire frequency may be the underlying factor that allowed these trees to establish where they once were not able to establish. Historically, low-severity surface fires would have killed off most of the small ponderosa seedlings before they could become mature. It is also possible that a large age cohort of *ca.* 160–200 years of age may also be present here. This age class could be attributed to the large gap in fire occurrences from the late 1700s to approximately 1840 (Grissino-Mayer 1995). This structural change may be attributed to climatic fluctuation, though, and not to the exclusion of fire via fire suppression.

These kipukas are truly relict areas by definition because they are relatively undisturbed by humans. A primary question that must be answered, however, is how representative of pre-settlement forests are they? If the forest composition has been altered by human intervention, how significant are the changes? By analyzing the age structure of the ponderosa forests, any changes that have occurred in the forest composition can be determined and analyzed to evaluate the probable underlying cause.

1.5.3. Objectives

To examine the age structure of the ponderosa forests on the minimally disturbed kipukas, the following objectives were addressed.

- Two kipukas that were least disturbed by human-related disturbances (*i.e.*, logging, fire suppression and logging) were selected for age structure analysis.
- The age structure data was used in combination with the fire history data to make inferences on how forest structure has changed over time due to changes in fire history.

1.6. Research Questions

Four major research questions will be addressed in this study:

1. How interrelated are the fire regimes of the kipukas and the Hoya de Cibola lava flow, and can temporal changes in the fire frequency on this lava flow indirectly affect fire frequency on the kipukas?
2. Does the age structure of the kipuka forests indicate that forest composition has been altered due to temporal changes in fire frequency?

3. How representative are the kipukas of pre-settlement forest structure and how severely have human-related disturbances altered these relict areas?
4. What can the agency that manages the monument do to preserve these relict areas and reduce the effects of human-related disturbances on them?

2. Literature Review

2.1. Relict areas and their Ecological Importance

This study analyzes the fire regimes of areas that have had minimal human-related disturbances (such as fire suppression and livestock grazing). Very few areas remain in the United States that have not been significantly disturbed by humans. A small number of areas in central Oregon, Idaho, North Dakota, and New Mexico have been analyzed to better understand the ecological importance of relict areas (Lindsey 1951; Quinnild and Cosby 1958; Driscoll 1964; Tisdale *et al.* 1969; Grissino-Mayer and Swetnam 1995, 1997).

2.1.1. El Malpais National Monument Research

Alton Lindsey (1951) conducted the first large-scale research on the lava flows of the malpais. Lindsey analyzed many aspects of the association between vegetation and habitat on the lava flows and cinder cones of the malpais area. He observed vegetation to be denser at higher elevations and less dense and shrubbier at lower elevations. He observed three major vegetation communities on the lava flows; (1) the Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) belt, (2) the ponderosa pine belt, and (3) the Apache-plume (*Fallugia paradoxa* (D. Don) Endl. ex Torr.) belt. The Douglas-fir belt was found to dominate higher elevations in the northern end of the area, both on the lava flows and on higher cinder cones. He also noted that Douglas-fir could grow at lower elevations on the lava flows than it could off the lava because Douglas-fir trees in the

adjacent Zuni Mountains grow at elevations over 310m higher than the elevations at which it grows on the northern end of the lava flow area.

The second vegetation community, the ponderosa pine belt, is the dominant vegetation cover in the malpais and generally occurs at lower elevations than the Douglas-fir belt (Lindsey 1951). An intriguing subset of this community is the stands of “bonsai” or “pygmy” ponderosa pines on the geologically young (*ca.* 3300 yrs) (Laughlin *et al.* 1993) McCarty’s lava flow. Here, Lindsey found many stunted, contorted ponderosas, none higher than five meters. His study found that ponderosa pines were “indicator species” for basalt, adding that ponderosa pines occur anywhere lava is found in the area. As is true for the Douglas-fir belt, ponderosa pines are also able to grow at lower elevations on the lava flows than off them because the porous nature of the lava tends to trap any available moisture, allowing it to pass through the cracks in the lava and away from the surface heat that would cause rapid evaporation.

The third vegetation community is the Apache-plume belt that occurs between the other two communities. This community is characterized by short, scrubby vegetation and the presence of piñon and one-seed juniper. This is the primary vegetation community on the upper slopes of the isolated kipukas, with some ponderosa pines mixed in. The Apache-plume community is most closely related to the shrub/conifer community described by Bleakly (1997).

Lindsey revisited the malpais region in 1981, eight years before it would become a national monument, and rephotographed landscapes pictured in photographs taken by him in 1951 from the same camera positions (Lindsey 1997). Lindsey considered the changes that he observed in vegetation cover to be “ecologically significant,” adding that

many of the things that he had originally seen were no longer present. While some of these changes could be attributed to natural processes, many were directly related to human disturbances, such as livestock grazing, fire suppression, and the construction of and interstate highway in the area.

2.1.2. Craters of the Moon National Monument, Idaho

A primary ecological importance of the study of relict areas is their use as control sites to study fluctuations in undisturbed ecosystems. One kipuka that was selected for such a study is the Carey kipuka in the Craters of the Moon National Monument, Idaho (Tisdale *et al.* 1965). Emphasis was placed on the ability to use the Carey kipuka to quantify anthropogenic changes that have affected surrounding areas. Areas such as this also provide excellent control areas to study vegetation dynamics and succession in undisturbed vegetation (Tisdale *et al.* 1965). This kipuka was described as virtually undisturbed, with only a few unconfirmed verbal reports of sheep grazing during the 1920s. The Carey kipuka is much larger (73 hectares) than any of the malpais kipukas analyzed for this study, and the lava flows surrounding the kipuka are somewhat younger in age (1,600 yrs). The Carey kipuka is topographically similar to the malpais kipukas, with a central ridge and a north/south orientation.

Unlike the malpais kipukas, the Carey kipuka is not forested. The vegetation cover is primarily sagebrush-grass (Tisdale *et al.* 1965). Three major vegetation communities were identified on the kipuka: (1) *Artemisia tripartite*/*Festuca idahoensis* Elmer, (2) *A. tridentata* Nutt./*Festuca idahoensis* Elmer/*Agropyron spicatum* Pursh, and (3) *A. longiloba* (Osterhout) Beetle/*Festuca idahoensis* Elmer/*Stipa thurberiana* Piper

(Tisdale *et al.* 1965). The parent substrate material is primarily loess, but soil characteristics vary slightly on the kipuka and are closely related to the different plant communities (Tisdale *et al.* 1965). Precipitation levels and temperature are similar to the malpais, except for the late-summer monsoonal precipitation that occurs in the Southwest.

The Carey kipuka was undergoing changes in grass composition. The principal grass type that was noted in 1965, *F. idahoensis* Elmer, was not present at all in 1941 when Egglar (1941) analyzed succession on the kipuka. By 1965, *Festuca* was incurring extremely high mortality rates on the kipuka as a whole. The primary reason given for this turnover was a short-term drought from 1959–1961, as normal climatic conditions in the area were reported to be marginal for this species. The authors also intended to investigate the possibility that disease might have caused widespread mortality in the grass. The mortality of *Festuca* has allowed other annual grasses (such as *Bromus tectorum* L.) to establish on the kipuka. Prior to this period, *Bromus* was confined only to small portions of the kipuka.

2.1.3. “The Island,” Central Oregon

Driscoll (1964) examined relationships between vegetation and substrate on an isolated plateau in the central Oregon juniper zone known as “The Island.” The plateau is approximately 101 hectares in size and has very steep vertical cliffs surrounding it. It has been relatively undisturbed, with only two known grazing occurrences in 1922 and 1928 (Driscoll 1964).

Driscoll delineated two primary vegetation associations:

Juniperus/Artemisia/Agropyron and *Juniperus/Purshia/Agropyron* (Driscoll 1964).

Shrub cover was visually estimated using small plots and tree cover was calculated by using aerial photography. The *Juniperus/Artemisia/Agropyron* association was dominant, covering approximately 87 hectares (Driscoll 1964). The trees occurred in groups or individually, and were unevenly spaced over the plateau. Driscoll also noted evidence of past wildfire in the form of charred stumps and logs.

The *Juniperus/Purshia/Agropyron* associated was dominant on the other 14 hectares of the kipuka. Trees in the association were somewhat shorter, still occurring in widely-spaced clusters. Soil moisture capacity was found to be much lower in this association compared to the other association.

The examination of vegetation associations on The Island provided information on what surrounding areas might have been like in the absence of human-related disturbance (Driscoll 1964). By examining vegetation associations on nearby disturbed areas with similar characteristics, Driscoll found that grazing adversely affected perennial abundance in the *Juniperus/Purshia/Agropyron* association. Instead, species such as *Bromus tectorum* L. were more abundant. These data illustrate how important relict areas could be to the management of surrounding disturbed areas.

2.1.4. Billings County, North Dakota

Quinnild and Cosby (1958) examined vegetation characteristics on two relatively undisturbed mesas in western North Dakota to compare the relict vegetation found on these two mesas with vegetation of adjacent valleys and of other more disturbed mesas

nearby. These two mesas, named “Big-Top” and “Two-Top,” are located in Billings County, North Dakota. A local rancher provided information that hay had been cut once on Big-Top mesa, but livestock grazing had never occurred on either mesa.

The study examined changes in vegetation that occurred because of fire. Quinnild and Cosby were able to partially examine fire events on Big-Top mesa by aging fire scars contained in junipers found on the edges of the mesa by counting tree rings. Although crossdating techniques were not applied, ring counts on Big-Top indicated a fire that occurred 16–17 years earlier, around 1940. To substantiate their data, they also aged some large sagebrush found on the mesa by counting growth rings and found that they appeared to be approximately 16–17 years old. Quinnild and Cosby were unable to find any evidence of fire on or around Two-Top mesa. Older, large sagebrush were noted growing on the mesa, one having a ring count of approximately 47 years.

Sagebrush is also a common shrub on most of the malpais kipukas. Although ponderosa pine is generally a more accurate means of establishing fire history, it is possible that sagebrush could be used to supplement the fire history data. The use of sagebrush in fire history studies in the malpais could also provide information on the successional dynamics of the shrub and its ability to establish after a fire event.

2.2. Anthropogenic Changes in Southwestern Fire Regimes

Numerous studies have documented the changes that have occurred in Southwestern forests due to human-related disturbances over the last 150 years. Three primary disturbances have been examined: livestock grazing, logging, and fire suppression. Few areas in the Southwest have escaped these disturbances.

Livestock grazing tends to reduce fire frequency by removing fine fuels that propagate fires. Savage and Swetnam (1990) detected effects of livestock grazing on fire regimes in the Southwest as early as 1829. This study, conducted in the Chuska Mountains along the New Mexico-Arizona Border, compared local changes in fire frequency with changes in other areas of the Southwest. Savage and Swetnam (1990) found that fire occurrences became uncommon after 1829 due to increased livestock grazing by Navajo populations in the area. This increase in livestock grazing also coincided with the beginning of the wettest period in the Southwest's history (Grissino-Mayer 1995, 1996; Grissino-Mayer and Swetnam 2000), which acted to further reduce fire frequency.

Other studies (Dieterich 1980; Swetnam and Dieterich 1985; Allen 1989) found that fire frequency decreased beginning *ca.* 1880. Areas in and around El Malpais show fire frequency beginning to decline *ca.* 1880, a date comparable to most other areas in the Southwest (Grissino-Mayer and Swetnam 1995). The fact that the decline in fire frequency began much earlier in the Chuska Mountains than was documented for surrounding areas suggests that livestock grazing does significantly affect fire regimes in ponderosa pine forests (Savage and Swetnam 1990).

The removal of grass cover by livestock along with the onset of fire suppression in the early 1900s have acted to reduce fire frequency beginning in the late 1800s in most areas, but ramifications are only now being felt with the occurrence of recent widespread, high-severity fires in the western U.S. Grazing removes ground fuels that propagate fires, but the removal of grass cover has also led to increased establishment of juvenile ponderosa pines in the Southwest by decreasing competition from grasses and increasing

the area available for establishment (Cooper 1960; Savage and Swetnam 1990). These dense, “dog-hair” thickets of ponderosa pines increase the likelihood of high-severity wildfires because they add ladder fuels for the vertical spread of wildfires. Forests with dog-hair thickets are unsuitable candidates for the introduction of prescribed burning without thinning, as any fire occurrence would most likely destroy the stand (Cooper 1960).

2.3. Pre-settlement Conditions in Ponderosa Pine Forests

The ponderosa forests that existed prior to widespread Euro-American settlement had little resemblance to current Southwestern forests. Cooper (1960) described numerous historical accounts that indicated widespread dominance of ponderosa pine in open, park-like forests. Instead of uneven-aged stands occurring over a wide area, Cooper stated that the age structure of the forests actually comprised numerous even-aged blocks, with all ages being represented if one were to examine the entire forest stand (Cooper 1960). These blocks were created by beetle outbreaks that produced large patches of dead, standing snags. Episodic wildfires, usually more severe than the normal stand-maintenance fires because of the increased fuel loads, would then sweep through the snag patch, consuming the dead trees. The grasses that dominated the areas between the trees would also be removed during the wildfire event, thus allowing seedlings to germinate and establish without competition from the grasses.

White (1985) does not dispute Cooper’s assessment of age structure characteristics in pre-settlement ponderosa forests, but he indicates that it may be oversimplified. Although widespread fires did act as agents to provide large areas for new

ponderosa establishment, White suggested that much larger age ranges were evident in these patches than Cooper first indicated. Regardless of how large the age range was in these large clusters, most researchers agree that pre-settlement ponderosa forests were most often composed of numerous large clusters of fairly even-aged stands driven by episodic wildfires more severe than the typical stand-maintenance fires (Cooper 1960, 1961; Morrow 1985; White 1985; Agee 1998).

2.4. Biogeography of Ponderosa Pine

2.4.1. Introduction

Ponderosa pine is one of the most widely distributed pine species in western North America (Oliver and Ryker 1990). Its drought tolerance allows it to persist and thrive in highly stressed environments (Agee 1998). Historically, ponderosa pine was a very important source of timber in the Western U.S. It is a fairly large tree, reaching heights of 46–55 meters and diameters of *ca.* one meter. Although a small number of ponderosa pines have been found to be over 500 years in age (Harlow and Harrar 1937; Keen 1937), this is a rare occurrence.

Ponderosa pine needles are generally 12–28 cm in length and are yellow-green. Cones are usually 7–15 cm in length. The bark of the younger trees is very dark and furrowed, so dark that they are sometimes called “black-jack” pines. As the trees mature, the bark takes on a cinnamon color and becomes very thick and plated. This very thick bark protects the inner cambium, the living tissue under the outer bark, from injury due to fire.

Pure stands of ponderosa pine can be found in the Black Hills of South Dakota, the Blue Mountains of Oregon, northeast of the Sierra Nevada, and in northern Arizona and New Mexico (Harlow and Harrar 1937). It is generally a climax species at lower elevations and a seral species at higher elevations in more mesic forests, where it often grows intermixed with Douglas-fir, grand-fir (*Abies grandis* Dougl. ex D. Don), lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.), and Rocky Mountain juniper (Oliver and Ryker 1990). Although many ponderosa seedlings are killed by fire, the thick bark allows it to out compete other species such as Douglas-fir and grand-fir that are much less fire tolerant when young. Fire suppression in the 20th century, though, has led to the decline of ponderosa pine in some of these mixed conifer forests due to increased competition from other conifers (Oliver and Ryker 1990; Grissino-Mayer *et al.* 1995).

2.4.2. Genetic Diversity

Three varieties of ponderosa pine are currently recognized, Pacific ponderosa pine (*Pinus ponderosa* Dougl. ex Laws. var. *ponderosa*), Rocky Mountain ponderosa pine (*Pinus ponderosa* var. *scopulorum* Engelm.), and Arizona pine (*Pinus ponderosa* var. *arizonica* Engelm.) (Little 1979). Oliver and Ryker (1990) stated that Arizona pine (*Pinus arizonica* Engelm.) is currently recognized as a separate species. Ponderosa pine has been known to hybridize with Jeffrey pine (*Pinus jeffreyii* Grev. & Balf.), Arizona pine, and sometimes Apache pine (*Pinus engelmannii* Carr.) (Oliver and Ryker 1990).

2.4.3. Site Preferences

Climate and topography within the natural range of ponderosa pine vary greatly. In eastern Oregon, precipitation ranges from 36–72 cm annually. Much of this precipitation occurs as snow, and July, August, and September are very dry (Oliver and Ryker 1990). In El Malpais National Monument, precipitation ranges from 28–58 cm annually, but the majority of precipitation occurs in July and August associated with the summer monsoon.

Although seasonality of precipitation may vary, temperature does not. Wherever the tree grows, average annual temperatures are between 5° and 10° C, and July to August average temperatures are between 17° and 21° C (Oliver and Ryker 1990). These temperature requirements result in lower altitudinal limits in the northern parts of its range. For example, elevations range from sea level to 1220 m in Washington and up to 3050 m in the southern Rockies (Oliver and Ryker 1990).

2.4.4. Relationship of Ponderosa Pine to Fire

Numerous studies have analyzed fire history in ponderosa pine forests in the western and southwestern U.S., primarily because of its susceptibility to repeated scarring. Historically, fire intervals were very short in most ponderosa pine forests, with intervals as short as 1.8 years reported in some areas (Dieterich 1980). Pre-settlement ponderosa forests were also characterized by a dense herbaceous understory component (Agee 1998). This dense ground cover, along with the continual deposition of pine needles due to shedding, created a continuous layer of fine fuels to propagate wildfires.

Although ponderosa pine seed dispersal is not directly dependant on fire, as is the case with jack pine (*Pinus banksiana* Lamb.) or lodgepole pine (Wright and Bailey 1982), fire acts as a thinning agent to maintain open forests and creates new opportunities for seedling establishment. Ponderosa pines have become adapted to low-severity, episodic wildfires, and thrive in these conditions. *Pinus ponderosa* has adapted very thick, plated bark to aid in protecting the cambium from serious injury due to fire (Keeley and Zedler 1998). Even smaller, suppressed ponderosa pines have been known to survive 4 to 5 wildfires before a gap makes normal growth possible (Keeley and Zedler 1998). Ponderosa pines have long needles that act to dissipate heat away from the apical meristem, as well as deep-rooting habits that protect the root system from damage due to severe heating (Wright and Bailey 1982). They have also developed the self-pruning habit that is common among many other fire-tolerant *Pinus* species (Keeley and Zedler 1998). Self-pruning branches that are close to the ground diminish the likelihood of fire reaching the crown.

3. El Malpais National Monument

3.1. General Setting

El Malpais National Monument (*malpais* is Spanish for “badlands” or “bad country”) was established December 31, 1987 to protect a unique, geologically young lava flow environment (USDI National Park Service 1990). The monument is located in northwestern New Mexico, on the southern edge of the Colorado Plateau, and is part of the much larger Zuni-Bandera volcanic field located in west-central New Mexico. The volcanic activity in the area is associated with the Jemez Lineament, which extends from northeastern New Mexico into central Arizona (Laughlin *et al.* 1993). This tectonic structure has supported volcanic activity for approximately 16 million years, the most recent of which occurred *ca.* 3000 years ago in El Malpais National Monument (Laughlin *et al.* 1993).

The region is characterized by a hot steppe climate (BSh in the Köppen classification system) with very warm summers and fairly cool winters. Drought conditions persist throughout most of the year, with the exception of late summer when monsoon rains in late July and August begin to recharge soil moisture (National Climatic Data Center 2000). The dry conditions in spring and early summer (May and June) create an extremely high fire danger in the region.

In the monument itself, precipitation is generally less than 43 cm per year, with the exception of El Niño years, when precipitation is usually higher (National Climatic Data Center 2002). The lowest yearly precipitation in the last 10 years occurred in 2001, with a total of 28 cm (Figure 3.1) (El Malpais National Monument Headquarters 2002).

The highest yearly precipitation in the last 10 years was 1997 with 61 cm (El Malpais National Monument Headquarters 2002).

The vast majority of northwestern New Mexico lies above 2000 m in elevation. Relief is negligible around the malpais, though, with the exception of the Zuni Mountains to the north and local cinder cones. The San Mateo Mountains rise just northeast of Grants, New Mexico, approximately 32 km northeast of the monument. Mount Taylor, the tallest stratovolcano in the Southwest, is found in this chain. The Zuni Mountains, which define part of the Continental Divide, are located just northwest of the monument. The Chain of Craters, also on the Continental Divide, are a group of cinder cones that extend southward along the western boundary of the monument. More than 20 cinder cones are found here, including Cerro Americana, Cerrito Arizona, Cerro Hueco, and Cerro Negro.

Inside the monument, elevations range from 2100 m in the south, to 2562+ m in the north (Figure 3.2). Several cinder cones are found here, the most famous being Bandera Crater. Here, tourist trails lead up inside the cinder cone through a breach in the southwestern wall. Ice caves also exist at the base of Bandera Crater in large collapses in the lava. Other cinder cones include Lost Woman, Cerro Bandera, and Cerro Encierro. The southern portions of the monument are generally devoid of major relief features, such as cinder cones. Several kipukas can be found scattered in this area, though. Upper elevations of the kipukas generally do not exceed 2350 m, and the kipukas rise only *ca.*

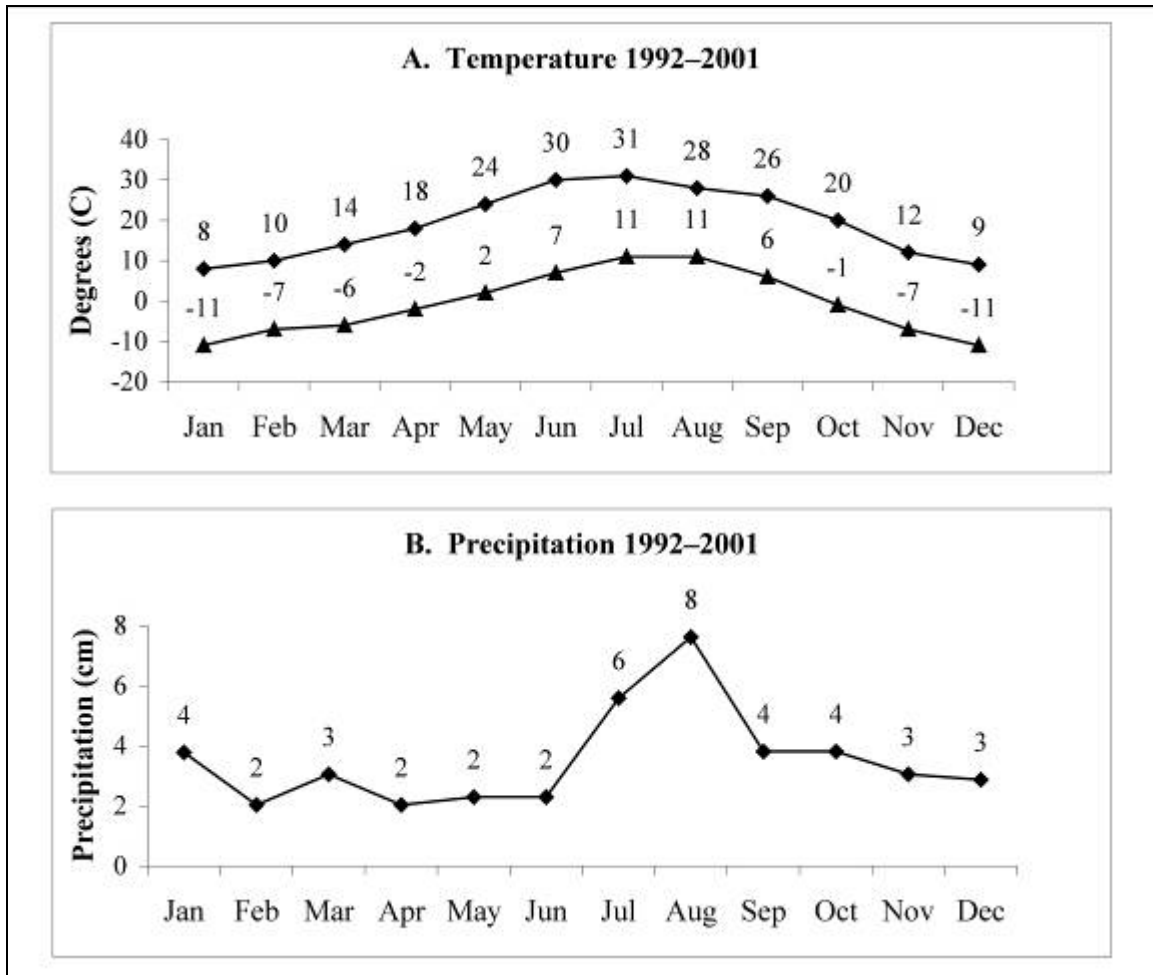


Figure 3.1. Average temperature and precipitation for ELMA. Top (A) shows average monthly maximum and minimum temperatures and bottom (B) shows average monthly precipitation from 1992–2001. The increase in precipitation during July and August is related to the summer monsoon. The total average annual precipitation is 42cm.

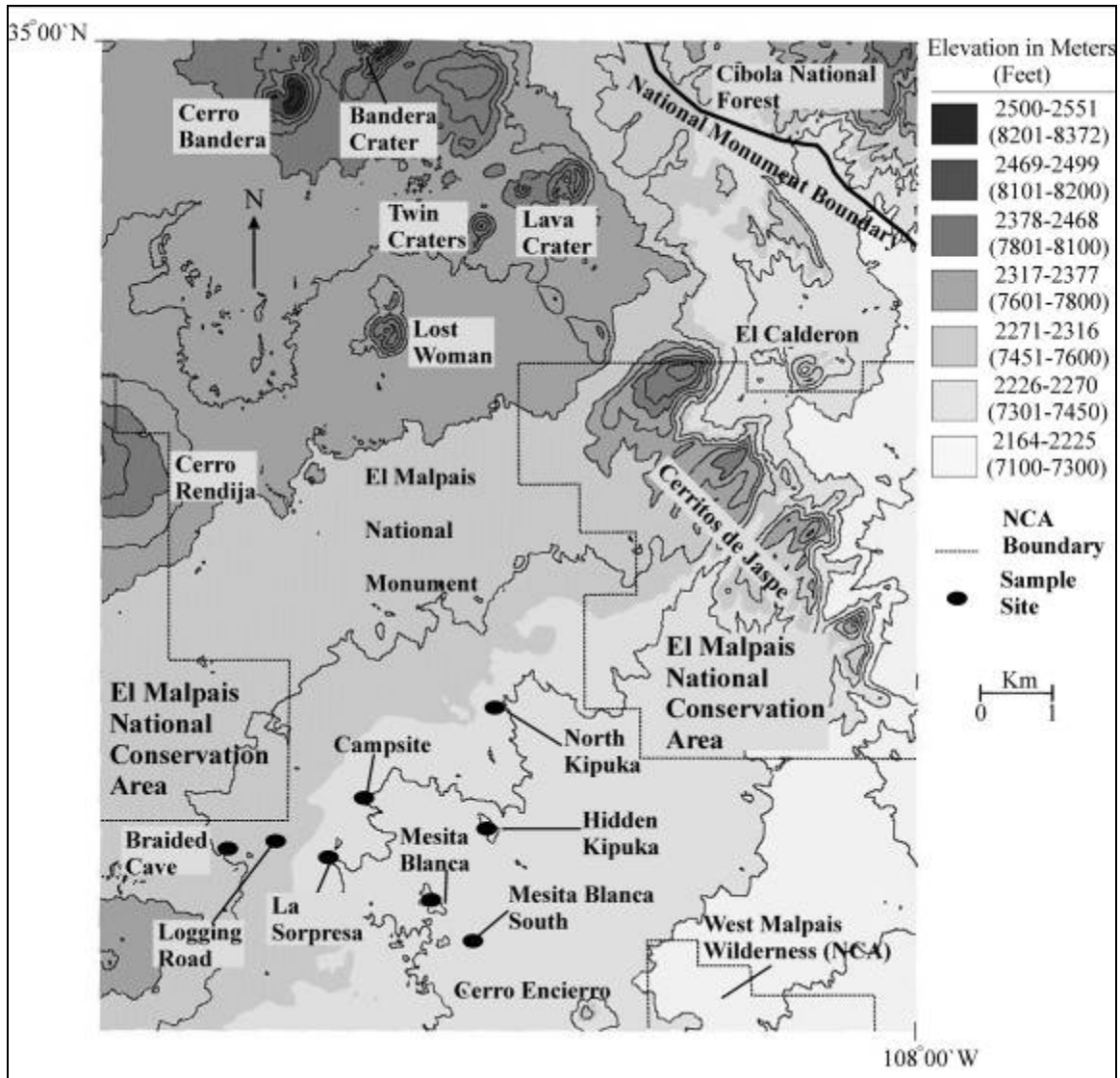


Figure 3.2. Digital elevation model of the Ice Caves topographic quadrangle. Source: United States Geological Survey. This figure shows the various cinder cones and mountain ranges in the monument. Notice the relative lack of relief in the southern portion, with the exceptions of Cerro Encierro, and the upper elevations of Mesita Blanca and Hidden Kipuka.

100 m above the surrounding lava flows. Although relief is minimal in the south, the lava flows have created a very broken and uneven surface.

3.2. Geology of El Malpais National Monument

El Malpais National Monument is made up of a patchwork of lava flows which occurred at different times in history. The oldest are the “old Quaternary basalt flows” that form the basal material over which the more recent eruptions occurred (Maxwell 1986). These older flows occurred during two intervals, *ca.* 600,000–700,000 years ago and *ca.* 150,000 years ago (Laughlin *et al.* 1993). These flows are highly weathered and have well developed soils that support grasslands, piñon-juniper woodlands, and open ponderosa pine forests.

