HUMAN RESPONSE TO ENVIRONMENTAL HAZARDS: 
SUNSET CRATER AS A CASE STUDY

by

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ABSTRACT

Natural disasters and rapid environmental changes have resulted in a continuum of responses by human societies throughout history. A model is proposed that incorporates cultural and environmental aspects of human response to natural disasters. The 11th century eruption of Sunset Crater volcano in northern Arizona is used as a case study in which the archaeological record and dendrochronological and geomorphological evidence are combined to characterize the nature of the human response. The model predicts that the population at Sunset Crater would have been pressured to move, or to move and make cultural or technological adaptations following the eruption. The model has utility in diverse conditions and can be used to interpret archaeological remains and facilitate modern disaster response.
CHAPTER ONE: INTRODUCTION

Environmental hazards occur throughout history, and human groups respond to those events in varied and complex ways. The response of prehistoric populations to disaster or catastrophe often cannot be directly observed in the archaeological record because of destructive effects or because of the subtlety of human responses. It is possible, however, to infer likely population responses based on an understanding of the social organizational conditions and environmental pressures placed on a society by a disaster or catastrophe (Dean 1988). To do this, a model of predicted responses given specific environmental and social circumstances are proposed and tested. The model is developed using observed responses to modern disasters. Paleo-environmental and archaeological data relating to the 11th century eruption of Sunset Crater volcano provide a case study that is used to evaluate the efficacy of the model in interpreting prehistoric disaster response. Models of this kind are simplifications of reality designed to explore salient aspects of human-environment interaction and are not intended to replicate general or specific instances of such interaction, nor should they be construed as such. This simplification enables interpretation of diverse environmental hazards and their effect on human groups in archaeological contexts.

Sunset Crater, a cinder cone volcano in northern Arizona (Figure 1), erupted during the prehistoric occupation of the region by Ancestral Puebloans. Early geological and archaeological investigations of the volcano revealed that the eruption had a significant impact on local human populations (Colton 1932). Abandonment of the area around the volcano and occupation of previously vacant localities is the basic response
postulated by early researchers (Colton 1946). Further investigation of the nature of the
human response to this event is used as a case study for a proposed model of human
response to environmental hazards.

The Sunset Crater eruption provides an ideal example for studying human
interactions with the environment. A comprehensive model of human behavior in
response to environmental stress requires a detailed understanding of both social
organization and environmental phenomena. In northern Arizona, an abundance of
dendrochronological research and samples facilitates investigations of climatic variations
on an annual scale that can be used to evaluate the effect of environmental hazards (Dean
et al. 2006; Dean and Robinson 1977; Salzer 2000). Many well-preserved archaeological
contexts exist in the area that can be used to infer prehistoric social organization and
complexity (Anderson 1990; Bradley 1994; Downum 1988; Elson 2006b). Human
phenomena such as disaster response must be examined via multiple lenses, if the
complex interplay between environment, culture, technology, and ideology are to be
understood. This project represents a specific facet of a larger multidisciplinary endeavor
incorporating geology, archaeology, dendrochemistry, and dendrochronology (Dean et al.
2006; Elson and Ort 2003; Ort et al. 2002; Ort et al. 2008; Sheppard, May, Ort,
Anderson, Elson 2005). The focus is specifically anthropological, but the project
depends on and contributes to multiple domains of inquiry.

The work begins with a review of terminology used in disaster literature and
differentiates between hazards, disasters, and catastrophes. The characteristics of
environmental events and the societies they affect that move an event along the
continuum between hazard and catastrophe are explored. A model is then presented that uses hazard criteria and social criteria to suggest a range of pressures and their responses. Sunset Crater is then introduced as a case study in which to test the effectiveness of the proposed model. The predicted human response is evaluated in comparison with that found in the archaeological record. A discussion of the model’s efficacy and wider applicability concludes the thesis.

