Spatial Relationships in Frost-Damaged High-Elevation Pines and Links to Major Volcanic Eruptions

by

Christine Lee Hallman

A Prepublication Manuscript Submitted to the Faculty of the

DEPARTMENT OF GEOSCIENCES

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

In the Graduate College
THE UNIVERSITY OF ARIZONA
2001

STATEMENT BY THE AUTHOR

This manuscript prepared for publication in the *Tree-Ring Research* has been submitted in partial fulfillment of requirements for the Master of Science degree at The University of Arizona and is deposited in the Antevs Reading Room to be made available to borrowers, as are copies of regular theses and dissertations.

Brief quotations from this manuscript are allowable without special permission provided that accurate acknowledgement of the source is made. Requisitions for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the Department of Geosciences when the proposed use of the materials is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

Christine Lee Hallman
(author's signature)

11/30/01
(date)

APPROVAL BY RESEARCH COMMITTEE

As members of the Research Committee, we recommend that this prepublication manuscript be accepted as fulfilling the research requirement for the degree of Master of Science.

Katherine Hirschboeck	Katherine K. Hirschboeck	11-30-01
Major Advisor(type name)	(signature)	(date)
Julia Cole	[signature]	11/30/01
(type name)	(signature)	(date)
Thomas Swetnam	Thomas W. Swetnam	11/30/01
(type name)	(signature)	(date)

Abstract

Frost injury in the annual growth rings of pines growing at upper treeline is a consequence of sudden freezing temperatures during the growing season (LaMarche & Hirschboeck 1984). This updated and spatially extensive frost-ring study involves the systematic identification of frost rings in high-elevation pines located in 16 western USA tree-ring sites whose chronologies range from 1692 BC to AD 2000. Several "notable frost events" were identified, based on the criteria of frost damage occurring in greater than 25% of trees at a given site *and* in two or more sites. The spatial variations between frost events indicate regional variations based on differences in elevation, latitude, and the location of polar outbreaks and their associated upper-level atmosphere circulation patterns. The 17 notable frost events correspond to previous frost ring and light ring evidence, and 13 of them are associated with climatically effective volcanic eruptions.

Introduction

Frost damage in rings of high-elevation pines is a consequence of abnormally low temperatures during the growing season. Frost-ring evidence of sudden and persistent freezing temperatures has been linked to climatically effective volcanic eruptions (LaMarche and Hirschboeck 1984). This research project involves a regional investigation of frost events in high-elevation bristlecone (*Pinus aristata* and *Pinus longaeva*) and foxtail pines (*Pinus balfournia)* from a variety of western United States tree-ring sites. Since bristlecone and foxtail pines are long-lived, they are well-suited for the documentation and/or discovery of unusually low temperatures during past millennia that may be linked to explosive volcanic eruptions. The main objectives of my research were to systematically identify frost rings at select high-elevation sites in long-lived species and determine any temporal or spatial climate variations of the frost rings within the western U.S. Other goals of my research include: a) to update existing frost-ring chronologies which ended prior to the 1982 and 1991 eruptions of El Chichón and Pinatubo, b) to investigate both bristlecone and foxtail pines for possible species-related and/or elevation differences in frost-ring formation, and c) to expand the work of previous frost-ring and light-ring investigators by increasing the number of sites previously studied, extending the geographic area represented, and investigating both bristlecone and foxtail pine sites.

Background Information

Frost injuries

When a severe cold episode occurs during a tree's growing season, extracellular ice formation and dehydration in stem tissues can crush and cause the abnormal development of tracheids and parenchyma cells, as well as tangentially displace, widen, and fuse rays in tree rings (Rhoads 1923; Hemenway 1926; Glock 1951; Glerum and Farrar 1966; LaMarche 1970). This permanent deformation is known as a frost ring (Fig. 1). The sudden onset and persistence of temperatures at or below freezing during the growing season may create the extracellular ice that produces a frost ring (Bailey 1925; Harris 1934). Specifically, two successive nights of -5° C and an intervening day of approximately 0°C are sufficient for the creation of a frost ring in pines (Glock and Reed 1940). Glerum and Farrar (1966) artificially froze pine, spruce, and tamarack seedlings to investigate frost-related formations within trees. They found that frost-ring formation varied based on cambial activity at the time of the frost, and on the intensity of the frost (e.g. the coldness of the temperatures and the length of the freezing period) (Glerum and Farrar 1966). Actively growing cells or differentiating tracheids were the most susceptible to frost damage, and the more intense the frost, the more the cells were injured. Frost rings can occur and be identified in the earlywood or the latewood of an annual ring. The location of frost damage within the annual ring can be used to infer the season in which the frost injury occurred if something is known about typical cambial phenology (LaMarche and Hirschboeck 1984).

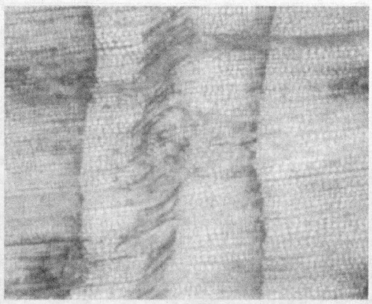
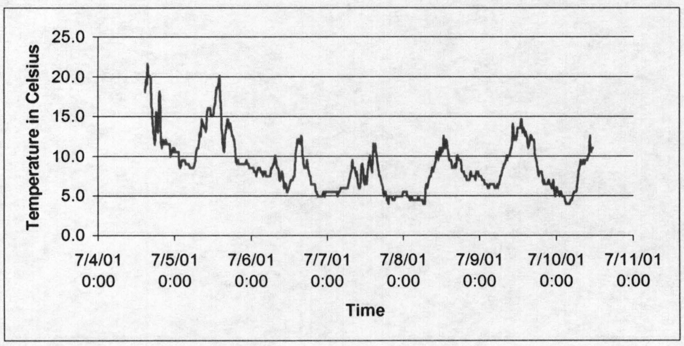


Figure 1. Severe frost damage in latewood of bristlecone pine from Sheep Mt., CA. Image by Chris Baisan.

The frequency and severity of frost damage is related to a tree's age, diameter, and elevation (Harris 1934; LaMarche 1970; Dunwiddle and LaMarche 1980). Young trees at high elevations are the most susceptible to frost damage. Seedlings have thinner bark and a higher surface-area-to-volume ratio than mature trees, making them more vulnerable to freezing temperatures. Longer periods of cold temperatures at high elevation make trees located in these areas more sensitive to frost injury. Bristlecone pines in the White Mountains, CA begin their growing season in late June to early July and growth ceases in mid to late August (Fritts 1969). Typical growing-season (June-August) diurnal temperatures in the White Mountains range from -9 to 24.8 °C (15.7 to

76.7 °F) according to Hall (1991). A week of temperature observations taken directly at the Campito Mt. site in July 2001 falls within this range (Fig. 2). According to Fritts's (1969) 3-year physiological study on ring growth in bristlecone pine in the White Mountains of California, in trees located at high elevations (greater than 3000 m), cambial activity begins and ends a week later than at lower elevations. Fritts (1969) also found that if the spring/summer was cooler than normal, the growing season of bristlecone pines started and extended later into September than in an average year. LaMarche and Hirschboeck (1984) proposed that this shift of the growing season during cool summers may increase a tree's susceptibility to latewood frost-ring formation. In addition, Fritts (1969) found that the timing of the onset and completion of cambial activity causes *young trees at high elevations* to be the most vulnerable to early and late frosts. In young trees, cambial activity begins a week earlier and ends two weeks later



than in older trees.

Figure 2. A week of instrumental temperature data from Campito Mountain, CA (measurements were recorded at 15 minute intervals). Source: Harlan (2001).

Light Rings

Another type of diagnostic feature found in some trees is a light ring (Fig. 3). A light ring contains earlywood cells with thin secondary walls (Filion et al. 1986), low maximum density, and light colored latewood cells (Szeicz 1996). Light-ring formation is the result of low temperatures at the end of the growing season (Filion et al. 1986; Szeicz 1996). Filion et al. (1986) suggested that the high frequency of light rings in black spruce of Quebec are *partially* due to the cooling associated with poleward shifting of a stratospheric aerosol veil after a major eruption. Szeicz (1996) investigated six spruce sites in Canada to identify light rings. In the study, "marked differences in key light-ring years" occurred between northwest and northeast Canada (p. 188). These differences were said to result from the influence of different air masses on the two regions of Canada. Szeicz (1996) further suggested that the light-ring spatial distribution in Canada indicated that large-scale synoptic circulation patterns after a major volcanic eruption are an important influence in light-ring formation. According to Wang et al. (2000), low summer temperatures do not always lead to the formation of light rings in black spruce. This study suggests that light rings may form under one of the following conditions: delayed springs, cool summers, or early-ending autumns.

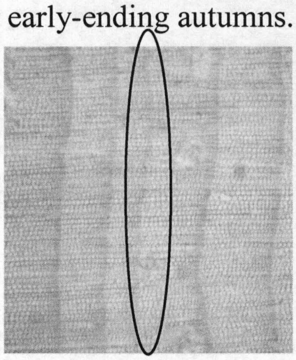


Figure 3. Light ring found in the foxtail site at Flower Lake, CA.

Applications

Frost and light rings provide several types of dendrochronological and dendroclimatological information. Marker frost-event and light-ring years have been used to crossdate and verify crossdating in many studies (Bailey 1925; Dunwiddle and LaMarche 1980; Filion et al. 1986). Frost injury has also been associated with a local climatic response to global-scale atmospheric activity, such as the atmospheric circulation response to a large explosive volcanic eruption (LaMarche 1970; LaMarche and Hirschboeck 1984; Filion et al. 1986; Banks 1991). Depending on location, frost rings may also furnish information on anomalous weather events (e.g. false spring, Stahle 1990) or anomalous atmospheric circulation patterns (Hirschboeck et al. 1996). Brunstein (1996) suggested that latewood frost rings might be used as a proxy for mountain snowpack levels.

Volcanic Eruptions and Climate

The effects of volcanic eruptions on climate have been modeled, observed, and studied over the years by a variety of investigators. Several factors that influence the degree to which a major volcanic eruption affects climate have been identified (Table 1). With these factors in mind, the more aerosols that reach the stratosphere, the greater the potential impact on global climate. Wexler (1956) suggested that after a major eruption, continental temperatures would drop much more rapidly than ocean temperatures. This increased temperature gradient would change winter and summer circulation and weather patterns in the Northern Hemisphere. For example, a decrease in summer temperatures and a "stronger westerly flow displaced southward" might occur, such that a mid-July weather chart would resemble a mid-May weather chart (Wexler 1956, p. 491). Later Lamb (1970) implied that the sub-polar low-pressure zone in the North Atlantic sector would be displaced southward in the first July after a large explosive eruption, and that the displacement might continue from 1 to 4 years (Lamb 1970). Lamb (1970), Minnis (1993), and several other researchers have noted that a general decrease in surface temperatures is likely to occur after a major volcanic eruption for 1 to 3 years. Porter (1986) and Scuderi (1990) further suggested that a cluster of major eruptions could trigger a glacial advance. Both Energy-Balance Models (EBM) and Global Circulation Models (GCM) have been used to model cooling effects for up to several years after major eruptions. Regional responses of winter warming and summer cooling have been predicted by some of these models (Robock 2000).

Table 1. Summary of Key Volcanic Eruption-Climate Interactions.

	Factor / Interaction	**Source**
Factors that influence climatic significance of major volcanic eruptions	Height of eruptive column Quantity of aerosols injected into stratosphere Sulfur content of ejecta Latitude of volcano Season of eruption/Prior atmospheric circulation patterns	Lamb 1970; Rampino & Self 1982; LaMarche & Hirschboeck 1984; Bradley 1988; AGU 1992; Jones et al. 1995; Robock & Mao 1995
Results of aerosol injection into stratosphere	Greater possibility that they will be dispersed globally Increased albedo	Wexler 1956; Lamb 1970; Robock 2000;
Consequences of major volcanic eruptions	General reduction in surface temperatures for a short time (1 to 3 years) Cluster of eruptions could trigger glacial advance	Porter 1986; Scuderi 1990; Minnis 1993

Observations of the regional climatic responses after recent eruptions have supported these model results. In a study of the temperatures following 15 large volcanic eruptions since 1866, Robock and Mao (1995) found that summer cooling occurred in the tropics, subtropics, and mid-latitudes and winter warming occurred in the northern high latitudes. Research by Genin et al. (1995), and Robock and Mao (1995) indicated warming over North America, and over Russia (Robock 2000), and cooling over the Middle East and Greenland after the 1991 Pinatubo eruption (Robock & Mao 1995). Genin et al. (1995) conducted an investigation of massive coral deaths in the Red Sea after the eruption of Pinatubo. Their study suggested that an anomalous cold-air outbreak in the winter of 1992 led to deeper vertical mixing in the sea that brought nutrients to the surface, leading to an increase in algae and suffocation of the corals. Continued research is needed to identify other specific regional weather and climate responses to volcanic-eruption forcing effects on global climate. Furthermore, because major volcanic eruptions are so infrequent, it is important to be able to study eruption-climate interaction prior to the instrumental record.

Pre-instrumental Records and Natural Archives

Pre-instrumental records and natural archives that have been used to evaluate climatically significant volcanic eruptions include historic records, ice cores, and tree rings. Through the evidence provided by early records and natural archives, possible anomalous weather and climate responses to volcanic eruptions can be investigated. Scuderi (1992) compiled historic data from various locations around the globe. In historic records, volcanic eruptions are described as dry fogs, spectacular sunsets, or other optical effects and are associated with widespread plagues, crop failure, and the collapse of major civilizations (Stothers and Rampino 1983; Scuderi 1992; Baillie 1999). Historic records of eruptions and their effects are biased toward populated regions of the world, however, and for more ancient eruptions the information obtained from such records is limited.

One of the best sources of information about eruptions in the pre-instrumental record is the *ice core record*. By measuring SO_4 peaks in ice cores, climatically significant volcanic eruptions can be temporally pinpointed (Zielinski 1994). Because they incorporate volcanic dust and aerosols, ice cores provide direct evidence of past volcanic eruptions (Zielinski 1995). Ice cores are dated by counting the annual ice layers or by calculating an accumulation rate based on established SO_4 peaks (Langway et al. 1995). Dating errors vary from one to three years for the last 1000 years and increase farther back in time (Zielinski et al 1994; Cole-Dai et al 1997). Other problems include wind erosion of deposited aerosols before being covered by new snow and sampling problems that may allow a peak to be missed (Zielinski 1995). Ice core records also can be biased by proximity to the erupting volcano (Zielinski et al 1994), i.e., a moderate eruption of a close volcano may leave the same SO_4 peak as a huge eruption on the other side of the globe.

Tree-rings are natural archives that can provide climatic information as well as accurate dates to the calendar year. The climatic responses recorded by tree rings have also been linked to volcanic eruptions (LaMarche & Hirschboeck 1984; Baillie & Munro 1988; Brunstein 1996). Unlike ice cores, tree-ring studies can only document a probable climatic response to a volcanic eruption and do not incorporate direct physical evidence of distant eruptions. Frost rings (LaMarche and Hirschboeck 1984; Scuderi 1990; Brunstein 1996; Salzer 2000), light rings (Filion et al. 1986; Szeicz 1996), ring width (Baillie and Munro 1988; Scuderi 1990), latewood density (Jones et al. 1995; D'Arrigo and Jacoby 1999), false springs (Stahle 1990), and tree-ring density (Briffa et al. 1998) all reflect temperature responses that may be linked to climatically effective volcanic eruptions.

Frost-Ring and Light-Ring Studies

LaMarche and Hirschboeck (1984) were the first to suggest that "latewood frost rings [in bristlecone pines] record adverse climatic effects that follow large and /or sulfur-rich volcanic eruptions" and are linked to unusual meteorological events (p. 3). The researchers stated that anomalously cool summers contribute to latewood frost injury by "delaying the onset of cambial growth at the beginning of the growing season and delaying all maturation at the end of the growing season"; thus, these trees are more susceptible to an early autumn frost (LaMarche & Hirschboeck 1984, p. 2). In their 1984 article, LaMarche & Hirschboeck classified "notable frost events" (NFEs) as events that occurred in at two or more locations *or* in 50% or more of the trees in any one locality. LaMarche and Hirschboeck (1984) proposed that a "southerly displacement of the general westerly flow and/or the more frequent development of an upper level trough accompanied by occasional outbreaks of unseasonably cold air from higher latitudes" can lead to sudden freezes and frost-ring formation (p.3). They concluded the article by suggesting that an improved and more extensive frost-ring chronology for the western US would provide additional information on the relationships between frost-ring formation and volcanic eruptions, atmospheric circulation, and unusual weather events.