After these older basalt flows, several distinct eruptions occurred (Fig 3.3). The oldest of these is the El Calderon Lava Flow (*ca.* 115,000 yrs BP, not mapped) in the northern part of the monument (Laughlin *et al.* 1993). This lava flow is highly weathered and supports vegetation similar to that of the old Quaternary basalt flows (Maxwell 1986). The Rendija Flow occurred at approximately the same time as the El Calderon Flow (Laughlin *et al.* 1993). The next eruption, which produced the Twin Craters Flow, was actually a series of eruptions that occurred to the west of El Calderon that formed the vents Twin Craters, Lost Woman, Cerro Candelaria, and Lava Crater. A radioisotopic date of 15,800 yrs BP was obtained for these eruptions, but the highly weathered surface features suggest this date may be inaccurate (Laughlin *et al.* 1993). It is more likely that these lava flows occurred between 50,000–100,000 years ago, as they have vegetation

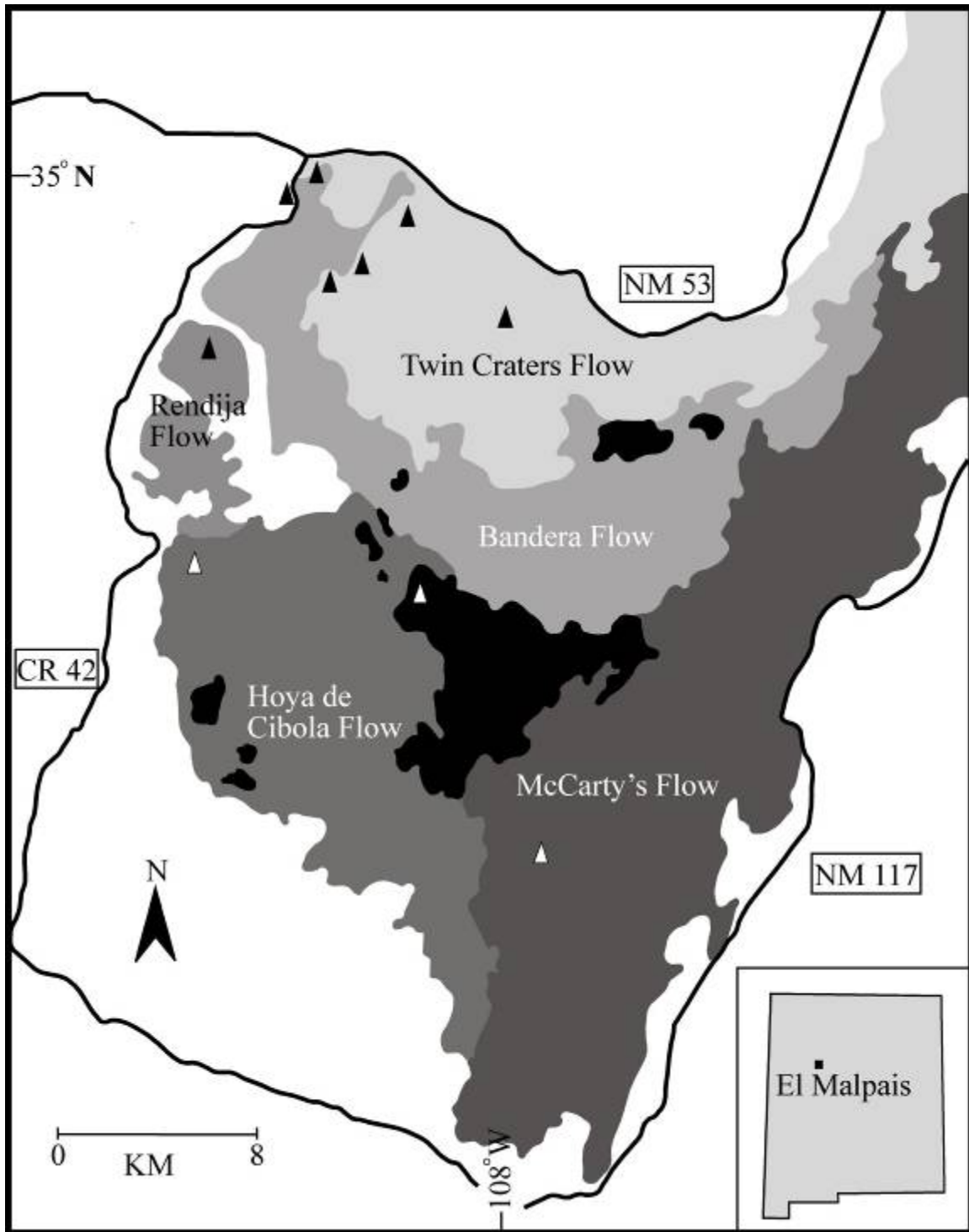


Figure 3.3. Major lava flows of ELMA. This figure shows the five major lava flows in El Malpais National Monument, New Mexico (inset). The black areas represent kipukas, and triangles denote prominent volcanic vents. Adapted from Grissino-Mayer (1996).

characteristics similar to that of the El Calderon Flow (USDI National Park Service 1992).

The third major flow is the Hoya de Cibola Lava Flow, found in the southwestern portion of the monument. Though no radioisotopic dates have been obtained for this flow (Laughlin *et al.* 1993), the degree of surface weathering suggests that it is somewhat younger than the Twin Craters series, possibly forming as recently as 30,000 years ago (USDI National Park Service 1992). Ponderosa pine forests are much less dense on this flow than on the older lava flows. This particular flow is very important to this study, as it contains all of the kipukas used for the reconstruction of fire history, with the exception of North Kipuka in the Bandera Flow. Although this flow does support some grassland, the soil is much less developed, and bare rock is visible over much of the lava flow.

The fourth major flow occurred *ca.* 10,000–11,000 years ago issuing from Bandera Crater. Accumulated lava that pooled during the eruption breached the southwestern rim of the cinder cone and flowed southward until it reached Cerro Rendija. The flow then turned southeast before eventually flowing northeast to the Rio San Jose Valley. Soils on this lava flow are very poorly developed, supporting negligible grass cover. The Bandera Flow consists of both *aa* (very broken and jagged) and *pahoehoe* (smoother and ropy) lava, and has a central collapse system (Big Tubes). Despite the poor soil development, the *pahoehoe* portions of the lava flow support large forests of Douglas-fir, ponderosa pine, Rocky Mountain juniper, one-seed juniper, and piñon (Carroll and Morain 1992; Bleakly 1997).

The final major lava flow in the malpais area is the McCarty's Lava Flow. This flow occurred between 3,160 and 3,200 years ago based on ¹⁴C-dates of charcoal found

beneath the flow near The Narrows (Laughlin *et al.* 1993). This lava flow has poorly developed soils and supports negligible grass cover. It does, however, support large forests of ponderosa pines with very unusual growth forms. The trees on this flow are very stunted, twisted, contorted, and are rarely more than three meters high. Forests here are described as “stultified” or “pygmy” forest (Lindsey 1951).

3.3. Plant Communities

Contrary to the barren wasteland that the name evokes, El Malpais actually has abundant plant life (Bleakly 1997). The lava flows act as aquifers that trap moisture that would normally be lost to evaporation. The broken, porous nature of the lava allows water to percolate through the surface away from the surface heat. Temperatures are generally much cooler under the surface of the lava flows, slowing evaporation.

Recent work (Carroll and Morain 1992; Bleakly 1997) revealed four distinct plant communities in the malpais: (1) mixed-conifer woodland, (2) shrub/conifer, (3) grass or grass/shrub, and (4) barren to sparse grass/shrub. The mixed-conifer zone is the most widespread of the malpais plant communities (Bleakly 1997). It is generally found on the four older lava flows (Bandera Flow, Hoya Flow, Twin Craters Flow, and El Calderon Flow), and is also present at higher elevations off the lava flows. Douglas-fir dominates this zone, mixed with Rocky Mountain juniper on the upper portions of the Bandera Flow, and on the upper elevations in the northern parts of the monument. As one moves southward through the monument, Douglas-fir loses its dominance to ponderosa pine. Piñon and one-seed juniper are also common in the lower elevations of this zone.

The mixed-conifer zone also supports many different shrubs, herbs, and grasses. The most common are wax currant (*Ribes cereum* Dougl.), Apache plume, skunkbush (*Rhus trilobata* Nutt.), rockspira (*Holodiscus dumosus* (Nutt. ex Hook.) Heller), James wild buckwheat (*Erigonum jamesii* Benth.), skyrocket (*Ipomopsis aggregata* (Pursh) V. Grant), running fleabane (*Erigeron flagellaris* Gray), Wright deervetch (*Lotus wrightii* (Gray) Greene), King lupine (*Lupinus kingii* S. Wats.), mullein (*Verbascum thapsus* L.), mountain muhly (*Muhlenbergia montana* (Nutt) A.S. Hitchc.), and blue grama (*Bouteloua gracilis* Willd. ex Kunth) Lag. ex Griffiths) (Bleakly 1997).

The mixed-conifer forest on the Bandera Flow is home to the oldest known living Douglas-fir trees in North America that have been accurately dated (Grissino-Mayer *et al.* 1997). The two oldest crossdated trees date to A.D. 719 and A.D. 1062 respectively. Numerous Douglas-fir trees have been found on the Bandera Flow in excess of 600 years of age (Lindsey 1951; Grissino-Mayer *et al.* 1997).

The shrub/conifer community is found only on the sedimentary substrates or cinders, and is not very common in the malpais (Bleakly 1997). This community contains the piñon-juniper woodlands that dominate the crests of the kipukas. Ponderosa pines are also found mixed with the piñon and juniper on the upper crests of the kipukas. The shrub/conifer community is also found on the Sandstone Bluffs, the Cerritos de Jaspe area, near the Chain of Craters on the west side of the monument, and on Little and Big Holes-in-the-Wall (kipukas).

Bleakly (1997) found that several kipukas (Hidden Kipuka, Mesita Blanca, and Encierro), as well as some other sedimentary areas, support plants found nowhere else in the monument. Some of these plants include dwarf blue-eyed grass (*Sisyrinchium*

demissum Greene), showy fameflower (*Talinum pulchellum* Woot. & Standl.), cream pincushion cactus (*Mammillaria heyderi meiacantha*), painted milkvetch (*Astragalus ceramicus* Sheldon), alderleaf mountain mahogany (*Cercocarpus montanus* Raf.), spike dropseed (*Sporobolus contractus* A.S. Hitchc.), and sandhill muhly (*Muhlenbergia pungens* Thurb.) (Bleakly 1997).

The grassland and grass/shrublands are found primarily on the older basalt flows that surround the younger lava flows of the malpais. Grasslands are more commonly found to the east and south of the monument, while the grass/shrublands are generally found on the west side and middle part of County Road 42 (Bleakly 1997). These older basalt flows are more highly weathered than the younger flows and have fairly well developed soils. The typical grasses in this community are the gramas, little bluestem (*Schizachyrium scoparium* (Michx.) Nash), three-awns (*Aristida* spp.), squirreltail (*Elymus longifolius* (J.G. Sm.) Gould), junegrass (*Koeleria macrantha* (Ledeb.) Schult.), and ring muhly (*Muhlenbergia torreyi* (Kunth.) A.S. Hitchc. ex Bush) (Bleakly 1997). The most common shrubs include rabbitbrush (*Ericameria nauseosus* Pallus ex. Pursh), gray horsebrush (*Tetradymia canescens* DC.), sages (*Artemisia* spp.), and broom snakeweed (*Gutierrezia sarothrae* (Pursh) Britt. & Rusby). One-seed junipers can also be seen growing in outcrops.

The barren to sparse grass/shrub community occurs primarily on the geologically recent McCarty's flow and the upper *aa* portions of the Bandera Flow. The soils here are very poorly developed, and the surface is usually too broken to support high densities of vegetation. Some shrubs survive on these lava flows, such as Apache plume, New Mexico olive (*Forestiera pubescens* Nutt.), and fragrant ash (*Fraxinus cuspidate* Torr.)

(Bleakly 1997). Very open, “bonsai” forests of ponderosa pine and piñon also grow here. Tree density is low because of the rugged terrain and lack of soil development.

3.4. Kipukas

Numerous kipukas of varying size, shape, and substrate are found in El Malpais National Monument. All of the kipukas sampled for this project are in relatively close proximity to one another (Figure 3.4). The substrate of most of the kipukas is sedimentary rock (sandstone or limestone) (Maxwell 1986). Two of the kipukas sampled for this study, La Sorpresa and North Kipuka, are lava kipukas. The Hoya de Cibola Lava Flow surrounds all of the kipukas sampled except North Kipuka, which is located within the Bandera Flow. Most of the kipukas exhibit few signs of direct human disturbance (*i.e.* logging or livestock grazing).

3.4.1. Mesita Blanca

Mesita Blanca is the largest of the kipukas sampled for this study (Figure 3.5). It is *ca.* 1.7 km long and *ca.* 460 m wide at its widest point. It has a northwest/southeast orientation, and the elevation of the upper crest is above 2275 m asl (above sea level). This kipuka is one of the sedimentary kipukas, comprised primarily of San Andres Limestone (Lower Permian) (Maxwell 1986). Access to Mesita Blanca is via a narrow road over the Hoya de Cibola Flow.

Open ponderosa pine forests are found on the adjacent lava flows encircling the kipuka. The upper crest is covered by denser piñon-juniper woodland, with a number of ponderosa pines mixed in. The lower slopes are covered by grasses, some shrubs, and a

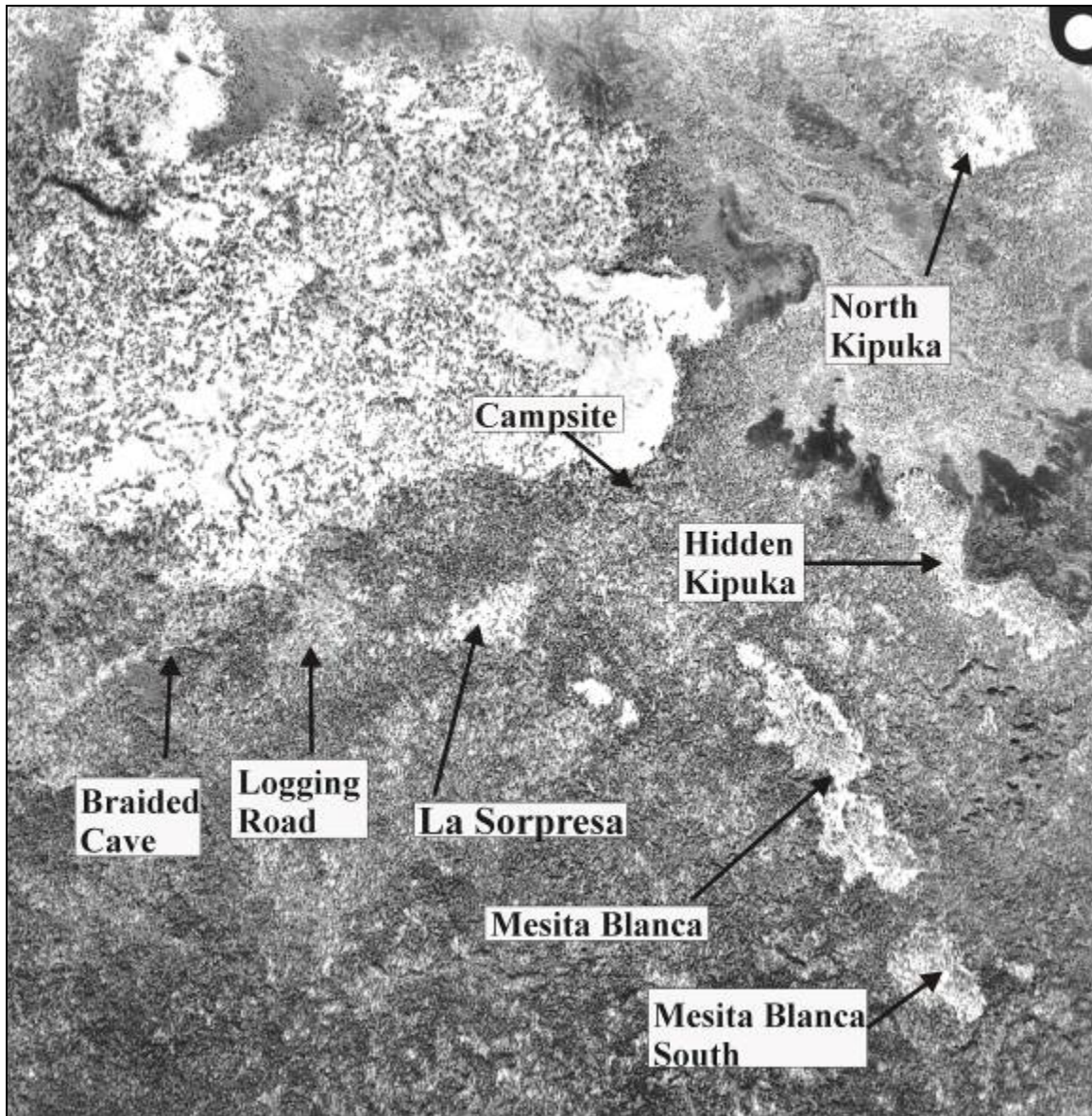


Figure 3.4. Air photo of the sample sites. This photograph shows the relative location of the sample sites to one another. Source: El Malpais National Monument. Photo was taken in 1956.

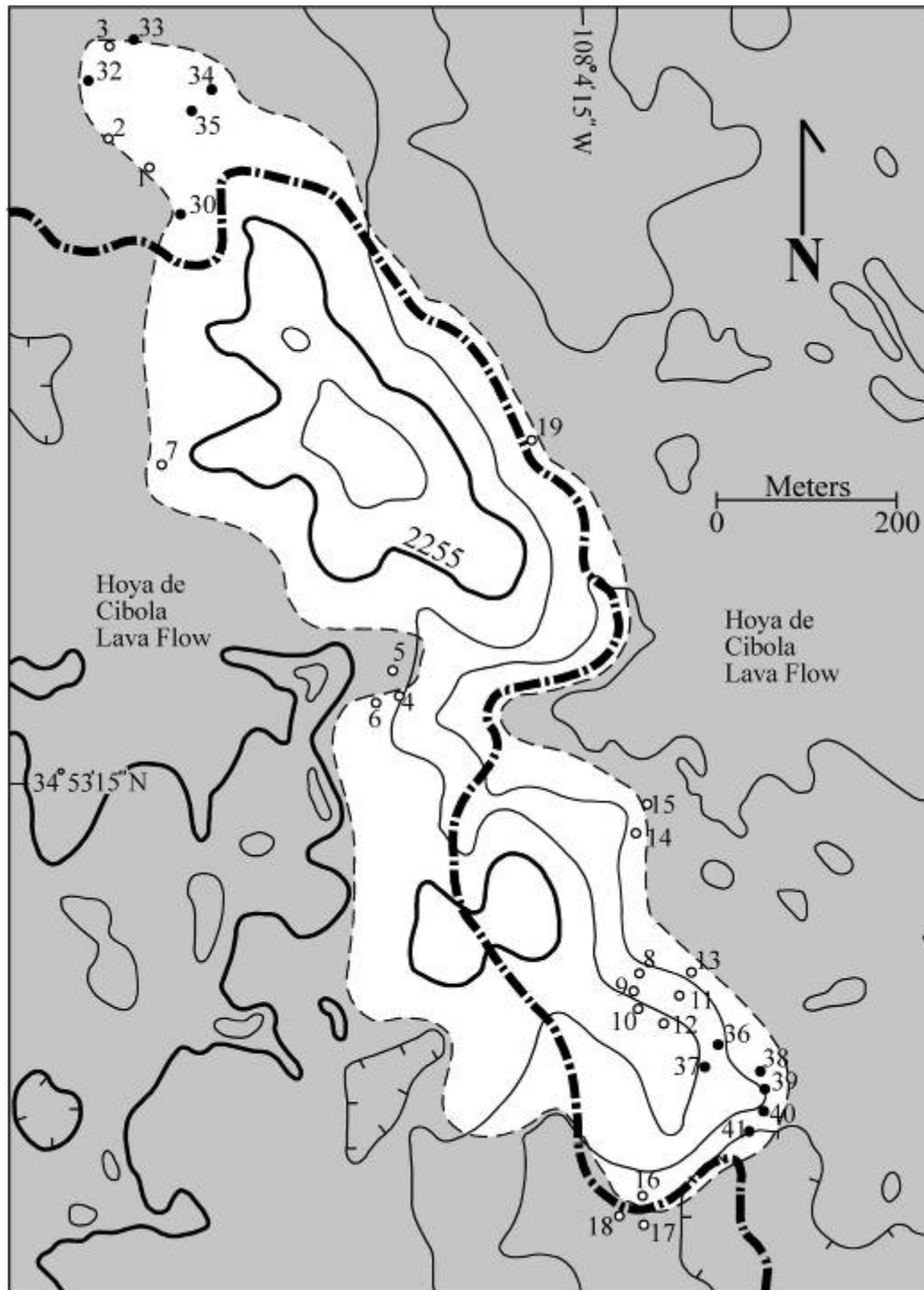


Figure 3.5. Map of Mesita Blanca. The map was digitized from the Ice Caves, NM topographic quadrangle. Source: United States Geological Survey. The dashed line indicates the boundary of the kipuka (lava interface), and the large black line is the access road. Samples with open dots were collected by Grissino-Mayer (1995), while samples with closed dots were collected for this study in May 2001.

few even-aged ponderosa pines. Gambel oak (*Quercus gambellii* Nutt.) grows in dense clusters on the eastern slope of the kipuka. Ground fuels at present appear adequate to support the spread of wildfire on the kipuka.

The extent of human-related disturbances on Mesita Blanca is still undetermined. The kipuka does not exhibit widespread signs of disturbance, but its location suggests that it may have been minimally disturbed by humans. Little Hole-in-the-Wall, one of the larger and more disturbed kipukas in the monument, lies approximately 1.1 km northwest of Mesita Blanca. Little Hole-in-the-Wall has been heavily grazed in the past by both sheep and cattle. I have observed animal enclosures on Mesita Blanca. This suggests that livestock grazing may have occurred at some time in the past, and park managers are attempting to assess its effects on the grass cover of the kipuka. Some human-related disturbance is also indicated by the reconstruction of fire history on the kipuka (Grissino-Mayer 1995). Although the kipuka actively recorded fire well into the 20th century, fire began a noticeable decline in frequency *ca.* 1940.

Although livestock grazing may have minimally altered the kipuka, no evidence of logging was visible anywhere on Mesita Blanca. It is also believed that fires have not been actively suppressed on this kipuka. Visual signs of wildfire, such as charred bark and fire-scarred trees, were evident most everywhere. The largest percentage of fire-scarred trees were located along the outer periphery of the kipuka, closest to the surrounding lava flow.

3.4.2. Hidden Kipuka

Hidden Kipuka (Figure 3.6) is located *ca.* one km northeast of Mesita Blanca. It is *ca.* 1.1 km long and *ca.* 350 m wide at its widest point. It has the same northwest/southeast orientation as Mesita Blanca. Elevation on the northern end of the kipuka rises to just over 2295 m asl with a very steep eastern slope. The southern end rises to approximately 2275 m asl with more gentle slopes down to the lava flows. The substrate is Glorieta Sandstone (Lower Permian) which has a very white coloring compared to the darker gray coloring of Mesita Blanca (Maxwell 1986). This kipuka is bordered on its west side by the Hoya de Cibola Lava Flow and on its eastern side by the younger Bandera Flow.

The area between the two kipukas is primarily open ponderosa pine forest with moderate grass cover. Numerous fire-scarred trees, both living and dead, were found in this area. No evidence of logging was found on the lava flow between the two kipukas. A present, ground fuels are moderate and adequate to carry fire. The fact that there is no road access and no stumps indicates that the kipuka was never logged.

Hidden Kipuka seems to be one of the finest examples of a relict area in the monument. Given that the Bandera Flow forms its eastern boundary, and that the Hoya Flow to the west is fairly broken and uneven in this area, it is highly unlikely that any livestock could make it safely out to the kipuka. No visual signs of livestock grazing (*i.e.* animal waste and hoof prints) were found anywhere on the kipuka, nor were there livestock exclosures such as the ones located on Mesita Blanca. It is also unlikely that fires have been actively suppressed here due to its remote location and relative

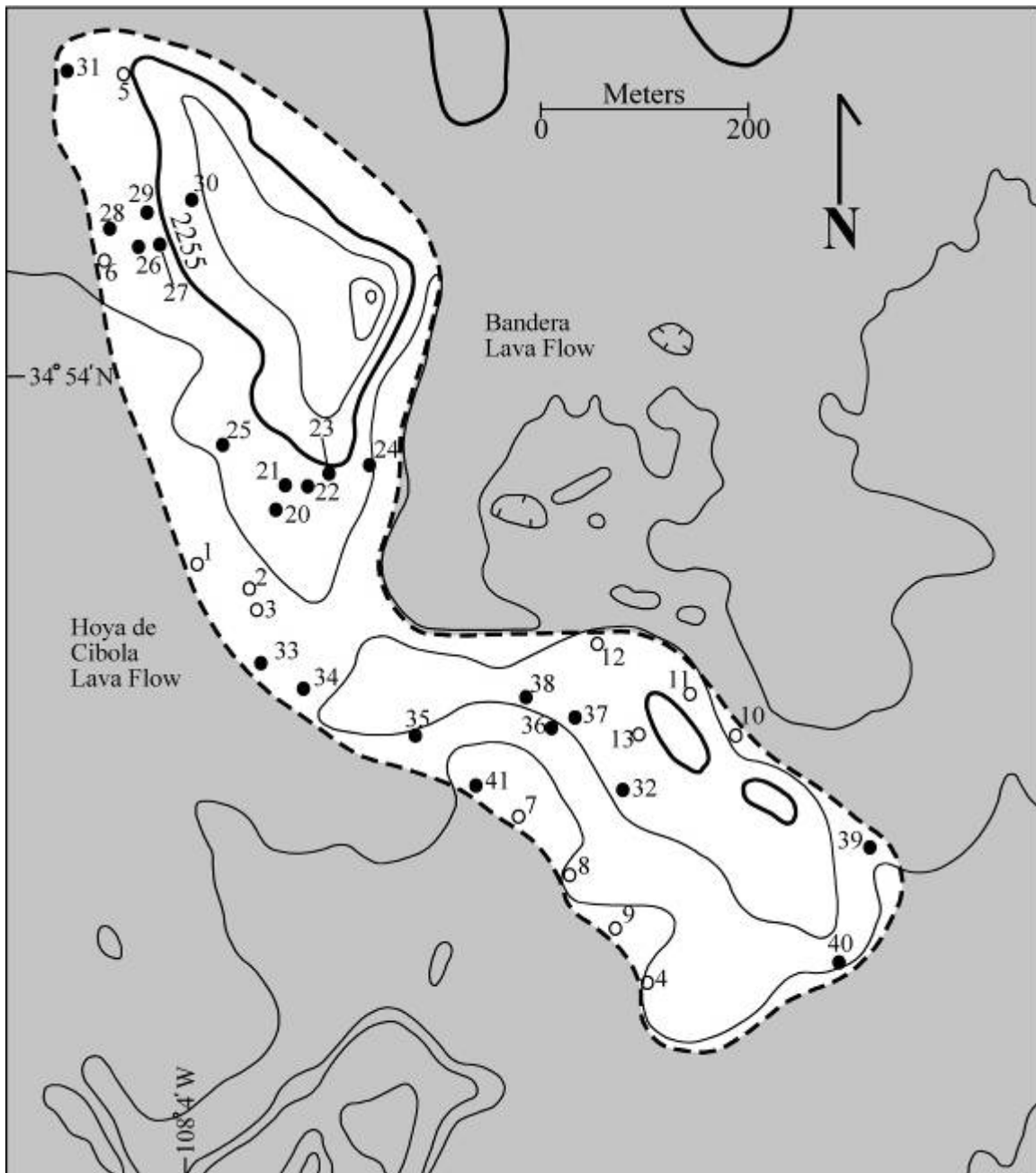


Figure 3.6. Map of Hidden Kipuka. The map was digitized from the Ice Caves, NM topographic quadrangle. Source: United States Geological Survey. The dashed line indicates the kipuka boundary. Samples with open dots were previously collected by Grissino-Mayer (1995), while samples with closed dots were collected for this study in May 2001. Notice the very steep eastern slope on the northern end of the kipuka compared to the more gentle-sloping south end.

inaccessibility. I did find, however, evidence (debitage and small pottery shards) that Native Americans had visited this kipuka.

The upper slope of Hidden Kipuka is dominated by piñon-juniper woodland. Grass cover is sparse on the upper slopes, but the lower slopes are densely covered with blue grama, squirreltail, sage, and rabbitbrush. The large ponderosa pines on the upper slopes and along the periphery were heavily masting in May 2001. Very little ponderosa pine regeneration was occurring on the eastern side of the kipuka compared to the western side, perhaps because the tree density is much higher on the Hoya de Cibola Lava Flow to the west than on the Bandera Lava Flow to the east. Numerous juvenile quaking aspen (*Populus tremuloides* Michx.) trees were growing along the edge of the lava flows surrounding the kipuka. The eastern slope had high densities of scrub oak and Gambel oak at lower elevations.

3.4.3. Mesita Blanca South

Mesita Blanca South (Figure 3.7) is a smaller kipuka located *ca.* 200 m south of Mesita Blanca. It is *ca.* 600 m long and 350 m wide at its widest point. It also has a northwest/southeast orientation. The elevation of the upper portion is just above 2275 m asl. It is comprised of the same San Andres Limestone (Lower Permian) as Mesita Blanca (Maxwell 1986). Piñon and juniper dominate the upper slope, mixed with a number of ponderosa pines. Grass cover is quite dense, both at lower elevations and upper elevations of the kipuka, but shrub cover is negligible. No evidence of logging was found anywhere on the kipuka, nor did we find visual evidence of livestock grazing.

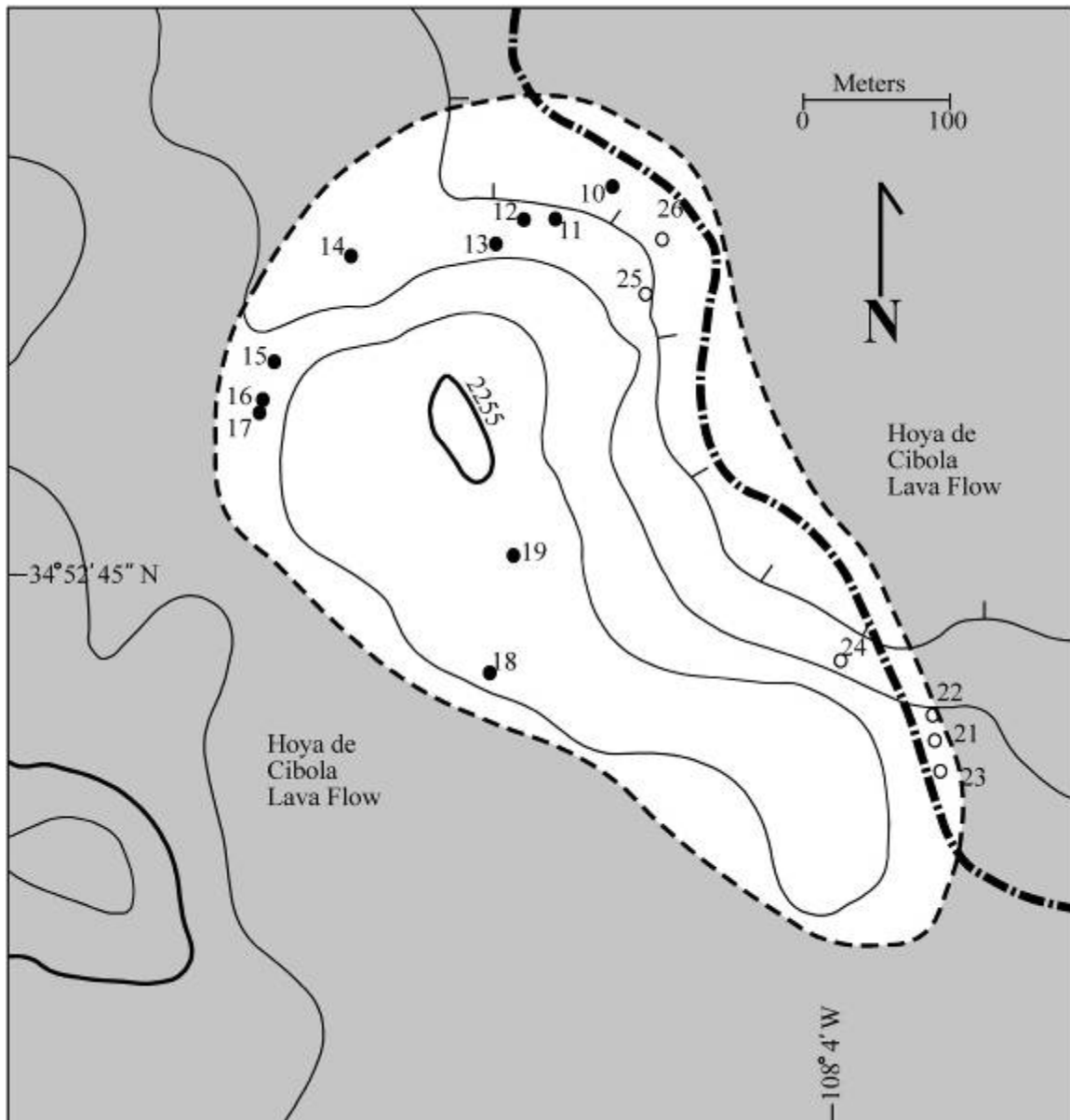


Figure 3.7. Map of Mesita Blanca South. The map was digitized from the Ice Caves, NM topographic quadrangle. Source: United States Geological Survey. Samples with open dots were collected by Grissino-Mayer (1995) while those with closed dots were collected for this study in May 2001. The dashed line indicates the kipuka boundary, and the large black line is the Mesita Blanca access road. Notice the large lava collapse on the northeastern side of the kipuka.