This thesis hopes to contribute to the ongoing dialogue between researchers in the environmental and social sciences. I build on a long tradition of archaeological research in northern Arizona, as well as some of the earliest work at the Laboratory of Tree-Ring Research, to construct a synthetic model of disaster response with wider implications. Modern academic and popular literature is replete with tales of the interplay of disasters and societies. It is my view that an integrated model of human disaster response can be applied to diverse archaeological problems, as well as to increasingly high-impact modern disasters.
Figure 1. Map of Arizona including Sunset Crater and the San Francisco Volcanic Field.
CHAPTER TWO: HUMAN RESPONSES TO NATURAL DISASTER

Researchers in anthropology, sociology and other fields have examined natural disasters in terms of how they impact human societies. This study incorporates some of these data and applies them to the analysis of the prehistoric eruption of Sunset Crater and its effects on the human population. Throughout, conventionally agreed upon terminology is employed, distinguishing hazards from disasters or catastrophes. The complicated characteristics of a hazard or a society that can affect the magnitude or severity of a hazard are discussed. Finally, dendrochronology is reviewed as a viable method for recognizing natural hazards in prehistory.

Definitions

The words “hazard”, “disaster”, and “catastrophe” are often used interchangeably in common language. For clarity, distinctions between these terms used in modern disaster research are followed here. Generally, any event with a potentially adverse effect on a human population can be a hazard, disaster, or catastrophe (Oliver-Smith 1996). The terms represent a range of severity, and the appropriate term depends on the nature of the event and its effect on humans (Smithers and Smit 1997). A natural hazard is an event that poses a threat to people, structures, and economic assets (Gaillard 2007). For example, migratory locust outbreaks have the potential to occur in areas dominated by agricultural fields resulting in crop damage and famine (Lima 2007), though they can also occur in uninhabited areas.
A hazard becomes a disaster when there are measurable human and economic costs associated with the event (Leroy 2006). The 1989 Loma Prieta earthquake in California is an example of a disaster with measurable human and economic costs that were not ruinous to the entire society (Tubbesing 1994). The damage caused by the 1980 eruption of Mount St. Helens in Washington is another example of a disaster (Foxworthy and Hill 1982).

A disaster becomes a catastrophe when a large percentage of the population is affected or killed or when the damage costs are extreme. The Johnstown floods of both 1889 and 1977 resulted in extensive damage to infrastructure and loss of life and are examples of catastrophic events (Spencer and Myer 2007). On a larger scale, in 1992, Hurricane Andrew caused between 35-40 billion dollars in damage to Florida and Louisiana (Wilson and Travers 1997:15) and damage to infrastructure was extreme. On a still wider scale, the tsunami of 2004 displaced 1.7 million people in areas adjacent to the Indian Ocean and was catastrophic on a regional scale (Rofi et al. 2006). Thus, the use of these different words is determined by the magnitude or severity of the hazard. The magnitude of a hazard is affected by several measurable event characteristics that interplay with societal differences resulting in unique experiences for human populations.

Factors Affecting Event Magnitude

The impact of an environmental disaster or catastrophe is determined by three main factors: timing, geographic extent, and social characteristics (Leroy 2006). The timing of an event can greatly affect how human populations are able to respond. Timing
includes the rate of onset as well as the duration of an event. The rate of onset of a natural hazard can affect the ability of a population to adapt to changing conditions (Troy et al. 2008). The slower the onset of the hazard, the more time a population has to adjust, adapt, or flee. Thus, a very rapid onset may result in a hazard becoming a disaster or catastrophe (Gaillard 2007). The duration of the event can also determine what kind of impact it will have on humans. A sudden, but short event could cause damage but be quickly adjusted to. A very long event, or one with enduring effects, may be classified as a catastrophe for a population that would have difficulty adapting to the new conditions.

The area of impact can also determine the severity of the event (Gaillard 2007). The larger the proportion of a resource procurement area (including fields, residential areas, and industrial infrastructure) that is affected, the more catastrophic an event is likely to be (Leroy 2006). This depends on both the magnitude of the event and the size of the community. A flood might be within the tolerance threshold of a society on the scale of the United States while the same flood would be catastrophic for a smaller, more geographically focused group like the prehistoric Hohokam (Graybill et al. 2006; Nials et al. 1986). In this way, the size of the population and the spatial extent of settlement or range can determine the classification of a natural hazard.