Baillie and Munro (1988) used extreme narrow rings in an oak chronology of over 7000 years to confirm LaMarche and Hirschboeck's (1984) frost ring in 1627 BC which was linked by the authors to the catastrophic eruption of Santorini (Thera). This discovery suggested that with the addition of more data, large-scale climatic responses to volcanism can be detected. Furthermore, Baillie (1999) stated that whatever the cause, frost rings and extreme sets of narrow rings may indicate times of crop failure, famine, and hence may be related to the demise of ancient civilizations.

Several investigators have indicated that light-ring formation in mid-latitude, high-elevation spruce is linked to cooler-than-normal temperatures during the growing season (Szeicz 1996), and that these anomalously cool temperatures may be linked to major volcanic eruptions (Filion et al 1986; Delwaide et al. 1991; Yamaguchi et al. 1993). Yamaguchi et al. (1993) further suggested that light-ring formation is related to May-September temperatures. Yamaguchi et al. (1993) and Szeicz (1996) implied that additional light-ring studies would provide more information on the link between light-ring formation and unusually cool temperatures during the spring and summer portions of the growing season.

In the most recent extensive study of frost rings in bristlecone pine, Brunstein (1996) suggested that the percentage of sampled trees that contained a frost ring is related to the "severity of climatic cooling that caused the event" (p. 69). Brunstein's (1996) results proposed that latewood frost rings on Almagre Mountain, Colorado might be linked to unusual atmospheric circulation as well as climatic cooling. No widespread frost rings were discovered for the 1982 eruption of El Chichón or the 1991 eruption of Pinatubo in Brunstein's Colorado bristlecone pine sites. Brunstein concluded that further studies of frost rings, light rings, ring width, and ring density could reveal climatic variations and trends in North America (Brunstein 1996).

Frost Rings as Indicators of Weather *and* Climate

According to Hirschboeck et al. (1996), "because frost rings represent short-lived events recorded in an annual growth ring that also contains climate information for a much longer period, they proved an excellent research base from which to evaluate anomalous circulations and extremes at varying timescales" (p. 217). Hirschboeck et al. (1996) proposed a "signature" synoptic circulation pattern for North American mid-latitude frost-ring formation that consists of a deep mid-tropospheric trough that steers Arctic air masses to lower latitudes, and which may be associated with blocking activity upstream (Fig. 4). This circulation feature is a short-term weather event that is the immediate cause of the anomalous freezing temperatures that produced the frost ring. The location of the cold-air trough, along with its persistence and eventual downstream movement will determine the spatial pattern of sub-freezing temperatures in the western U.S., as well as the spatial distribution of frost-ring occurrence in other high-elevation bristlecone pine sites in the West. The 1965 freeze event associated with the circulation pattern shown in Fig. 4 produced frost rings in California, Nevada, Arizona, and Colorado indicating that a very large region was affected by the event. The longer-term and large-scale circulation pattern from which this short-term synoptic pattern emerged may also reflect a regional seasonal climatic anomaly that is conducive to frost-ring formation in high-altitude bristlecone pines. LaMarche (1970) and LaMarche and Hirschboeck (1984) suggested that the cool summers that may contribute to frost-ring formation in the western U.S. "seem to be characterized by … frequent developments of a deep trough at the 700-mbar level in the middle troposphere" (LaMarche and Hirschboeck 1984, p. 3).

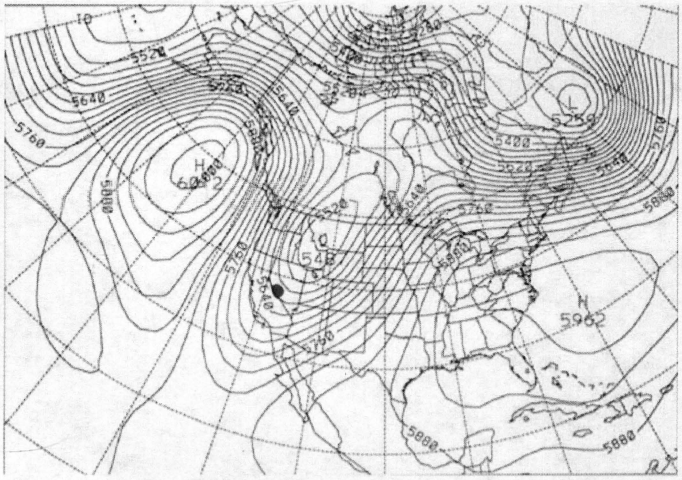


Figure 4. 500mb Synoptic Circulation Pattern for the second day (September 18th) of the freeze event that formed a 1965 frost ring at the location designated by the black dot indicated (after Hirschboeck et al. 1996).

Stahle (1990) used a synoptic climatological approach to investigate frost injury recorded in deciduous trees located in Southcentral USA. Stahle attributed the frost injury to unusual climatological and meteorological events in late winter and early spring. An abnormally warm winter allows trees to begin the growing season earlier. The resultant new tissue is susceptible to outbreaks of subfreezing air. This warm winter - cold spring sequence is referred to as a "false spring". The evidence for a false spring event is as follows: crushed vessels at the beginning of the ring, distorted rays and parenchyma cells, and lesions between the terminal parenchyma cells. The meteorological parameters for a false spring include a frost event and a warm spell. A frost event is defined with temperatures of $-5^{o}C$ or less on or after March 1st in Texas or March 21st in Oklahoma and Missouri following a warm spell. A warm spell is a "10 day warm spell starting 13 days before the frost event with a mean daily minimum temperature of 4.4°C or more and with no daily temperature below -2.8°C during this 10 day period" (Stahle 1990, p. 228). Stahle linked the spatially extensive false spring events in Southcentral USA to ENSO variability using the Southern Oscillation Index (SOI), but also suggested that volcanic forcing in extreme cases (i.e. Tambora 1815) may also play a role in their formation. With the above mentioned specific weather conditions in mind, Stahle (1990) suggested the potential study of tree rings and meteorology or "dendrometeorology."

A regional weather anomaly associated with frost-ring formation is consistent with the kinds of regional climatic responses that other tree-ring researchers have noted after major volcanic eruptions, although these responses vary by latitude, region, season, and whether the temperature response is that of cooling or warming. For example, several tree-ring studies have identified both a warming and cooling response after major volcanic eruptions in different regions, observations that have been supported by recent modeling results. Lough and Fritts (1987) used a network of western North American semi-arid tree-ring chronologies that span from 1602 to 1900 to reconstruct seasonal and annual temperatures. Their results suggested that major volcanic eruptions led to a winter warming in the western United States and a summer cooling for the remainder of the United States.[1] Lough and Fritts (1987) state that the "magnitude and spatial extent of the reconstructed cooling and warming varies seasonally" (p. 219). D'Arrigo and Jacoby

---

[1] Robock and Mao (1995) later noted that Lough and Fritts (1987) did not correct for any El Niño-Southern Oscillation (ENSO) signal and did not incorporate volcanic eruptions south of 10°S. Robock and Mao observed summer cooling in the tropics, subtropics, and mid-latitudes and winter warming in the northern high latitudes.

(1999) confirmed Lough and Fritts' (1987) results of summer cooling in Eastern Canadian forests. They used maximum latewood density to reconstruct temperatures at 13 treeline sites in northern North America. Tree-ring density was used because, statistically, it showed a stronger and more consistent short-term related volcanic signal (i.e. cooler summer temperatures) than ring width alone. D'Arrigo and Jacoby (1999) evaluated the spatial patterns of tree growth after four known volcanic eruptions and concluded that regional variations in tree growth reflect volcanic-induced cooling and a spatial pattern of cooler atmospheric circulation patterns.

Both instrumental records and tree rings indicate that the regional climatic response to a major volcanic event appears to vary by latitude, region, and season. The previous LaMarche & Hirschboeck (1984), Hirschboeck et al. (1996), and Brunstein (1996) investigations indicated a relationship between frost-ring formation and sub-freezing temperatures. This evidence of a regional response to sub-freezing temperatures leads to further questions: 1) Can large-scale patterns of frost events provide information on locations of sub-freezing temperatures? 2) Does the relationship established by LaMarche and Hirschboeck (1984) hold up in the western United States for the more recent climatically effective eruptions of El Chichón and Pinatubo and if not, why not? 3) Why do we see a frost-ring response in some trees and sites and not others? 4) How would a more extensive systematic frost-ring investigation compare to prior research?

Methodology

To address these questions, I re-analyzed and compiled frost-ring data from sixteen sites in the western USA. The study sites consisted of 14 bristlecone pine and two foxtail pine sites. The sites are located in four geographic regions: the Great Basin (GB), Sierra Nevada (SN), Arizona (AZ), and along the Front Range of the Rocky Mountains (FR) (Fig. 5). The easternmost species in the study is *Pinus aristata* while the far western species is *Pinus balfournia*. The species located in the central portion of the study area is *Pinus longaeva*. Elevation, slope, and other characteristics for the sites are listed in Table 2. Elevation of the sites ranges from 3048 to 3657m (Fig. 6). The ages of the samples ranged from 1692 BC to AD 2000. The core samples were collected and crossdated in the 1980s, 1990s, 2000, and 2001 while the cross sections were collected and dated in 1994 by a variety of researchers at the University of Arizona's Laboratory of Tree-Ring Research in Tucson, Arizona (Table 3). These sites were chosen to fill the geographic gap of frost-ring sites in the LaMarche and Hirschboeck (1984) research (Fig. 7). Long-line plots, visual crossdating, and COFECHA were utilized in the crossdating of the 1980s and 1990s collections by other researchers (Table 3). The newest increment cores collected in the summers of 2000 and 2001 were crossdated by creating skeleton plots and comparing them to previously created master chronologies. After investigating approximately 900 tree-ring samples, I compiled a list of 503 individual frost-ring years, four light-ring years, and 12 frost-damaged years. In comparison, LaMarche and Hirschboeck's (1984) study was based on 116 total frost-ring years. This research is the most extensive collection of frost-ring dates yet assembled for the western United States.

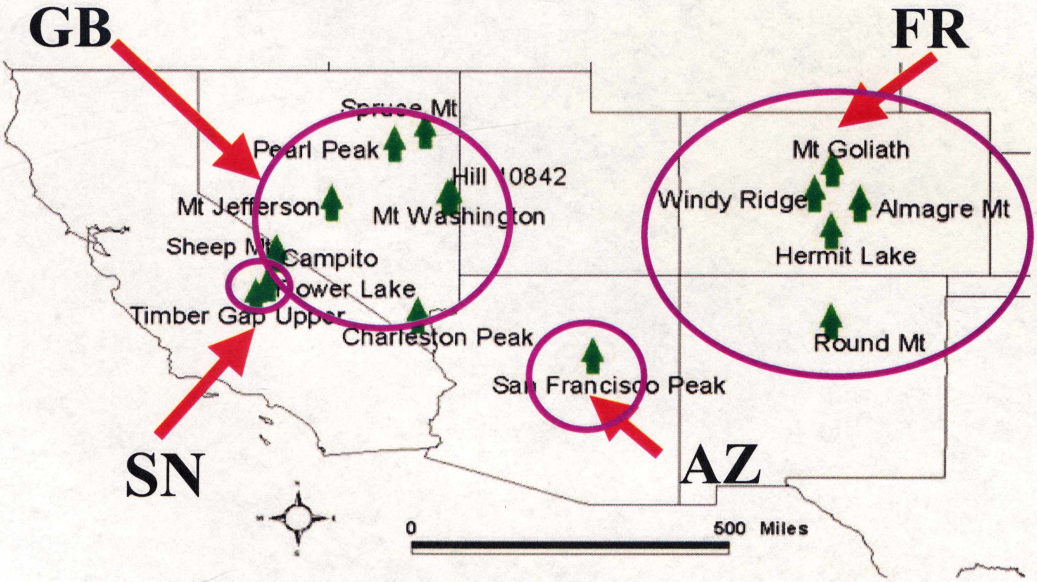


Figure 5. Study Area. GB = Great Basin, SN = Sierra Nevada, AZ = Arizona, and FR = Front Range and Southern Rocky Mountains.

Table 2. Site Characteristics. Sites included in this research but not in LaMarche and Hirschboeck (1984) are noted with an *.

Site	Species	Elevation	Slope	Aspect	Strata	State	Region
Mt Washington	*Pinus longaeva*	3415	10	S	limestone	NV	Great Basin
Sheep Mt	*Pinus longaeva*	3475	20	S	dolomite	CA	Great Basin
Spruce Mt*	*Pinus longaeva*	3110	20	E,W	limestone	NV	Great Basin
Mt Jefferson*	*Pinus longaeva*	3300	30+	S,SE	limestone	NV	Great Basin
Hill 10842*	*Pinus longaeva*	3048	20 to 40	S,SW	limestone	NV	Great Basin
Pearl Peak*	*Pinus longaeva*	3170	45	SE	limestone	NV	Great Basin
Charleston Peak*	*Pinus longaeva*	3425	30+	NW,NE	limestone	NV	Great Basin
Campito Mt	*Pinus longaeva*	3400	25	NW	sandstone	CA	Great Basin
Flower Lake*	*Pinus balfournia*	3291	25	S, SSE	granite, granodiorite	CA	Sierra Nevada
Timber Gap Upper*	*Pinus balfournia*	3261	40	S	gneiss, schist	CA	Sierra Nevada
San Francisco Peaks*	*Pinus aristata*	3600	30+	SE, S, SW ,W	basalt, andesite	AZ	Arizona
Windy Ridge*	*Pinus aristata*	3570	5 to 30	S,SE	granite	CO	Front Range
Mt Goliath*	*Pinus aristata*	3535	20 to 30	S	granite	CO	Front Range
Hermit Lake	*Pinus aristata*	3657	25 to 40	S	sandstone	CO	Front Range
Almagre Mt	*Pinus aristata*	3536	15 to 46	E, NE	granite	CO	Front Range
Round Mt*	*Pinus aristata*	3270	5	S	sandstone	NM	Front Range

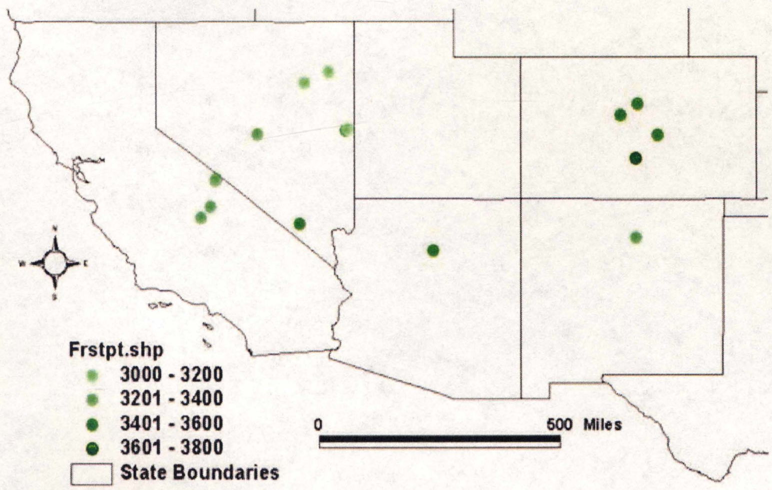


Figure 6. Elevation variation shown by color gradation. Darker dots are sites at higher elevation.

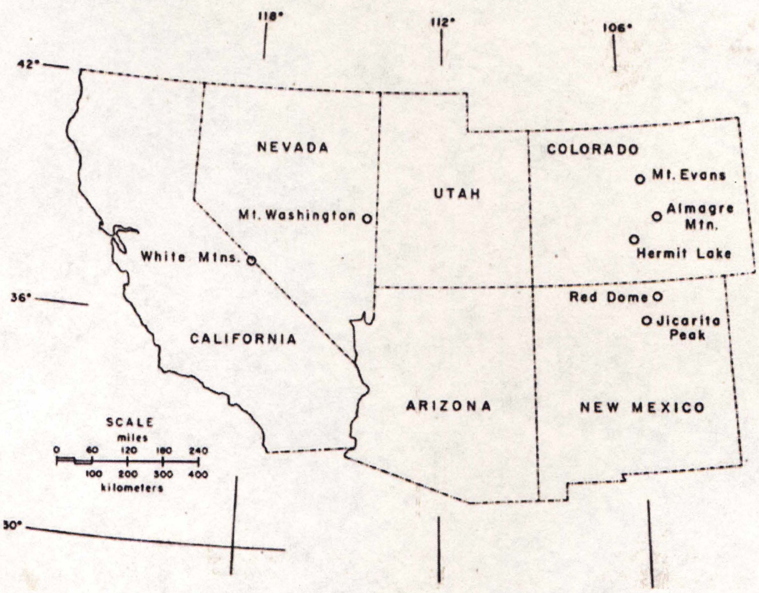


Figure 7. LaMarche & Hirschboeck (1984) site map.