However, livestock grazing is a possibility given the site's close proximity to Mesita Blanca. It is unlikely that fires were actively suppressed on this kipuka either.

3.4.4. North Kipuka

North Kipuka (Figure 3.8) is located *ca.* 1.6 km north-northeast of Hidden Kipuka. It is *ca.* 500 m long and just over 300 m wide. Elevations rise to *ca.* 2275 m asl at the northern end of the kipuka. This kipuka is one of the lava kipukas, composed primarily of the old Quaternary Basalts that form the bedrock for most of the monument (Maxwell 1986). This substrate is highly weathered and has adequate soil development to support grass cover.

This kipuka was heavily logged in the past. Numerous cut stumps were found on the kipuka. Twelve of the 17 fire-scarred samples taken from this kipuka were logged stumps. The kipuka supports high levels of ponderosa pine regeneration along its periphery. Piñon and juniper dominate the upper slopes, although the density of the piñon-juniper woodland is not as high on this kipuka as it is on some of the other kipukas, such as Mesita Blanca and Hidden Kipuka. Because of its highly weathered, well-developed soils, grass cover is very heavy, providing ample surface fuel to carry wildfire.

Because this kipuka is surrounded by the Bandera Lava Flow, which has very poorly developed soil and minimal grass cover, its fire history should be different than that of the other kipukas surrounded by the Hoya Flow. It is highly unlikely any wildfire can spread to this kipuka from the adjacent lava flows. Fire must instead originate on the kipuka itself via lightning or some other ignition source.

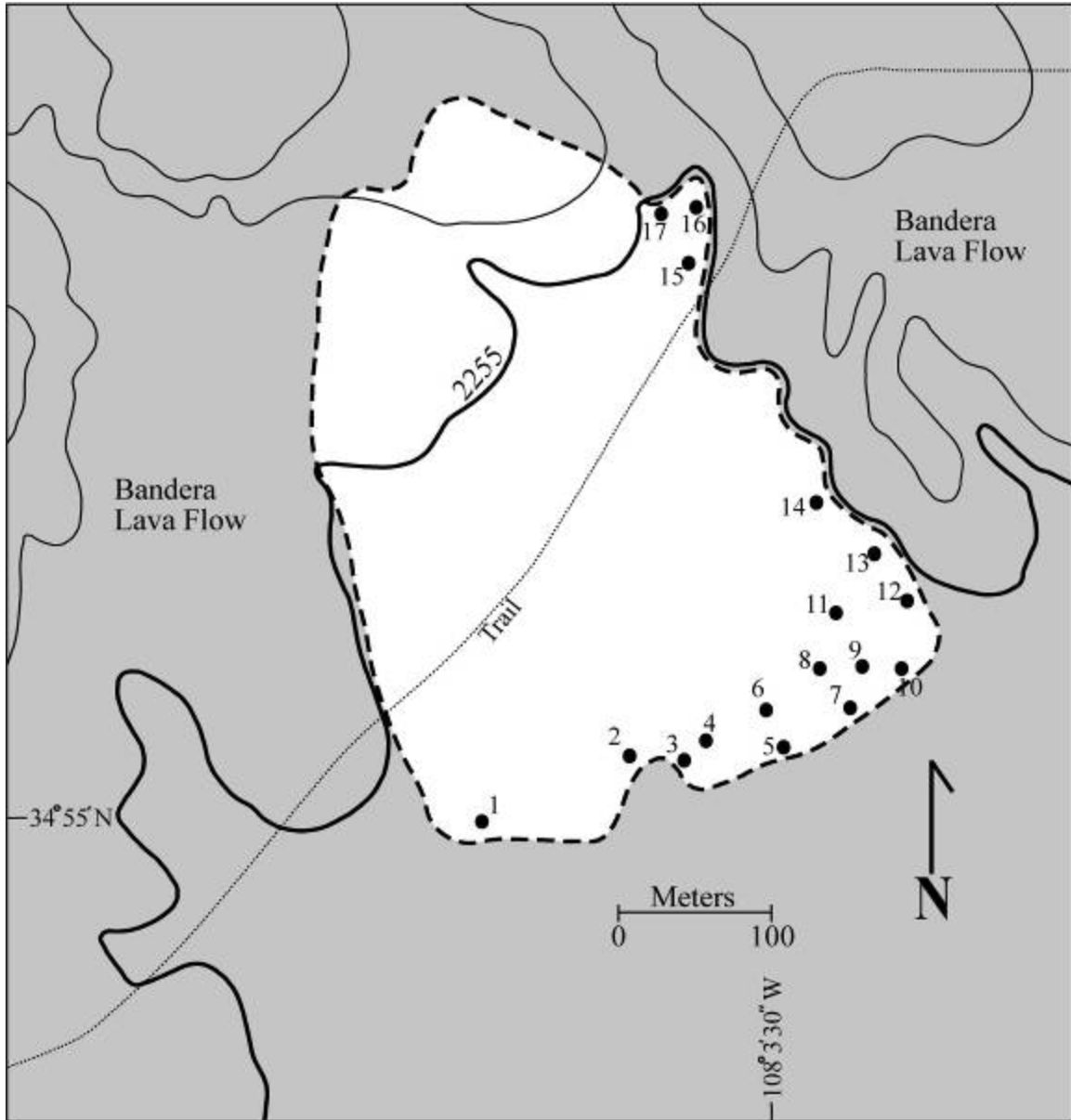


Figure 3.8. Map of North Kipuka. The map was digitized from the Ice Caves, NM topographic quadrangle. Source: United States Geological Survey. All fire-scarred samples are shown with closed dots and were collected for this project in May 2001. The dashed line indicates the kipuka boundary, while the small dotted line is the access trail.

3.4.5. La Sorpresa

La Sorpresa (Figure 3.9) is located just inside the southernmost periphery of Little Hole-in-the-Wall, *ca.* 1.2 km northwest of Mesita Blanca. It is just over 500 m long and 500 m wide. Elevations range from just under 2275 m asl on the eastern side to over 2290 m asl on the western side of the kipuka. Like North Kipuka, La Sorpresa is composed of the old Quaternary Basalt. The forest cover on this kipuka differs from that found on the other kipukas. Although piñon-juniper woodlands do exist on the upper slopes, the trees are more widely spaced. Piñon and juniper are as common as ponderosa pine throughout. Grass cover is very dense over the entire kipuka, providing ample fuel to carry wildfire. A number of large, standing snags are found on this kipuka, and several showed visible evidence of lightning damage.

La Sorpresa has been heavily logged in the past as indicated by the numerous cut stumps scattered about. The two kipukas south of La Sorpresa exhibited the same characteristics. La Sorpresa did not seem to have been heavily grazed in recent years, as no signs of animal waste were located. Many more fire-scarred samples than could be collected for this study were found, the majority being very large trees with multiple fire scars.

3.5. Lava Flow Areas

Three sites were sampled on the Hoya de Cibola lava flow to examine how its broken topography affects fire regimes on the kipukas, as well as to increase our knowledge of the spatial extent of wildfires in the monument. The majority of fires that affect the kipukas likely spread to them across the adjacent lava flows. Therefore,

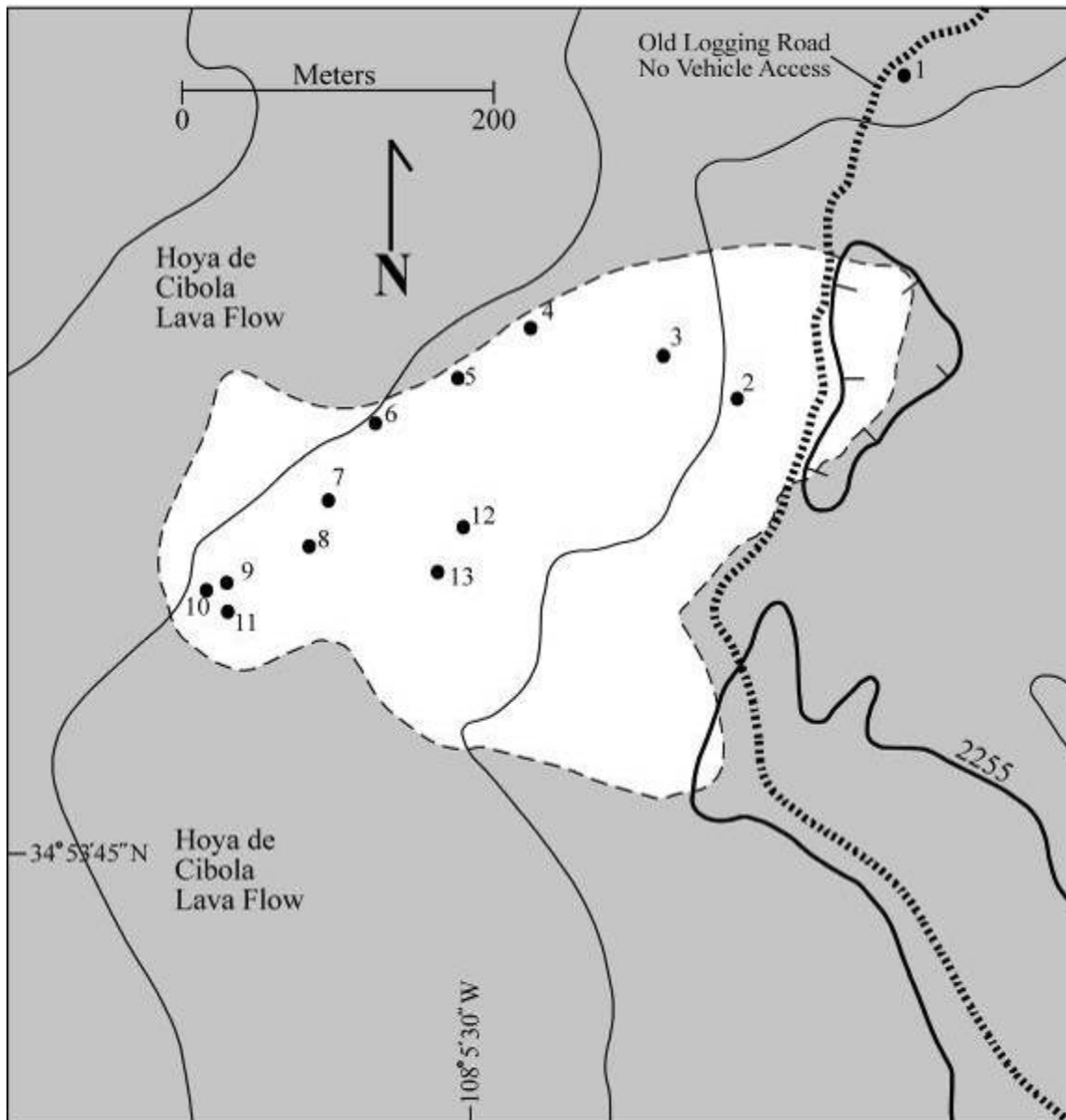


Figure 3.9. Map of La Sorpresa. The map was digitized from the Ice Caves, NM topographic quadrangle. Source: United States Geological Survey. Samples shown were collected in May 2001. The dashed line indicates the kipuka boundary, and the large dotted line is the access road. Notice the large lava collapse along the northeast corner.

sampling sites on the adjacent lava flows will provide valuable information on their influence of fire regimes of the kipukas. Also, fires have been actively suppressed in recent decades on most of the accessible lava flow areas, so it is important to examine the effects of this fire suppression on the fire regimes of the kipukas.

3.5.1. Campsite

The Campsite area (Figure 3.10) is located *ca.* 1.1 km northwest of Mesita Blanca, at the junction of the Mesita Blanca access road and Rd. #305. The area sampled represents *ca.* 0.1 km² (~330 m x 280 m). This lava flow supports open ponderosa pine forest with some bunch grasses and small shrubs. Although some weathering has occurred, much bare rock is still visible over much of the lava flow. The area around Campsite is very broken and uneven topographically, but elevation remains fairly constant at *ca.* 2275 m asl. Visible signs of wildfire, such as fire-scarred trees or charcoal on bark, can be found throughout the area.

The presence of a large number of cut stumps in the area suggests that extensive logging was conducted. Also, very large quantities of animal waste are located throughout this site. Campsite is located on the southernmost periphery of Little Hole-in-the-Wall, a very large kipuka that has been heavily grazed in the past.

Surface fuel loads in the area were high, consisting of large limbs, pine needles, bunch grasses, and some large downed trees. A number of dead standing snags were observed, providing vertical fuel. A large number of seedlings and juvenile ponderosa pines were also present.

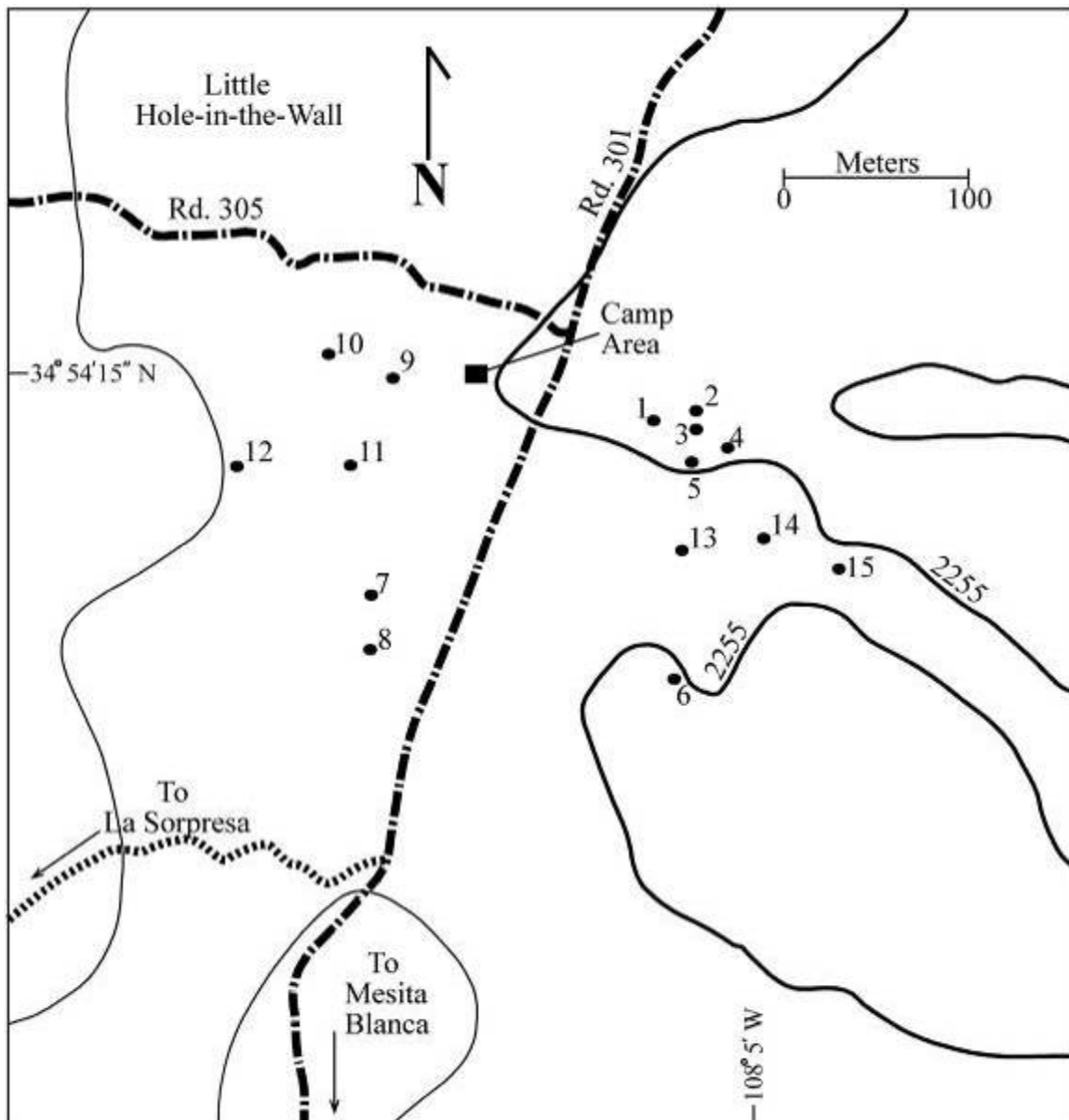


Figure 3.10. Map of Campsite. The map was digitized from the Ice Caves, NM topographic quadrangle. Source: United States Geological Survey. Samples are indicated by black dots and were taken in May 2001. The large dashes lines are unimproved dirt/lava roads, and the small dashed line is the abandoned logging road that provides access to La Sorpresa.

3.5.2. Logging Road

The Logging Road site (Figure 3.11) is located *ca.* 1.6 km west/southwest of Campsite and *ca.* 0.7 km west of La Sorpresa. The area sampled represents *ca.* 0.02 km² (170 m x 130 m). Elevation is between 2301 m and 2307 m asl throughout the sample area. The entire area is open ponderosa pine forest, but grass cover was minimal, most likely due to grazing (this site is immediately adjacent to Little Hole-in-the-Wall). A large stock tank (intermittent water source) was observed *ca.* 0.5 km to the north of the area. Large quantities of livestock (cattle) waste were noted over the entire area.

As the name implies, this area was heavily logged at some point in the past. Numerous large stumps were found throughout the site, and many of them were sampled. Large numbers of ponderosa pine seedlings and juvenile trees were also noted at this location, more so than at the Campsite area. Although a number of fire-scarred trees were noted and sampled, visual evidence of fire, such as charcoal on the bark of mature trees, was not as extensive as at the Campsite area.

3.5.3. Braided Cave

The Braided Cave site (Figure 3.12) is located *ca.* 0.5 km west of the Logging Road site. The area sampled represents *ca.* 0.08 km² (350 m x 240 m). Elevation is around 2307 m asl throughout the entire area. Braided Cave is part of the very long lava tube system that extends through the monument. These tubes are around 8–10 meters high in some areas, and are much cooler than the surrounding areas on the surface. The samples were taken between the access road and the caves themselves. The sample area looks much like that of the Logging Road site, with open ponderosa pine forest and

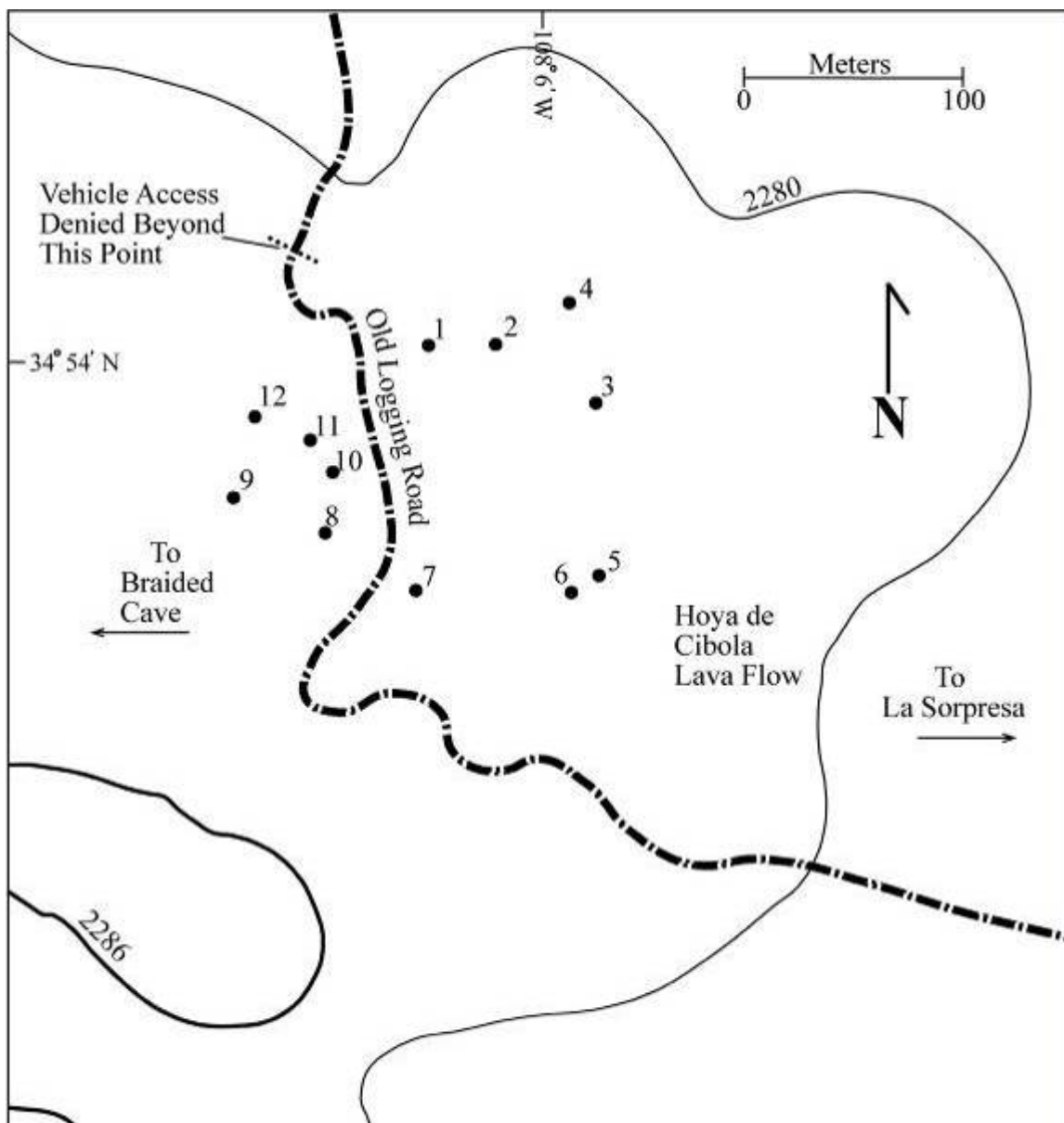


Figure 3.11. Map of Logging Road. The map was digitized from the Ice Caves, NM topographic quadrangle. Source: United States Geological Survey. Samples are shown with black dots and were taken in May 2001.

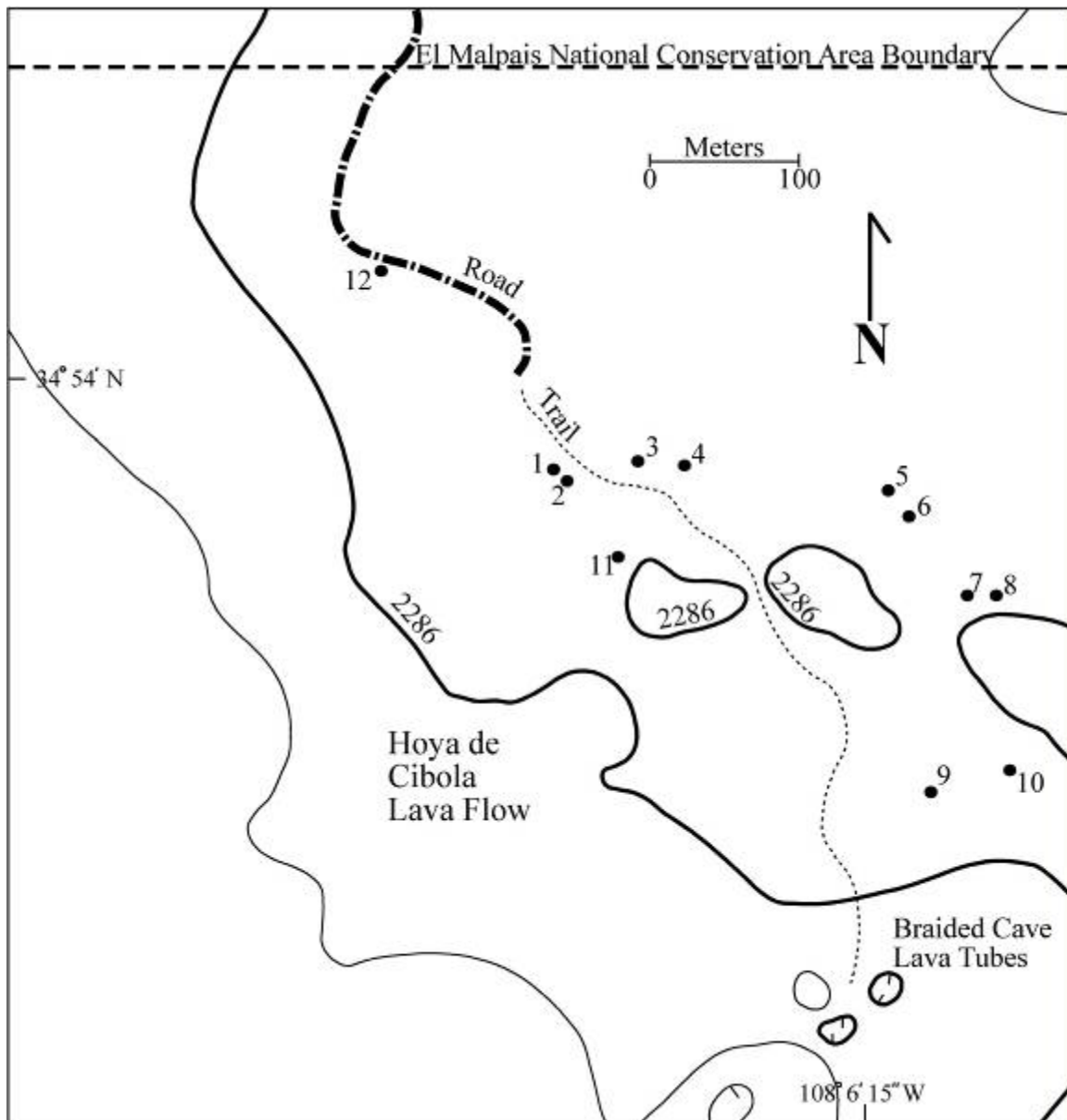


Figure 3.12. Map of Braided Cave. The map was digitized from the Ice Caves, NM topographic quadrangle. Source: United States Geological Survey. Samples are shown with black dots and were taken in May 2001.

minimal grass cover. Douglas-fir seedlings and juvenile trees were observed in this area. This location exceeds the southernmost extent for this species in the monument according to Bleakly (1997). The presence of young Douglas-fir trees at this site could indicate that fires have been excluded in this area for quite some time.

Much like the Logging Road site, this area has been extensively logged and grazed in the past. Large quantities of livestock (cattle) waste were found throughout the area, and numerous cut stumps were found. Seedling and sapling numbers were comparable with that of the Logging Road site. It is possible that widespread livestock grazing has impeded fire spread at both of these sites, allowing the high numbers of seedlings and the subsequent establishment of Douglas-firs.

4. Methods

4.1. Fire History

4.1.1. Field Methods

To examine the fire history of the malpais kipukas, a field team (consisting of myself, Michael Armbrister, Beth Atchley, and Henri Grissino-Mayer) collected fire-scarred sections from five different kipukas; Hidden Kipuka, Mesita Blanca, Mesita Blanca South, North Kipuka, and La Sorpresa. In addition, three sites were sampled on the Hoya de Cibola Lava Flow: Braided Cave, Logging Road, and Campsite. The lava flow sites were sampled to examine the spatial extent of wildfires and to examine the ability of fire to spread from the lava flows to the kipukas. All fire-scarred samples were collected in May 2001.

Ponderosa pine was the target species for the fire history because of its susceptibility to repeated scarring. A few fire-scarred piñon and Rocky Mountain juniper snags were found and sampled. All of the fire-scarred sections were taken with a cross-cut saw to comply with current tool regulations for wilderness areas. Complete cross-sections were taken from non-living, fire-scarred logs, stumps, and standing snags. Partial sections were extracted from a few fire-scarred living trees to gain information on fire occurrences in the 20th century. Very little wood was removed with these sections to minimize damage to the living tree. Samples were collected over a relatively wide geographic area to attain adequate spatial distribution. All samples were wrapped in plastic wrap to protect them for transportation back to the laboratory. Relevant data (tree height, crown density, diameter at breast height, visible injuries, *etc.*) were recorded on

standard field specimen sheets. All cross-sections were numbered and drawn to facilitate re-assembly, if needed.

4.1.2. Laboratory Methods

All samples were placed in the University of Tennessee Herbarium freezer (-40° C) for 48–72 hrs to kill any insects that may have been present. Fire-scarred sections that needed to be reassembled were glued and mounted on plyboard. All samples were sanded using ANSI 40-grit (500–595µm) to ANSI 400-grit (20.6–23.6µm) sandpaper (Orvis and Grissino-Mayer 2002) to ensure visibility under standard magnification.

Samples were crossdated with the El Malpais Long Chronology (Grissino-Mayer 1995, 1996) to attain dates for the fire scars contained in the ring series. The samples were visually crossdated by (1) recognizing “signature” rings such as the very narrow 1900 and 1904 rings, the narrow 1880 ring, or the very wide 1816 and 1817 rings followed by the very narrow rings in the 1820s; (2) creating skeleton plots of the ring series and matching them against the master chronology; or (3) comparing fire scars in the sample to master fire charts previously created (Grissino-Mayer 1995) or to other dated pieces and confirming the match with surrounding signature rings.

If qualitative crossdating was not successful, quantitative crossdating was performed by measuring the ring widths on each sample with a movable stage micrometer and entering the ring measurements into COFECHA. All dates indicated by COFECHA were visually verified using surrounding marker rings to ensure that accurate crossdating had been achieved.

Once the entire tree-ring series was successfully dated, I assigned dates to all included fire scars. To determine the seasonality of the fire event, the intra-annual position of the fire scar in the ring was noted (Dieterich and Swetnam 1984; Baisan and Swetnam 1990). Determining the seasonality of previous wildfire events is very important for developing prescribed fire plans. In the Southwest, the seasonality of a fire event falls into one of five generally accepted categories (Grissino-Mayer 1995):

- *Dormant season fire (D)*: The fire scar is located between the latewood of the previous ring and the earlywood of the following ring. The fire could actually have occurred in either of the two calendar years, from the end of the previous year's growing season to the beginning of the following year's growing season. In the American Southwest, these fires are generally interpreted as having occurred in the spring, just prior to the beginning of the growing season rather than the fall of the previous year's growing season. Modern climate and fire reconstructions indicate that fall fires are relatively rare (Baisan and Swetnam 1990).
- *Early season fire (E)*: The fire scar is positioned in the first one-third of the earlywood.
- *Middle season fire (M)*: The fire scar is positioned in the middle one-third of the earlywood.
- *Late season fire (L)*: The fire scar is positioned in the latter one-third of the earlywood.
- *End of growing season fire (A)*: The fire scar is positioned in the latewood.

Following determination of the date and seasonality of every fire scar contained in each sample, relevant data (scar date/season, inner/pith date, outer/bark date) were recorded on standard fire dating sheets. Each fire-scar date was also verified by an independent observer to ensure correct dating was achieved.

4.2. Statistical Analyses

To begin the statistical analyses, all relevant information for each sample (fire-scar dates, inner and outer ring dates, *etc.*) was entered into FHX2, a computer program that supports the compilation, organization, and analysis of large quantities of tree-ring data for fire history investigation (Grissino-Mayer 1995, 2001b). This software is designed specifically for (1) entering and archiving of fire history data, (2) creating graphs that visually depict both temporal and spatial characteristics of the site of fire history, and (3) conducting statistical analyses on fire-free intervals and seasonal change (Grissino-Mayer 2001b).