In addition to the measurable dimensions of the timing and area of impact of the natural hazard, characteristics of societal organization can either help or hinder the population’s adaptation to changed environmental conditions (Plunket and Uruñuela 2005). Institutions such as rigid hierarchies (e.g., local, state, and federal government bureaucracy) can make a community less flexible and thus less able to quickly adjust to
changing conditions (Oliver-Smith 1996). On the other hand, a rigid hierarchy could also provide critical leadership in a time of crisis (Passerini 2000). Likewise, religious or social restrictions, such as food prohibitions, can make a society less able to deal with the changed environment following a natural hazard, making it disastrous or catastrophic (Leroy 2006). A group with a low degree of complexity can quickly adapt and recover from an event, particularly when community leadership aids in recovery (Nolan 1979).

The factors that determine how a society is able to respond to an environmental disaster or catastrophe are further enumerated by Reycraft and Bawden (2000). These include resource distribution, amount of capital investment in resource exploitation, level of technological efficiency, type of economic system, prior experience with the event, population density, wealth, degree of sociopolitical complexity, and geographic extent of a given polity. Some of these factors may be difficult to discern in archaeological contexts, but others, including economic system, prior experience, density, complexity, and geographic extent are identifiable. In northern Arizona, comprehensive survey and excavation data can be used to determine economic system, density, sociopolitical complexity, and geographic extent (Anderson 1990; Bradley 1994; Downum 1988; Elson 2006b). Dendroclimatological evidence is used to determine prior experience (Salzer 2000).

The criteria listed above suggest that the impact and severity of a natural hazard are relative to the group that experiences it and that social responses are complex and varied. Therefore, when studying natural hazards in the prehistoric past, it is imperative that environmental data be coupled with information on the structure of the society and
the community that experienced them (Coombes and Barber 2005). In this way, natural hazards can be understood separately from the disasters or catastrophes they wreak on human populations as related, though distinct phenomena.

Recognizing Natural Hazards in Prehistory

Prehistoric environmental hazards can be recognized using a variety of methods. Climatic anomalies that affect human populations, including El Niño-Southern Oscillation (ENSO) and other long-term, wide-ranging temperature and precipitation trends, are recognized using coral records (Grattoli and Eakin 2007), speleothem records (Brook et al. 2006), zooarchaeology (Vrba 1995), pack rat middens and palynology (Latorre et al. 2006), and dendrochronology (Salzer and Kipfmueller 2005). These methods can identify long-term change and most provide a chronological signal. More rapid environmental hazards such as earth movements (landslides, earthquakes, etc.) or weather events (hurricanes, tsunamis) are investigated using geomorphology (Douglass et al. 2005), invertebrate taphonomy (Donato 2008), dendrochronology (Sheppard and Jacoby 1989), and other methods that emphasize smaller scale events or episodic events. Of all of these paleoenvironmental methods, a volcanic eruption is effectively studied using dendrochronology because of the discipline’s focus on both gradual and rapid environmental changes, the ability to date the eruption, and the presence of dendrochronological materials in archaeological contexts allowing investigation and dating of human response to volcanic disasters.
Dendrochronology, as developed by A.E. Douglass (1909), is the study of ring-width variation in trees for the purpose of dating events or reconstructing climate and other environmental features. Like all plants, trees depend on adequate precipitation and appropriate temperature for growth. Insufficient warmth or moisture results in reduced tree productivity and decreased growth, while favorable conditions result in increased growth. In many temperate locations, including the southwestern United States, trees experience a dormant season during which growth ceases. This annual cycle of growth and dormancy is evidenced in the yearly rings on the cross-section of a tree (Telewski and Lynch 1991). The width of each ring corresponds to the ability of the tree to put on new xylem in a given growing season, i.e., the availability of water and warmth. Therefore, some trees provide an annual proxy record for the climate in which they grow (Fritts 1976).

Because tree growth is annual, it is possible to correlate individual tree rings with specific calendar years (Douglass 1941). The unique pattern of wide and narrow rings that develops from poor and favorable conditions makes chronology-building beyond the age of a single tree possible. Ring-width variation occurs in a nonrepeating pattern that is shared by trees growing under the same conditions. Crossdating is thus possible between living trees, dead trees, fallen trees, and preserved ancient wood (Stokes and Smiley 1968).