Table 3. Collection and Analysis of Samples. Collections in 2000 and 2001 (denoted with *) were analyzed for the first time in this investigation.

Site	Year Collected	Collected By	Crossdated By	Samples reanalyzed for this study (approximate)
Mt Washington	1983	Graybill/Rose	McCoomis	50
Sheep Mt	1983	Graybill/ Rose/McCarthy	McCoomis	25
	1985	Graybill/Shaw/ Funkhouser	McCoomis	40
	1990	Graybill	Parks	15
	1991	Graybill/Rose	Parks	25
	2000*	Baisan/Hallman	Hallman	20
	2001*	Adams/Ababneh/Hallman	Hallman	20
Spruce Mt	1986	Graybill/ Rose	Adams	25
Mt Jefferson	1981	Graybill/ Rose	Graybill	40
Hill 10842	1985	Graybill/Shaw/Funkhouser	McCoomis	35
Pearl Peak	1986	Graybill/Rose/McCarthy	Adams	50
Charleston Peak	1985	Graybill/Shaw/Funkhouser/Rose	McCoomis	50
Campito Mt	1983	Graybill	Graybill	20
Flower Lake	1987	Rose/ Adams	Rose/Adams	50
Timber Gap Upper	1987	Adams/ Rose	Adams/Rose	35
San Francisco Peaks	1998	Salzer/Adams/ Parks	Salzer	230
Windy Ridge	1986	Graybill/McCarthy	Adams	40
Mt Goliath	1984	Graybill/Shaw/Xiang-ding	Graybill	40
Hermit Lake	1984	Graybill/Shaw/Xiang-ding	Graybill	45
Almagre Mt	1984	Graybill/Shaw/Xiang-ding	Graybill	35
Round Mt	1994	Touchan/Allen	Touchan	15

While identifying frost rings in my first site, Pearl Peak, Chris Baisan (personal communication, 1999) suggested that a scale to describe the confidence of a particular frost-ring designation would add more information to the frost-ring record being compiled. Such a frost-ring scale would allow the inclusion of all "potential" frost rings to the regional investigation. The scale would better document frost-ring variations and provide information on potential frost rings that may have been omitted by previous investigators. Accordingly, I devised a scale of "1-to-3" to categorize the degree to which frost damage was identifiable; "1" represents a possible frost ring and "3" represents a definite frost ring (Table 4).

Table 4. Frost-ring Scale.

Scale	Description	Criteria	Example
1	Possible frost ring	some minor bending of cells on less than 1/3 of the ring boundary	8a
2	Probable frost ring	degree of bending increases and occurs along approximately half of the ring boundary	8b
3	Definite frost ring	frost damage along the entire ring boundary with definite bending and deformation of cells	8c and 8d

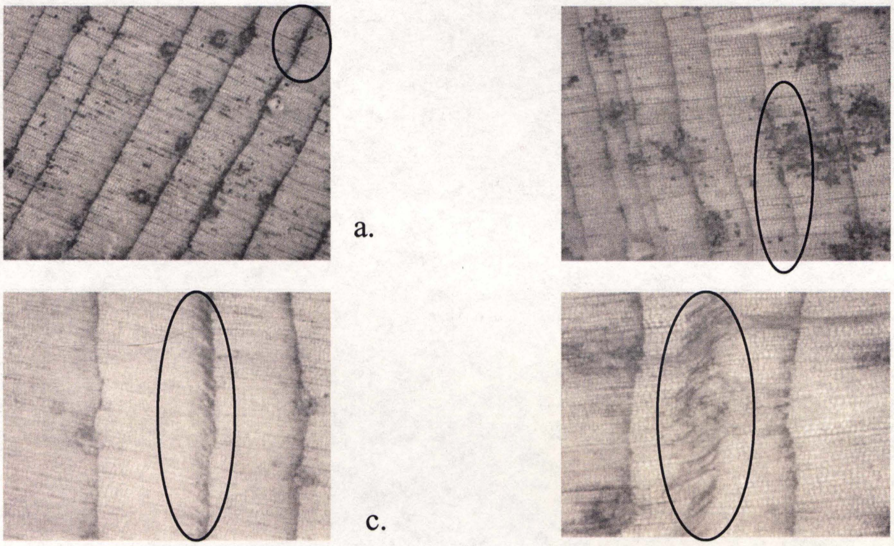


Figure 8. Categories 1(a), 2(b) and 3(c & d), respectively. C is slight and d is extreme. Images c and d by Chris Baisan.

The frequency of frost-ring years for each sample from each site was compiled. The tabulation consisted of the percent of trees at that site that had frost or light rings in a given year. Multiple samples from a given tree were combined into a list of frost-ring years for that individual tree. The number of frost rings was tallied by individual category (e.g. 3, 2, or 1) and by year. The number of possible frost rings (based on the sample size for that frost year) was determined. The total percentage of frost rings was calculated by dividing the total number of frost rings (categories 1-3) or light rings by the number of trees that contained information for that year (Appendix 1). For example, Sheep Mt has 12 trees that include the year AD 627. Nine of those trees have frost rings in AD 627; thus, 9/12 or 75% of the trees from Sheep Mt as old as AD 627 had frost rings in that year. The years with 25% or more frost or light rings per site that were *also* present in two or more sites were designated as *notable frost events*. This designation is different from LaMarche and Hirschboeck's (1984) definition of a notable frost event as one that occurred in 50% of the trees in a single site *or* occurred at two or more sites. My NFE definition is less stringent in the percent of trees affected, but more spatially stringent in that an event must occur in two sites *and* in at least 25 % of the trees. In the LaMarche and Hirschboeck (1984) definition, it is possible for a notable frost event to occur in two sites but only in one tree at each site. Due to individual variation in trees and the desire to identify regional patterns, I wanted a more spatially rigorous definition.

Software designed by Henri Grissino-Mayer (1995) to analyze fire-scar events (FHX2) was used to graphically identify common frost events between sites. The software allows one to input event data, in my case frost events, by year and season. Figure 9 displays the frequency of frost-ring occurrence over time in a format that allows site-to-site comparison. The sites are arranged by region, Mt. Washington (Wash) to Campito Mt. (Campito) are in the Great Basin (GB), Flower Lake (Flower) and Timber Gap Upper (Timgapu) are in the Sierra Nevada (SN), San Francisco Peaks (SanFran) is in Arizona (AZ), and Windy Ridge (Windy) to Round Mt. (Round) are in the Front Range (FR). After tabulating the frequency of every frost-ring year, I plotted the following types of frost-ring records: frost rings found in greater than or equal to 50% of the trees for a given site (✱), frost rings found in less than 50% and greater than or equal to 25% of the trees for a given site (◆), and frost rings found in multiple trees but not equal to 25%

of the trees for a given site (▮). The horizontal dashed line in Figure 9 shows the time period covered by each chronology. Frost-rings years that are concurrent within a region or regions are clearly identified when the symbols line up vertically (e.g. AD 1761).

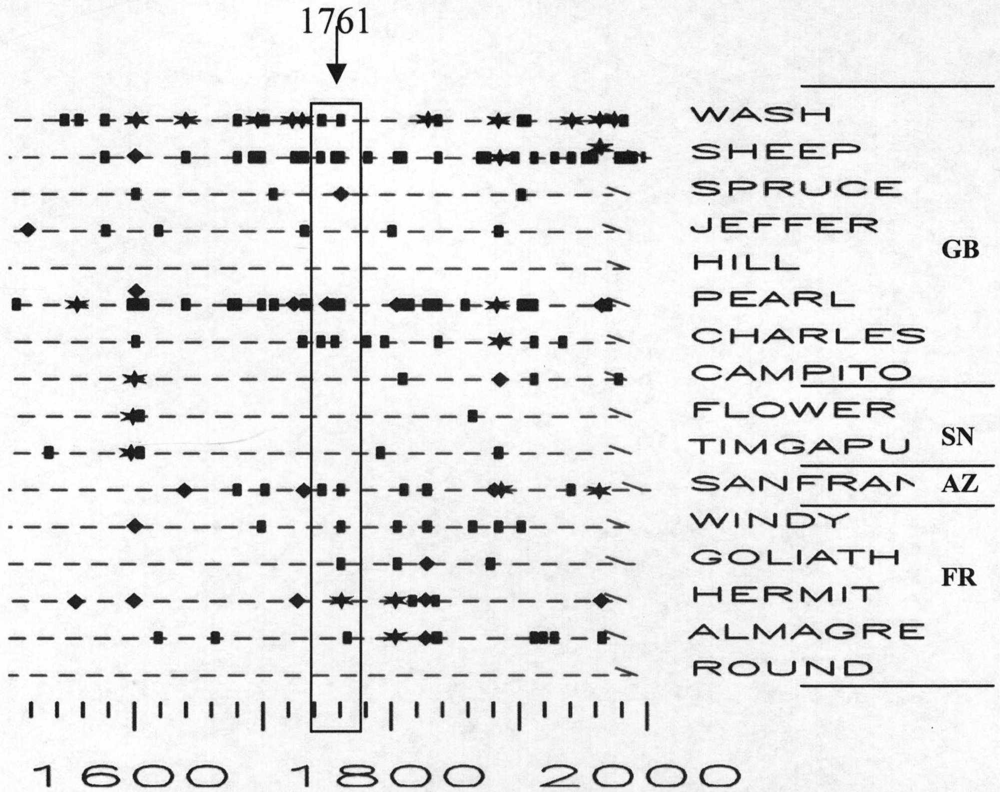


Figure 9. Frost Events from AD 1500 to AD 2000 by site, with the frost rings in 1761 highlighted by the box (GB = Great Basin, SN = Sierra Nevada, AZ = Arizona, FR = Front Range.

Maps were produced showing the distribution of the sites that contain a NFE in a given year (See Appendix 2). Each map shows the sites for which a chronology existed during the given year of that particular NFE (light gray dots). The sites highlighted with dark black represent sites that have a NFE for a given year. For example, in Figure 10, 16 sites contained the year 1965, and five of those 16 sites recorded NFE in 1965.

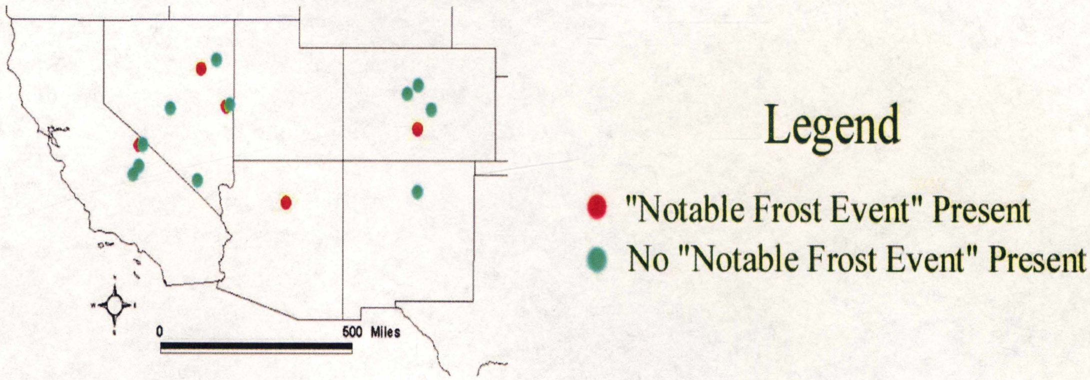


Figure 10. Example map for the notable frost event in 1965.

Results and Discussion

Frost-Ring Scale

By developing a scale to categorize the degree to which frost damage was identifiable, all "potential" frost rings were included in the frost-ring compilation. The results from the frost-ring scale indicate that frost-ring damage can vary from tree to tree and even within the same tree. For instance, in sites that contained the NFE in 1884, frost damage varies from category 1-to-3, and some trees had no frost damage for that year. Even within the same tree, cores from different parts of the tree can show varying degrees of frost damage. All of the notable frost events found in this study occurred in the latewood portion of the ring. More earlywood frost rings occurred in the earlier part of the record when trees were younger the number of chronologies that exist decreases as one goes back in time, hence a systematic bias exists favoring earlywood frost formation in the early portion of the samples (chronologies).

Time Plot Results

An examination of Figures 11a-c identifies the 17 NFEs based on the criteria: (1) greater than or equal to 25% of the trees at a given site exhibiting a frost ring, *and* (2) occurring in multiple sites in the study area. Figures 11a-c also contain frost events that do not meet the criteria associated with NFEs, but add to the overall regional patterns. For instance the frost ring in AD 1601 is considered notable in 8 sites, but also occurs in multiple trees of two other sites. Arrows on the timeplot figures (Figs. 11a-c) indicate NFE years.

By incorporating notable frost events and frost damage found in multiple trees interesting regional patterns emerge. Although no NFEs are found in AD 1680 or AD 1902, multiple trees from 4 sites show frost damage in both of those years. AD 1699 is another year that does not contain any NFEs, but on Mt. Washington, CA more than 50% of the trees have a frost ring in 1699, and three other sites have frost damage in multiple trees in that year. No NFEs occur in AD 1837 or AD 1912, but five sites have frost injuries in both of these years. Other NFE years are substantiated by frost damage in multiple trees in additional sites (e.g. AD 1200, 1453, 1601, 1640, 1725, 1732, 1761, 1805, 1828, 1884, and 1965).

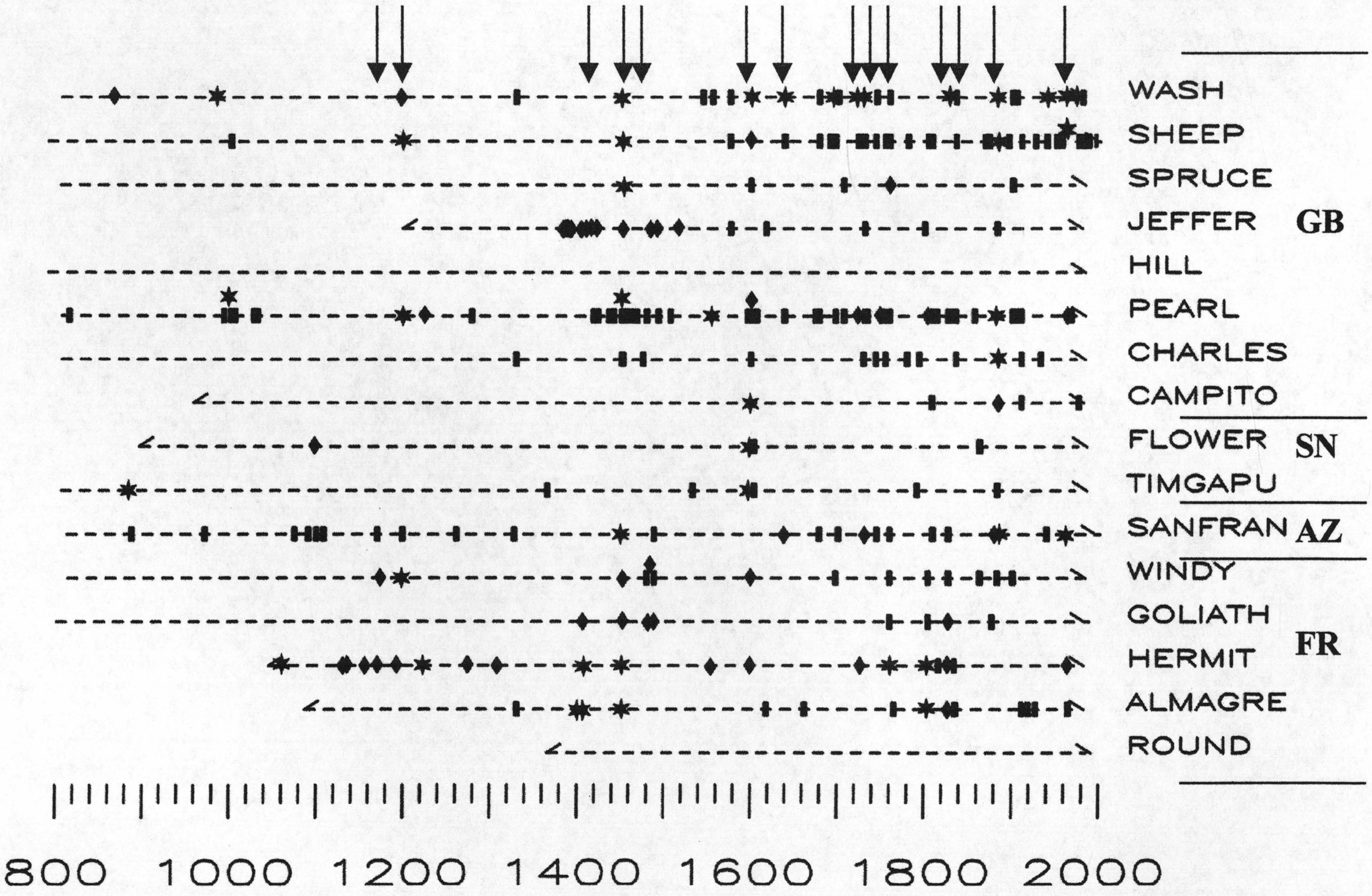


Figure 11a. Frost events from AD 800 to AD 2000 by site. ▮ = multiple trees, ◆ = greater than or equal to 25%, ✶ = greater than or equal to 50%.