The FHX2 software allows the user to easily examine the percentage of trees scarred for any given year, as well as temporal and spatial patterns of past wildfires. The percentage-scarred class is a tool for examining the areal extent of past wildfires (Swetnam 1990), based on the assumption that a greater percentage of scarred trees at a given site represents a more widespread fire occurrence. The number of “recorder” trees scarred is used to calculate the percentage scarred. A tree becomes a recorder when it is previously scarred by wildfire and the ring pattern is very clear, thus indicating that the ring series contains every fire that scarred that particular tree. A tree is a “non-recorder” before it has been scarred for the first time. Sometimes, a tree may revert to non-recorder

status after it has been scarred. This occurs when a large portion of the outer surface is burned off, decayed, or obscured by beetle galleries. In FHX2, these non-recorder years are referred to as “null years,” and are not included in the percentage-scarred analysis. It is possible for a tree to contain fire scars in these null years, but it is not possible to be certain that all fires are recorded.

In this study, I used two percentage-scarred classes to analyze fire events for the individual sample sites: all-scarred and 25% scarred. Applying the 25% scarred filter creates a more normally distributed data set by eliminating small-scale, more local wildfires that can skew the data. To analyze fire events for the combined sample sites, I used the all-scarred class and a 10% scarred class. Using the 25% scarred class filter on extremely large data sets would have eliminated too many fires, so for large data sets the 10% scarred class is more useful.

I used ten primary statistics to analyze the historical range of variability for each site: (1) Mean Fire Interval (MFI), (2) Weibull Median Interval (MEI), (3) Weibull Modal Interval (MOI), (4) standard deviation (SD), (5) coefficient of variation (CV), (6) minimum fire interval (Min), (7) maximum fire interval (Max), (8) lower exceedence interval (LEI), (9) upper exceedence interval (UEI), and (10) maximum hazard interval (MHI) (Grissino-Mayer 1995, 1999). All statistical categories were calculated with a minimum number of two samples scarred over the period of reliability established for each site. The period of reliability is the period of time considered to be suitable for conducting statistical analyses (Grissino-Mayer 1995). The period of reliability for each site was established using a minimum of two fire-scarred samples and a minimum of five samples overall for that period. The period of reliability is also bracketed by a beginning

year (first occurrence) and ending year (last occurrence). The same descriptive statistics were calculated for the combined sites and for the entire sample area.

4.2.1. Measures of Central Tendency

Fire frequency was analyzed using the Weibull distribution, which is a flexible statistical distribution that can be fit to a wide variety of fire interval data (Grissino-Mayer 2001b). The Weibull Median Interval (MEI) and Weibull Modal Interval (MOI) are the primary measures of central tendency used in this study. The MEI is the fire interval that corresponds to the 50th percentile of the distribution (Grissino-Mayer 2001b). Because the MEI represents the midpoint in a theoretical distribution fit to the actual data, it provides a measure of central tendency not easily influenced by larger values in the actual data set. The MOI is the interval that represents the greatest amount of area under the probability density function (Grissino-Mayer 2001b). A recent study (Grissino-Mayer 1999) demonstrated that the MOI could be a more superior measure of central tendency, and more efficient at identifying Southwestern fire structure independent of variables such as environmental gradient and habitat type. The Mean Fire Interval (MFI) represents the average of all fire intervals.

4.2.2. Measures of Dispersion

Standard deviation (SD) was calculated to show variability about the Mean Fire Interval. Sites with higher values of the MFI, however, usually exhibit greater variability about the mean. The coefficient of variation (CV) is a standardized statistic which combines both the standard deviation and MFI, allowing for intra-site comparison of

variability in fire intervals (Grissino-Mayer 1995). This is very important, as comparison would be impossible due to the differences in MFI for each site. By using the coefficient of variation to measure variability, comparisons can be made between two sites with very different MFIs. Higher values for the coefficient of variation indicate more variability in the length of fire intervals.

4.2.3. Measures of Range

The minimum fire interval and maximum fire interval represent the shortest and longest actual fire-free intervals. The Lower Exceedence Interval (LEI) and the Upper Exceedence Interval (UEI) delineate the theoretical fire intervals corresponding to the 12.5 and 87.5 percentiles in the distribution (Grissino-Mayer 2001b). These intervals highlight extremes in the data set, with the LEI delineating the shorter intervals and the UEI delineating the longer intervals. Fire intervals falling outside the exceedence intervals are deemed significantly long or short intervals.

The final measure of range used for this study is the Maximum Hazard Interval (MHI). The MHI is the longest theoretical fire-free interval that an ecosystem can sustain before it should burn (Grissino-Mayer 1995, 1999). In all previous fire history studies, an 87.5% threshold level was used to calculate the MHI. However, this study used a 50% threshold level because, once the interval passes the 50% threshold level, that particular ecosystem may burn. Using the 87.5% threshold level would likely yield unusually high MHIs that are uncharacteristic of the area being studied.

4.2.4. Measures of Shape

For each site, the Weibull probability density function (pdf) was graphed to visually depict the shape of each fire interval distribution (Grissino-Mayer 1999). The pdf shows the probability that a fire will occur at a given interval. All probability density function graphs represented at least 90% of the cumulative distribution, and were calculated for the all-scarred and 25% scarred classes. Probability density function graphs were also created for the combined kipukas, the combined lava flow sites, and for the entire study area. The density functions were calculated at the all scarred class and 10% scarred class to account for the very large sample sets. Skewness and kurtosis were calculated to provide additional information about the shape of the distributions.

A problem associated with the pdf is its sensitivity to extremely long fire intervals. For example, a site where fire was frequent but also had a few longer fire-free intervals will be positively skewed. If the number of unusually long intervals increases, the shape of the distribution will tend to flatten (*i.e.* lower values of kurtosis) and will appear more symmetric. This also affects the MHI, as the pdf is a major component of the MHI calculation (Grissino-Mayer 1999). Therefore, it is possible that both the pdf and the MHI can be adversely affected by unusually long fire intervals. This is problematic when analyzing 20th century fire regimes, as intervals tend to be much longer due to fire suppression and other human-related disturbances.

4.3. Seasonal Analyses

The FHX2 statistical package also allows the user to analyze seasonal changes in fire regimes over time by pinpointing the dominant season for a selected period. Seasonal analyses were accomplished by compiling data from all sample sites into one

large data set. To obtain low resolution information on changes in fire seasonality, the data were analyzed using 15-year intervals from 1686 to 1940. The analyses compared the percentage of early-season fires (D and E events) to the percentage of late-season events (M, L, and A).

4.4. Master Fire Charts

I visually examined past fire events using the graphics module in FHX2 to produce master fire charts (Grissino-Mayer 2001b). On these charts, horizontal lines are drawn that each represent a single sample, and tick marks are drawn along the line that each represent a dated fire scar for that given year in that sample. Non-recorder years are represented by the dashed parts of the lines, while recorder years are represented by the solid portions of the lines. I examined these master fire charts to analyze temporal and spatial patterns of wildfires, and to identify any changes that might have occurred over time.

4.5. Age Structure

Age structure analysis was used in conjunction with fire history analysis to determine whether human-induced changes in the fire regime are causing changes in forest composition on the minimally disturbed kipukas. Two kipukas, Mesita Blanca and Hidden Kipuka, were selected for sampling.

4.5.1. Field Methods

Ten-meter wide belt transects were laid down at 100 m paced intervals along the central ridges of the kipukas. The transects were perpendicular to the central ridge of each kipuka, extending to the lava interface on each side. From all possible transects, five were randomly chosen on Hidden Kipuka and three were chosen on Mesita Blanca. All transects were further divided by slope position to assess the ages of the trees on different parts of the kipukas (*i.e.*, ages of the ponderosas on the lower slopes versus those on the upper slopes) (Figure 4.1). The numbering system starts on the west side of each kipuka:

- Slope Position 1- edge of adjacent lava (west side)
- Slope Position 2- transition/lower slope (west side)
- Slope Position 3- mid/upper slope (west side)
- Slope Position 4- crest/central ridge
- Slope Position 5- mid/upper slope (east side)
- Slope Position 6- transition/lower slope (east side)
- Slope Position 7- edge of adjacent lava (east side)

Each transect extended 10 m out onto the lava flow on each side of the kipuka to determine the ages of the trees in the adjacent lava-flow forests.

Cores were taken from living ponderosa pine trees on the kipukas with an increment borer (Stokes and Smiley 1996). All cores were taken parallel to the slope and as close to the ground as possible to ensure the maximum age was attained (Stokes and

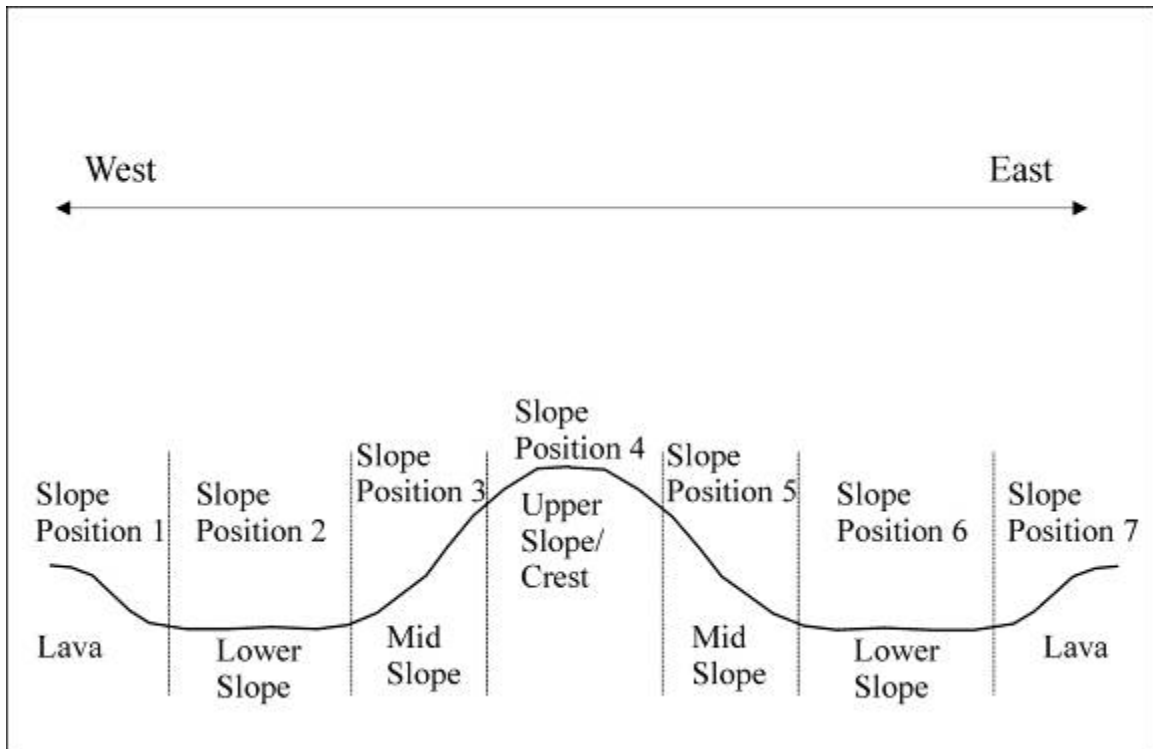


Figure 4.1. General cross-section of a kipuka showing slope positions.

Smiley 1996). This process causes no damage to the tree, and the injury is usually sealed naturally in a few weeks. Any living trees not large enough to be cored were aged by counting branch nodes. All cores were placed in labeled paper straws to protect them during transport back to the laboratory.

4.5.2. Laboratory Methods

All cores were air dried then glued to core mounts. The cores were sanded using the same sanding technique (ANSI 40-grit (500–595 μ m) to ANSI 400-grit (20.6–23.6 μ m)) (Orvis and Grissino-Mayer 2002) as the fire-scarred samples. After sanding, the tree-ring patterns from all cores were crossdated to the El Malpais Long Chronology to ensure that accurate establishment dates and tree ages were assigned. Even though the outer dates of the cores are known (2001), the living cores must still be crossdated. Because these trees are located on raised areas composed primarily of porous limestone, the probability of having missing rings is increased. By matching the ring series with the master chronology, missing rings, if any, were isolated, allowing the assignment of the exact year of formation for each tree ring (Stokes and Smiley 1996). In the event a core could not be dated graphically or visually, it was measured using a movable stage micrometer and the ring widths entered into COFECHA for statistical crossdating.

A small percentage of the cores taken from both kipukas did not contain the pith. In this case, pith estimators (Applequist 1958) were used to estimate the pith age. Pith estimation works by matching a pre-fabricated ring template with the inner rings on a given core. For pith estimation to be possible, inner-ring curvature must be present. Once the ring pattern is successfully matched, the additional rings on the template are

counted and added to the inner age of the core. For example, a core with an inner date of 1900 that shows eight inner rings missing on the ring template will have an estimated pith date of 1892. This process was used for every core that did not contain the inner pith ring.

All dated cores were entered into Excel for graphical and statistical analysis. Histograms were used to visually analyze the age structure in three different ways: (1) by transect number, (2) by slope position, and (3) for each kipuka as a whole. The most important areas for the age structure analyses were the lower slopes of the kipukas. These areas are adjacent to the ponderosa pine forests on the lava flows. Therefore, any additional seed germination should be visible on the lower slopes due to the proximity of older, mature trees. Historically, ponderosa pine seedlings were removed from these lower slope areas by low-severity, stand maintenance fires, before they were able to establish. If unusually large numbers of seedlings or juvenile ponderosa pine trees (*i.e.* <100 yrs) are present on the lower slopes of the kipukas, I can infer that structural changes are occurring due to changes in fire regimes.

5. Results

5.1. Crossdating

Nearly 450 fire scars were recorded on 86 samples from eight different sites on the lava flows and kipukas (Table 5.1). The majority of the trees sampled were ponderosa pine, while a small number (3) were piñon or juniper. Thirty-nine samples were included from previous work conducted on Mesita Blanca and Hidden Kipuka (Grissino-Mayer 1995; Grissino-Mayer and Swetnam 1995). Most of the samples had inside/pith dates between A.D. 1600 and the present, although some samples recorded inner dates as far back as the late 1300s. One sample crossdated with a pith date of A. D. 1275 but was not included in this study because no fire information was obtained. It will eventually be measured and added into the El Malpais Long Chronology to increase that chronology's sample depth.

A number of “signature” or “marker rings” were particularly useful in dating the samples to the master chronology. These included the 1900-1902-1904 very narrow rings, the 1880 micro-ring, the 1842-1847-1851 narrow rings, the very wide 1816 and 1817 rings followed by the very narrow rings in the 1820s, the 1806 micro-ring (also a large fire year in the monument), and the very wide 1793 and 1710 rings. Years with widespread fires were also helpful in dating many of the fire history samples (Figure 5.1): 1695, 1755 (primarily on North Kipuka), 1806, 1843, 1856, 1876, 1893, 1933, and 1976.

Table 5.1. Sample information for all sample sites.

Site Name	Number of Samples	Fire Years	Scars per Tree		
			Min.	Max.	Avg.
Braided Cave	10	27	2	14	6.0
Campsite	11	17	2	10	5.8
Hidden Kipuka	31	28	2	8	3.9
La Sorpresa	11	25	1	11	6.2
Logging Road	8	19	5	11	7.4
Mesita Blanca	28	49	2	16	6.7
Mesita Blanca South	16	33	3	21	6.8
North Kipuka	10	19	1	5	2.8
Totals/Average	125	217	1	21	5.7

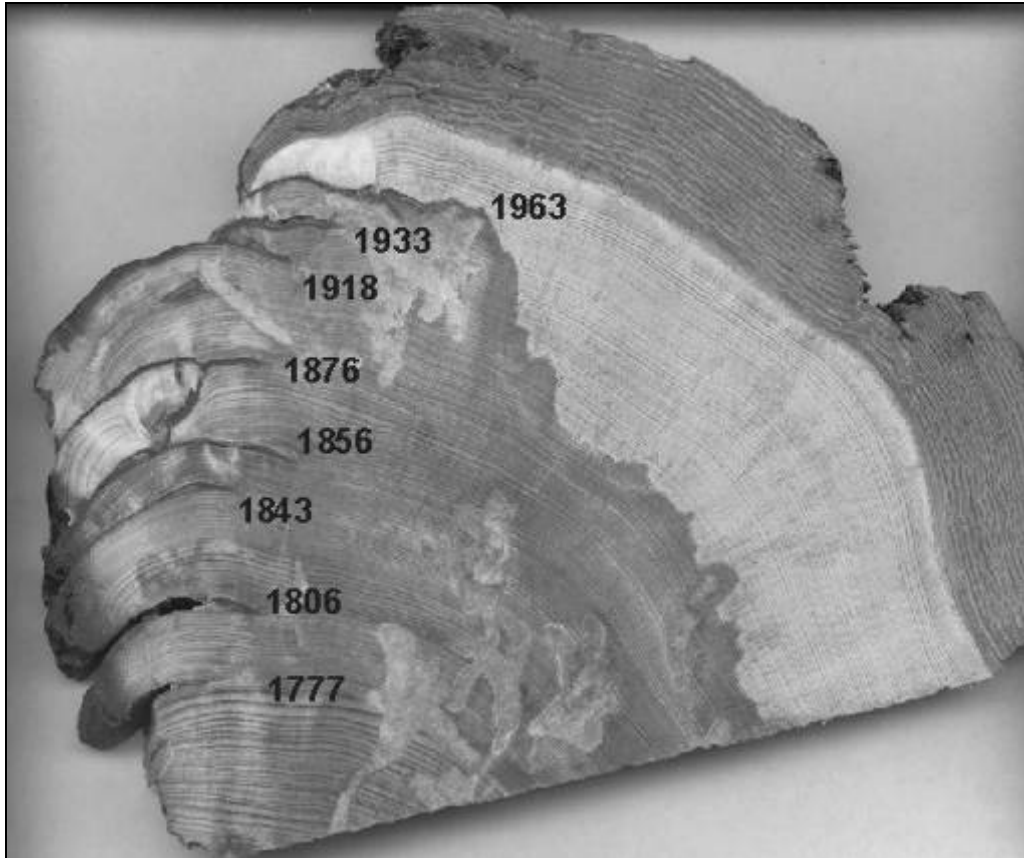


Figure 5.1. Sample LSP02 from La Sorpresa. This sample shows the marker fire years that were helpful in dating some of the more difficult samples.

5.2. Period of Reliability

Mesita Blanca and Mesita Blanca South had the longest periods of reliability, beginning at 1658 (Table 5.2). Four samples on Mesita Blanca and two samples on Mesita Blanca South recorded fires much earlier than this, but they were primarily non-recorders and the sample depth was not adequate to begin earlier. The shortest periods of reliability came from La Sorpresa and the Logging Road, each beginning at 1806. Again, all of these sites have trees recording fires earlier than this date, but adequate sample depth was not available. The period of reliability for all sites ends between 1929 and 1935. All sites except North Kipuka recorded a major fire in 1976, but the period of reliability ends prior to this because the large gap during that period is most likely caused by human-related disturbances (*i.e.* fire suppression).

Table 5.2. Period of reliability information for each sample site: BRC- Braided Cave, CMP- Campsite, KIP- Hidden Kipuka, LSP- La Sorpresa, LRD- Logging Road, MES- Mesita Blanca, MBS- Mesita Blanca South, and NKP- North Kipuka.

Site Name	Begin Year	Earliest Fire	Latest Fire	Period of Reliability		
				Begin	End	Length (yrs)
BRC	1623	1637	1976	1695	1933	238
CMP	1704	1763	1976	1777	1933	156
KIP	1570	1624	1976	1695	1935	240
LSP	1502	1612	1976	1806	1933	127
LRD	1616	1679	1976	1806	1933	127
MES	1386	1447	1989	1658	1933	275
MBS	1490	1562	1976	1658	1933	275
NKP	1675	1715	1959	1755	1929	174

5.3. Fire Records

5.3.1. Kipukas

Mesita Blanca had the longest kipuka fire chronology, recording fire events extending back to 1447, although sample depth was not adequate to include these older samples in the final analysis (Figure 5.2). Four samples, three collected by Grissino-Mayer (1995) and one collected for this study, show repeated fire occurrences from the mid-1400s through the mid-1500s. The oldest and best preserved samples found on the kipuka were located along the periphery next to adjacent lava flows, where the broken topography helps to protect remnant samples from subsequent fires. Most samples, however, were located on the midslope and upper crests of the kipukas, where ponderosa pines tend to intermix with the piñon-juniper woodland. Large numbers of fire-scarred trees were not found on the lower kipuka slopes due to the historical absence of ponderosa pine forests there. Grasses and small shrubs historically dominated these areas.

The Mesita Blanca South fire chart (Figure 5.3) showed a somewhat similar pattern to that of Mesita Blanca, although the sample depth of older, relict wood was not as extensive. One sample was found that recorded fire events back to 1562. The overall number of samples that recorded 19th and 20th century fire occurrences were greatly increased by this site, with seven trees recording fire events during this period. Many of the samples from this kipuka were difficult to crossdate because of ring deterioration due to beetle galleries. Fire records created by Grissino-Mayer (1995) and by this study for Mesita Blanca were very helpful in successfully crossdating these samples.

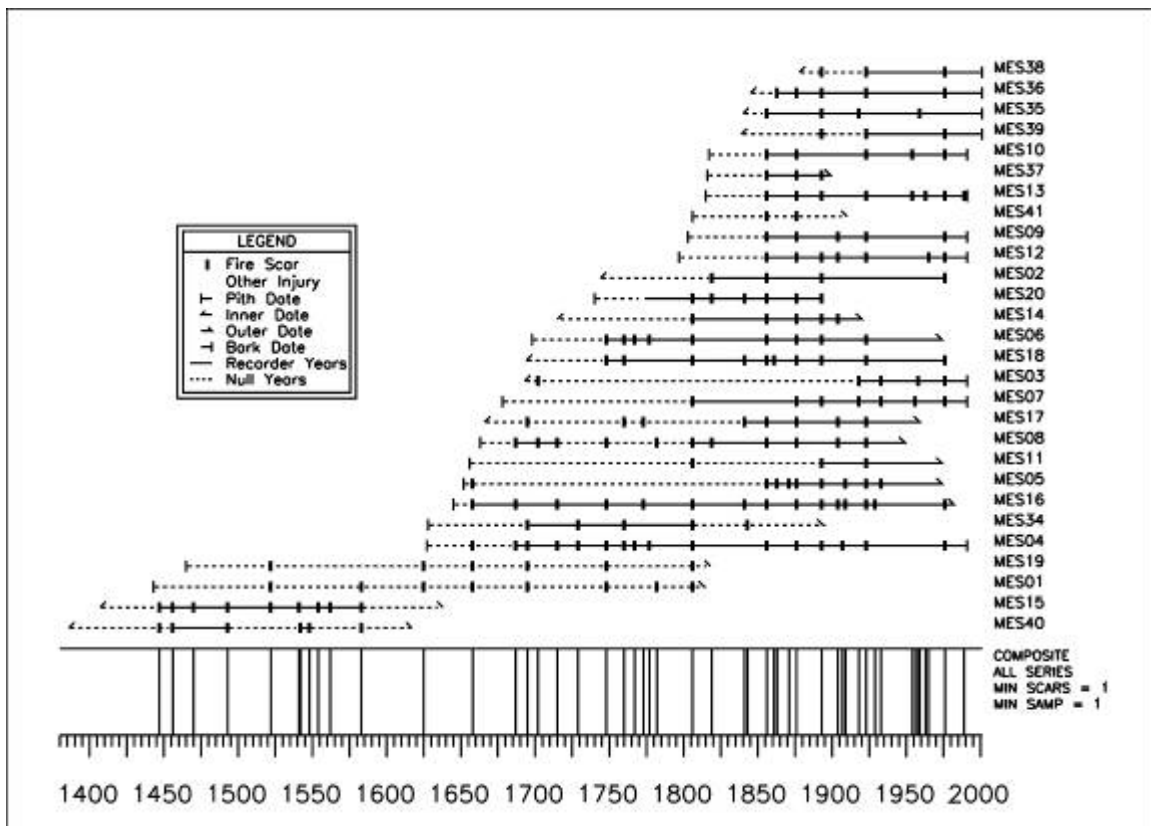


Figure 5.2. The master fire chart for Mesita Blanca. This kipuka recorded fire events back to the mid-1400s. Notice the gaps in fire occurrence between 1782–1806, and 1824–1842. Fires became more widespread and synchronous after 1800. Each horizontal line represents one sample and each vertical tick mark indicates a dated fire scar. The composite represents each year in which a fire was recorded.

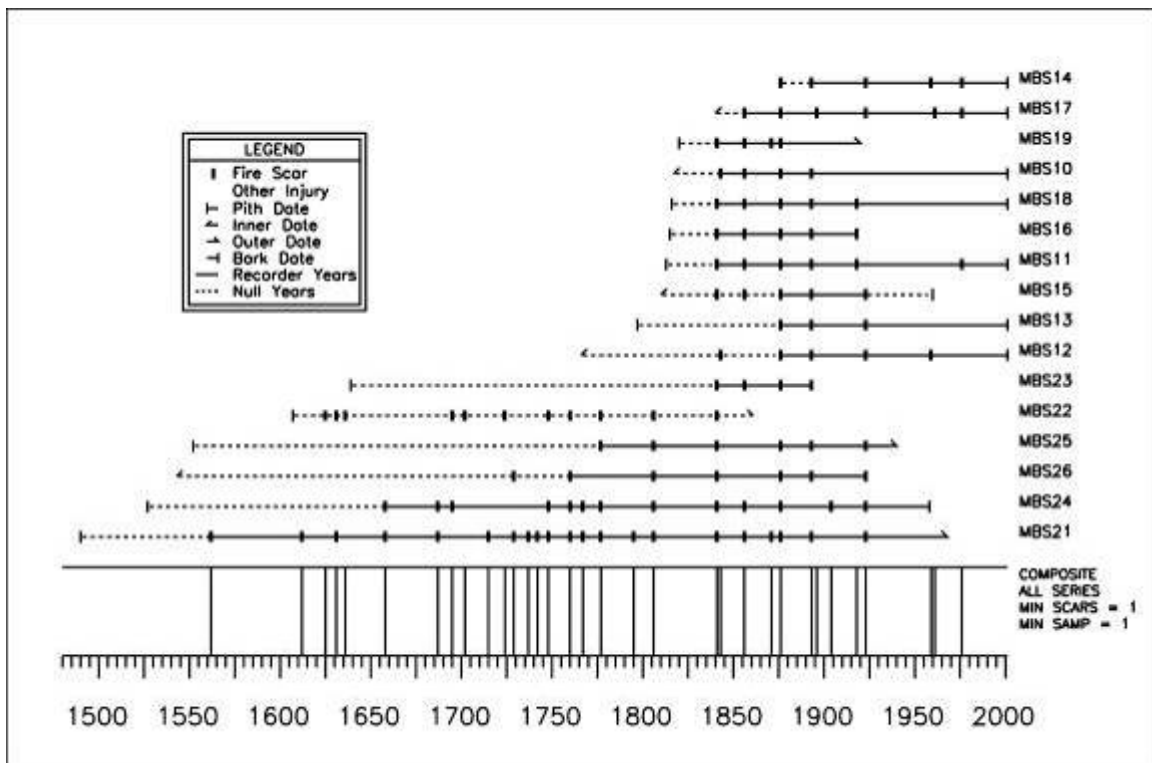


Figure 5.3. The master fire chart for Mesita Blanca South. This kipuka has a very similar fire regime to Mesita Blanca due to its close proximity. Notice the large gap from 1806–1843.

The La Sorpresa fire record (Figure 5.4) was very similar to Mesita Blanca and Mesita Blanca South in the 19th century. Numerous well preserved, multiple fire-scar samples were found on this kipuka. Many of these specimens were stumps left behind from the extensive logging that occurred on this kipuka. One sample recorded fire events back to the early 1600s. The fire hiatus between 1789 and 1843 was clearly visible. Fire frequency increased in the late 18th century, and then became more synchronous across the area in the 19th century.

The fire record for Hidden Kipuka (Figure 5.5) showed a somewhat different historical fire regime than that of Mesita Blanca, Mesita Blanca South, and La Sorpresa. The number of widespread fires, especially in the 19th century, was slightly lower than that found on the other kipukas. Fire events were very synchronous, though, and the presence of signature fire years (*i.e.*, 1843, 1893, and 1923) recorded on the lava flows and other kipukas indicates that the Hoya de Cibola lava flow does influence fire regimes on this kipuka, albeit to a lesser extent. Five trees on Hidden Kipuka contained fire events dating into the mid-1600s. The fire record showed only three fire events scarring more than one tree from 1933–1976.

North Kipuka (Figure 5.6) had the most unique fire record of any site in this study because it is completely surrounded by the Bandera lava Flow, a very broken, geologically young (*ca.* 10,000 yrs) (Laughlin *et al.* 1993) lava flow that supports negligible grass cover for the spread of wildfire. The vast majority of the fires that occur on this kipuka must originate on it via lightning. The signature fire years found for most of the other sites were not present on North Kipuka. A major fire in 1755 occurred in

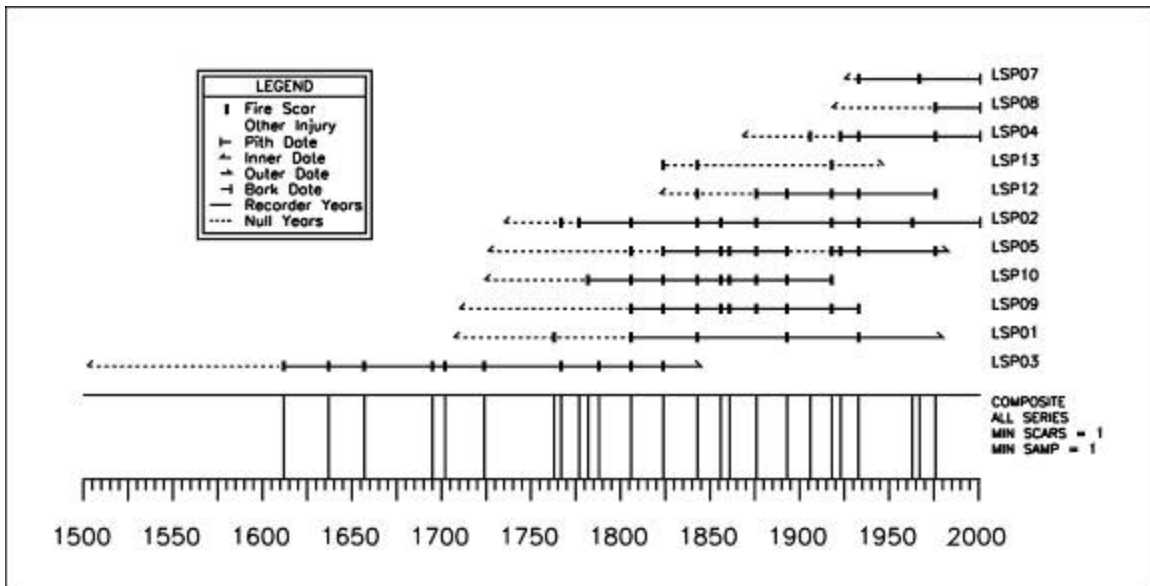


Figure 5.4. The master fire chart for La Sorpresa. Although the chronology is not as temporally extensive, the 18th and 19th century pattern is very similar to Mesita Blanca and Mesita Blanca South. The primary difference is the 1824 fire, which does not show up on the other kipukas. In addition, no conspicuous gap in fire occurrence was noted after 1750.