As participants in an ecosystem, trees record other environmental data as well. Anything that positively or negatively affects the growth of a tree is potentially observable in ring-width variation. Numerous natural hazards that can affect humans can
also affect trees. Mass earth movements such as landslides or earthquakes have been studied using dendrochronology (Sheppard and Jacoby 1989; Stefanini 2004). Similarly, floods, tornados, and hurricanes have all been the focus of recent tree-ring research (Rodgers III et al. 2006; Sheppard, May, Ort, Anderson, and Elson 2005; St. George and Nielson 2003). Tree rings are well suited to the study of the cycles of both natural and human-affected fire regimes (Swetnam and Baisan 2003). Dendrochronology is an ideal tool for researching prehistoric natural hazards.

This study uses dendrochronology in two ways. First, tree rings are used chronologically to indicate the timing of events that took place around the eruption of Sunset Crater. This is possible through the preservation of wood in archaeological contexts. Architectural elements in the roofs of pre- and posterupton habitations contain wood with rings that span the eruption period. Based on tree-ring dates derived from these samples, it is possible to determine when settlements were established, occupied, and abandoned, giving clues to population dynamics before and after the eruption. This enables the study of disaster response.

Dendrochronology is also used in an environmental study of the effects of the volcanic eruption on the landscape inhabited by the people of northern Arizona. If the magnitude of a hazard depends on the nature of the event, it is important to fully understand that event when interpreting human response. The timing of the eruption of Sunset Crater is visible in tree rings because of the visible impact that eruption had on the environment where the trees were growing prior to their use in human constructions. The deposition of fine ash affected the chemical composition of the soils beneath trees
and may be reflected in the growth rings following the eruption year (Sheppard, Ort, Speakman, Anderson, and Elson 2005). Airborne ash and other particles may have damaged needles resulting in reduced ring growth. Widespread fires sparked by the eruption may also be visible in preserved trees. Dendrochronological evidence of any of these environmental impacts could be absolutely dated, providing evidence of the beginning of the eruption, the rate of onset of environmental disturbances, and the duration of their effects.
CHAPTER THREE: MODELING HUMAN RESPONSE

It is possible to combine archaeological and paleoenvironmental evidence to understand the response of human populations to the eruption of Sunset Crater. Previous research suggests that human responses to natural disasters vary by both the characteristics of the disaster event and the characteristics of the society responding to that event (Gaillard 2007; Nolan and Nolan 1993; Ort et al. 2008). In order to aid in the interpretation of prehistoric disaster response, I have created a model based on specific kinds of event criteria and societal criteria (Table 1), both of which are visible in the archaeological and dendrochronological record. The model then uses modern analogies to suggest kinds of responses by human groups to natural disasters. The goal of this model is to identify the social and environmental pressures that were placed on human groups in the wake of the Sunset Crater volcanic eruption and to understand the human adaptive response to these effects. Though it is a simplification of reality, the model is not meant to limit the possibilities that were available to prehistoric groups or to simplify their behaviors. Rather, it is a tool meant to aid interpretation of the archaeological record.

The model is used to assess a specific prehistoric event, but it can also be applied to modern environmental hazards affecting modern populations. In conjunction with the greater goals of anthropology, this project seeks to understand past human behavior so that it may be instructive in the present. Although differences in technology exist between past and modern societies, understanding how the prehistoric population reacted to the eruption of Sunset Crater may still be useful in predicting the response of
populations to similar hazards in the future. This could enable greater preparation, possibly reducing the severity of hazards and aiding in the recovery of affected societies.

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<td>Population Density</td>
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<td>Duration of effects</td>
<td>Prior experience with hazard</td>
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<td>Geographic extent of effects</td>
<td>Sociopolitical complexity</td>
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Table 1. Conditions used in construction of the model of human response to environmental hazard (see Reycraft and Bawden 2000:1-4).