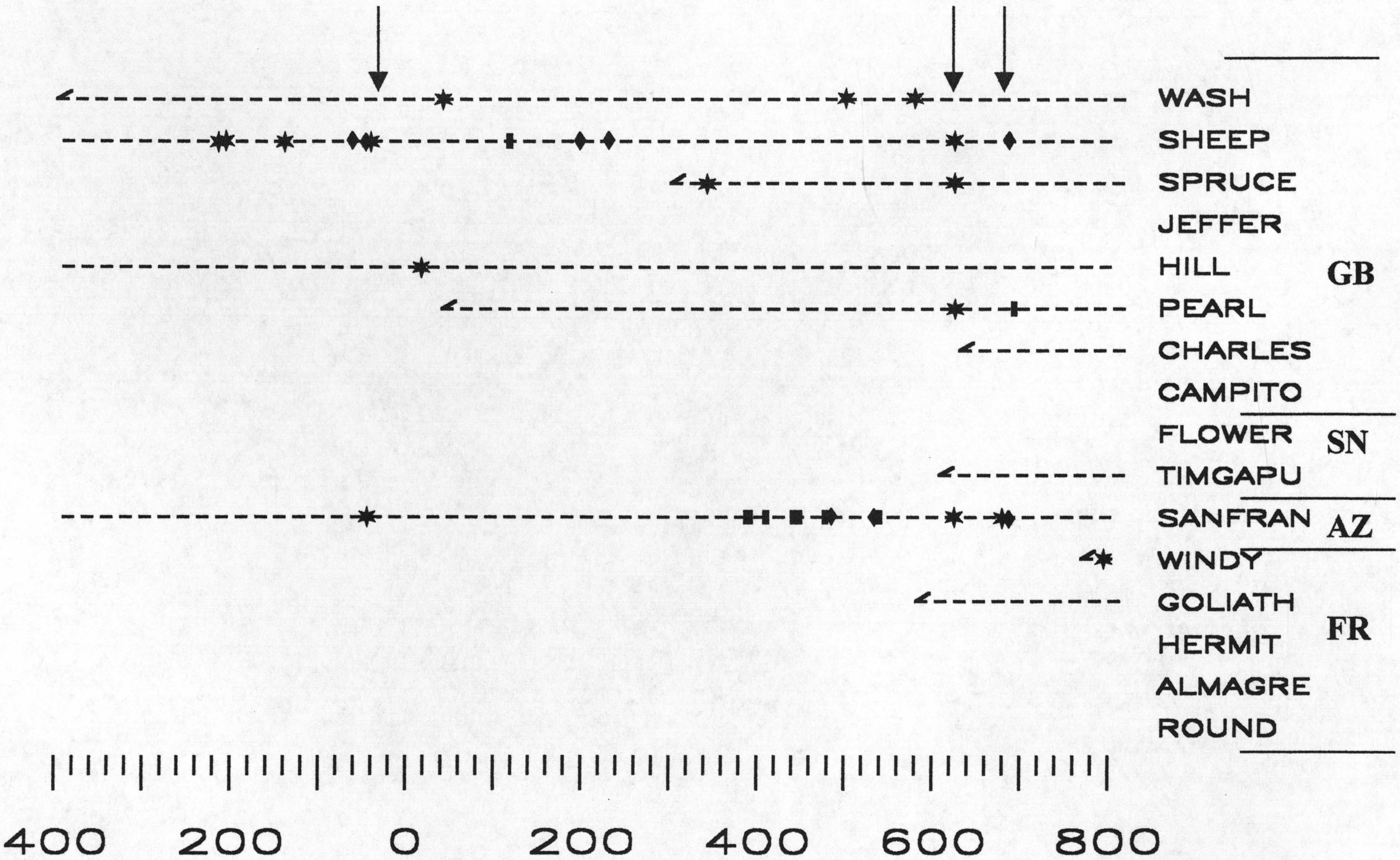


Figure 11b. Frost events from -400 to AD 800 by site. Note -400 = 401 BC. ▮ = multiple trees, ◆ = greater than or equal to 25%, ✶ = greater than or equal to 50%.

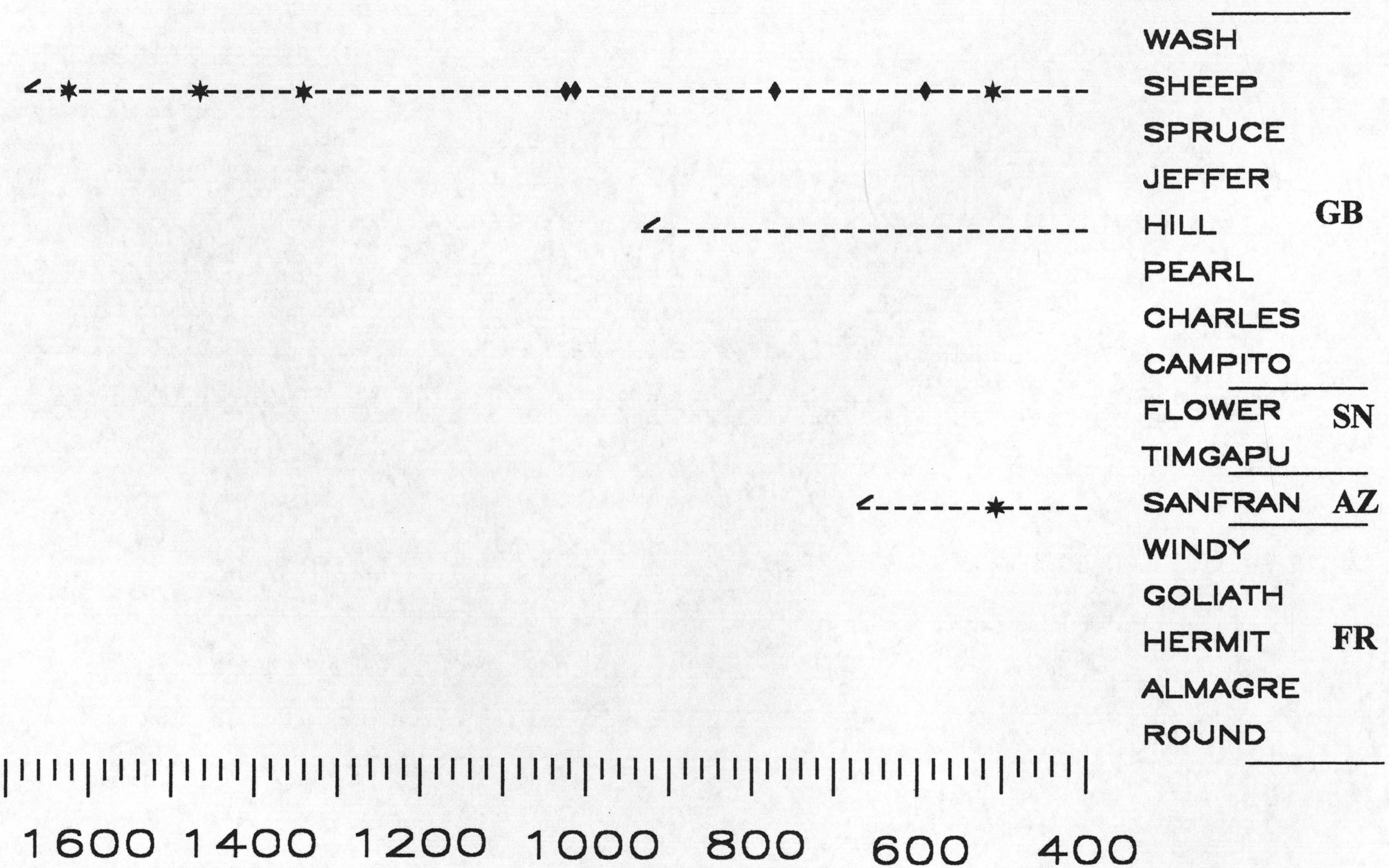


Figure 11c. Frost events from - 1691 to - 400 by site. Note -1691 = 1692 BC. ▮ = multiple trees, ◆ = greater than or equal to 25%, ✶ = greater than or equal to 50%.

Spatial Results

Maps were constructed for the years associated with the 17 notable frost events to examine the regional variation between sites in a given frost-event year. Figures 12 - 15 illustrate the spatial patterns of regional frost rings that occur in a given year (see also Appendix 2). Table 5 lists the NFEs that occur in the western U.S. by region. I have created four categories of NFEs based on their locations. The "Entire West" category includes the whole study area except Arizona (Fig. 12) (e.g., the NFE in 1601 occurred in three of the four regions - Sierra Nevada, Great Basin, and Front Range). The "Great Basin & Front Range" category contains eight NFEs, with two of those also occurring in the "Arizona" region (Fig. 13). Nine of the 17 NFEs occur over a large portion of the study area (i.e. Entire West and Great Basin & Front Range in Table 5). Six NFEs occur in the "Great Basin & Arizona" region (Fig. 14). Two NFEs are present only in the "Front Range" region (Fig. 15). Frost events in 1453 and 1601 are the most spatially extensive; with ten and eight sites exhibiting those frost events, respectively. All of the NFEs, except 1408 and 1484, are located in two or more different regions, thus, 15 of the NFEs cover a large area. Notable frost events in 1408 and 1484 are in close proximity to each other, but are only notable in the Front Range Only region.

Table 5. Notable Frost Events, with * also found in Arizona.

Entire West Includes Sierra Nevada, Great Basin, & Front Range (excluding Arizona)	**Great Basin & Front Range**	**Great Basin & AZ Only**	**Front Range Only**
1601	1200	43 BC	1408
	1225	AD 627	1484
	1453*	687	
	1725	1640	
	1761	1732	
	1805	1884	
	1828		
	1965*		

Note that as one travels back in time, the number of available chronologies for frost-ring detection decreases. There are 15 of the 16 site chronologies that exist for the NFEs in 1200 and 1225. The NFE in 687 can potentially be found in nine sites while the NFE in 627 can potentially be found in eight sites. Lastly, only four sites exist for the NFE in 43 BC (See Appendix 2). Thirteen of the 17 NFEs are associated with major volcanic eruptions (Table 6, Appendix 2).

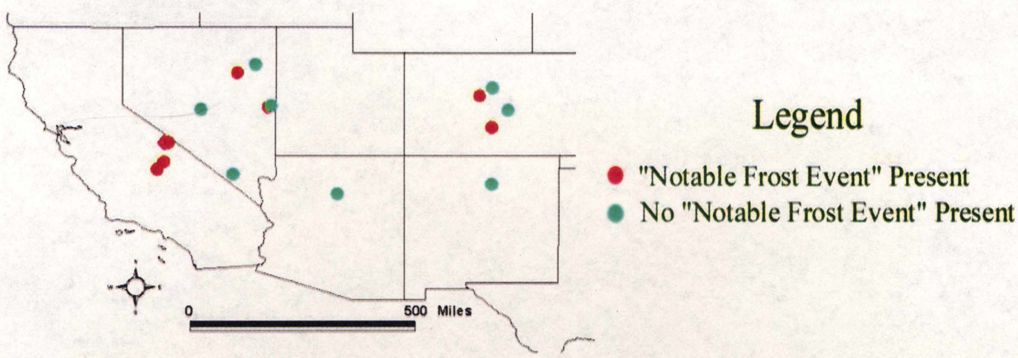


Figure 12. Map of sites with 1601 frost event.

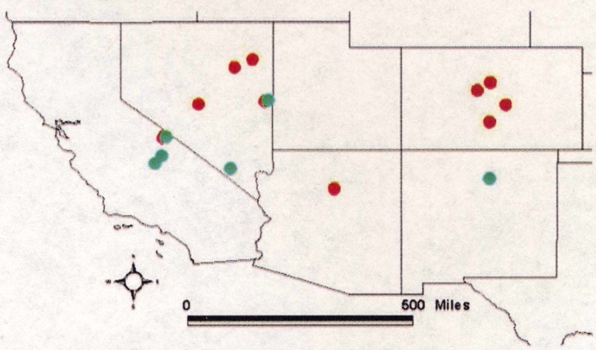


Figure 13. Map of sites with 1453 frost event.

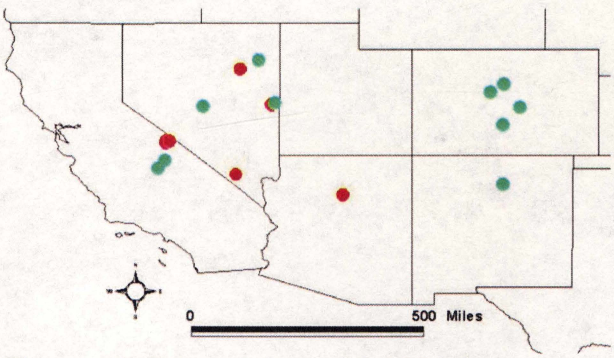


Figure 14. Map of sites with 1884 frost event.

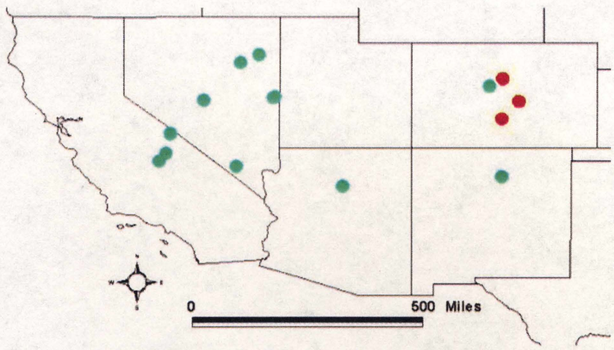


Figure 15. Map of sites with 1408 frost event.

Table 6. Synthesis of Present and Previous Research.

This Work	LaMarche & Hirschboeck 84	Stahle 90	Brunstein 96	Light Rings Multiple Studies	Sulfate Peaks in Ice Cores from Greenland & Antarctica	Eruption Association
43 BC	42 BC		42 BC		50+/-30, -43	Etna
AD 627	628		*		622, 622+/-3, 639+/-15	Unnamed
687	*				691, 692	Unnamed
1200	*				1205,1200+/-50	Oshima
1225			*		1227, 1228, 1229	
1408			*			
1453	*		*	*	1450,1450+/-, 1454-57	Kelut/Kuwae
1484			*		1480, 1483, 1484	Kelut/Mt.StHelens
1601	*			*	1599, 1600, 1602	Huaynaputina
1640	*			1639	1639, 1640, 1645+/-7	Llaima/Komaga-take
1725			*		1720, 1727	
1732	*			*	1730-36, 1730	
1761	*		*	1759		Michoacan
1805	*		*	*	1803	4 eruptions
1828	*	*	*		1826	Kelut
1884	*			*	1883, 1884	Krakatau
1965	*	*	*	*	1963, 1964	Agung

Legend: * = agreement with new frost-ring chronologies. Note: Light rings - Filion et al 1986, Delwaide et al 1991, Yamaguchi et al 1993, and Szeicz 1996; Ice cores - Hammer et al 1980, Delmas et al 1992, Zielinski et al 1994, Langway et al 1995, Zielinski 1995, Clausen et al 1997, Cole-Dai et al 1997, and Crowley 1999; Historic records - 43BC and AD627 - Stothers and Rampino 1983.

Updating Existing Frost-Ring Chronologies

After updating the existing frost-ring chronologies, no widespread notable frost event was identified in association with the 1982 eruption of El Chichón or the 1991 eruption of Pinatubo. However, multiple trees from Mt. Washington, NV and Sheep Mt., CA do show frost damage in 1982. Also, in preliminary results, multiple trees from the 2001 Campito Mt., CA collection record a frost ring in 1982. The 2001 Campito Mt. results are not complete since not all of the cores have been crossdated.

A sampling strategy was developed before going into the field in July 2001 to increase the likelihood of finding evidence of Pinatubo-related frost rings. According to Fritts (1969) young trees at the upper treeline edge are thought to be more susceptible to frost damage than those trees located in the middle of the forest. Therefore bristlecone pines from Sheep Mt. and Campito Mt. were sampled at the extreme upper-border forest and some very young trees were specifically chosen in hopes of finding a frost ring in response to the 1991 eruption of Pinatubo. In the 2001 Sheep Mt. and Campito Mt. collections, an earlywood frost ring occurs in two trees from Sheep Mt. and one tree from Campito Mt in 1992. All three trees were younger than 50 years.