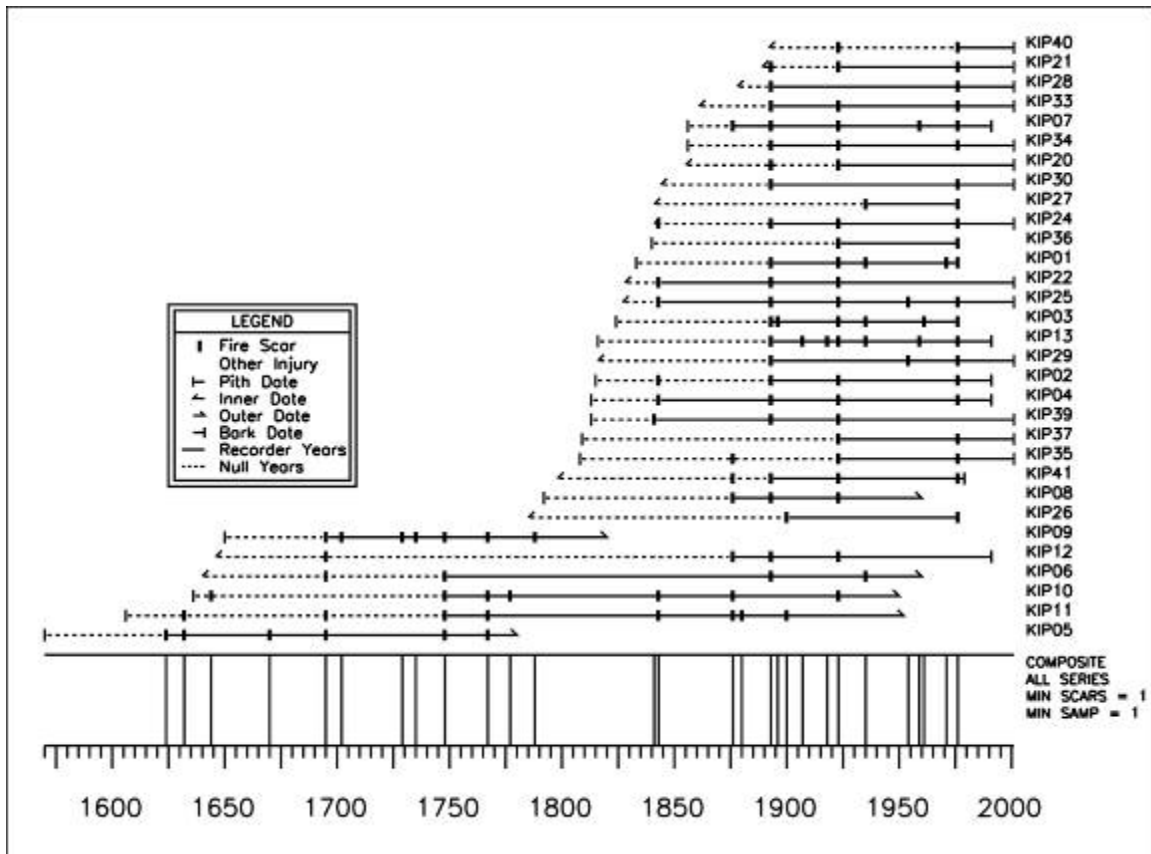


Figure 5.5. The master fire chart for Hidden Kipuka. The fire regime tends to be somewhat different than Mesita Blanca. Although some of the marker fire years are present, the number of fire events is lower here. This is most likely attributed to the inability of fire to spread over the Bandera Lava Flow due to decreased fuel availability. An obvious gap in fire occurrence can be seen between *ca.* 1775–1842.

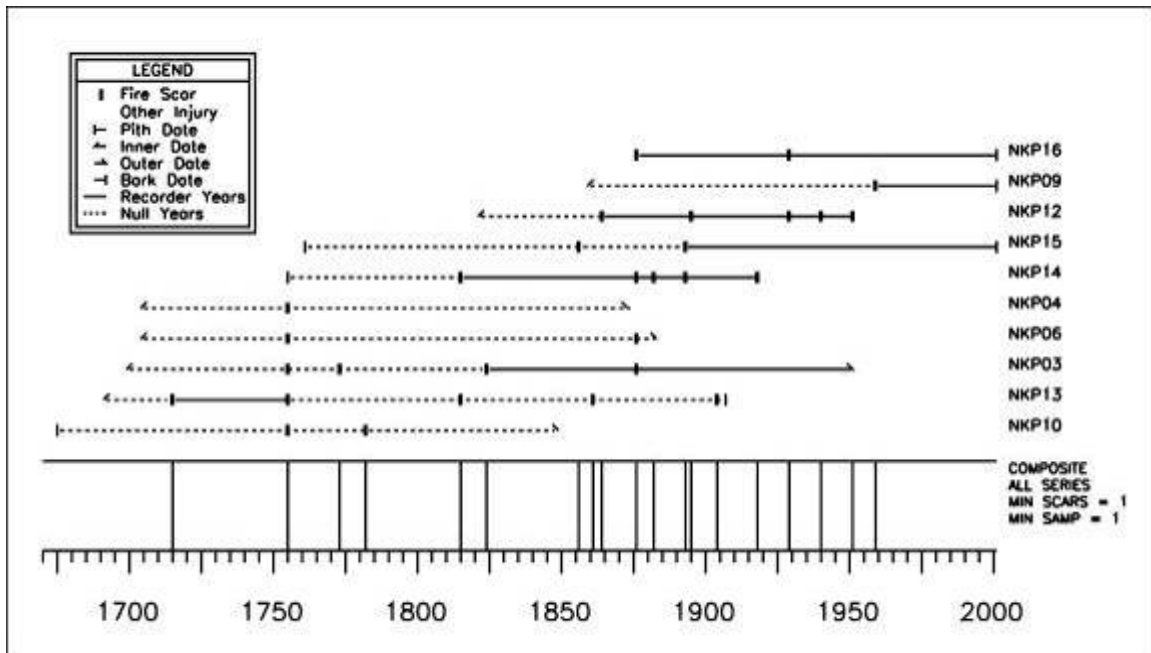


Figure 5.6. The master fire chart for North Kipuka. Notice the difference between this kipukas and the others. This kipuka lies entirely in the Bandera Lava Flow and is also on the east side of the lava tubes system. The 1755 fire is recorded on every sample old enough to have been able to record it.

every sample old enough to record it. Only four other fire years represented by more than one fire-scarred sample were observed.

The combined fire record for all kipuka sites resulted in a very long fire chronology with a high sample depth (86 samples) (Figure 5.7). Fires have occurred on the malpais kipukas at least since the mid-1400s. Fires occurred with regularity until the mid-1930s, when fire frequency began a noticeable decline. Fires tended to be more frequent, but less widespread, in the late 1700s. During the 1800s, fires became more synchronous and widespread. Unlike many areas of the Southwest, these kipukas have been recording fire events well into the 1900s.

5.3.2. Lava Flow Sites

Three sites on the Hoya de Cibola Lava Flow were targeted to examine the spatial and temporal aspects of fire in the southern portions of the monument, and to examine the degree to which fires on the Hoya Flow affect the fire regimes of the kipukas. All three sites are in close proximity to Mesita Blanca, Mesita Blanca South, and La Sorpresa. None of the sites provided temporally extensive chronologies, but they did provide essential information on 18th and 19th century fire events.

All of the fire records from the three lava flow sites exhibited the same 19th century fire pattern as Mesita Blanca, Mesita Blanca South, La Sorpresa, and to a lesser extent Hidden Kipuka. The signature 19th century fires (1806, 1843, 1856, 1876, and 1893) occurred at one or all of the lava flow sites that were sampled for this study. This suggests that the Hoya de Cibola lava flow, at least in the 19th century, had a substantial influence on the fire regimes of the adjacent kipukas by helping propagate fire spread.

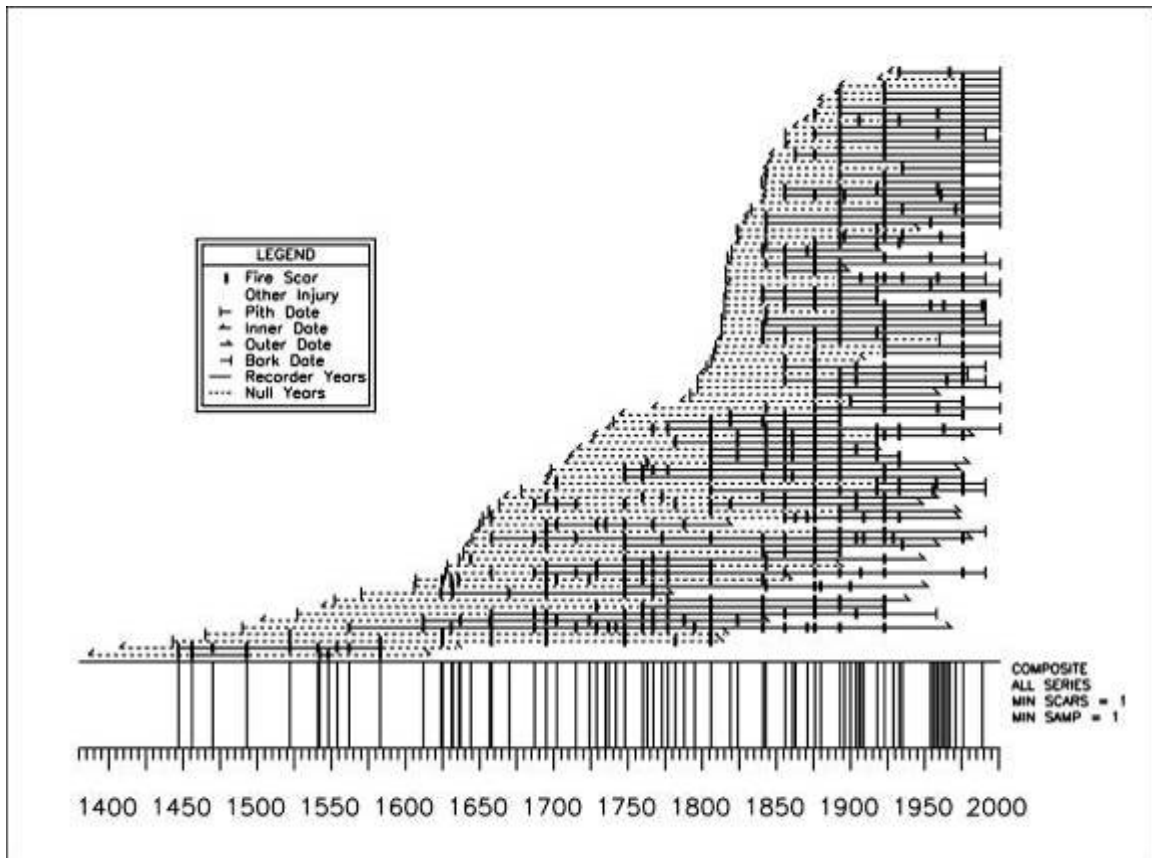


Figure 5.7. The master fire chart for the combined kipukas. Notice the increase in fire events in the mid-late 1700s. After 1923, fires became more sporadic. The next widespread fire did not occur until 1976.

The Campsite fire chart (Figure 5.8) exhibited all of the signature fire years. The sample depth was adequate to conduct fire interval analyses back to 1777. Fires were synchronous from the late 18th century until 1933, when fire events noticeably terminated. Only one sample recorded a fire between 1933 and 1976. Only two samples contained less than two scars, and the majority contained more than four.

One major difference in the Logging Road fire history (Figure 5.9) with other fire histories reconstructed in this study was the 1824 fire. This fire was one of the most widespread fires in the last 400 years in the malpais (Grissino-Mayer 1995). The fire hiatus at this site occurred from 1760–1806. The 19th century fire years were similar to those observed at the other sites. Although the 1933 fire is present, it is not as widespread at this site, although sample depth is low after 1925.

Braided Cave (Figure 5.10) had the longest fire chronology of the three lava flow sites sampled for this study. Sample depth was adequate to analyze fire events back to 1695. A number of well-preserved, multiple-scarred samples were found at this site. The increase in fire frequency in the middle and late 1700s was more pronounced at this site than the other lava flow sites. The 1824 fire is also present, as it was at Logging Road. Two well-defined gaps were present at this site: 1703–1733 and 1824–1856.

The combined lava flow sites yielded a chronology that recorded fire events back to the late 1300s (Figure 5.11). Although sample depth was too low to analyze fire events prior to 1695, these samples indicate how long fire has been a part of the malpais ecosystem. Fire frequency increased in the late 1700s, just as it did on the kipukas. Fires also became more synchronous and widespread after 1800. The gap in fire occurrences noted by Grissino-Mayer (1995) from 1782–1806 was clearly visible on the lava flow

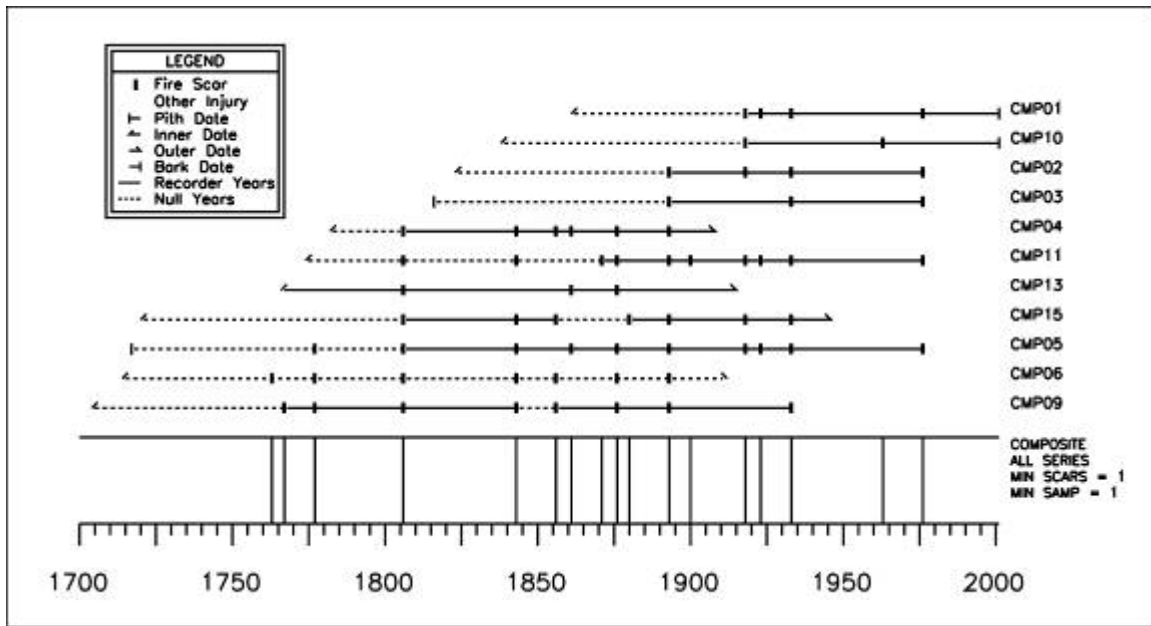


Figure 5.8. The master fire chart for Campsite. Notice the same 19th century fire pattern as the kipukas, indicating that the lava flows do directly influence the fire regimes of the kipukas. Two large gaps occur from 1777–1806, and from 1806–1843. Only one widespread fire occurred since 1933.

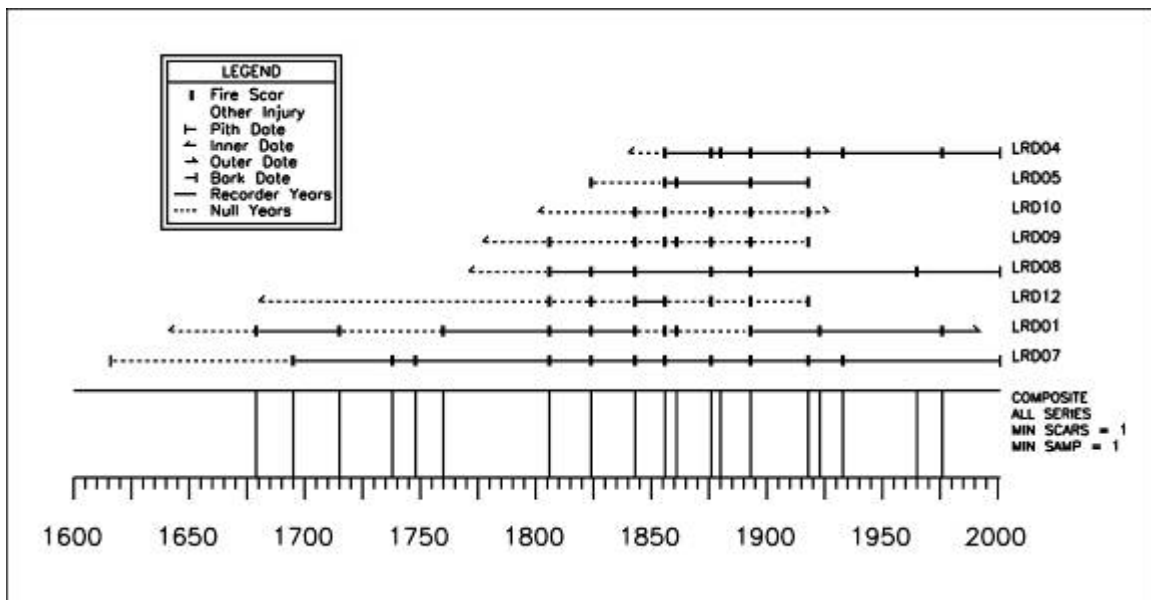


Figure 5.9. The master fire chart for Logging Road. The 1824 fire found at La Sorpresa is also found at this site. Fires were less common after 1933. A noticeable gap in fire occurred between 1760–1806.

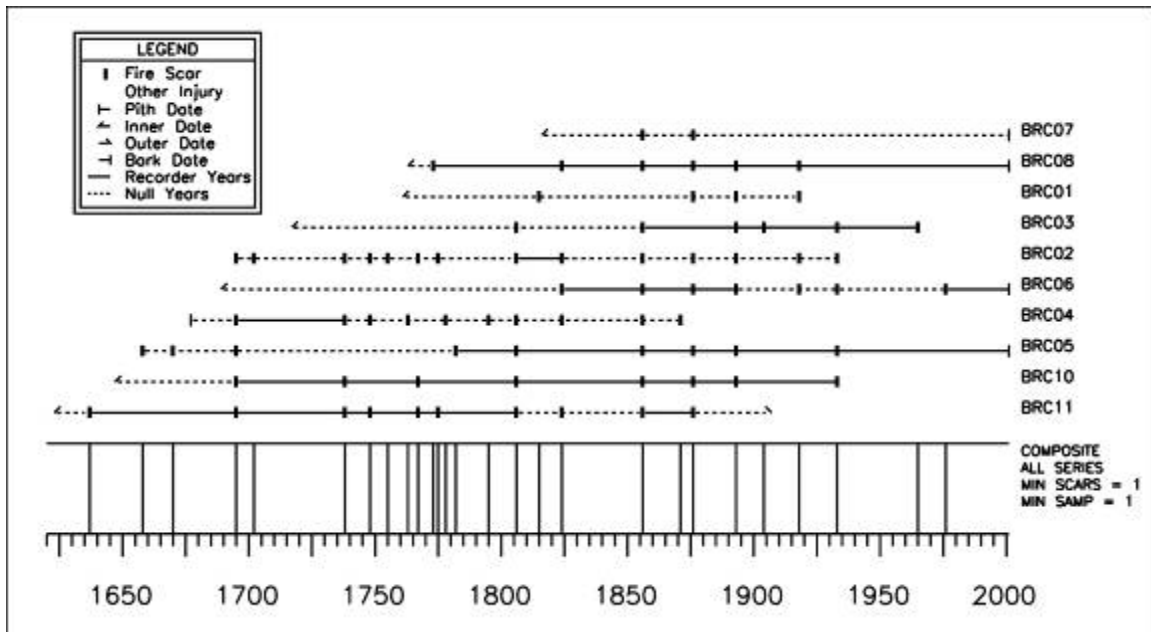


Figure 5.10. The master fire chart for Braided Cave. This is the longest reconstruction from the lava flow sites. Notice the increase in fire frequency during the mid-late 1700s, followed by a fire hiatus from 1824–1856. Fires were again uncommon after 1933.

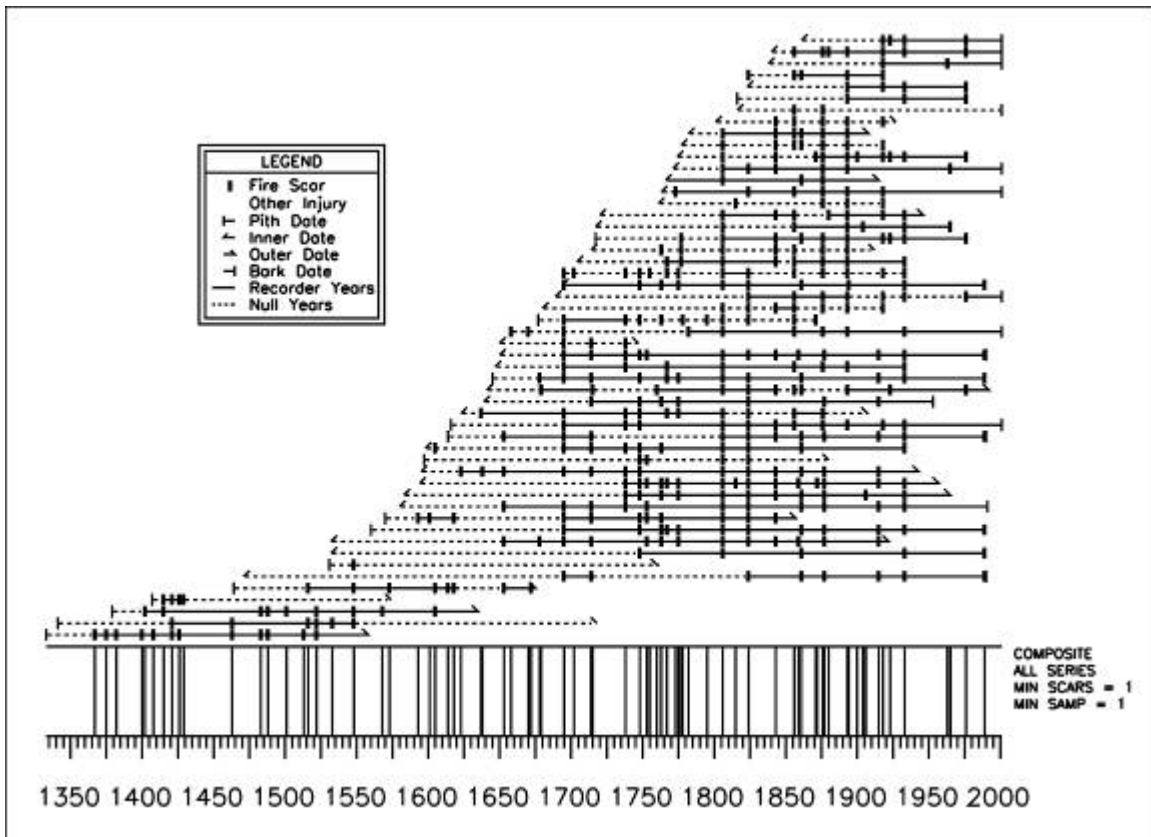


Figure 5.11. The master fire chart for the combined lava flow sites. The increase in fire events is also noticeable in the mid-late 1700s. Notice the large gap from 1782–1806. Fires became uncommon from 1933–1976. Only one fire was recorded after 1976.

sites. Fires became scarce from 1933–1976, and only one fire event was recorded after 1976.

5.3.3. Combined Fire Record

All samples from both the kipukas and lava flow sites were combined into one large record to analyze large-scale patterns in malpais fire regimes (Figure 5.12). Prior to 1800, fires were less synchronous between sites. Following 1800, fire events became more synchronous between sites. The kipukas exhibited a larger number of smaller-scale, episodic wildfires in the 20th century than did the Hoya de Cibola Lava Flow. The increase in fire frequency during the late 1700s was again clearly visible. One long fire hiatus was visible from 1824–1841. All of the large-scale fires that occurred on the lava flow after 1800 are visible on the kipukas, with the lone exception of the 1824 fire, which only scarred three samples on the kipukas.

5.4. Descriptive Statistics

5.4.1. Mean Fire Interval

Three kipukas, Mesita Blanca, Mesita Blanca South, and La Sorpresa, had similar MFIs in both percent-scarred classes, likely because of their close proximity to one another (Table 5.3). North Kipuka had the highest MFI at 43.5 yrs (all-scarred and 25% scarred). The MFIs for Hidden Kipuka were also high at 30 yrs (all-scarred) and 38 yrs (25% scarred). Logging Road (15.9 yrs) and Campsite (17.3 yrs) had MFIs similar to those of Mesita Blanca, Mesita Blanca South, and La Sorpresa, also likely due to their

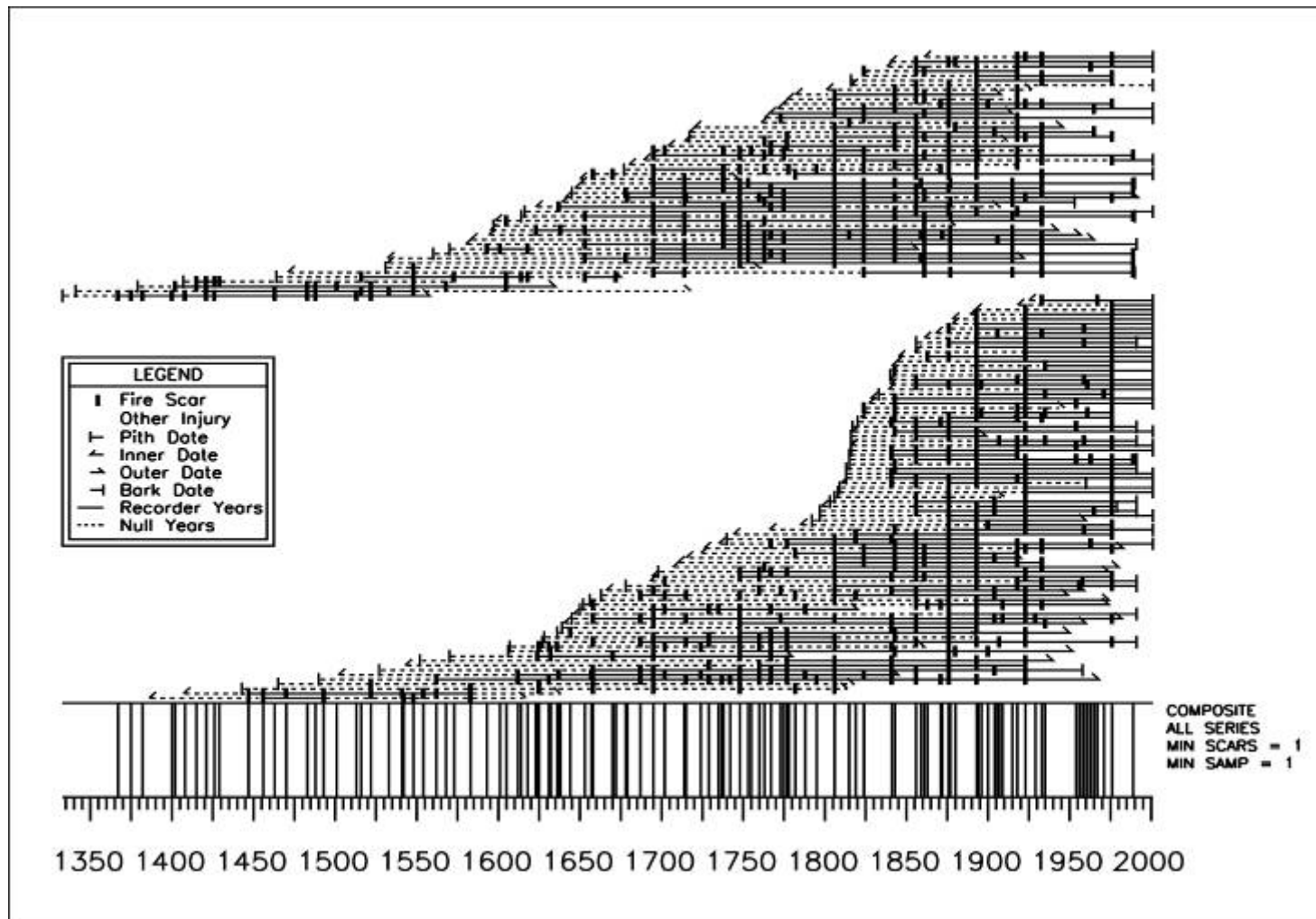


Figure 5.12. The composite master fire chart for all sites. Lava flow sites are on top, and kipuka sites are on bottom. Widespread fires on the kipukas ceased after 1933 when fires on the lava flows were reduced. Notice that only one sample was scarred in the 1989 fire on the kipukas.

Table 5.3. Descriptive statistics for each site for (A) all scarred and (B) 25% scarred. See Table 5.2 for site abbreviations.

A	MFI	MEI	MOI	SD	CV	Min	Max	LEI	UEI	MHI
MES	12.0	11.3	9.5	6.66	0.56	4	29	4.9	19.7	48.5
MBS	16.6	14.7	10.1	10.81	0.65	2	35	5.3	29.2	332.4
LSP	14.1	13.8	12.9	6.62	0.47	5	25	7.0	21.5	35.6
KIP	30.0	26.0	15.2	23.44	0.78	7	76	8.4	55.1	>1000
NKP	43.5	42.8	41.3	21.11	0.49	17	61	23.2	64.5	182.5
BRC	21.6	21.0	19.4	10.36	0.48	8	43	10.4	33.5	83.1
CMP	17.3	15.9	12.1	10.98	0.63	5	37	6.2	29.7	189.9
LRD	15.9	15.8	15.9	5.69	0.36	5	25	9.7	21.9	26.5
B	MFI	MEI	MOI	SD	CV	Min	Max	LEI	UEI	MHI
MES	14.7	14.4	13.6	6.52	0.44	5	29	7.5	22.3	36.7
MBS	20.4	19.7	18.1	9.97	0.49	7	35	9.7	31.7	78.5
LSP	14.1	13.7	12.9	6.62	0.47	5	25	7.0	21.5	35.6
KIP	38.0	35.9	30.4	22.63	0.60	17	76	15.7	62.4	485.6
NKP	43.5	42.8	41.3	21.11	0.49	17	61	23.2	64.5	182.5
BRC	21.6	21.0	19.4	10.36	0.48	8	43	10.4	33.5	83.1
CMP	17.3	15.9	12.1	10.98	0.63	5	37	6.2	29.7	189.9
LRD	15.9	15.8	15.9	5.69	0.36	5	25	9.7	21.9	26.5

close proximity. Braided Cave, farther away from those three kipukas, had a higher MFI in both percent-scarred classes (21.6 yrs).

5.4.2. Weibull Median Interval (MEI) and Weibull Modal Interval (MOI)

The MOI was lower than the MEI at each site in both percent-scarred classes, with the exception of the Logging Road site where the two were almost equal (Table 5.3). MOIs ranged from 9.5 yrs (all-scarred class) at Mesita Blanca to 41.3 yrs at North Kipuka (both percent-scarred classes). Three sites, Hidden Kipuka, Mesita Blanca, and Mesita Blanca South, had higher MOIs in the 25% scarred class because the filter excluded a number of shorter fire intervals. MEIs ranged from 13.7 yrs at La Sorpresa (25% scarred) to 42.8 yrs at North Kipuka (both classes).

5.4.3. Standard Deviation (SD)

Logging Road had the lowest standard deviation (5.69 yrs) in both percent-scarred classes (Table 5.3). La Sorpresa and Mesita Blanca also had low standard deviations, each below 7.00 yrs in both percent-scarred classes. Hidden Kipuka had the highest standard deviation in both classes at 23.44 yrs (all-scarred) and 22.63 yrs (25% scarred). North Kipuka was also high at 21.11 yrs (both classes). Braided Cave (10.36 yrs) and Campsite (10.98 yrs) had similar values in both percent-scarred classes.