Species Differences

Variations between sites and species in frost-ring response were observed in this study. Bristlecone pine sites that were investigated extended farther into the past and therefore had more potential for extending the frost event record. Although there are some foxtail sites that extend back farther, they were not studied. Over equivalent time periods, bristlecone sites tended to contain more frost rings than foxtail sites and the bristlecone sites higher in elevation and/or latitude had the most frost events. On the other hand, the foxtail pine sites tended to have more light rings. The only NFE for the Sierra Nevada (foxtail) sites was 1601. The lack of other NFEs may be a result of differences in species response, elevation, or the location of sub-freezing temperatures during the other NFE years.

Comparison to Previous Work

A comparison of this new frost-ring compilation with previous work indicates that the 17 notable frost events coincide with events identified by several prior investigations, most of which are associated with volcanic eruptions (Table 6). For instance, the frost ring that occurs in AD 1453 is documented in other frost-ring and light-ring chronologies and coincides to within 1-3 years of the 1452 eruption of Kuwae, SW Pacific (VEI = 6)[2] and possibly the 1451 eruption of Kelut, Java (VEI = 3+). Independent dating of this event comes from ice core data (Table 6). The widespread frost ring that occurs in 1965 is associated with the 1963 eruption of Agung, Bali (VEI = 4). Evidence for this eruption includes other frost-ring and light-ring chronologies, ice core data, and instrumental data (Table 6).

In their 1984 paper, LaMarche and Hirschboeck used a contingency table analysis to examine the probability of joint occurrence between frost rings and major volcanic eruptions. I performed a similar analysis based on my list of NFEs. Table 7 shows the contingency analysis results for both LaMarche & Hirschboeck (1984) and for the current

[2] Note that Volcanic Explosivity Index (VEI) is taken from Simkin and Siebert (1994). VEI is a measure of eruption explosivity, but it is not necessarily a reliable indicator of climatically effective eruptions (Robock 2000).

study. According to Lamb (1970), Minnis (1993), and others, surface temperatures are likely to decrease 1-3 years after a climatically effective eruption. The typical residence time for stratospheric aerosol veils is 2-3 years (Self & Rampino 1981); hence, a 3-year time period was used by LaMarche & Hirschboeck (1984) to evaluate possible "joint occurrence" between a volcanic eruption and a subsequent frost-ring response. They calculated the expected frequency of joint occurrences of eruptions and frost rings based on the probability of joint occurrence in two random, completely independent series and compared these to the observed joint occurrence (within a 3-year time period of an eruptions and subsequent frost ring (Table 7). They then used a chi-square analysis to show that the observant number of joint occurrences was highly unlikely to have arisen by chance alone (> 99.9% confidence level, $p<0.0005$). Using the same methodology, for the period 1882-2000 (without including El Chichón[3]) the chi-square test indicates significance, but at a slightly lower confidence level (>99% confidence level, $p<0.01$). For the longer 1500-1880 time period, however, the probability of joint occurrences between volcanic eruptions and NFE is not significantly greater than expected by chance ($p<0.5$). The difference between LaMarche & Hirschboeck and this study may be due to the fact that I used a more spatially rigorous definition of a NFE. My NFE criteria emphasized frost events that occurred in the largest number of trees *and* in multiple sites so that only the most severe and widespread frost events would be analyzed. To accurately compare the statistics of the two studies, one would have to use exactly the same criteria when classifying NFEs.

[3] LaMarche & Hirschboeck's (1984) analysis was based on eruptions having DVI > 500, however El Chichón had a DVI < 400 (NCDC 2001). Results for the 1882-2000 record are shown with and without El Chichón in Table 7.

Table 7. Data and results of contingency analysis of frost ring occurrence following major volcanic eruptions. In this work 1882-2000, figures in parenthesis include El Chichón.

	LaMarche & Hirschboeck (1984)		**This work**	
Period	1882-1968	1500-1880	1882-2000	1500-1880
No. of triads	29	127	39 (39)	127
No. of volcanic events	4	15	5 (6)	15
Observed frequency per triad	0.14	0.12	0.13 (0.15)	0.12
No. of frost events	5	12	2 (2)	7
Observed frequency per triad	0.17	0.09	0.05 (0.05)	0.55
Expected frequency of joint occurrences	0.024	0.011	0.0065 (0.0075)	0.007
Expected no. of joint occurrences	0.7	1.4	0.25 (0.29)	0.889
Observed no. of joint occurrences	4	6	2 (2)	2
χ^2	16.0	14.7	7.3 (5.76)	0.66
p	< 0.0005	< 0.0005	< 0.01 (0.02)	< 0.5

Comparisons to Temperature Reconstructions

Previous researchers have used tree rings to reconstruct temperatures in North America and the Northern Hemisphere. By comparing my notable frost events to temperature reconstructions, many of the sub-freezing temperatures indicated by my events were supported by climate reconstructions from other investigations (Table 8). The temperature reconstructions in Table 8 were based on tree-ring widths and/or latewood density from foxtail pines and bristlecone pines, spruce, and larch. Fifteen of my seventeen NFEs were associated with negative anomalies or reconstructed cool periods from various studies. The notable frost-ring years of 1408 and 1484 did not correspond with any major cool periods shown in Table 8, but these frost events were also restricted to the Front Range of the Rocky Mountains and may represent a localized cooling only. Table 8 also contains 28 negative anomalies or cool periods that are not associated with any of my NFEs.

Table 8. Reconstructed negative anomalies and cool periods compared to this work.

This Work NFEs	Negative Anomalies	Location of Cooler Temperatures	Source
43BC	43BC - 22BC	Arizona	Salzer 2000
	AD 94-103	Arizona	Salzer 2000
	176; 177-194	Sierra Nevada; Arizona	Scuderi 1993; Salzer 2000
	230-235	Arizona	Salzer 2000
	268-279	Arizona	Salzer 2000
	368-381	Arizona	Salzer 2000
	470-486	Arizona	Salzer 2000
	535, 536, & 541; 534-553	Sierra Nevada; Arizona	Scuderi 1993; Salzer 2000
AD 627	AD 627	Arizona	Salzer 2000
	663-669	Arizona	Salzer 2000
687	685; 683-700	Sierra Nevada; Arizona	Scuderi 1993; Salzer 2000
	729-736	Arizona	Salzer 2000
	794	Sierra Nevada	Scuderi 1993
	804-824	Arizona	Salzer 2000
	846-859	Arizona	Salzer 2000
	881	Sierra Nevada	Scuderi 1993
	897-902	Arizona	Salzer 2000
	987-991	Arizona	Salzer 2000
	1094-1120	Arizona	Salzer 2000
1200	1195-1219	Arizona	Salzer 2000
1225	1225-1245	Arizona	Salzer 2000
	1258-1271	Arizona	Salzer 2000
	1330-1364	Arizona	Salzer 2000
1408			
1453	1453; 1450s	Northern Hemisphere; Global	Briffa et al. 1998; Mann et al. 1998
1484			
	1512-1527	Arizona	Salzer 2000
1601	1601-1610; 1599-1612; 1601; 1601; 1590-1610; 1599-1612	Western North America; Sierra Nevada; ; North America & Europe; Northern Hemisphere; Global; Arizona	Briffa et al. 1992; Graumlich 1993 and Scuderi 1993; Jones et al. 1995; Briffa et al. 1998; Mann et al. 1998; Salzer 2000
	1620-1629; 1626	Western North America; Global	Briffa et al. 1992; Mann et al. 1998
1640	1640-1649; 1636-53; 1641; 1641; 1642; 1636-1653	Western North America (California); Sierra Nevada; North America & Europe; Northern Hemisphere; Global; Arizona	Briffa et al. 1992; Graumlich 1993 and Scuderi 1993; Jones et al. 1995; Briffa et al 1998; Mann et al. 1998; Salzer 2000
	1669-1678; 1669; 1661-1683	Western North America; North America & Europe; Arizona	Briffa et al. 1992; Jones et al. 1995; Salzer 2000
	1695-1704; 1703; 1699	Western North America; Sierra Nevada; North America & Europe	Briffa et al. 1992; Scuderi 1993; Jones et al. 1995
1725	1725	North America & Europe	Jones et al. 1995
1732	1732	North America & Europe	Jones et al. 1995
1761	1761-1770; 1760s1763-1771	North America; Northern North America; Arizona	Fritts 1991; Briffa et al. 1994; Salzer 2000
1805	1800-1820;	Northern Hemisphere;	Jacoby & D'Arrigo 1989
	1810-1819; 1810s; 1816-1818; 1820; 1810-1825	Western North America; Northern North America; Northern Hemisphere; Global; Arizona	Briffa et al. 1992; Briffa et al. 1994; Briffa et al. 1998; Mann et al. 1998; Salzer 2000
1828	1817-1836	Sierra Nevada	Scuderi 1993
	1838; 1835-1854	Global; Arizona	Mann et al. 1998; Salzer 2000
	1860s;1864 & 1870	Northern North America; Global	Briffa et al. 1994; Mann et al. 1998
1884	1880s	Western North America; Global	Briffa et al. 1992 and Mann et al. 1998
	1890s	Northern North America	Briffa et al. 1994
	1911-1920; 1912; 1900-1912; 1911-1930	North America; North America & Europe; Global; Arizona	Fritts 1991; Jones et al. 1995; Mann et al. 1998; Salzer 2000
	1941-1950	North America	Fritts 1991
1965	1964-1973; 1960s	Western North America; Global	Briffa et al. 1992; Mann et al. 1998

Definitions of negative anomalies by source are as follows: Cool interval by Jacoby & D'Arrigo 1989; Departures from 1901-1970 instrumental average by Fritts 1991; Greatest negative reconstructed extremes by Briffa et al. 1992; Extreme negative anomalies by Graumlich 1993 and Scuderi 1993; Cool decades (below mean) by Briffa et al. 1994; Extreme negative years for MXD by Jones et al. 1995; Extreme low tree-ring density by Briffa et al. 1998; More negative than -0.35 (reconstructed + raw data after 1902) by Mann et al. 1998; Anomalous cold intervals (diverge from the mean at least 1.1 standard deviations) by Salzer 2000.

Discussion

The results of this systematic identification of frost rings expand previously known temporal and spatial distributions of frost events in the western USA. Three notable frost events occurred in the 1400s, 1700s, and 1800s while two NFEs occurred in the 600s, 1200s, and 1600s (Table 10). Only one NFE occurred in the 40s BC and the 1900s and no NFEs occurred in the remaining centuries.

Table 10. Notable Frost Events by century. Centuries *not* shaded are represented by samples from all 16 sites.

Time period	Number of NFEs	Time period	Number of NFEs
-1600 to 0	0	1000s	0
0s	1	1100s	0
100s	0	1200s	2
200s	0	1300s	0
300s	0	1400s	3
400s	0	1500s	0
500s	0	1600s	2
600s	2	1700s	3
700s	0	1800s	3
800s	0	1900s	1
900s	0		

The results of this investigation have several implications. The most widespread notable frost event in 1601 corroborates other below-normal temperature reconstructions and historic records and falls into the same time period as the so-called 'Little Ice Age'. By combining my findings with other research and archives, the extent and severity of this time period is evident. Another interesting finding is the lack of NFEs in the 1900s when compared to the previous three centuries. Only one "notable frost event" occurred in the last century, in 1965. The lower frequency of widespread frost damage in high-elevation pines in the 1900s may indicate that regional responses to global warming have mediated sub-freezing temperatures that would normally occur after climatically effective eruptions in the 1900s, such as El Chichón and Pinatubo.

Recent Eruptions

After updating the frost-ring chronology, no evidence for a widespread frost-ring response was found after the 1982 eruption of El Chichón or the 1991 eruption of Pinatubo. Multiple trees from both Mt. Washington and Sheep Mt. do contain frost rings in 1982, but they do not meet the notable frost event criteria. Preliminary results from the 2001 collection at Campito Mt. indicate that a 1982 frost ring occurs in multiple trees in that location. According to Robock (2000) the 1982 response may have been masked by a strong El Niño in 1982-83 and/or affected by the higher latitude of El Chichón such that the eruption was not conducive to global dispersion of volcanic aerosols[4]. Low sample depth in the years after the Pinatubo eruption may be one reason a *widespread* frost ring has not been found in association with this event. In the 2001 collection on Sheep Mt. and Campito Mt., two trees from Sheep Mt. and one tree from Campito Mt. that are younger than 50 years (more sensitive to frosts due to age) show an earlywood frost ring in 1992. Also, tree rings for 1992 tend to be narrower at these sites. Brunstein (personal communication, 2000) stated that no frost ring associated with the 1991 eruption of Pinatubo has been found at sites he examined in the Front Range of the Rocky Mountains. According to Delwaide (personal communication, 2000), subarctic spruce in Canada exhibit a 1992 light ring.

---

[4] El Niño events occurred in 1965, 1982, and 1991 (Robock 2000; COAPS 1998). This masking effect may have played a role in the frost-ring samples after El Chichon and Pinatubo, but did not after Agung.

Spatial Patterns

Spatial patterns that emerged in this new compilation indicate differences in frost-ring frequency with species, elevation, and latitude. Bristlecone pines tended to exhibit more frost events than foxtail pines while foxtail pines tended to exhibit more light rings. Spatial variations were identified between the Front Range of the Colorado Rockies, the Great Basin, the Sierra Nevada, and Arizona, and within each individual region. Higher latitude and higher elevation pines were more temperature sensitive and, in general, exhibited more frost rings.

Pearl Peak, NV had the highest frequency of frost rings (186 frost rings) even though the chronology is not as long as other sites (Appendix 1). The Pearl Peak, NV site is at a high elevation and is situated topographically in a valley, or cirque, within the mountain range. The site's high frost-ring frequency could therefore be related to cold-air drainage effects. Hill 10842, NV and Round Mountain, NM were lower elevation sites that were more precipitation sensitive (Adams and Baisan, personal communication 2000). They recorded no NFEs and only a few frost rings.

The maps of notable frost-ring distribution (Appendix 2) suggest that local, regional, and Entire West subfreezing weather events have occurred in the past. Most of the notable frost events occur over a large area. In years such as 1601 and 1453, the frost-ring evidence suggests that sub-freezing temperatures covered large portions of the western U.S. at some point during that growing season. For the years AD 1408 and AD 1484, sub-freezing temperatures occurred over the Front Range of the Rocky Mountains only. At other times (e.g. 627, 1640, 1884), the sub-freezing temperatures were limited to the central and western portions of the study area (CA, NV, AZ).

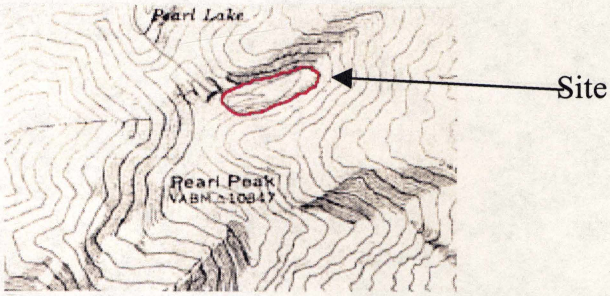


Figure 14. Topographic map with a circle around the Pearl Peak site.

Conclusions

This investigation has identified locations and regional variations of sub-freezing temperatures in western North America during the growing season using a systematic method of frost-ring identification. After examining hundreds of samples and identifying hundreds of frost rings, seventeen notable frost events were identified, nine of which cover large portions of western US. Specific findings are:

- The use of a frost-ring identification system based on three different degrees of frost damage allowed for a scaling of the degree of frost injury at a given site or sites. Most of the frost rings identified were of category 3 (definite frost ring class), but the supporting evidence provided by categories 1 and 2 suggested that the inclusion of all "potential" frost rings adds more information to the overall pattern of frost-ring distribution.

- The frost-ring scale results showed that the degree of frost damage varies between trees and within a tree itself. For example, 64.4% of the trees located on Sheep Mt. have the 1884 NFE, but within that percentage the degree of frost damage varied from 1 to 3. Even within the same tree, multiple cores taken showed that damage within the tree also varied from 1 to 3 on the frost-ring scale.

- One NFE occurred in the study area in both the 1900s and 40s BC while three occurred in each of the following centuries: 1400s, 1700s, and 1800s. Two NFEs are found in each of the centuries: 600s, 1200s, and 1600s. No NFEs occurred the remaining centuries investigated.

- The most spatially extensive NFEs occurred in 1601 ("Entire West"), 1453 ("Great Basin & Front Range", plus Arizona), and 1965 ("Great Basin & Front Range", plus Arizona).

- Frost rings tended to occur more frequently in bristlecone pine study sites while light rings tended to occur more frequently in foxtail pine study sites. This may be due to differences in species response or elevation or location of sub-freezing temperatures.

- Although no *widespread* frost event that fits the spatially stringent criteria was identified after the 1982 eruption of El Chichón or the 1991 eruption of Pinatubo, evidence of a more mild or less widespread frost event did occur after these events on Campito Mt., Mt. Washington, and Sheep Mt.

- For the period 1882-2000 the new compilation supports LaMarche & Hirschboeck's (1984) results. A chi square test indicates that the joint occurrence of a volcanic eruption and subsequent notable frost event is statistically significant ($p<0.01$) over the most recent part of the record. However, for the earlier period of 1500-1880 the probability of joint occurrences between volcanic eruptions and NFEs was not found to be statistically significant ($p<0.5$). The lack of significance in the new compilation may be due to its more rigorous criteria for notable frost events.

- The new compilation supports the conclusions of previous studies that have demonstrated a frost-ring / eruption connection. Specifically 13 of the 17 NFEs found in this investigation corresponded with volcanic eruptions while all of the 17 NFEs corresponded to other studies that reported frost rings, light rings, historical data, or ice core evidence.

For further study into frost-ring formation, microsite studies should be conducted to determine other factors that influence frost-ring formation in a given site (i.e. slope, aspect, wind direction, etc). The addition of a larger database of frost and light rings would allow more spatial patterns to emerge. By expanding this research farther back in time, more temporal patterns may appear. By investigating other species at similar elevations, species response to sub-freezing temperatures may be better understood.

Acknowledgements

Contributions by Dr. Katie Hirschboeck, Dr. Tom Swetnam, and Dr. Julie Cole to this research and manuscript were indispensable. Rex Adams, Chris Baisan, and Tom Harlan provided both academic guidance and suggestions throughout this investigation. I would also like to acknowledge V. LaMarche, D. Graybill, M. Salzer, R. Touchan, and others from the Laboratory of Tree-Ring Research, University of Arizona, Tucson, Arizona for their contributions to my data collections.

References Cited

Adams, R. 2000 and 2001. Personal communication. Laboratory of Tree-Ring Research, University of Arizona, Tucson, AZ.

American Geophysical Union. 1992. Volcanism and Climate Change. *American Geophysical Union Special Report May 1992.*

Bailey, I. 1925. The "Spruce Budworm" Bicoenose. 1. Frost rings as indicators of the chronology of specific biological events. *Botanical Gazette* 80:93–101.

Baillie, M., and M. Munro. 1988. Irish Tree Rings, Santorini and Volcanic Dust Veils. *Nature* 332:344–346.

Baillie, M. 1999. New Frontiers in Science. *Bonrgeno Conference Proceedings: May 1999.*

Baisan, C. 1999 and 2000. Personal communication. Laboratory of Tree-Ring Research, University of Arizona, Tucson, AZ.

Banks, J. 1991. A Review of the Use of Tree Rings for the Quantification of Forest Disturbances. *Dendrochronologia* 9:51–70.

Bradley, R. 1988. The Explosive Volcanic Eruption Signal in Northern Hemisphere Continental Temperature Records. *Climatic Change* 12:221–243.

Briffa, K., P. Jones, F. Schweingruber, and T. Osborn. 1998. Influence of Volcanic Eruptions on Northern Hemisphere Summer Temperatures over the Past 600 Years. *Nature* 393: 450–454.

Briffa, K., P. Jones, and F. Schweingruber. 1992. Tree-Ring Density Reconstructions of Summer Temperature Patterns across Western North America since 1600. *Journal of Climate* 5: 735-754.

________. 1994. Summer Temperatures across Northern North America: Regional reconstructions from 1760 using tree-ring densities. *Journal of Geophysical Research* 99(D12): 25835-25844.

Brunstein, C. 1996. Climatic Significance of the Bristlecone Pine Latewood Frost-ring Record at Almagre Mountain, Colorado, U.S.A. *Arctic and Alpine Research* 28(1):65–76.

Brunstein, C. 2000. Personal communication. U.S. Geological Survey, Denver, Colorado.

Clausen, H., C. Hammer, C. Hvidberg, D. Dahl-Jensen, J. Steffenson. 1997. A Comparison of the Volcanic records over the past 4000 years for the Greenland Ice Core Project and Dye3 Greenland Ice cores. *Journal of Geophysical Research* 102(C12): 26,707-26,723.

Cole-Dai, J., E. Mosley-Thompson, and L. Thompson. 1997. Annually Resolved Southern Hemispheric Volcanic History from Two Antarctic Ice Cores. 1997. *Journal of Geophysical Research* 102(D14): 16,761-16,771.

COAPS, 1998. http://www.coaps.fsu.edu/lib/elninolinks/. Florida State University, Tallahassee, FL, accessed on December 4, 2001.

Crowley, T. and K. Kim. 1999. Modeling the Temperature Response to Forced Climate Change over the Last Six Centuries. *Geophysical Research Letters* 26(13): 1901-1904.

D'Arrigo, R., and G. Jacoby. 1999. Northern North American Tree-Ring Evidence for Regional Temperature Changes after Major Volcanic Events. *Climatic Change* 41:1–15.

Delmas, R., S. Kirchner, J. Palais, and J. Petit. 1992. 1000 Years of Explosive Volcanism Recorded at the South Pole. *Tellus* 44B: 335-350.

Delwaide, A., L. Filion, and S. Payette. 1991. Spatiotemporal Distribution of Light Rings in Subarctic Black Spruce, Quebec. *Canadian Journal of Forestry Research* 21: 1828-1832.

Dunwiddle, P., and V. LaMarche. 1980. A Climatically Responsive Tree-ring Record from *Widdringtonia cedarbergensis*, Cape Province, South Africa. *Nature* 286:796–797.

Filion, L., S. Payette, L. Gauthier, and Y. Boutin. 1986. Light Rings in Subarctic Conifers as a Dendrochronological Tool. *Quaternary Research* 26:272–279.

Free, M. and A. Robock. 1999. Global Warming in the Context of the Little Ice Age. *Journal of Geophysical Research* 104(D16):19057-19070.

Fritts, H. 1969. Bristlecone Pine in the White Mountains of California: Growth and ring-width characteristics. *Papers Laboratory of Tree-Ring Research 4,* University of Arizona Press: Tucson.

Fritts, H. 1991. *Reconstructing Large Scale Climatic Patterns from Tree-Ring Data: a diagnostic analysis*. The University of Arizona Press, Tucson.

Genin, A., B. Lazar, and S. Brenner. 1995. Vertical Mixing and Coral Death in the Red Sea Following the Eruption of Mount Pinatubo. *Nature* 377(12):507-510.

Glerum, C., and J. Farrar. 1966. Frost Ring Formation in Stems of Some Coniferous Species. *Canadian Journal of Botany* 44:879–886.

Glock, W. 1951. Cambial Frost Injuries and Multiple Growth Layers at Lubbock, Texas. *Ecology* 32(1):28-36.

Glock, W. and E. Reed. 1940. Multiple growth layers in the annual increments of certain trees at Lubbock, Texas. *Science* 91: 98-99.

Graf, H., I. Kirchner, A. Robock, and I. Schult. 1993. Pinatubo Eruptions Winter Climate Effects: Model versus Observations. *Climate Dynamics* 9:81–93.

Graumlich, L. 1993. A 1000-year Record of Temperature and Precipitation in the Sierra Nevada. *Quaternary Research* 39: 249-255.

Grissino-Mayer, H.D. 1995. *Tree-ring Reconstructions of Climate and Fire History at El Malpais National Monument*, Arizona, Tucson, 407 pp.

Hall, C. 1991. *Natural History of the White-Inyo Range, Eastern California*. University of California Press, Berkeley.

Hammer, C., H. Clausen, and W. Dansgaard. 1980. Greenland Ice Sheet Evidence of Post-glacial Volcanism and Its Climatic Impact. *Nature* 288(20): 230-235.

Harlan, T. 2001. Personal communication and data. Consultant for Laboratory of Tree-Ring Research, University of Arizona, Tucson, AZ.

Harris, H. 1934. Frost Ring Formation in Some Winter – Injured Deciduous Trees and Shrubs. *American Journal of Botany* 21:485–495.

Hemenway, A. 1926. Late Frost Injury to Some Trees in Central Kentucky. *American Journal of Botany* 13:364–367.

Hirschboeck, K. 1980. A New Worldwide Chronology of Volcanic Eruptions. *Palaeogeography, Palaeoclimatology, Palaeoecology* 29:223-241.

Hirschboeck, K., F. Ni, M. Wood, and C. Woodhouse. 1996. Synoptic Dendroclimatology: Overview and outlook. In *Tree Rings, Environment and*

Humanity. (eds. J.S. Dean, D.M. Meko, and T.W. Swetnam). Radiocarbon 1996. Tucson: 205–223.

Jacoby, G. and R. D'Arrigo. 1989. Reconstructed Northern Hemisphere Annual Temperature since 1671 Based on High-Latitude Tree-Ring Data from North America. *Climatic Change* 14:39-59.

Jones, P., K. Briffa, and F. Schweingruber. 1995. Tree-ring Evidence of the Widespread Effects of Explosive Volcanic Eruptions. *Geophysical Research Letters* 22(11):1333–1336.

Lamb, H. 1970. *Climate: Present, Past, and Future. Vol. 1.* Methuen, London.1970.

LaMarche, V. 1970. Frost-Damage Rings in Subalpine Conifers and Their Application to Tree-Ring Dating Problems, In *Tree-ring analysis with special reference to Northwest America,* eds. J.H.G. Smith and J. Worrall, 7:99–100. The University of British Columbia Faculty of Forestry Bulletin.

LaMarche, V., and K. Hirschboeck. 1984. Frost Rings in Trees as Records of Major Volcanic Eruptions. *Nature* 307:121–126.

Langway, C., K. Osada, H. Clausen, C. Hammer, and H. Shoji. 1995. A 10-century Comparison of Prominent Bipolar Volcanic Events in Ice Cores. *Journal of Geophysical Research*. 100(D8): 16,241-16,247.

Lough, J., and H. Fritts. 1987. An Assessment of the Possible Effects of Volcanic Eruptions on North American Climate Using Tree-Ring Data, 1602 to 1900 A.D. *Climatic Change* 10:219–239.

Minnis, P., E. Harrison, L. Stowe, G. Gibson, F. Denn, D. Doelling, and W. Smith. 1993. Radiative Climate Forcing by the Mount Pinatubo Eruption. *Science* 259:1411–1415.

Mann, M., R. Bradley, and M. Hughes. 1998. Global-scale Temperature Patterns and Climate Forcing over the Past Six Centuries. *Nature* 392: 779 - 787.

NCDC, 2001. http://www.ngdc.noaa.gov/paleo/ei/ei_cover.html. DVI data available at ftp://eclogite.geo.umass.edu/pub/mann/WEBB/volcanic.dat, accessed on November 10, 2001.

Pollack, J., O. Toon, C. Sagan, A. Summers, B. Baldwin, and W. van Camp. 1976. Volcanic Explosions and Climatic Change: A Theoretical Assessment. *Journal of Geophysical Research* 81(6):1071–1083.

Porter, S. 1986. Pattern and Forcing of Northern Hemisphere Glacier Variations during the Last Millennium. *Quaternary Research* 26:27–48.

Rampino, M., and S. Self. 1982. Historic Eruptions of Tambora (1815), Krakatau (18883), and Agung (1963), Their Stratospheric Aerosols, and Climatic Impact. *Quaternary Research* 18:127–143.

Rhoads, A. 1923. The formation and Pathological Anatomy of Frost Rings in Conifers Injured by Late Frosts. *US Dept of Agriculture Bulletin* 1131:1-15.

Robock, A. 2000. Volcanic Eruptions and Climate. *Reviews of Geophysics* 38(2):191-219.

Robock, A., and J. Mao. 1995. The Volcanic Signal in Surface Temperature Observations. *Journal of Climate* 8:1086–1103.

Salzer, M. 2000. *Dendroclimatology in the San Francisco Peaks Region of Northern Arizona, USA*. Ph.D. dissertation. University of Arizona, pp. 211.

Schneider, S., and C. Mass. 1975. Volcanic Dust, Sunspots, and Temperature Trends. *Science* 190(4216):741–746.

Scuderi, L. 1990. Tree-Ring Evidence for Climatically Effective Volcanic Eruptions. *Quaternary Research* 34:67–85.

Scuderi, L. 1992. Climatically Effective Volcanism. *Quaternary Research* 37:130–135.

Scuderi, L. 1993. A 2000-year Tree Ring Record of Annual Temperatures in the Sierra Nevada Mountains. *Science* 259: 1433-1436.

Sear, C., P. Kelly, P. Jones, and C. Goodess. 1987. Global Surface – Temperature Responses to Major Volcanic Eruptions. *Nature* 330:365–367.

Self, S., M. Rampino, and J. Barbera. 1981. The Possible Effects of Large 19th and 20th Century Volcanic Eruptions on Zonal and Hemispheric Surface Temperatures. *Journal of Volcanology and Geothermal Research* 11:41–60.

Simkin, T. and L. Siebert. 1994. *Volcanoes of the World*, 2nd ed. Geoscience Press, Inc. Tucson, Arizona.

Stahle, D. 1990. *The Tree-Ring Record of False Spring in the Southcentral USA*. Ph.D. Dissertation, Arizona State University. 272 pp.

Stothers, R., and M. Rampino. 1983. Volcanic Eruptions in Mediterranean Before A.D. 630 from Written and Archeological Sources. *Journal of Geophysical Research.* 88(B8): 6357–6371.

Szeicz, J. 1996. White Spruce Light Rings in Northwestern Canada. *Arctic and Alpine Research* 28(2):184–189.

Wang, L., S. Payette, and Y. Begin. 2000. A Quantitative Definition of Light Rings in Black Spruce (*Picea mariana*) at the Arctic Treeline in Northern Quebec, Canada. *Arctic, Antarctic, and Alpine Research* 32(3): 324-330.

Wexler, H. 1956. Variations in Insolation, General Circulation and Climate. *Tellus.* 8:480-494.

Yamaguchi, S., L. Filion, and M. Savage. 1993. Relationship of Temperature and Light Ring Formation at Subarctic Treeline and Implications for Climate Reconstruction. *Quaternary Research* 39: 256-262.

Zielinski, G., P. Mayewski, L. Meeker, S. Whitlow, M. Twickler, M. Morrison, D. Meese, A. Gou, and R. Alley. 1994. Record of Volcanism since 7000 BC from the GISP2 Greenland Ice Core and Implications for the Volcano-Climate System. *Science* 264: 948-952.

Zielinski, G. 1995. Stratospheric Loading and Optical Depth Estimates of Explosive Volcanism over the Last 2100 Years Derived from the Greenland Ice Sheet. *Journal of Geophysical Research* 100(D10): 20,937-20,955.

Appendix 1
Complete List of Frost-ring Years by Site

Legend: # = number of sampled trees, % = is percent of sampled trees with frost or light ring in the given year, *= earlywood frost ring, FR= frost ring, LR= light ring, D= damage. Minus dates are not calendar dates (i.e. -42 is 43 BC).