5.4.4. Coefficient of Variation (CV)

The coefficient of variation provided a means of comparing the variability of fire regimes at sites with different means. Hidden Kipuka had the highest coefficient of

variation in the all-scarred class at 0.78, but decreased to 0.60 in the 25% scarred class (Table 5.3). The lowest coefficient of variation was at Logging Road (0.36, both percent-scarred classes). Although standard deviation was high at North Kipuka, the coefficient of variation was relatively low at 0.49 (both classes). Mesita Blanca South's coefficient of variation dropped from 0.65 in the all-scarred class to 0.49 in the 25% scarred class. La Sorpresa's coefficient of variation remained unchanged in both classes (0.47), as did Braided Cave (0.48) and Campsite (0.63). The coefficient of variation on Mesita Blanca dropped from 0.56 in the all-scarred class to 0.44 in the 25% scarred class.

5.4.5. Minimum and Maximum Fire Interval (Min and Max)

Hidden Kipuka had the longest fire-free interval at 76 yrs (both classes) (Table 5.3). North Kipuka also had long fire-free intervals, with the longest being 61 yrs (both classes). Logging Road (25 yrs) and La Sorpresa (25 yrs) had the shortest maximum fire intervals. Mesita Blanca's maximum fire interval was also low at 29 yrs. Mesita Blanca South had the lowest minimum fire interval in the all-scarred class at 2 yrs. Hidden Kipuka and North Kipuka had minimum fire intervals of 17 yrs in the 25% scarred class. The minimum fire intervals for Campsite, Logging Road, and La Sorpresa remained unchanged in both percent-scarred classes at 5 yrs.

5.4.6. Lower Exceedence Interval (LEI) and Upper Exceedence Interval (UEI)

North Kipuka had the highest LEI (23.2 yrs) and UEI (64.5 yrs) in both percent-scarred classes (Table 5.3). Hidden Kipuka, however, had the highest range between LEI and UEI, indicating higher variability in fire intervals. The LEI and UEI for Campsite,

Logging Road, and La Sorpresa remained unchanged from the all-scarred class to the 25% scarred class. Mesita Blanca had the lowest LEI (4.9 yrs) and UEI (19.7 yrs) in the all-scarred class, but increased to 7.5 yrs and 22.3 yrs respectively in the 25% scarred class.

5.4.7. Maximum Hazard Interval (MHI)

Logging Road had the lowest MHI in both percent-scarred classes at 26.5 yrs (Table 5.3). La Sorpresa also had a relatively low MHI in both classes at 35.6 yrs. Mesita Blanca's MHI declined from 48.5 yrs in the all-scarred class to 36.7 yrs in the 25% scarred class. Hidden Kipuka had long MHIs in both classes with an MHI of >1000 yrs found in the all-scarred class. North Kipuka also had high MHI values at 182.5 yrs. Campsite had the highest MHI of the lava flow sites at 189.9 yrs (both classes).

5.4.8. Probability Density Functions (pdf)

Mesita Blanca's all-scarred pdf (Figure 5.13A) showed a distribution that was positively skewed but had kurtosis values near zero. When the 25% scarred filter was applied (Figure 5.13B), the distribution became less positively skewed but more platykurtic. Mesita Blanca South's pdf (Figure 5.14) indicated a distribution that was only slightly positively skewed (0.42 for all-scarred, 0.14 for 25% scarred), but very platykurtic. Kurtosis values ranged from -1.25 for the all-scarred class to -1.54 for the 25% scarred class. The pdf for La Sorpresa was minimally skewed (-0.04) in both percent-scarred classes, but kurtosis values (-1.12) indicated a platykurtic distribution.

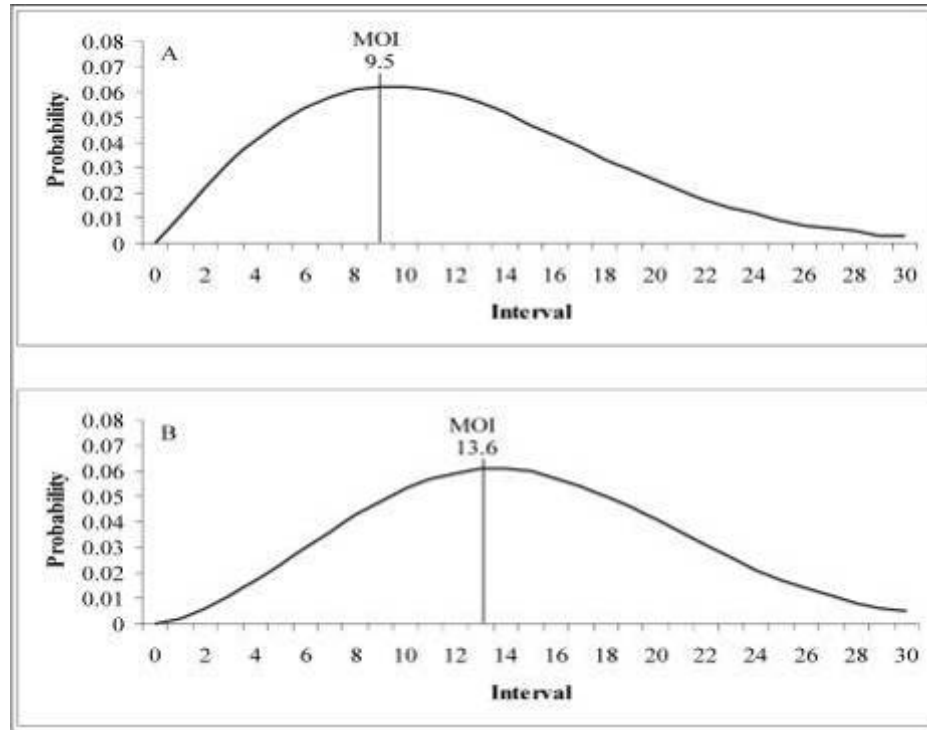


Figure 5.13. The pdf for Mesita Blanca. Top (A) is all-scarred and bottom (B) is 25% scarred. The skewness and kurtosis are (A) 0.93 and 0.08, and (B) 0.44 and -0.65.

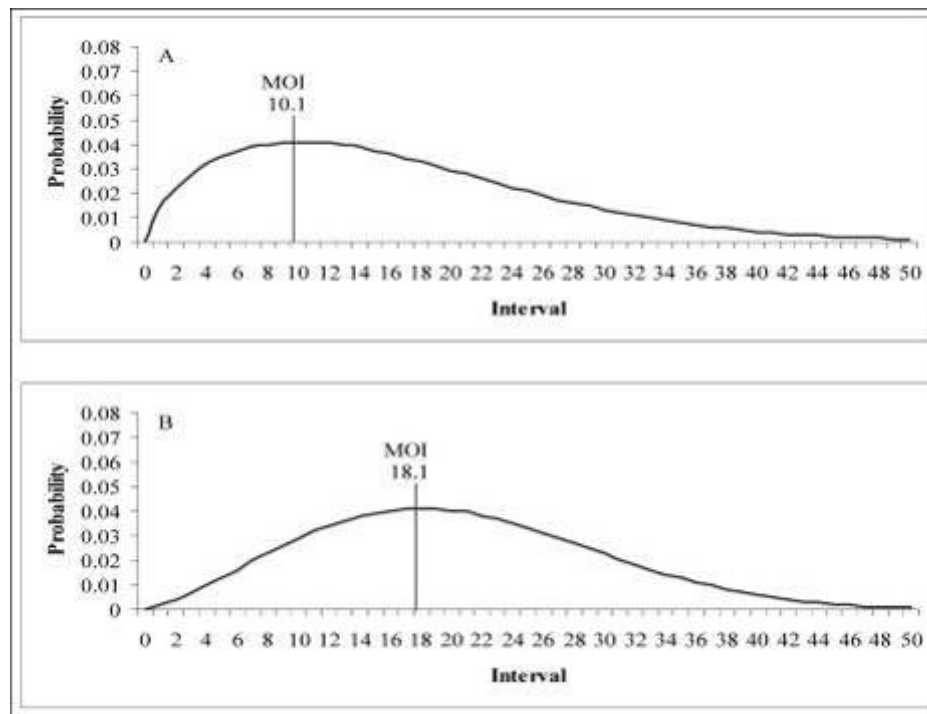


Figure 5.14. The pdf for Mesita Blanca South. Top (A) is all-scarred and bottom (B) is 25% scarred. The skewness and kurtosis are (A) 0.42 and -1.25, and (B) 0.14 and -1.54.

Visual inspection of the pdf graph does show some lengthening of the upper tail of the distribution (Figure 5.15).

Both Hidden Kipuka (Figure 5.16) and North Kipuka (Figure 5.17) exhibited very flat pdf distributions caused by long fire-free intervals lengthening the upper tails of the distribution. Hidden Kipuka's pdf was positively skewed and platykurtic in both percent-scarred classes. The pdf for North Kipuka was also platykurtic, but the distribution was negatively skewed.

Descriptive statistics for Logging Road indicated a near normal distribution. The pdf was slightly skewed (-0.39) in both percent-scarred classes, and kurtosis values were near zero (-0.13) (Figure 5.18). Braided Cave's pdf was positively skewed in both classes (0.64), and the curve was somewhat platykurtic (-0.54) (Figure 5.19). Campsite was also positively skewed in both classes (0.51), and platykurtic at -1.10 (Figure 5.20).

5.4.9. Combined Analyses

Descriptive statistics were calculated for the combined kipukas, all lava flow sites, and the entire study area (Table 5.4). The descriptive statistics for all of the kipuka sites yielded low values for MFI, MEI, and MOI in the all-scarred class. MFI was calculated at 7.9 yrs, the MEI was 7.2 yrs, and the MOI was 5.3 yrs. These values rose slightly in the 10% scarred class to 9.9, 9.5, and 8.4 yrs respectively. Standard deviation was 5.1 yrs for all-scarred, as well as for 10% scarred. The coefficient of variation was higher (0.64) for the all-scarred class than the 10% scarred class (0.51). Minimum and maximum fire intervals remained unchanged. Maximum hazard intervals were 36.8 yrs

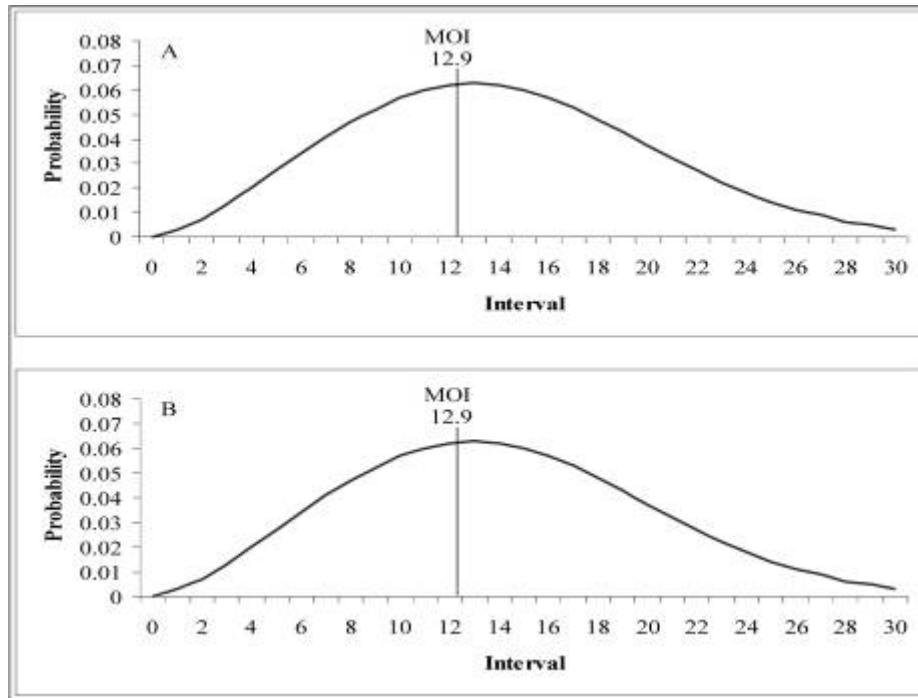


Figure 5.15. The pdf for La Sorpresa. Top (A) is all-scarred and bottom (B) is 25% scarred. The skewness and kurtosis are -0.04 and -1.12 for both.

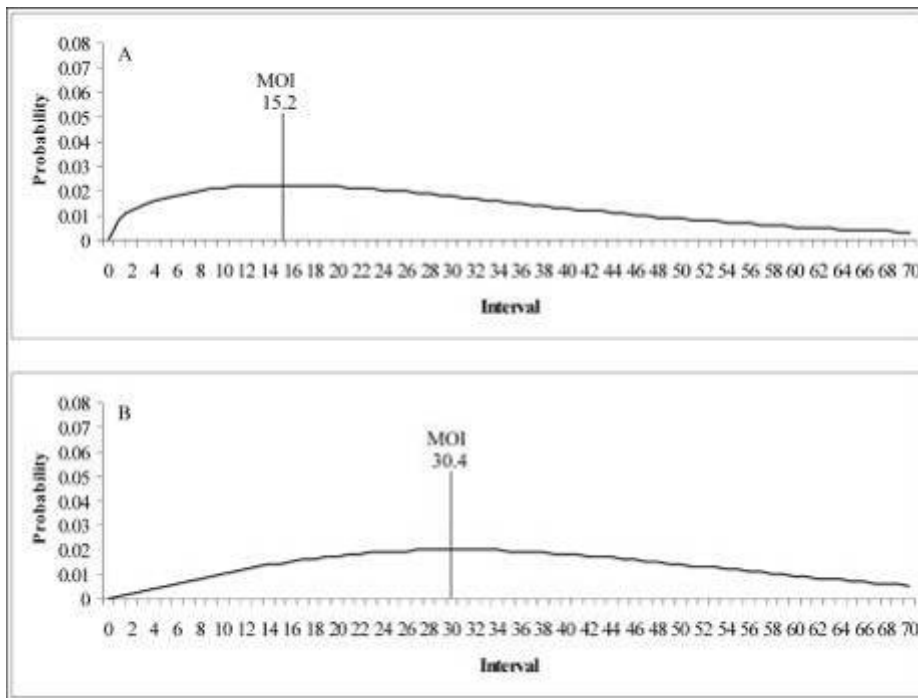


Figure 5.16. The pdf for Hidden Kipuka. Top (A) is all-scarred and bottom (B) is 25% scarred. The skewness and kurtosis are (A) 0.97 and -0.54, and (B) 0.72 and -1.12.

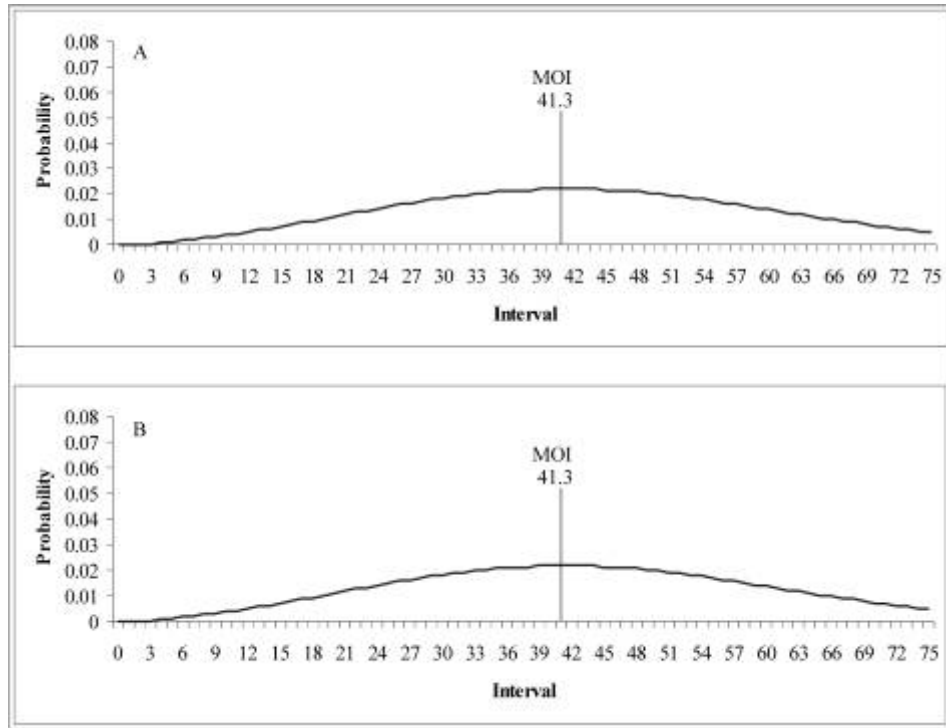


Figure 5.17. The pdf for North Kipuka. Top (A) is all-scarred and bottom (B) is 25% scarred. The skewness and kurtosis are -0.33 and -1.89 for both.

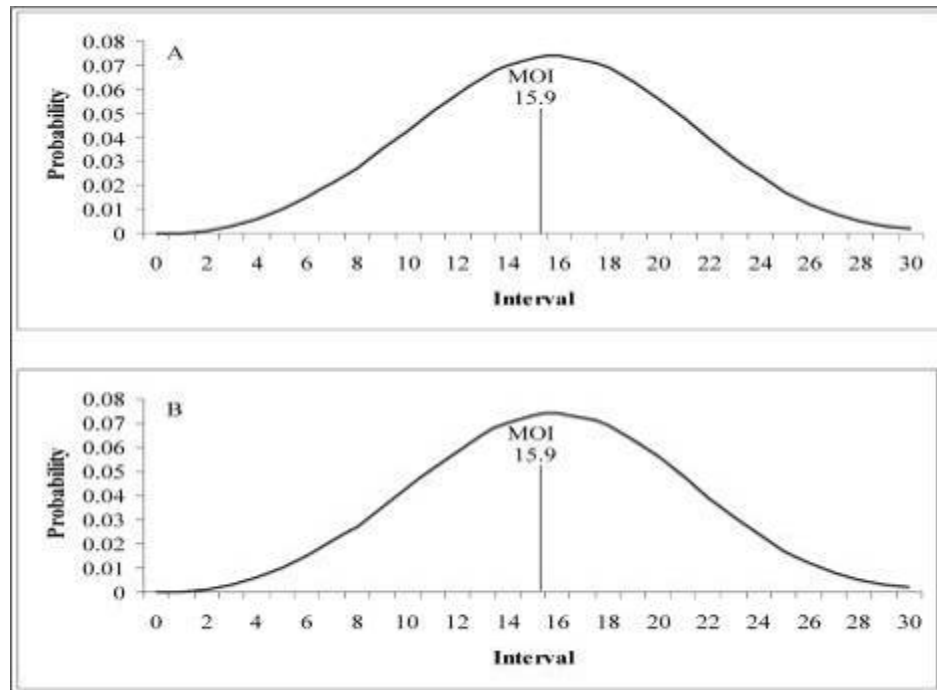


Figure 5.18. The pdf for Logging Road. Top (A) is all-scarred and bottom (B) is 25% scarred. The skewness and kurtosis are -0.39 and -0.13 for both.

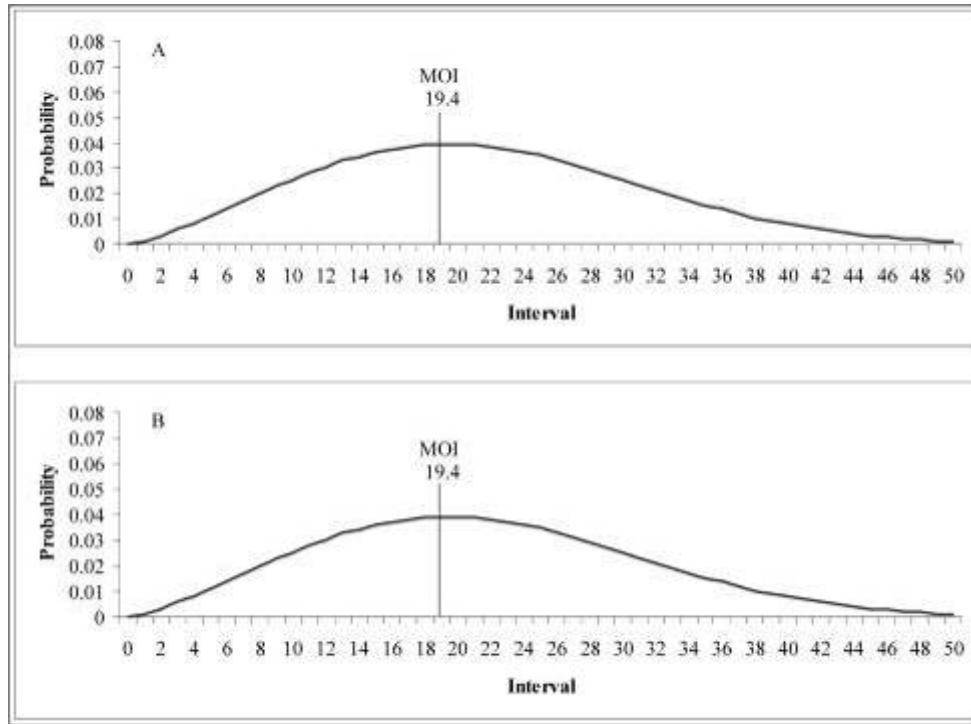


Figure 5.19. The pdf graph for Braided Cave. Top (A) is all-scarred and bottom (B) is 25% scarred. The skewness and kurtosis are 0.64 and -0.54 for both classes.

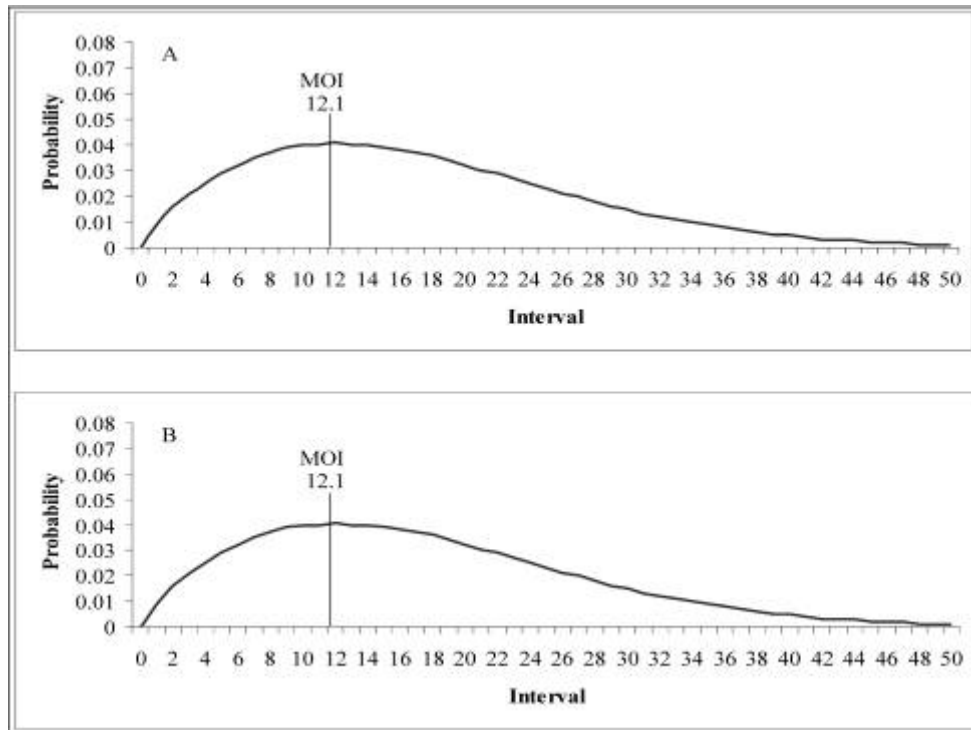


Figure 5.20. The pdf for Campsite. Top (A) is all-scarred and bottom (B) is 25% scarred. The skewness and kurtosis are 0.51 and -1.10 for both classes.

Table 5.4. Descriptive statistics for the combined kipukas, combined lava flow sites, and all sites combined for the all-scarred class (A) and 10% scarred class (B).

A	MFI	MEI	MOI	SD	CV	Min	Max	LEI	UEI	MHI
Kipukas	7.9	7.2	5.3	5.09	0.64	2	19	2.7	13.8	36.8
Lava Flows	9.9	8.3	4.0	7.67	0.77	1	29	2.5	18.7	562.6
All Sites	5.9	5.3	3.7	3.81	0.65	1	17	1.9	10.4	20.4
B	MFI	MEI	MOI	SD	CV	Min	Max	LEI	UEI	MHI
Kipukas	9.9	9.5	8.4	5.07	0.51	2	19	4.4	15.8	26.2
Lava Flows	11.3	9.5	4.7	8.24	0.73	1	29	2.8	21.2	776.8
All Sites	9.2	8.0	5.2	6.11	0.67	1	24	2.8	16.4	93.2

for all-scarred and 26.2 yrs for 10% scarred. These values are quite low considering how high the MHI values were for Hidden Kipuka.

The combined lava flow sites yielded a much higher MHI than the kipukas. The all-scarred MHI was 562.6 yrs, while the 10% scarred MHI was 776.8 yrs. Standard deviation was 7.67 yrs for all-scarred and 8.24 yrs for 10% scarred. Variability was much higher for the lava flow sites than for the kipukas. The coefficient of variation was above 0.70 for both percent-scarred classes. The MOI for both classes was lower on the lava flows than on the kipukas. The all-scarred MOI was 4.0 yrs, and the 10% scarred MOI was 4.7 yrs.

The descriptive statistics for the entire study area provided very important information concerning the historical variability of fire regimes in the southwestern portions of El Malpais National Monument. In the all-scarred class, the MOI was 3.7 yrs. The standard deviation was 3.81 yrs, while the coefficient of variation was 0.65. The LEI and UEI indicated that 75% of the fire intervals occurred between 1.9 yrs and 10.4 yrs. Both the MFI and MEI were also low at 5.9 yrs and 5.3 yrs respectively. The MHI was 20.4 yrs.

The statistics changed slightly in the 10% scarred category. The MOI increased to 5.2 yrs, and both the MFI and MEI also increased. The standard deviation was 6.11 yrs, and the coefficient of variation was 0.67. The maximum fire interval increased to 24 yrs. The new MHI was 93.2 yrs, much higher than the 20.4 yrs calculated for the all scarred class.

PDF graphs showed distributions for all three combined sample sets that were positively skewed in both percentage-scarred classes (Figure 5.21, Figure 5.22, Figure 5.23). All three PDF graphs indicated that a large number of significantly short fire intervals were present that helped contribute to distributions that were positively skewed.

5.5. Seasonal Change Analyses

The seasonal analysis showed the change in seasonality from predominantly late-season (MLA) fires to predominantly early-season (DE) fires *ca.* 1800 (Figure 5.24). The analyses covered 115 years prior to 1800, and 140 years after 1800. Four intervals were excluded prior to 1800 because adequate sample depth (at least 10 fire scars with seasonal information) was not available. One interval was excluded after 1800. With the lone exception of 1836–1850, all intervals after 1800 recorded at least 50% of the fires as late-season (M, L, A) events. Prior to 1800, no interval recorded more than 25% of the fires as early-season events.

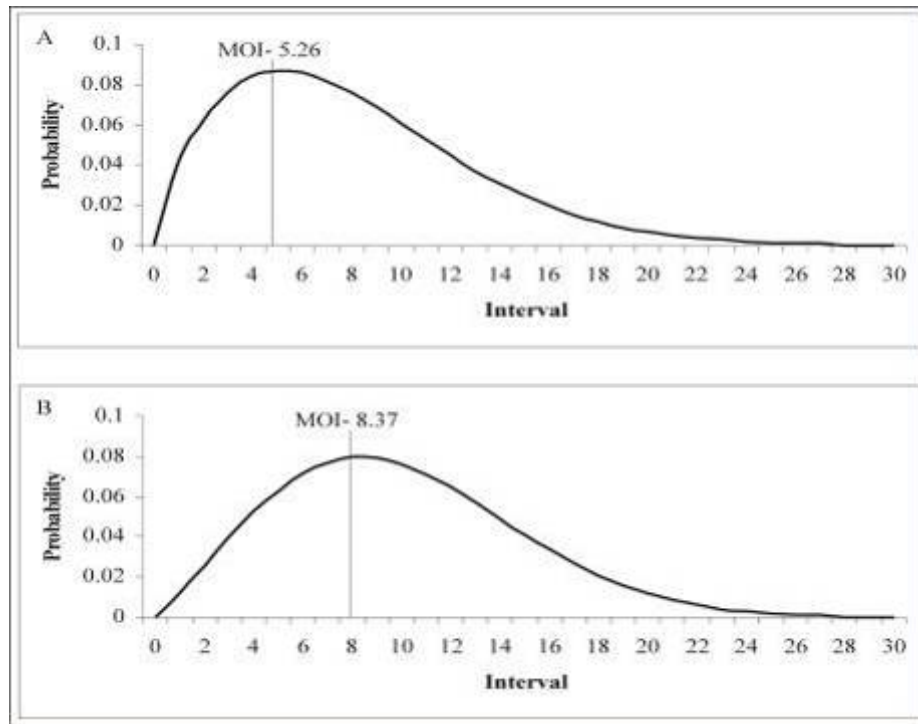


Figure 5.21. The pdf for all kipukas. Top (A) is all-scarred and bottom (B) is 10% scarred. The skewness and kurtosis are (A) 0.82 and -0.57, and (B) 0.27 and -1.29.

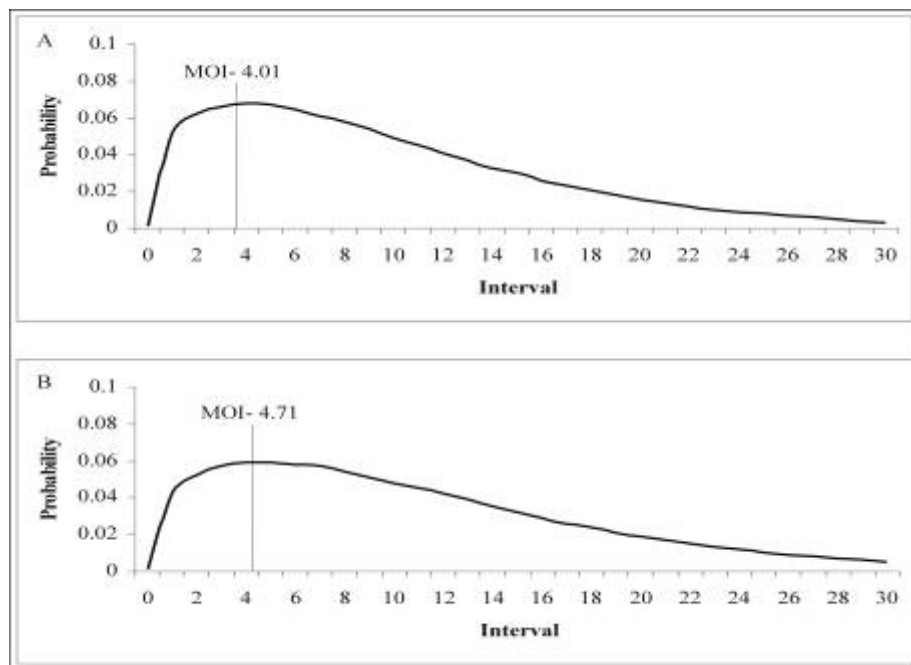


Figure 5.22. The pdf for all lava flow sites. Top (A) is all-scarred and bottom (B) is 10% scarred. The skewness and kurtosis are (A) 0.94 and -0.10, and (B) 0.47 and -0.96.