Almagre Mt

AD	#	%	
1329	8	12.5	
1332	8	25	
1349	9	11.1	
1375*	11	9.1	
1388*	11	9.1	
1406	12	66.7	
1408	12	75	
1453	13	76.9	
1480	14	7.1	
1484	14	7.1	
1607	18	5.5	
1616*	20	5	
1619*	20	10	
1648	22	4.5	
1661*	23	4.3	
1663	23	8.7	
1683*	25	4	
1761	27	3.7	
1765	27	3.7	
1766	27	7.4	
1791*	27	3.7	
1805	28	60.7(64.3)	FR(LR)
1828	28	28.6	
1831	28	3.6	
1835	28	10.7	
1837	28	7.1	
1866	30	3.3	
1884	33	3	
1894*	33	3	
1912*	33	12.1	
1919*	33	9.1	
1928*	33	6.1	
1941	33	3	
1943*	33	3	
1957	33	3	
1965	33	9.1	

TOTAL: 36

Campito Mt

AD	#	%
1453	10	10
1601	12	58.3
1731*	13	7.7
1809	13	15.4
1884	13	38.5
1912	13	15.4
1978	13	15.4
1982	13	7.7

TOTAL = 8

Charleston Peak

AD	#	%
1158	8	12.5
1179	10	10
1331	22	14
1350	24	4
1351	24	4
1406	26	4
1423	27	4
1453	28	14
1454	28	7
1477	28	7
1480	28	3.5
1526	29	3
1527	29	3
1532	30	3
1553	31	3
1595	31	3
1601	31	6
1674	31	3
1692*	32	3
1710	32	3
1731*	33	12
1732	33	3
1745	33	12
1753	33	3
1756	33	6
1761	33	3
1781	33	6
1795	33	6
1810	33	3
1832	33	3
1837*	33	9
1863	33	3
1884	33	63
1897	33	3
1902	33	3
1904	33	3
1912	33	12
1914	33	3
1934*	33	12
1941	33	3
1947*	33	3

TOTAL = 41

Flower Lake

AD	#	%	
1099	3	33	
1238	6	D	
1494	16	D	
1527	16	D	
1557	16	D	
1601	17	64.7	
1605	18	D2	
1662	18	D	
1677	18	D	
1702	18	5.6	
1709	18	5.6	
1716	18	D	
1752	18	D	
1853	19	D	
1862	19	D	
1864*	19	10.5	
1913	19	5.3	LR
1965	19	5.3	LR

TOTAL = 18

Hermit Lake

AD	#	%	
1060*	2	50	
1136	4	25	
1139	4	25	
1157*	4	25	
1171	4	25	
1192	4	25	
1225	4	50	
1275	4	25	
1309	4	25	
1408	9	88.9	
1428*	12	8.3	
1453	12	75	
1456	12	8.3	
1484	12	8.3	
1486	12	8.3	
1488	12	8.3	
1556	19	31.6	
1572	20	5	
1587	20	5	
1599	20	5	
1601	20	20(25)	FR(LR)
1624	22	4.5	
1664*	25	4	
1676*	26	3.8	
1678*	26	3.8	
1711*	27	3.7	
1720*	28	3.6	
1725	28	28.6	
1761	29	55.2	
1785	30	3.3	
1805	28	57.1(64.3)	FR(LR)
1815	28	3.6	
1817	28	7.1	
1828	28	39.3	
1831	28	3.6	
1835	28	10.7	
1865*	30	3.3	
1902	31	3.2	
1919*	31	3.2	
1941	32	6.25	
1965	31	25.8	

TOTAL = 41

Hill 10842

AD	#	%
18*	1	100
639	14	7.1
1384*	32	3.1

TOTAL = 3

Mt Goliath

AD	#	%
1136	8	12.5
1225	6	16.7
1329	9	11.1
1373*	11	9.1
1378*	11	9.1
1384*	11	9.1
1399*	12	8.3
1406	13	7.7
1408	14	28.6
1453	16	25
1484	17	29.4
1490	17	29.4
1526	17	5.9
1536	20	5
1556	22	4.5
1567*	23	4.3
1619*	26	3.8
1641	27	3.7
1761	32	15.6
1790	32	3.1
1800	32	3.1
1805	32	18.75
1823	32	3.1
1828	32	28.1
1866	32	3.1
1878	32	6.25
1946	31	3.2

TOTAL = 27

Mt Jefferson

AD	#	%
1388*	4	25
1389*	4	25
1390*	4	25
1391*	4	25
1394*	4	25
1405*	4	25
1412*	4	25
1417*	4	25
1423*	4	25
1453	7	28.6
1455	7	14.3
1482*	11	9.1
1485*	11	36.4
1492*	11	27.3
1518*	12	41.7
1519*	12	8.3
1520*	12	8.3
1526*	14	7.1
1528*	14	7.1
1532*	14	7.1
1536*	15	6.7
1542*	15	6.7
1557*	17	5.9
1558*	17	5.9
1569*	17	5.9
1578*	17	11.8
1583*	17	5.9
1618*	17	5.9
1619*	17	11.8
1622*	17	5.9
1638*	19	5.3
1660*	19	5.3
1670*	20	5
1692*	22	4.5
1708*	22	4.5
1720*	22	4.5
1731*	23	8.7
1732	23	8.7
1745	23	4.3
1751*	24	4.2
1754	24	4.2
1801*	27	7.4
1829*	27	3.7
1832*	27	3.7
1843*	27	3.7
1870*	30	3.3
1872*	30	3.3
1884	30	20
1885*	30	3.3
1902	30	3.3
1947*	30	3.3
1948*	30	3.3
1954*	30	3.3
1969*	30	3.3
1971*	30	3.3
1979*	30	3.3

TOTAL = 56

Mt Washington

AD	#	%
44	1	100
502	1	100
582*	1	100
869	3	33
985	4	50
1076	6	16.7
1171	7	14.3
1200	8	37.5
1259	8	12.5
1280	8	12.5
1282	8	12.5
1331	10	20
1453	13	100
1457	13	7.7
1470	14	7.1
1485	16	6.25
1546	18	11.1
1557	18	11.1
1564	18	11.1
1577	18	27.8
1596	18	11.1
1601	18	66.7
1640	18	44.4
1680	19	21.1
1699	19	47.4
1702	19	15.8
1725	19	42.1
1732	19	68.4
1746	19	21.1
1761	19	10.5
1828	19	78.9
1837	19	10.5
1867	20	5
1878	20	5
1884	20	100
1890*	20	5
1902*	20	10
1906	20	15
1912	20	5
1923	20	5
1941	20	50
1965	20	75
1978	20	60
1982	20	20

TOTAL = 44

Pearl Peak

AD	#	%
226*	5	20
229	5	20
231	5	20
235*	5	20
252	5	20
259	5	20
279*	5	20
283	5	20
291*	5	20
309	5	20
311	5	20
314*	5	20
347*	7	14
356	7	14
360	7	14
374	7	14
371	7	14
400	8	12.5
401*	8	12.5
410	8	12.5
429	9	11
444	9	11
447	9	11
513	10	10
533	10	10
537	11	9
571	11	9
575	11	9
587	12	8
597	12	8
627	12	58
694	13	23
695	13	8
705*	12	8
817*	13	15
822	13	8
834	14	7
878	15	7
884	15	7
922	16	6
943	16	6
962	16	6
964	16	6
985	17	6
986	17	6
989	17	6
995	17	12
1003	17	59
1004	17	12
1005	17	6
1008	17	6
1029	17	12
1033	17	6
1064	18	5.5
1077	19	5
1120	20	5
1159	21	5
1174	21	5
1200	21	43
1207	21	5
1214	21	5
1218	21	5
1221	21	5
1225	22	27
1231	22	4.5
1245	22	4.5
1258	22	4.5
1274	22	4.5
1280	22	9
1309	23	4
1311	23	4
1325	23	4
1333	23	4
1334	23	4
1347	24	4
1348	24	4
1367	24	4
1373	24	4
1420	24	12.5
1425	24	8
1432	24	4
1436	24	4
1438	24	12.5
1440	24	4
1443	24	33
1446	24	4
1453	24	71
1454	24	4
1455	24	17
1456	24	8
1457	24	21
1459	24	8
1460	24	4
1463	24	4

1464	24	8	1711	28	3.5
1469	24	4	1720*	28	7
1470	24	21	1725	28	32
1481	24	8	1728*	28	4
1483	24	4	1732	28	18
1495	24	12.5	1735	28	7
1509	24	12.5	1737	28	3.5
1510	24	4	1743	28	3.5
1533	25	4	1745*	28	3.5
1546	25	4	1753	28	7
1553	25	4	1754	28	25
1557	25	84	1755	29	3
1562	25	4	1757	29	3
1565	25	4	1761	29	14
1582	25	4	1764	29	3
1583	25	4	1777	29	3
1588	25	4	1800*	29	3
1595	25	4	1801	29	3
1598	25	8	1805	29	28
1601*	25	40	1809	29	17
1602	25	8	1815*	29	7
1603	25	8	1820	29	3
1608	25	8	1827	29	3
1613	25	4	1828	29	14
1614	25	4	1829	29	3
1620	25	4	1831	29	3
1640	26	23	1832	29	10
1642	27	4	1835	29	7
1650	27	4	1837	30	10
1657	27	4	1854	30	3
1662	27	4	1858	30	7
1664	27	4	1862	30	3
1668	28	3.5	1867	30	3
1669	28	3.5	1872*	30	3
1671	28	3.5	1884	29	52
1676	28	11	1885	29	3
1678	28	3.5	1898	29	3
1680	28	7	1900*	29	3
1685	28	3.5	1902*	29	21
1690	28	3.5	1907	29	7
1697	28	3.5	1912	29	7
1698	28	3.5	1965	29	37
1699	28	7	1969*	29	7
1701	28	3.5	1970	29	3
1708*	28	14	1971	29	3
1709	28	7	1978	29	3

TOTAL = 186

Round Mt		
AD	**#**	**%**
1791	10	10
TOTAL = 1		

San Francisco Peaks	**#**	**%**
Minus	1	100
-508	5	20
-167	5	60
-42	7	14.3
-7		
AD	13	7.7
172*	12	8.3
259	12	8.3
268	13	7.7
322	13	7.7
337	14	14.3
389	17	17.6
393	17	11.8
411	17	5.9
413*	17	5.9
435*	16	18.75
443*	16	12.5
449*	15	6.7
469	15	13.3
479	15	40
484	14	7.1
497	13	7.7
522	13	46
536	13	15.4
541	14	92.9
627	20	5
674	19	57.9
681	18	27.8
687	19	5.3
688	19	5.3
691	19	5.3
694	21	4.8
736	21	4.8
739	23	4.3
796	27	3.7
858	31	3.2
877	36	5.6
889	38	2.6
896*	36	2.8
956	37	5.4
973	40	2.5
995	43	2.3
1006*	45	2.2
1016	45	2.2
1017	44	2.3
1049	44	2.3
1057	45	2.2
1074	45	24.4
1076	48	6.25
1092	50	10
1101	49	2
1105	48	16.7
1109	48	2.1
1116	48	2.1
1117	44	15.9
1171	44	2.3
1190	42	21.4
1200	38	2.6
1222	40	2.5
1229	38	2.6
1249	38	5.3
1262	40	2.5
1309*	40	2.5
1310*	41	2.4
1311	43	2.3
1312*	42	4.8
1329	44	2.3
1346	41	2.4
1356	41	2.4
1357	40	2.5
1358	41	2.4
1408	41	2.4
1409	39	2.6
1417	39	2.6
1422	41	2.4
1440	40	2.5
1452	40	55
1453	41	2.4
1472	42	4.8
1490	46	2.2
1544	46	2.2
1546	43	2.4
1565	42	2.4
1569	39	2.6
1595	38	2.6
1601	37	2.7
1615*	35	31.5
1640	39	2.6
1666	40	2.5
1674	40	2.5

1678	40	2.5
1679	40	15
1680	40	2.5
1684	40	2.5
1699	41	17.1
1702	42	2.4
1711	42	2.4
1718	42	2.4
1723*	42	2.4
1725	42	31
1732	42	2.4
1742	42	2.4
1744	43	16.3
1746	43	2.4
1747	44	13.6
1761	40	17.5
1810	43	18.6
1828	40	2.5
1835	39	2.6
1837	41	2.4
1842	41	2.4
1843	40	2.5
1858	40	2.5
1868	40	30
1882	40	65
1884	40	2.5
1906	40	2.5
1924	40	2.5
1931	40	2.5
1934*	40	2.5
1936	40	22.5
1941	40	75
1965	39	2.6
1982		

TOTAL = 122

Sheep Mt		
Minus	**#**	**%**
-1626	1	100
-1465	2	50
-1342	2	50
-1025	3	33
-1014	3	33
-764	4	25
-594	3	33
-512	2	50
-213	2	50
-205	2	50
-139	2	50
-60	3	33
-44	3	33
-42	3	100
AD		
119	5	20
162	6	16.7
198	7	28.6
226	7	14.3
230	8	12.5
232	8	25
360*	9	11.1
425	10	10
525	10	10
541	10	10
588	11	9.1
592*	11	9.1
608	11	9.1
627	12	75
652	12	8.3
672	13	7.7
687	13	30.8
717	13	7.7
883	15	6.7
893	15	6.7
910	15	6.7
911*	15	6.7
937	16	6.25
967*	16	6.25
985	16	6.25
986*	16	6.25
1003	17	17.6
1004*	17	5.9
1033*	17	5.9
1045	16	6.25
1056*	15	6.7
1057*	15	6.7
1076	15	6.7
1078*	15	6.7
1099	15	6.7
1200	15	53.3
1225*	15	6.7
1259*	15	6.7
1331	17	11.8

1332	17	5.9	1782*	32	15.6
1388*	18	5.6	1786	32	3.1
1453	20	50	1789	32	3.1
1454	20	5	1790*	32	3.1
1455	21	4.8	1798	43	2.4
1456	21	4.8	1799	44	2.2
1457	21	4.8	1805	57	5.3
1458	21	4.8	1809	57	8.8
1459	21	4.8	1829*	57	1.8
1460	21	4.8	1837	57	7
1461	21	4.8	1840	57	1.8
1462	21	4.8	1841*	57	1.8
1463	21	4.8	1857	59	1.7
1464	21	4.8	1859	59	1.7
1465	21	4.8	1861*	58	1.8
1470	21	4.8	1870*	58	3.4
1485	21	4.8	1875*	59	3.4
1522*	22	4.5	1884	59	64.4
1523*	22	4.5	1885	59	1.7
1555*	24	4.2	1895*	59	1.7
1573*	24	4.2	1897*	59	3.4
1577	24	8.3	1912	59	6.8
1578*	24	4.2	1923	60	1.7
1601	24	41.7	1924*	60	1.7
1627	24	4.2	1925	60	1.7
1640	24	8.3	1927*	60	1.7
1649	24	4.2	1928*	60	6.7
1654*	24	4.2	1932	63	1.6
1658	24	4.2	1934*	63	3.2
1659	24	4.2	1939*	63	4.8
1673	24	4.2	1941	63	4.8
1680	31	9.7	1947*	63	4.8
1684	31	3.2	1950*	63	4.8
1692*	31	16.1	1952	63	7.9
1693*	31	3.2	1954*	63	6.3
1697*	31	9.7	1955	63	3.2
1699	31	12.9	1964*	63	4.8
1702	31	3.2	1965	63	27
1720	32	3.1	1967	63	1.6
1725	32	15.6	1974	63	1.6
1731*	32	15.6	1978	63	9.5
1732	32	9.4	1979	63	1.6
1738	32	3.1	1980	63	1.6
1745*	32	12.5	1982	63	15.9
1756*	32	6.25	1987	46	6.5
1761	32	15.6	1992	20	10
1775*	32	3.1	1996	20	5

TOTAL = 147

Spruce Mt

AD	#	%
344*	1	100
627	4	100
869*	6	16.7
1003	7	14.3
1453	9	44.4
1457	9	11.1
1498	9	11.1
1520*	9	11.1
1577	10	10
1578	10	10
1601	13	15.4
1664	13	7.7
1696	13	7.7
1700*	13	7.7
1708*	13	15.4
1720*	13	7.7
1732*	13	7.7
1761	13	38.5
1779	13	7.7
1800*	14	7.1
1829	14	7.1
1902*	14	21.4
1939*	14	7.1
1965	14	7.1

TOTAL = 24

Timber Gap Upper

AD	#	%	
885*	2	50	
1099*	7	14.3	
1118	9	11.1	
1200	12	8.3	LR
1205*	12	D	
1216	13	8.3	
1249	13	8.3	
1260	16	D	
1315	16	D	
1333	16	6.25	LR
1334	16	6.25	LR
1337	16	6.25	
1352	16	6.25	LR
1353	16	6.25	
1367*	16	18.75	
1378	16	6.25	
1394	16	6.25	
1406*	16	6.25	
1422*	16	6.25	
1453	17	6.25(11.8)	FR(LR)
1467	17	D	
1488	17	5.9	
1534*	17	11.8	
1538	17	5.9	
1578	17	D	
1601	17	64.7	
1605	17	11.8	LR
1617	17	5.9	LR
1680	18	5.6	LR
1702	18	5.6	
1730	18	D	
1746	18	D	
1792	18	2D	
1815	17	D	
1827	17	D	
1884	17	5.9(+D)	
1901	17	D	
1934	17	5.9	LR
1982	17	5.9	

TOTAL = 39

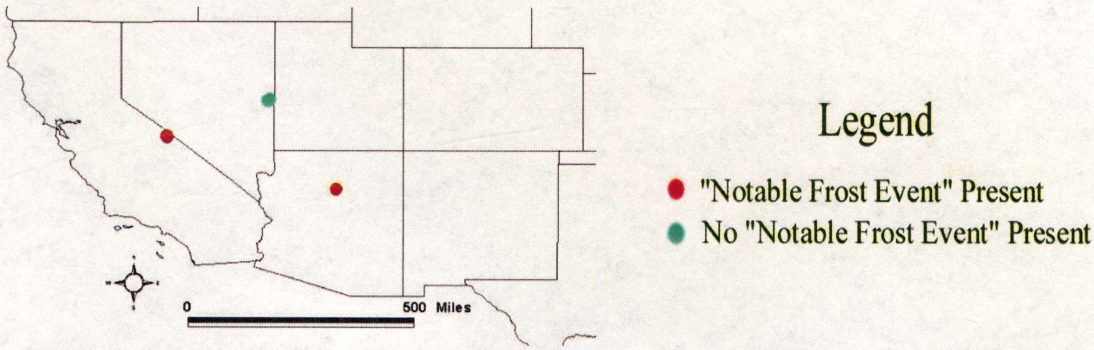
Windy Ridge

AD	#	%
797	1	100
1175	4	25
1200	4	50
1299*	6	16.7
1375	8	12.5
1428	14	7
1451	15	6.7
1453	15	26.7
1461*	15	6.7
1481	15	13.3
1484	15	26.7
1485	15	6.7
1486	15	6.7
1490	17	17.6
1511	17	5.9
1559	19	5.3
1601	23	37.8
1609	23	4.3
1611	23	4.3
1618*	23	4.3
1654	24	4.2
1699	24	16.7
1705	24	4.2
1724	24	4.2
1749	24	4.2
1761	24	20.8
1769	25	4
1792	25	4
1805	26	11.5
1828	26	19.2
1864	26	11.5
1878	26	3.8
1884	26	11.5
1895	25	4
1902*	27	14.8
1903*	27	3.7
1915*	27	3.7
1954	27	3.7
1982*	27	3.7