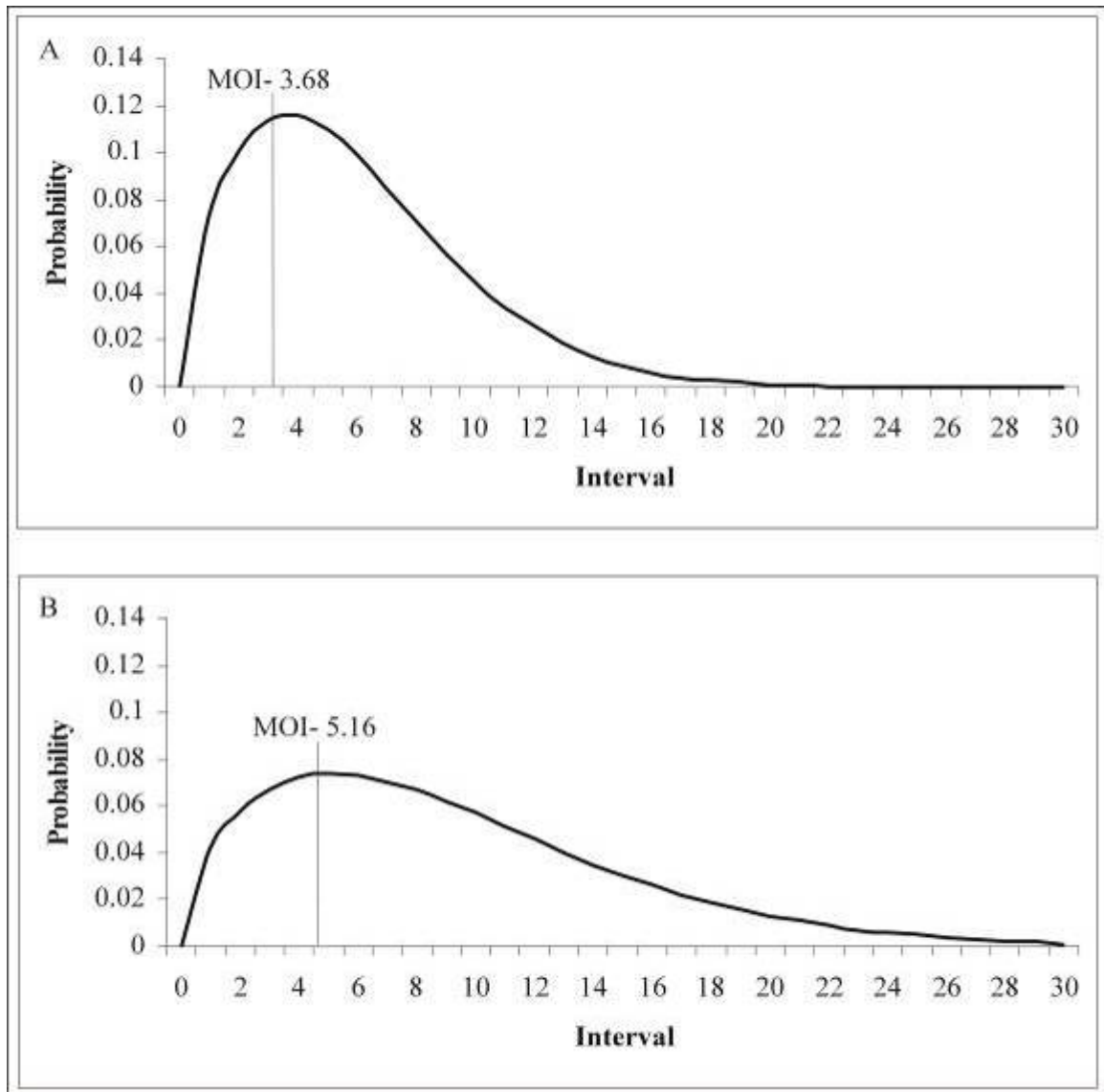


Figure 5.23. The pdf for all sites. Top (A) is all-scarred class and bottom (B) is 10% scarred. Skewness and kurtosis are (A) 0.78 and -0.04, and (B) 0.69 and -0.31.

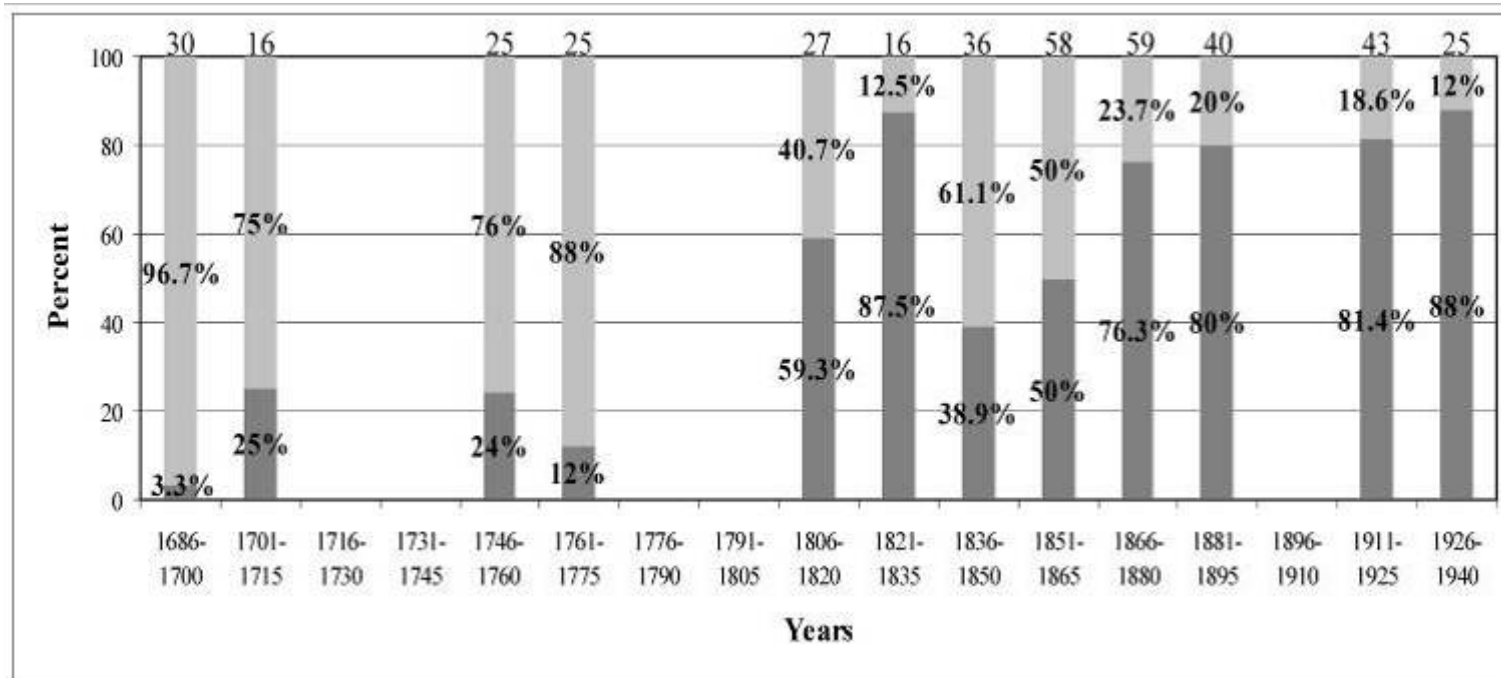


Figure 5.24. Seasonal change analyses. Seasonal information in 15-year increments for all sites combined from 1686–1940. The lower (dark gray) portions of the bars represent early-season (D and E) events. The upper (light gray) portions represent late-season (M, L, A) events. Five intervals were excluded because a minimum of ten fire scars were required to be added into the analysis. Numbers at the top of each bar indicate the number of scars for that period. After 1800, the pattern clearly changes from an early-season fire regime to a late-season fire regime.

5.6. Age Structure Results

5.6.1. Hidden Kipuka

Sixty-three trees were cored along five transects to analyze the age structure of the ponderosa pine forests on Hidden Kipuka. I was able to determine the innermost date for 55 trees using the El Malpais Long Chronology. Eight trees were not dated because of irregular growth patterns or severe deterioration of the wood. We counted branch nodes for 119 seedlings that were too small to be cored. Transect one covered 2750 m², transect two covered 2200 m², transect three covered 3800 m², transect four covered 3100 m², and transect five covered 2300 m².

Large numbers of seedlings were noted growing on the lower kipuka slopes. The largest numbers of seedlings were located on slope position 2 (43 in 850 m²) (Figure 5.25). Conversely, only one seedling was noted on slope position 4 (~3500 m²). Only four trees were found on slope positions 2 and 6 in excess of 140 yrs old. Seedling germination was much higher on the western side of the kipuka (slope positions 1, 2, and 3). Transects three and four contained the largest number of cored trees. The other transects were dominated by younger seedlings. A total of 122 seedlings were observed on all five transects (14.2 km²) (Figure 5.26). Two trees were sampled in excess of 300 yrs old.

5.6.2. Mesita Blanca

We cored 141 trees from three different transects to study age structure of the ponderosa pine forests on Mesita Blanca. I was able to determine inner ages for 132 trees. Nine trees were discarded because they could not be dated accurately. We counted

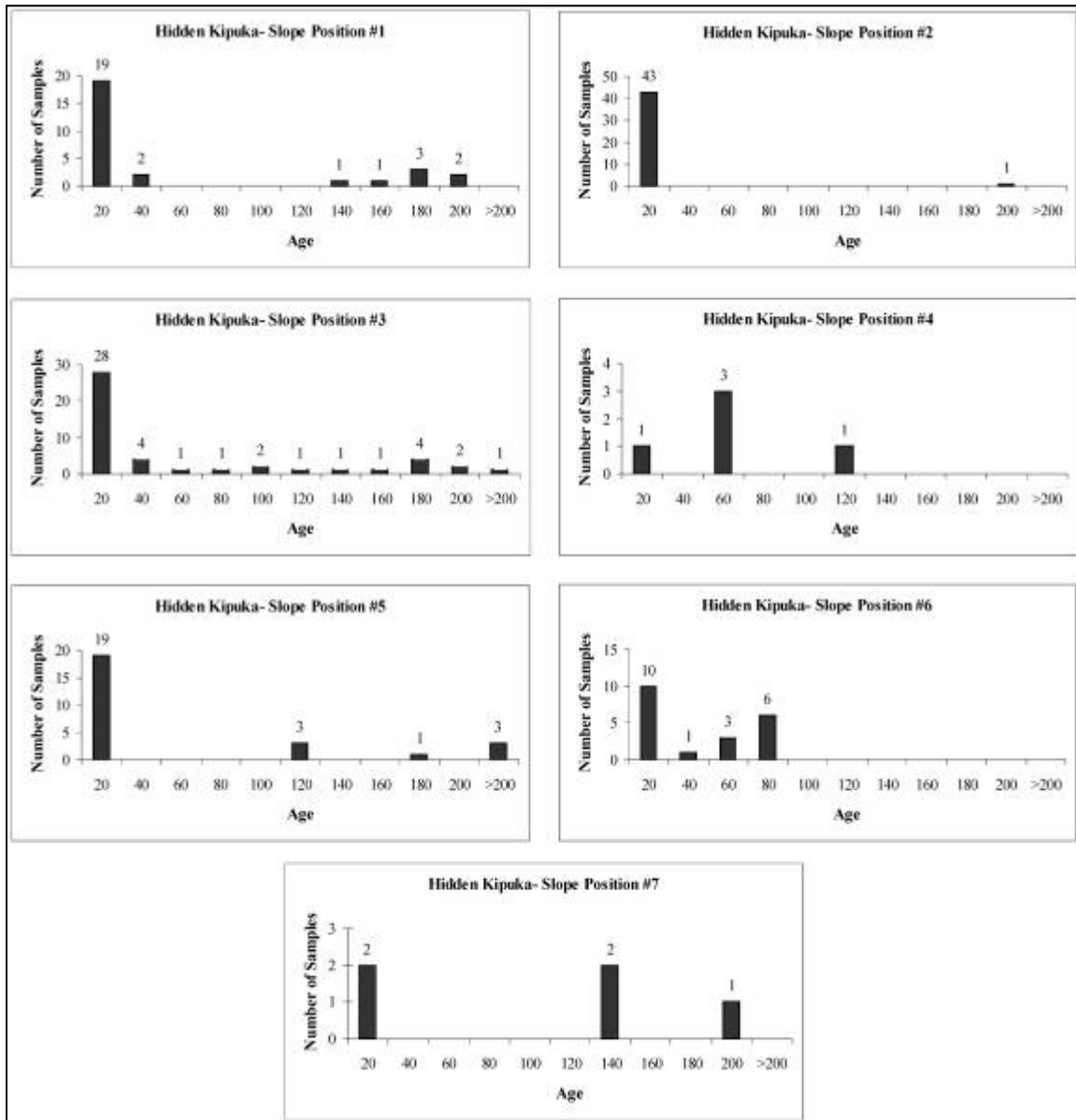


Figure 5.25. Age structure histograms for Hidden Kipuka. The histograms show each of the seven slope positions sampled on Hidden Kipuka. The histograms are shown with 20-year age classes.

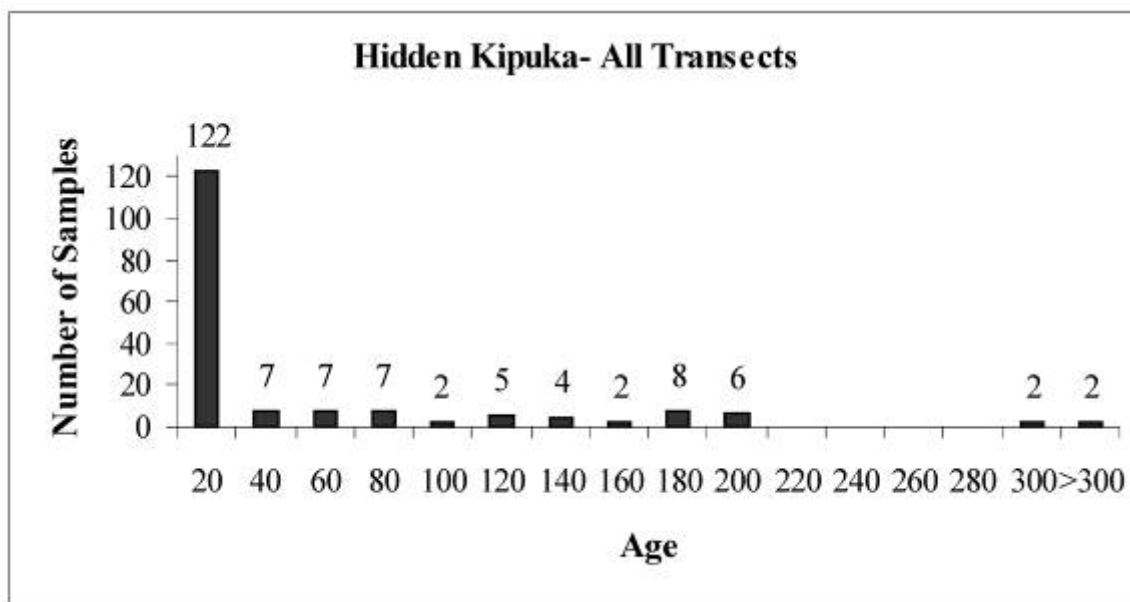


Figure 5.26. Age structure histogram showing all transects for Hidden Kipuka.

branch nodes for 33 seedlings that were too small to core. Transect one covered 3500 m², transect two covered 4000 m², and transect three covered 2500 m².

The lower slopes of Mesita Blanca were also dominated by trees 40 yrs old or less (Figure 5.27). Twenty-one trees were observed in this age class on slope position 2 (500 m²), and 22 trees were included in this age class on slope 6 (600 m²). Conversely, no seedlings were noted on slope position 4 (~2300 m²). Many more trees in excess of 100 yrs were sampled on Mesita Blanca, the majority of them being located on slope positions 3, 4, and 5. Tree germination was not noticeably different from the east side to the west side, although the access road that passes over the west side of the kipuka may have had some (minimal) impact on the ability of trees to establish near the adjacent lava flow. A large age cohort of 100–160yrs was found on transect 2, and a large number of trees on transect 1 were between 120-160yrs. Sixty-four trees were sampled that were <40 yrs on Mesita Blanca (Figure 5.28). All but 24 of these occurred on slope positions 2 and 6.

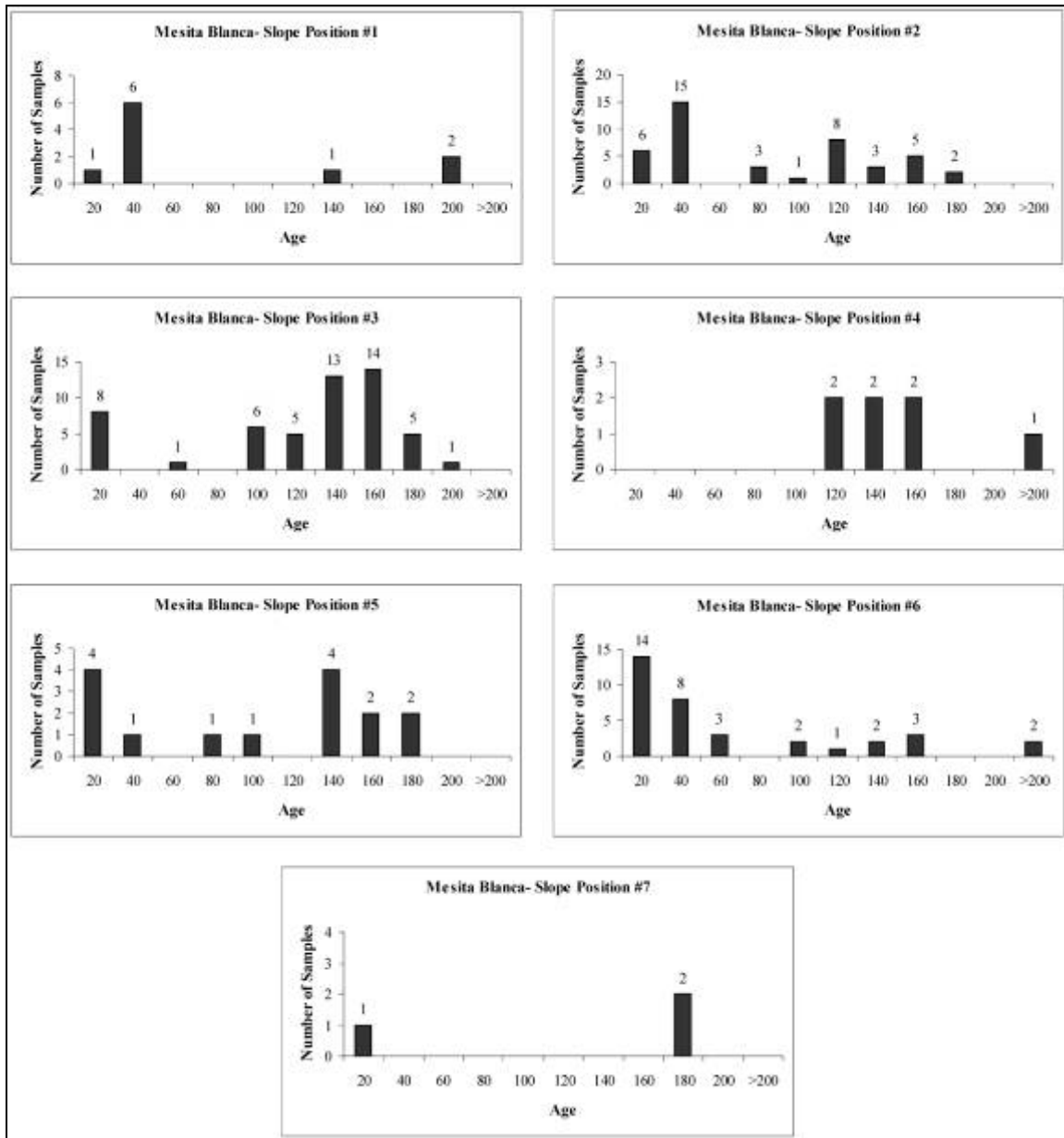


Figure 5.27. Age structure histograms for Mesita Blanca. These histograms show all slope positions sampled on Mesita Blanca.

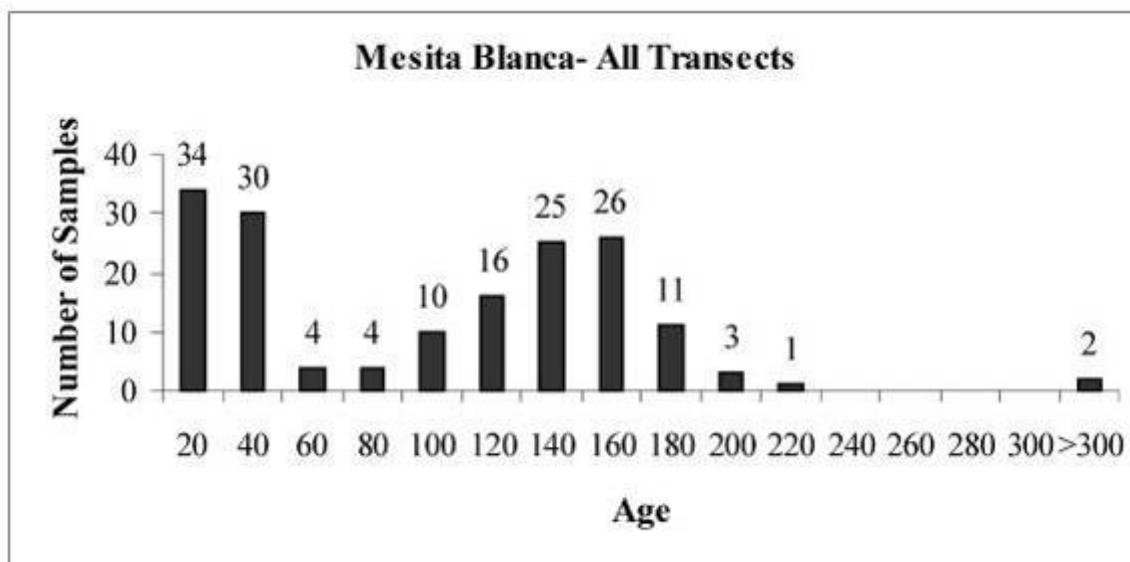


Figure 5.28. Age structure histogram showing all transects for Mesita Blanca.

6. Fire History of El Malpais National Monument

6.1. Discussion of Fire Records

Mesita Blanca's fire chronology substantiates the historical presence of fire in the central areas of the malpais (Grissino-Mayer 1995). It is possible that an extensive, long-term fire chronology could be constructed from this kipuka that would provide adequate sample depth to analyze wildfire events over a 600–700 year time span. Although La Sorpresa's fire chronology was not as extensive as Mesita Blanca's, La Sorpresa contained numerous multiple fire-scarred samples that should be targeted for future research. The hiatus in fires *ca.* 1790 noted by Grissino-Mayer (1995) was visible on Hidden Kipuka from 1789–1841. Samples collected at North Kipuka provided information about fire regimes in previously unexamined parts of the monument.

The analyses of fire regimes on the adjacent Hoya de Cibola Lava Flow also provided pertinent information. Although none of the three sites provided temporally extensive fire chronologies, they provided essential information on 18th and 19th century fire events. The opportunity does exist, however, to develop more extensive chronologies due to the amount of well-preserved, relict wood.

The descriptive statistics provided a means to examine the historical range of variation for each site and the combined sites. Generally, the distributions of fire-free intervals became more normal (*i.e.* symmetric) and less skewed when filters were applied (*i.e.* 10% scarred or 25% scarred). The all-scarred records, however, were just as important. The all-scarred class represents the fact that not all fires were large-scale fires. For example, the fire regime of Hidden Kipuka was characterized by numerous small-

scale, sporadic wildfires. Therefore, it is possible that the all-scarred record, although more skewed, may be a more accurate representation of the past fire regime in a given area.

The coefficient of variation allowed comparisons of different sites with different means, and proved useful in helping analyze maximum hazard intervals for each site. Sites with higher coefficients of variation primarily exhibited higher values for the maximum hazard interval. For example, La Sorpresa had the lowest maximum hazard interval of any kipuka (36 yrs) for the all-scarred class. It also had the lowest coefficient of variation. The highest coefficient of variation was found on Hidden Kipuka, which also had the highest maximum hazard interval. However, the coefficient of variation on Mesita Blanca was 0.44 in the 25% scarred class, compared to 0.47 on La Sorpresa, and Mesita Blanca also had a slightly higher maximum hazard interval than La Sorpresa. Although the relationship is not one-to-one, in general, lower values for the coefficient of variation were accompanied by lower maximum hazard intervals.

6.1.1. Kipukas

One goal of this study was to examine the historical range of variation of the fire regimes of the kipukas. Although the kipukas are somewhat similar in vegetation cover and proximity to one another, they did exhibit differences in their respective fire regimes. The historical fire regimes of Mesita Blanca and La Sorpresa were very similar, likely because of their close proximity to one another. Each showed similar minimum and maximum fire intervals, coefficients of variation, lower and upper exceedence intervals, and maximum hazard intervals. Their 19th century fire regimes were nearly identical,

with both having recorded all of the major widespread fires. I hypothesize that if the fire record for La Sorpresa was extended farther back in time, it would likely be very similar to that of Mesita Blanca. Fires could be expected to occur *ca.* once every 12–20 yrs on both kipukas, based on the statistical analyses. Based on the MHIs calculated for each site, it is unlikely that either site could sustain more than *ca.* 35–45 yrs without fires becoming likely.

Mesita Blanca South sustained longer fire-free intervals in the past than either La Sorpresa or Mesita Blanca, shown by a higher maximum fire interval and a higher upper exceedence interval. The fire regime was also more variable on Mesita Blanca South when analyzing all fire intervals. With the high variability in the all-scarred class, expected fire intervals could range from as low as 10 yrs to as high as 25 yrs on this kipuka. Mesita Blanca South did, however, exhibit the same synchronous 19th century fire pattern as Mesita Blanca and La Sorpresa.

The fire regime on Hidden Kipuka was somewhat different from Mesita Blanca, Mesita Blanca South, and La Sorpresa. Although some of the widespread fires found on the other kipukas were visible on Hidden Kipuka, its location with respect to the Bandera Lava Flow changed the pattern to some degree. First, fire-free intervals were more variable on Hidden Kipuka, more so than at any other site. This is likely due to the lack of available fuel to carry fire across the Bandera Lava Flow, which borders Hidden Kipuka on its eastern side. This younger (*ca.* 10,000 yrs) lava flow exhibits poor soil development and very low vegetation density. An unprecedented fire-free interval occurred from 1788–1841 likely due to climatic variability in the Southwest. Interestingly, two widespread fires were recorded at other sites during this period, 1806

and 1824, but neither carried to Hidden Kipuka. No fire was recorded that scarred more than eight of the 31 samples from this kipuka until 1893. Only two widespread fires, in 1923 and 1976, occurred since 1893.

Hidden Kipuka was characterized by a number of small-scale, sporadic wildfires, with occasional widespread fires occurring. Fire intervals will, therefore, be somewhat longer on this kipuka than on Mesita Blanca, Mesita Blanca South, or La Sorpresa. The mean fire interval suggests that fires can be expected to occur *ca.* once every 30 yrs based on all fire events observed in the fire-scar record. The MOI, however, suggests a much lower interval of 15 yrs. When only widespread occurrences were analyzed, the MOI was 30 yrs. Given that historical variability was so high on this kipuka, the all-scarred calculations may be slightly more accurate in depicting what the current fire regime might be on this kipuka, as it does not exclude this variability from the analysis. However, unusually long fire-free intervals can be expected on this kipuka, with intervals possibly as high as 50–55 yrs based on upper exceedence intervals.

The fire record on North Kipuka was unlike any other site sampled for this study. This kipuka is unique because it is located entirely within the Bandera Lava Flow. The past fire regime was characterized by infrequent, sporadic wildfires likely originating on the kipuka. It is unlikely that fires could have spread across the Bandera Flow given the lava flow's low vegetation density. Only two fires, in 1755 and 1876, scarred more than two trees. Although fires were small-scale, variability was very low on this kipuka. The MOI suggested that fires could be expected to occur *ca.* once every 41 yrs, but upper exceedence intervals indicated that fire-free intervals as high as 64 yrs could be expected.

6.1.2. Lava Flow Sites

Fire regimes abruptly changed on the Hoya de Cibola Lava Flow *ca.* 1933, likely because of increased fire suppression efforts. After 1933, fire events became scarce on the Hoya Flow, and no widespread fire events were recorded at either of the three lava flow sites until 1976. However, all lava flow sites recorded frequently occurring fire events throughout the presettlement period (*i.e.* <1880).

Two gaps occurred at Braided Cave, 1695–1738 and 1824–1856. Comparison between sites for the 1695–1738 gap was difficult, as only Logging Road had samples extending back to that period. However, Grissino-Mayer (1995) found only one recorded fire event (1714) on this portion of the Hoya de Cibola Lava Flow during that period. Grissino-Mayer's samples were collected *ca.* 3.2 km west/southwest of Braided Cave, adjacent to the grasslands that border the monument on its western boundary. Interestingly, one sample was scarred in 1714 at Logging Road, which is farther east from Grissino-Mayer's Hoya de Cibola samples than Braided Cave. It is possible that the very broken terrain around Braided Cave made it impossible for that particular fire to carry over the lava flow. Instead, the fire of 1714 may have spread to Logging Road from Little Hole-in-the-Wall.

These two extended fire-free periods are responsible for the higher maximum hazard interval at Braided Cave. However, Braided Cave seemed to have fewer short fire intervals than other sites, shown by the lower exceedence interval of 10 yrs. Therefore, it is possible that fire-free intervals were longer at this site, possibly due to the very broken topography around the cave system. The three fire interval calculations (MFI, MEI, and MOI) indicated that fires could be expected to occur *ca.* once every 20 yrs. The upper

exceedence interval, however, suggested that fire-free intervals as long as 30 yrs were not unlikely. Fires have become uncommon at this site since 1933.

Statistically, fire-free intervals at the Logging Road site represented a near-normal distribution. The MOI was almost equal to the MFI and MEI, and the coefficient of variation was the lowest found for any site. Values for skewness and kurtosis were also very close to zero, indicating a near normal distribution. The drawback to this site is that the period of reliability only covers 1806–1933. In general, fire events in the monument in the 19th century were synchronous spatially, more so than previous centuries.

Therefore, the statistics for the Logging Road site are more homogeneous because of the lack of older, relict samples. The 19th century pattern is very clear, however, and can be used to predict what the 20th century fire regime might have been like. The data indicated that fires could be expected *ca.* once every 15 years. The upper and lower exceedence intervals indicated that the majority (75%) of all fire intervals were between 7 and 22 years. The maximum hazard interval of 27 yrs has also been surpassed recently, as a fire has not been recorded at this site after 1976. This indicates that the threat of fire is currently high at the Logging Road site.

The Campsite fire record was constrained by the same problem as Logging Road, as the period of reliability was relatively short (1777–1933). Two very distinct gaps occurred during that period, from 1777–1806 and 1806–1843. The number of recorder trees from 1777–1806 was very low, so it is possible that some fire events were missed during that period. The sample depth was adequate, however, from 1806–1843, indicating that this is a true gap in fire occurrences. Fire intervals were quite variable at this site, indicated by the relatively high coefficient of variation (0.63). Based on

statistical analyses, fires could be expected *ca.* once every 12 to 15 years. The upper exceedence interval suggested that the majority of fire intervals would likely not exceed 30 yrs. Only one sample recorded a fire from 1933–1976, and the 1976 fire was more predominant at this site than at either Logging Road or Braided Cave. This particular fire may have spread more easily through this site, as the topography is less broken here. A large area of grassland (Little Hole-in-the-Wall) is adjacent to the Campsite location, which contains more fine fuels for the spread of wildfire.

6.2. Large-Scale Patterns in Fire Regimes

6.2.1. Combined Sample Sites

The combined data for the kipukas yielded a very long master fire chronology, spanning from 1447 to the present. The fire record showed that wildfire was a common disturbance on the kipukas until *ca.* 1933. After 1933, fire frequency began to decline, with only small-scale, sporadic wildfires occurring until the 1976 fire, which was found on almost every sample. Only one sample (MES 13) recorded a fire since the 1976 fire, that in 1989.

Although each individual kipuka showed somewhat different temporal characteristics in their fire regimes, the combined analyses revealed the overall spatial characteristics of fire on the kipukas in this area of the monument. When all fire events were analyzed, the data indicated that a fire could be expected to occur on the kipukas *ca.* once every 5–8 years, based on calculations for the MFI, MEI, and MOI. The data also suggested that a widespread fire could be expected across all kipukas *ca.* once every 8–10 years. The maximum fire-free interval was 19 yrs.

The combined lava flow sites exhibited similar characteristics as the kipukas, especially the synchronous fire pattern that began *ca.* 1800. Variability in fire intervals was higher at the lava flow sites, both in terms of all fires and widespread fires. This higher variability likely caused maximum hazard intervals to be higher on the lava flow than the kipukas. The MOI, however, was lower in both cases on the lava flow.

Two very prominent gaps occurred for the lava flow sites. The first was from 1695–1738, although one major fire occurred in this interval (1714). Following this period, fire frequency increased and fires were more sporadic. The second gap occurred from 1782–1806. After this gap, fire events became more widespread and synchronous. Fires ceased after 1933 until 1976. This 1976 fire was found at nearly every site sampled for this project. Only one fire is recorded after 1976, that being the 1989 Hoya de Cibola fire. This indicates that this fire event was confined to the western edge of the Hoya Flow, near the grasslands that border the monument.

The lava flow sites exhibited a much higher maximum hazard interval than the kipukas. Although this maximum hazard interval might seem inordinately high, it is equivalent to previous maximum hazard intervals calculated for the Hoya de Cibola Lava Flow. Grissino-Mayer (1995) found fire intervals to be longer at more southerly sites than those at more northerly sites in the monument. The data indicated that fires could be expected to occur *ca.* once every 4–10 yrs (all fires), and *ca.* once every 5–11 yrs (widespread fires). The upper exceedence intervals indicated that the majority of fire-free intervals would likely not exceed 18–20 yrs.

For sites that result in such high values for the MHI, it is possible that other statistical measures may be a more accurate representation of the maximum sustainable

fire-free interval. The all-scarred MHI for the combined lava flow sites was over 700 years, and the 10% scarred MHI was over 500 years. Although these statistics are supported by previous research (Grissino-Mayer 1995), it is unlikely that this ecosystem could sustain such an extended fire-free interval. These statistics are high because the lava flow sites experienced some longer fire-free intervals, and because variability in fire intervals was high. In situations such as this, the UEI may be a more accurate representation of the maximum sustainable fire-free interval. The UEI is not easily skewed by high variability or extremely long fire-free intervals. This could also be applied to individual sites such as North Kipuka and Hidden Kipuka, whose high variability and long fire-free intervals also yielded high values for the MHI.

6.2.2. All Sites

The combined analyses for all sites provided an extensive fire record for most of the southwestern portion of El Malpais National Monument. Wildfire has been a regular disturbance for at least the last 600+ years. A trend towards more frequent fires was apparent in the mid-to late 1700s, followed by a well-defined gap that occurred from 1782–1806, related to climatic fluctuation in the Southwest (Grissino-Mayer 1995; Grissino-Mayer and Swetnam 2000). Although several widespread fires occurred before 1800, fires after 1800 became more widespread and synchronous. This is likely due to increased fuel loads caused by an increase in precipitation in the area after 1800 (Swetnam and Betancourt 1990; Grissino-Mayer 1995; Grissino-Mayer and Swetnam 2000). The last large-scale, synchronous fire event found between both sites occurred in 1933. This fire was more widespread on the lava flow, but a number of kipuka samples

recorded this fire as well. After 1933, fire events became very sporadic, and the number of hectares burned was greatly reduced, shown by the lack of a large-scale fire occurrence. It was not until 1976 that a large-scale fire occurrence was recorded.

The statistical analyses bracketed the range of variation in the fire regimes of the southwestern portion of the monument over the period 1695–1933. Historically, wildfires occurred *ca.* once every 4–6 yrs, and a widespread fire occurred *ca.* once every 5–10 yrs. The overall variability in fire-free intervals was higher when analyzing only the widespread fires. The majority (75%) of fire intervals were between 2–16 yrs, and the maximum fire-free interval was 24 yrs. When all fires were analyzed, the maximum hazard interval was 20 yrs, but increased to 93 yrs when analyzing only the widespread fires.

One of the primary goals of this project was to determine whether effective fire suppression on or near the Hoya de Cibola Lava Flow could significantly reduce fire occurrence on the minimally disturbed kipukas. The combined analyses indicated that this is a distinct possibility. As fire frequency declined on the Hoya Flow following 1933, fires began to decline on the kipukas. A number of smaller-scale, episodic wildfires occurred on the kipukas throughout the mid-1900s, but a 43 yr period occurred from 1933–1976 without a large-scale wildfire. This gap is unprecedented on all of the kipukas, except Hidden Kipuka and North Kipuka, during their periods of reliability. This gap is most certainly uncharacteristic of the fire regime that occurred throughout the 19th century. From 1800–1900, six fires occurred that scarred 25% or more of the total number of samples for the combined kipukas. From 1900–2000, only two fires, 1933 and 1976, scarred more than 25% of the total number of samples. The reduction of fire

frequency on the adjacent Hoya de Cibola Lava Flow has therefore had an affect on fire frequency of the kipukas.

6.2.3. North Kipuka

Grissino-Mayer (1995) indicated a north/south gradient in fire frequency in the monument, with fire-free intervals being shorter in the northern parts of the monument. This is due primarily to decreased effective moisture in the south causing forest cover to be less dense. Also, the younger Hoya de Cibola Lava Flow has less developed soil cover, providing fewer fine fuels for the spread of wildfire. When North Kipuka was compared to other sites in the Hoya Flow, the pattern was different, suggesting also a possible east/west gradient in fire regimes in the monument. The dividing line for this pattern is Big Tubes, the extensive collapse system found in the Bandera Lava Flow. North Kipuka is the only site in this study located on the eastern side of the collapse system. Grissino-Mayer (1995) also sampled one site on the eastern side of the collapse system, a cinder cone known as Lost Woman. When the fire record from North Kipuka was compared to that of Lost Woman, a distinct pattern emerged. More fires on North Kipuka were synchronous with those at Lost Woman than with the other kipukas (Figure 6.1).

It is possible that fire regimes on the eastern side of the collapse system are different than those found on the western side of the collapse. Fire-free intervals should be somewhat longer on the eastern side of the collapse than those found at sites on the western side of the collapse system for several reasons. First, vegetation density on the Bandera Lava Flow itself is too low to provide ample fuel for frequent wildfires. Second,

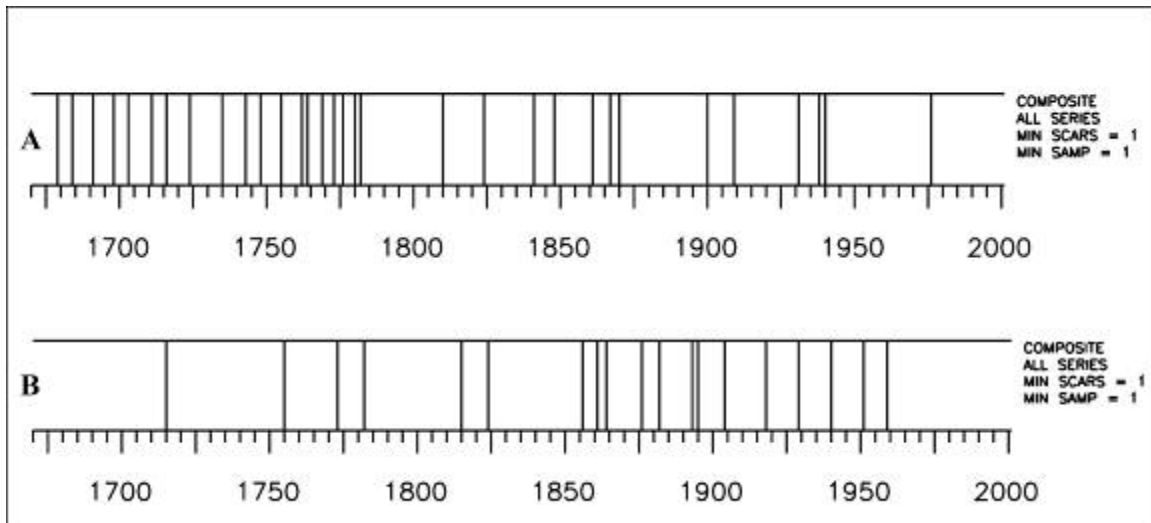


Figure 6.1. Composite fire data for Lost Woman and North Kipuka. “A” shows the Lost Woman composite and “B” shows the North Kipuka composite. North Kipuka showed more synchronous fire events with Lost Woman than any of the other kipukas.

the topography is very broken and jagged on the Bandera Lava Flow, not conducive for the spread of wildfire. Fire-free intervals on Lost Woman were shorter than North Kipuka because it is located in the Twin Craters Lava Flow, which has better soil development and higher vegetation density than the Bandera Flow. The geologically young (*ca.* 3200 yrs) McCarty’s Lava Flow is located to the east of the Bandera Lava Flow. This flow has very poor soil development and it is unlikely that fires could carry across it to the Bandera Flow. Finally, it is unlikely that fires from the Hoya de Cibola Lava Flow could make it across the collapse system. In many places, the collapse can be 10 m or more in depth, and few fuels exist along this collapse system. This is the first indication of this east/west pattern, and more data are needed before solid conclusions can be derived. This does, however, provide a new avenue for research in the monument that should be pursued.

6.3. Age Structure Analysis

6.3.1. Hidden Kipuka

Hidden Kipuka appears to have an inordinate number of young seedlings on its lower slopes. Establishment rates were higher on the western side of the kipuka, possibly due to the more dense, mature ponderosa pine forests found on the Hoya de Cibola Lava Flow. The field team counted 43 seedlings on the lower western side of the kipuka (850 m²), compared to 28 on the mid/upper slope on the western side (3700 m²). The lack of mature trees located on the lower kipuka slopes indicated that these areas are currently being seeded by the adjacent lava flows. Overall, 53 trees were found that were 20 yrs old or younger on the lower slope positions (~1800 m²). This high establishment rate may be uncharacteristic of presettlement conditions in ponderosa pine forests of the Southwest, as seedling establishment should be sporadic at best (Cooper 1960). These trees have likely established since the last recorded fire event on the kipuka in 1976. Their occurrence also substantiates that fire has been non-existent on this kipuka since 1976.

Interpreting the age structure for Hidden Kipuka was limited by the relatively low number of trees (55) that could be accurately dated. Five transects were randomly sampled on the kipuka, and none had dense forest cover. Therefore, more sampling may be required in the future to increase the sample depth. Large numbers of juvenile (<100 yrs) ponderosa pine stands exist on the lower slopes of the kipuka, but these transects were not sampled due to the random sampling method. The data did, however, enumerate the large numbers of seedlings present on the kipuka that would not likely be found if fire regimes more closely resembled that of presettlement times.

6.3.2. Mesita Blanca

Two very distinct age cohorts were visible on Mesita Blanca. The first was a large age cohort <40 years old. These relatively young trees are most likely related to a decrease in fire occurrences since *ca.* 1933. Of the 64 trees found in this age class, 43 of them were located on the lower slopes of the kipuka (1100 m²), and just over half of them occurred on the western side. Only 17 trees were found on the lower slopes that were more than 120 years old. Higher numbers of trees in the 120 yr age class would have indicated that ponderosa pine forests were common on the lower slopes before human disturbances were introduced into the monument. The lack of trees in this age class indicates that tree germination over the last 200+ years was sporadic at best on these lower slopes, until *ca.* 40 years ago. The majority of trees older than 120 yrs are located on the mid-and upper slopes of the kipuka, as well as on the adjacent lava flow.

The other predominant age class was the 120–180 yr age class, located primarily on the mid/upper slopes and crest of the kipuka. Here, ponderosa pines were historically intermixed with piñon-juniper woodland. This age class could be linked to a long, relatively fire-free interval from 1806–1856, possibly attributed to the wetter conditions that prevailed after *ca.* 1800 (Grissino-Mayer 1995, 1996).

6.4. Research Questions

Four primary research questions were outlined in this study. These questions were addressed to: (1) increase our knowledge of spatial and temporal characteristics of fire regimes in El Malpais National Monument, New Mexico, and (2) to assess how characteristic the kipukas are of presettlement vegetation.

1. How interrelated are the fire regimes of the kipukas and the Hoya de Cibola Lava Flow, and can temporal changes in fire frequency on this lava flow indirectly affect fire frequency on the kipukas?

From 1600–1799, 31% of the fires recorded on the Hoya de Cibola Lava Flow were synchronous with the kipukas (all-scarred class). From 1800–2000, 47% of the fires recorded on the lava flow were synchronous with the kipukas (all-scarred class). A greater increase in synchronicity was visible when a 10% filter was applied to examine the widespread fire events. From 1600–1799, only 15% of the widespread fire occurrences were synchronous between the lava flow and kipukas. From 1800–2000, 61% of the widespread fire occurrences were synchronous. This represents a 66% increase in the synchronicity of fire events after 1800 for the all-scarred distribution, and a 400% increase in the 10% scarred class. Therefore, in recent times (*i.e.* the last 200 years), the Hoya de Cibola Lava Flow has had an increasing effect on the fire regimes of the kipukas located in it. The most likely explanation for this change to a more synchronous fire pattern after 1800 is climatic change. Precipitation levels have been higher since 1800 in the American Southwest than any other period in the last 2000 years (Grissino-Mayer 1995; Grissino-Mayer and Swetnam 2000). This increase in precipitation resulted in increased fuel production in the malpais area, which acted to synchronize fire patterns by creating a more homogeneous fuel loading across the malpais landscape. The increased fuel loads likely caused an increase in hectares burned.

Another indicator that the fire regimes of the Hoya Flow and the kipukas are interrelated is the reduction in both the number and frequency of fire occurrences in the 20th century on the kipukas. Fire events were significantly reduced on the Hoya de Cibola Lava Flow after 1933, due primarily to increased fire suppression efforts and the

introduction of technological advances in fighting wildland fires. Coincidentally, fire events on the kipukas began to decline with the reduction of fire on the adjacent lava flow. No major wildfire occurred in either habitat type following 1933 until 1976. This represents a 43-year fire-free interval, which is longer than any fire-free interval recorded over the period of reliability. Because fire suppression efforts did not occur directly on the kipukas, the resulting decline in fire frequency during this period must be due to some external factor.

I initially hypothesized that the inability of fire to spread across the Hoya de Cibola Lava Flow since the mid-1900s has affected fire regimes on the kipukas. Many smaller-scale, patchy wildfires likely originated on the kipukas from natural ignition sources (*i.e.* lightning). However, the larger-scale wildfires were carried to the kipukas via the adjacent Hoya de Cibola Lava Flow. These results illustrate the degree to which these two ecosystems are interrelated. If the fire regimes of the kipukas were independent of the Hoya Flow, fire events would likely not have declined on the kipukas when fire frequency declined on the adjacent lava flow. Therefore, I speculate that any changes in fire frequency on the Hoya de Cibola Lava Flow will likely affect the fire regimes on the kipukas. The smaller-scale, sporadic wildfires recorded between 1933 and 1976 are not representative of the presettlement fire regime, and will not be sufficient to control fuel build-up during the wettest period in the last 2000 years for the American Southwest. Also, only one sample has recorded a fire since 1976, representing a 26 yr fire-free interval that exceeds the maximum hazard interval calculated for the kipukas. The maximum threshold level has therefore been reached, indicating that fires are probable.

2. Does the age structure of the kipuka forests indicate that forest composition has been altered due to temporal changes in fire frequency?

The age structure for Hidden Kipuka revealed inordinate numbers of ponderosa pine seedlings (*ca.* 53 in $\sim 1750 \text{ m}^2$) that had established on the lower slopes of the kipuka, as opposed to only 69 seedlings on the other four slope positions ($\sim 11.3 \text{ km}^2$). These numbers may not be representative of the establishment rates for the presettlement era (Cooper 1960). These seedlings have established since 1976, and without fire to control seedling establishment, these areas will likely become overgrown with dense, “dog-hair” ponderosa pine thickets, not representative of the presettlement forest structure. If allowed to establish and mature, these trees will increase fuel loads to unprecedented levels on the kipuka. Increasing the fuel loads will increase the possibility for high-severity, stand-replacement fires on the kipuka. It will also place at risk the piñon-juniper woodlands that occur on the upper slopes and crest of the kipuka. These woodlands are likely present because fire frequency was much lower on the upper areas of the kipuka, given that these two species are not fire tolerant. A high-severity wildfire would adversely affect these areas, possibly causing irreversible damage to an ecosystem found primarily on the sedimentary kipukas.

The structural changes that occurred on Hidden Kipuka are more prominent on the western side of the kipuka. The parent trees of the numerous seedlings and juvenile trees found on the lower slopes are likely the mature ponderosa pines on the adjacent lava flow. Forest density is much higher on the Hoya de Cibola Lava Flow than on the Bandera Lava Flow because soil development is higher on the Hoya Flow. Therefore, the majority of seedling recruitment is occurring on the western slope adjacent to the Hoya

Flow. Without controlling this seedling establishment, the western slope of this kipuka will likely become overgrown with ponderosa pine thickets sooner than the eastern slope.

The age structure for Mesita Blanca also revealed structural changes likely attributed to changes in the fire regime via fire suppression. Large numbers of trees less than 40 yrs were found growing on the lower kipuka slopes. Given that very few trees were found on these areas older than 100 yrs, it is likely that the lower slopes of the kipuka are not in the former range of ponderosa pine in the monument. The majority of mature ponderosa pine trees were located on the upper slopes of the kipuka, intermixed with piñon-juniper woodland, and on the adjacent lava flow. Seedling establishment was somewhat higher on the western slope of the kipuka because the access road traverses the eastern side. Forest density, though, is relatively equal on the Hoya Flow on both sides of the kipuka. Without fire to control ponderosa pine establishment, trees on the lower kipuka slopes will likely increase in density. Increased establishment rates will lead to increased fuel load, increasing the risk of high-severity wildfires, including placing at risk the piñon-juniper woodlands that exist on the upper kipuka slopes.

The age structure for both Mesita Blanca and Hidden Kipuka indicated that structural characteristics of the ponderosa pine forests have changed. In the last *ca.* 70 yrs, ponderosa pine trees have begun to establish on areas not formerly in their pre-settlement, local distribution within the monument. Historically, grasses and small shrubs dominated the lower kipuka slopes. Currently, numerous juvenile ponderosa pine trees have begun to encroach onto the lower kipuka slopes (Figure 6.2). Because these changes only began in the last century, they can likely be attributed to the indirect effects of fire suppression on the adjacent Hoya de Cibola Lava Flow.



Figure 6.2. Young ponderosa pines on Mesita Blanca. These young pines were photographed on the lower slopes of Mesita Blanca in May 2001.

3. How representative are the kipukas of presettlement forest structure and how severely have human-related disturbances altered these relict areas?

The kipukas of the monument are considered relict areas because they are relatively undisturbed by direct human impacts. The effect, if any, of livestock grazing on both Hidden Kipuka and Mesita Blanca are still undetermined. These kipukas are, however, undergoing recent changes in forest structure that are likely attributed to fire suppression on the adjacent lava flows. Young, even-aged stands of ponderosa pine are now encroaching onto areas historically dominated by grasses and small shrubs. Frequently occurring wildfires during the presettlement period removed these trees before they could become established. These changes, although currently minor, may become irreversible over time. Very few areas remain in the United States that have not been severely altered by human-related disturbances, such as livestock grazing, logging, and fire suppression. These relict areas should be preserved due to their ecological value. The kipukas are unique in that they likely preserve examples of presettlement forests not found in other areas of the Southwest. If the kipukas are to remain as examples of presettlement forests, fire should be reintroduced as an integral part of the ecosystem.

4. What can the agencies managing the monument do to preserve these relict areas and reduce the effects of human-related disturbances on them?

The agencies that manage the forests in and around El Malpais National Monument are in a precarious situation. Allowing fires to burn as they once did before Euro-American settlement is problematic due to the proximity of human development. The primary tool at the disposal of managers is the implementation of prescribed burning practices. Before these can be implemented, many areas of the monument will have to be thinned to prevent fires from becoming uncontrollable. In May 2001, forest thinning was

observed in some parts of the monument. These practices will have to be expanded to other remote locations in the monument to reduce forest density.

If current policy allows, the trees growing on the lower slopes of Hidden Kipuka and Mesita Blanca should be considered for removal (preferably by methods with low environmental impact) for two primary reasons. First, the juvenile ponderosa pines that have established on the lower slopes in the last *ca.* 100 yrs are likely outside their pre-settlement, local distribution within the monument. The age data for both kipukas revealed inordinate numbers of seedlings and large numbers of juvenile ponderosa pines currently growing on the lower slopes. If it is the managements' desire to preserve these kipukas as examples of presettlement vegetation, these trees should be removed.

Historically, the lower slopes of these kipukas were dominated by grasses and small shrubs. These trees will, in time, increase in density relative to the grasses and shrubs that currently dominate the areas. Secondly, if allowed to continue, these trees will change the fuel load characteristics of both kipukas, likely increasing the risk of high severity, crown destructive fires. A high severity wildfire could place at risk the piñon-juniper woodlands that have historically occupied the upper slopes and crests of the kipukas. This ecosystem is of great importance because it exists primarily on the sedimentary kipukas (Bleakly 1997).

It is unlikely that prescribed burning practices would be sufficient to remove these trees from the lower kipuka slopes. Many of them have matured to the point that they could be resistant to wildfires. Prescribed burns could, however, likely remove the large numbers of seedlings that have established on the lower kipuka slopes. Mechanical removal would be required for the larger, mature trees. Once removed, naturally

occurring wildfires should be allowed to burn under currently accepted wildfire prescriptions.

7. Conclusions

7.1. Major Conclusions

1. Numerous well-preserved, fire-scarred samples at El Malpais National Monument yielded spatially and temporally extensive fire chronologies on the Hoya de Cibola Lava Flow and several kipukas.

Nearly 450 fire scars were dated from eight different sites on the Hoya de Cibola lava flow and kipukas. A number of samples contained 15–20 fire scars, while the overall average was 6 scars per tree. A few living trees were also sampled that increased our knowledge of 20th century fire regimes in the monument. The master fire chart for the combined kipukas spanned from the mid-1400s to the present, and the master fire chart for the lava flow sites spanned from the mid-1300s to the present. The combined data sets yielded an extensive fire chronology back to the mid-1300s, with a sample depth of 138 trees.

2. The presettlement period (*i.e.* <1880) was characterized by wildfires that occurred frequently in the monument.

The reconstruction of fire history in the monument indicated that fires have been a common occurrence for at least the last *ca.* 600 years. The reduction of fire frequency *ca.* 1880 and the subsequent cessation of fire events on the lava flows after the 1930s indicate that human-related disturbances have nearly eliminated the low-severity, stand maintenance fires that occurred in the monument prior to Euro-American settlement. To preserve this ecosystem as it was prior to Euro-American settlement, fire should be re-introduced, either by allowing naturally occurring fires to burn, or by the application of

prescribed burning techniques. Allowing naturally occurring fires to burn is problematic due to the proximity of human development, and the fact that some land adjacent to the monument is privately owned. Furthermore, many of the open, park-like ponderosa stands that existed prior to widespread Euro-American settlement have been replaced by dense, “dog-hair” thickets of ponderosa pine (Grissino-Mayer 1995, 1997 *et al.*). These areas will certainly have to be thinned before any prescribed burning practices could be used.

3. Statistical and graphical analyses of fire events helped define the historical range of variability of fire regimes at El Malpais National Monument.

Fire charts graphically depicted the historical variability that existed in the fire regimes of El Malpais National Monument. Descriptive statistics provided critical data for examining the frequency and variability of past fire events and the majority of the fire-free intervals (75%) from all combined sites fell between 2–10 yrs when analyzing all fires. When the more widespread occurrences were analyzed, the majority (75%) fell between 3–16 yrs. The minimum fire interval in both cases was one year, and the maximum intervals were 17 yrs (all-scarred) and 24 yrs (10% scarred). Variability was relatively high, shown by coefficients of variation of 0.65 (all scarred) and 0.67 (10% scarred). The MFI, MEI, and MOI were 6 ± 4 yrs, 5 ± 4 yrs, and 4 ± 4 yrs (where $\pm 4 = 4$ sd in yrs), respectively, when analyzing all fire events. These intervals increased to 9 ± 6 yrs, 8 ± 6 yrs, and 5 ± 6 yrs when analyzing the more widespread fire occurrences. The maximum hazard interval was 20 yrs for all fire intervals, and increased to 93 yrs for the widespread fire intervals. These data should provide baseline information for those in

charge of decision-making at the monument to aid in the design and implementation of fire management policy.

4. Fire regimes on the Hoya de Cibola Lava Flow and its kipukas have interrelated fire regimes over the last *ca.* 200 years, indicating that changes in fire frequency on the Hoya Flow may affect the fire regimes of the kipukas.

Visual examination of the fire charts for the combined lava flow sites and the combined kipukas indicated that fire events after 1800 were more synchronous than in previous centuries. After 1800, 48% of all fires were synchronous between the Hoya de Cibola Lava Flow and the kipukas. Additionally, the synchronicity increased to 61% for widespread fire events (10% scarred). This demonstrates the degree to which these two ecosystems are interrelated. Also, fire events on the kipukas were significantly curtailed after 1933, when fires become scarce on the Hoya Flow. If the fire regimes of the kipukas were independent of the fire regime found on the Hoya Flow, the kipukas would likely not have seen a decline in fire frequency that coincided with the decline of fire frequency on the Hoya Flow. Therefore, it is almost certain that changes in the fire regime on the Hoya Flow will cause changes in the fire regimes of the kipukas.

Although fires were not actively suppressed on the kipukas, the ability of fire to carry to them from the adjacent lava flow has been reduced. This has resulted in only patchy, sporadic fires occurring on the kipukas in the last *ca.* 70 years. Without frequently occurring wildfires, fuel loads will likely continue to increase on the kipukas. Increased fuel loads may cause future fire events to become high-severity, stand-replacing fires. Ponderosa pines enjoy a relatively wide spatial distribution in the monument, and could likely recover from such an event in time. The piñon-juniper

woodlands on the kipukas, however, could incur considerable damage in such an event, and may have difficulty recovering.

5. Age structure analyses indicated structural changes in ponderosa pine forests on the kipukas.

The age structure on both Mesita Blanca and Hidden Kipuka revealed inordinate numbers of young ponderosa pines that have recently established on the lower slopes of the kipukas. This recent increase in ponderosa pine establishment indicates that fire suppression in adjacent areas of the monument has facilitated changes in forest structure on the kipukas. The majority of older trees were located on the adjacent lava flows, or on the upper slopes and central ridges of the kipukas, intermixed with piñon-juniper woodlands. The near absence of older, mature trees on the lower kipuka slopes indicates that these areas may be outside the pre-settlement, local distribution of ponderosa pine in the monument. These younger trees were able to establish along with the grasses and shrubs that currently dominate these areas because of the reduction of fire on the kipukas.

Although the kipukas have not incurred direct impacts from human-related disturbances, they do appear to be undergoing structural changes likely attributed to indirect effects of human disturbances. These indirect effects are currently visible on both Mesita Blanca and Hidden Kipuka as young, even-aged ponderosa pine stands that are encroaching on the grasslands that currently dominate the lower kipuka slopes. Continued establishment of ponderosa pine on the lower kipuka slopes will likely continue in the absence of fire, changing the structural characteristics of the forests on both kipukas and leading to increasing fuel loads on the kipukas. To preserve the kipuka

ecosystems as they once were, these young ponderosa pines should be considered for removal from the lower slopes.

7.2. Future Research at El Malpais National Monument

Many parts of the monument remain that have not been systematically sampled to study the historical variability of fire. One avenue of possible research is the investigation of possible differences in fire regimes between the eastern and western sides of the Big Tubes collapse system. Only two areas, North Kipuka (this project) and Lost Woman (Grissino-Mayer 1995), on the eastern side of Big Tubes have been sampled and analyzed. I observed that fire events on North Kipuka were more similar to Lost Woman than to other areas in the Hoya de Cibola lava flow. Grissino-Mayer (1995) indicated that a north/south gradient in fire frequency exists in the monument. It is also possible that an east/west gradient also exists.

Many more kipukas exist in El Malpais National Monument than could be sampled for this project. At least four kipukas are located on the southern end of the Hoya de Cibola Lava Flow, south of Mesita Blanca and Mesita Blanca South. Three other kipukas, known as “The Islands,” are located in the McCarty’s Flow on the east side of the monument. We found no evidence of past fires on these kipukas, although we could use age structure analyses to analyze successional patterns on these kipukas. La Sorpresa contained many multiple-scarred trees, some as cut stumps, which should be sampled and analyzed. A multi-century fire record, equivalent to that of Mesita Blanca, could possibly be constructed for La Sorpresa.

The age structure data on Hidden Kipuka could be strengthened by sampling additional transects. Just over 60 cored trees were dated from this kipuka. Additional information could be obtained about the structural changes of ponderosa pine forests by sampling more transects. It is also possible that other undisturbed kipukas in the monument could be analyzed in the same manner to assess whether the same changes are visible in other parts of the monument. The kipukas located in the southern edge of the Hoya Flow could possibly be prime candidates for such research. However, more field reconnaissance is needed to ascertain the feasibility of using these kipukas for such research.

El Malpais National Monument also presents a unique opportunity to examine the frequency of lightning fires over time. A recent study (Allen 2002) examined the importance of lightning as an ignition source in the nearby Jemez Mountains, New Mexico. Allen specifically examined whether lightning or anthropogenic influences were the driving force behind shaping the landscapes of the Southwest. He stated that, although the Native American influence on fire regimes of the American Southwest cannot be ignored, regional-scale similarities among fire chronologies in the Southwest indicated that climatic fluctuation and surface fuel conditions were likely the primary mechanisms driving the fire regimes.

El Malpais, however, offers a place to conduct such research in the absence of widespread human involvement. Areas in El Malpais, such as North Kipuka, are so isolated that pre-settlement human-related changes in fire frequency would be minimal. North Kipuka is located in the Bandera Lava Flow, and its broken terrain and low vegetation density also make it difficult for fire to spread. Therefore, it is likely that the

majority, if not all, of the fires occurring in the past (*i.e.* pre-1880) on this kipuka originated on the kipuka itself. In the absence of humans, these fires would all be of natural origin. Any resulting fire history reconstruction would also likely be a reconstruction of lightning ignitions as well.

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Vita

Daniel Lewis was born in Knoxville, Tennessee on November 6, 1974, to Larry and Linda Lewis. He graduated from Horace Maynard High School (Union County) in 1993. He then enlisted in the United States Air Force where he served for three years as a Strategic Aircraft Maintenance Specialist on B-1B bombers at Dyess Air Force Base, Abilene Texas. He was honorably discharged in 1996, receiving a Gulf War Defense Medal and small arms marksmanship awards. He returned to Knoxville, Tennessee and earned his Bachelor of Arts in Geography from the University of Tennessee in 2000. In fall 2000, he was accepted into the graduate program in the Department of Geography, pursuing a Master of Science degree.

Daniel has participated in research projects in Tennessee, Florida, Mississippi, New Mexico, Oregon, Virginia, and Costa Rica. He is a member of the Tree-Ring Society, Gamma Theta Upsilon, and the Association of American Geographers. He has also presented at the Association of American Geographers annual meeting, as well as participated in the 13th annual North American Dendroecological Fieldweek at the Lubrecht Experimental Forest, Montana. He graduated with his Master of Science in Geography in August 2003 and seeks to continue to work in the field of dendrochronology.