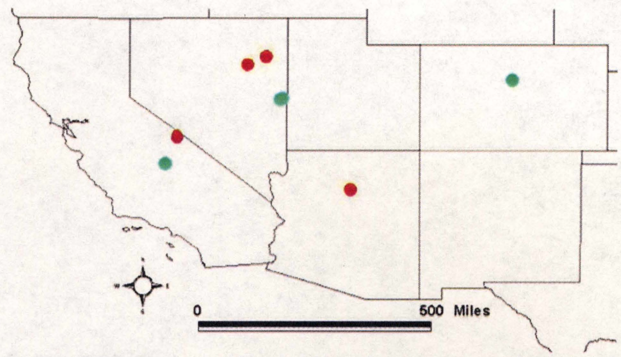
TOTAL = 39

Appendix 2
Notable Frost-Ring Maps by Year

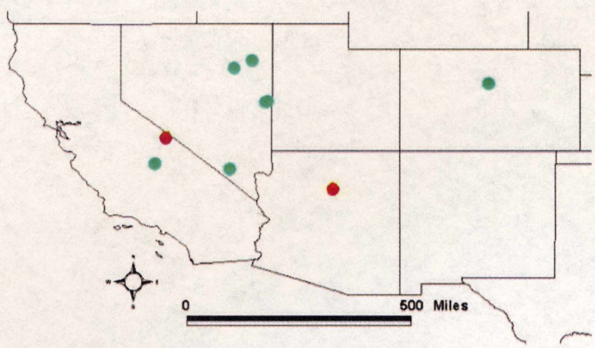
The following maps were created with an elementary GIS that contained two layers of geographic information and one database file. The base layer included six states and the other layer contained the site locations. The regional layer was acquired from the default data in ArcView, a GIS software package. The site location coverage was created by entering the site characteristics, including latitude and longitude into a database (Table 2). This database was imported into ArcView and converted into a map with the site locations determined by the latitude and longitude in the original database. The database file contained the notable frost-ring years as determined by frequency and the site where that frost event was found. The notable frost event table was first created as a database then input into the GIS as a table. This table was linked to the site coverage so that when queried by NFE year, the correct site location would be selected and shown in a darker color. The separate frost event table had to be created so that one query could be made that linked both the site location and the given notable frost-ring year. To query the databases, one uses a tool in ArcView called the 'query builder'. The 'query builder' allows the user to input phrases (i.e. [Year] = "1965") that will select records, or in this case, locations based on the input phrase (i.e. all locations with a NFE in 1965 will be selected). The GIS will eventually be archived on a server at LTRR.



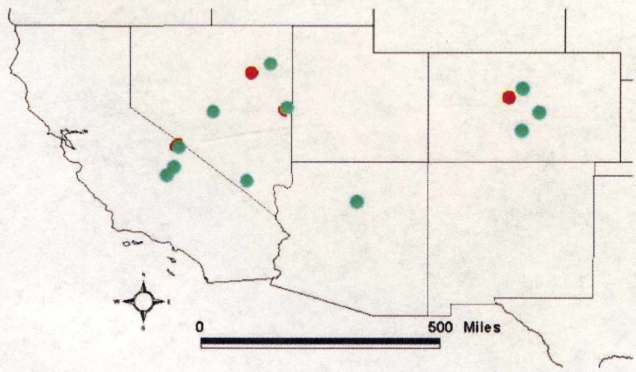
Notable frost event in 43 BC. Present in 2 of 4 sites. Associated with the 43 BC eruption of Etna, Italy (VEI=3?).



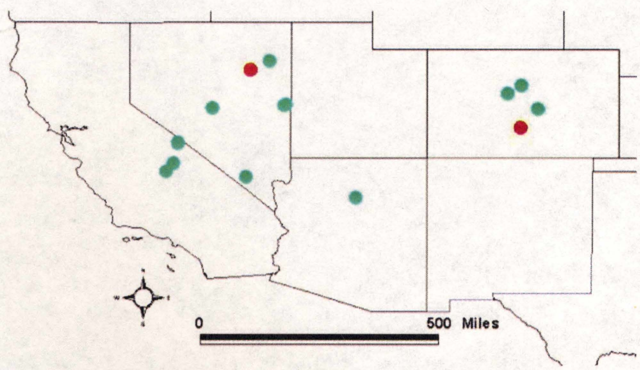
Notable frost event in AD 627. Present in 4 of 8 sites. Associated with the historical records of an eruption in AD 626 or 627 (Strothers and Rampino 1983).



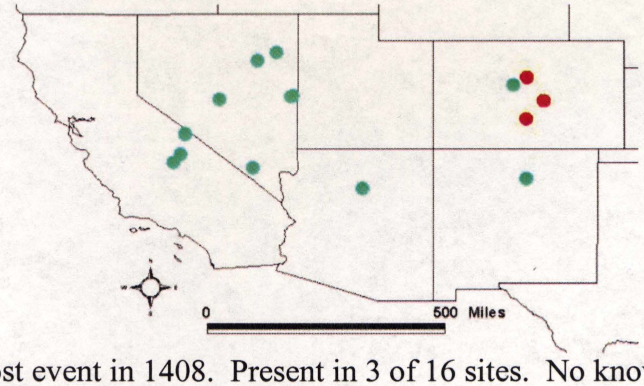
Notable frost event in 687. Present in 2 of 9 sites. Associated with an unknown eruption in 660+/- (VEI=4+).



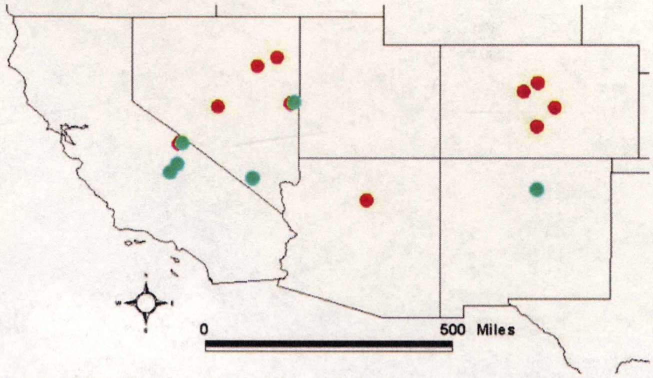
Notable frost event in 1200. Present in 4 of 15 sites. Associated with the 1200+/-50 eruption of Oshima, Japan (VEI=4).



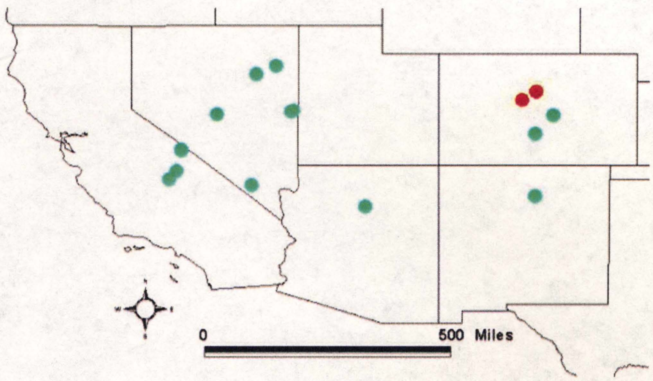
Notable frost event in 1225. Present in 2 of 15 sites. No known eruption.



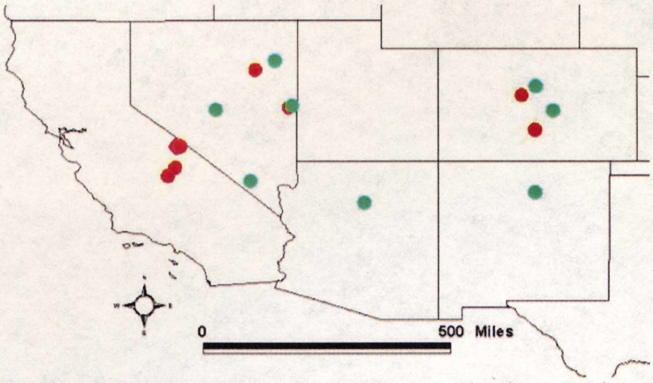
Notable frost event in 1408. Present in 3 of 16 sites. No known eruption.



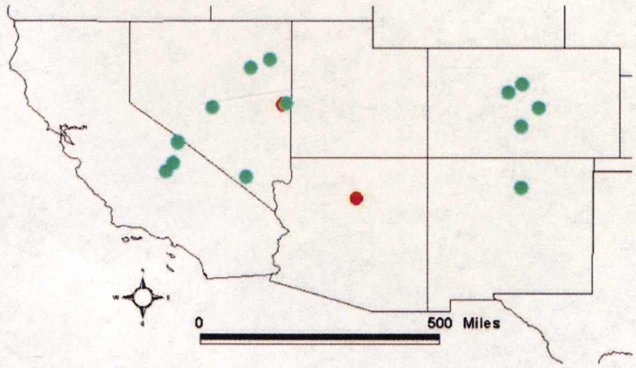
Notable frost event in 1453. Present in 10 of 16 sites. Associated with the 1451 eruption of Kelut, Java (VEI=3+) and 1453 eruption of Kuwae, South Pacific (VEI=6).



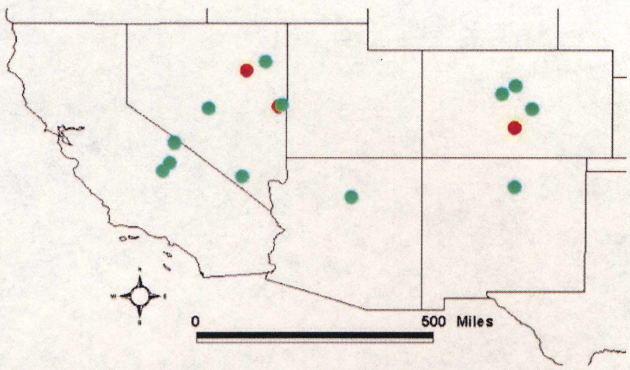
Notable frost event in 1484. Present in 2 of 16 sites. Associated with the 1481 eruption of Kelut, Java (VEI=4) and 1482 eruption of Mt. St. Helens, Washington (VEI=5).



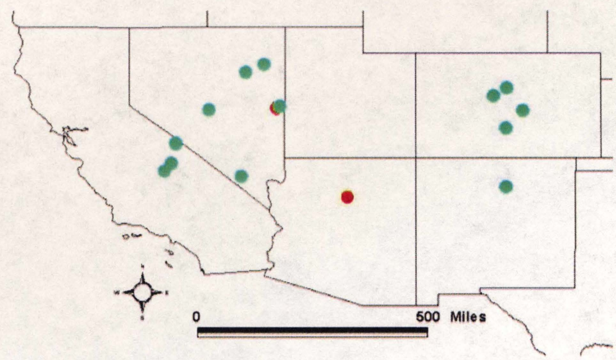
Notable frost event in 1601. Present in 8 of 16 sites. Associated with the 1600 eruption of Huaynaputina, Peru (VEI=6?).



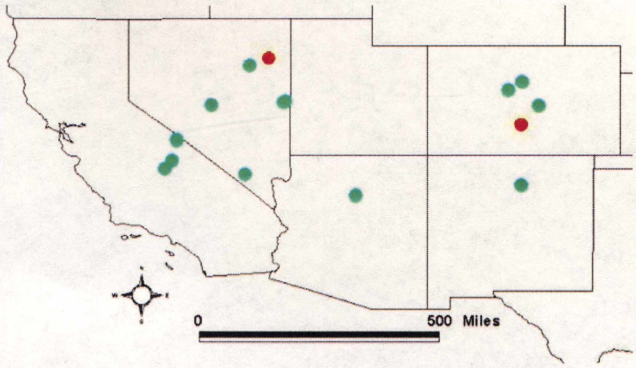
Notable frost event in 1640. Present in 2 of 16 sites. Associated with the 1640 eruption of Llaima, Chile (VEI=4) and 1640 eruption of Komaga-take, Japan (VEI=5).



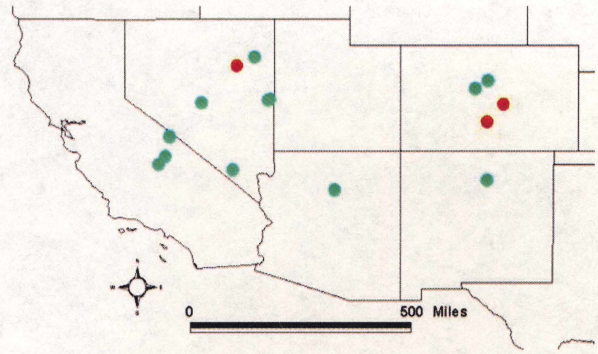
Notable frost event in 1725. Present in 3 of 16 sites. No known eruption.



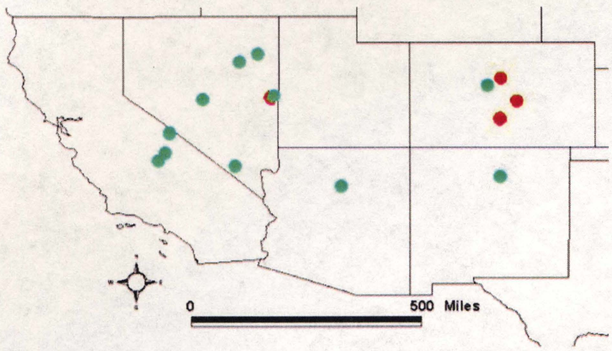
Notable frost event in 1732. Present in 2 of 16 sites. No known eruption.



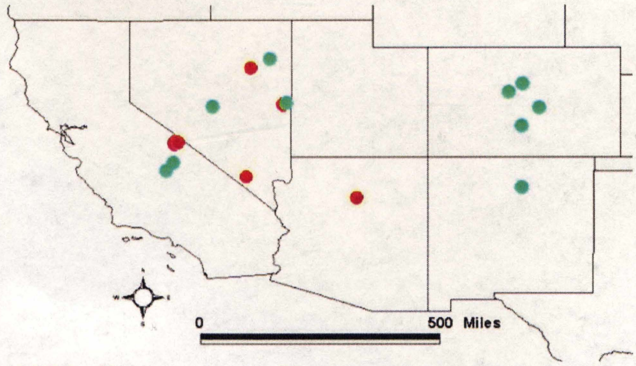
Notable frost event in 1761. Present in 2 of 16 sites. Associated with the 1759 eruption of Michoacan, Mexico (VEI=4).



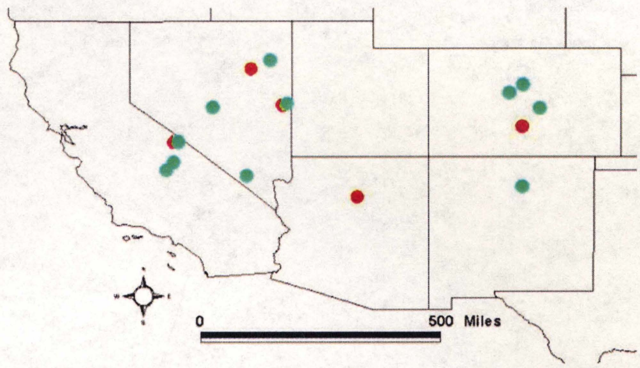
Notable frost event in 1805. Present in 3 of 16 sites. Associated with 4 eruptions with a VEI=3.



Notable frost event in 1828. Present in 4 of 16 sites. Associated with the 1828 eruption of Kelut, Java (VEI=4?).



Notable frost event in 1884. Present in 6 of 16 sites. Associated with the 1883 eruption of Krakatau, Indonesia (VEI=6).



Notable frost event in 1965. Present in 5 of 16 sites. Associated with the 1963 eruption of Agung, Indonesia (VEI=4).