Hazard Criteria

A model that seeks to interpret human response to disasters must take into account those aspects of a hazard that most affect human behavior. These are timing considerations and geographic extent of hazard conditions. Three categories are used to classify disaster conditions: rate of onset of disaster conditions, duration of disaster conditions, and geographic extent of disaster effects (see also Reycraft and Bawden 2000:1-2). Each of these is examined using dendrochronological and geomorphological methods.
Tree rings are capable of recording the timing of an event and the geographic extent of influence of an event. Tree-ring data can distinguish a disaster with a sudden onset (volcanos) from one with a gradual onset (climate change). Onset of an event is determined in two ways. The initial occurrence of affected rings marks the first year of hazard impact. If the same ring in all trees shows impact simultaneously, the event can be said to have come about all in one season. If only some trees show a response followed by more trees in subsequent years, the event can be characterized as gradual. Identifying the source of disturbance in tree rings is another means of determining rate of onset. According to the law of uniformitarianism (Lyell 1889), an identified event in prehistoric trees can be assumed to have had the same onset as in modern observed instances of that event. For example, a tornado identified in ancient wood can be assumed to have occurred as rapidly as a tornado today.

The duration of an event can be estimated by the number of rings/years showing effects. For example, a drought can be said to have lasted many years if many successive rings show evidence of low precipitation (Adams and Kolb 2005). Additionally, the geographic extent of an event can be determined through comprehensive sampling of living trees or of archaeological wood of known provenance. For example, the frequency and extent of past spruce beetle outbreaks in the Rocky Mountains in Colorado have been recognized by extensively sampling both living and dead trees (Veblen et al. 1991). Therefore, dendrochronology has great utility in characterizing the nature of certain types of environmental hazard.
Social Criteria

A disaster is of interest archaeologically when it is known how it affected human populations. Here we find an ideal arena for cooperation between dendrochronology and archaeology. The archaeological record may not reveal explicit information on environmental hazards, but it can be informative as to the vulnerability of a given population to disaster or catastrophe. Vulnerability can be defined as the characteristics of a group that affect its ability to anticipate, contend with, and recover from a disaster (Blaikie et al. 1994:9) as well as the ability or inability to adapt to any external stress placed on livelihood and well-being (Kelly and Adger 2000:328). Many of the conditions determining the vulnerability of a population detailed above are not readily visible archaeologically. For this reason, they have been condensed to three main criteria; the density of population, the level of previous experience with a given kind of hazard, and the degree of sociopolitical complexity (see also Reycraft and Bawden 2000:1-2). These compressed criteria enable greater comparability between contexts while maintaining the integrity of the model, which is a purposeful simplification of reality designed to highlight critical variables.

The density of a given population can be viewed as the degree of aggregation or dispersion. Archaeologically, this information is gathered largely from site settlement patterns and architecture (Gilman 1987). Prior experience with a hazard refers not only to a specific event (i.e., volcano) but also to other hazards that might have prepared a population’s response. Disasters and catastrophes are visible archaeologically as abandonment episodes or changes in subsistence strategy coupled with
paleoenvironmental data suggesting environmental stress or stress due to sociocultural factors.

Judging the degree of sociopolitical complexity of an archaeological culture can be difficult, largely because of the ambiguity of the term “complex.” Used here, it refers to a social or political system consisting of many independent and interactive parts that also interact with the environment (Lekson et al. 1994:16). The degree of complexity can be measured by the presence of diverse or hierarchical religious, political, and physical infrastructure (architecture/site type/site size). Though difficult to identify directly in the archaeological record, sociopolitical complexity, as defined here, is expressed as diversity of artifact assemblages and architecture that can indicate hierarchical or diverse community organization (Bayman 2001:269). Specific room types and arrangements can be evidence of ritual participation that may indicate regional interaction (Adams 1983). Exotic goods procured from distant sources can indicate access to extensive trade networks and be further evidence of interactive parts of a social or political system (Janetski 2002; Mauss 1990). Each of these three variables, (population density, prior experience, and complexity), can both positively and negatively affect the vulnerability of a population to an environmental disaster or catastrophe.

Evaluation of Criteria

For the purpose of simplicity, population density is evaluated as endpoints of either aggregated or dispersed, though it is understood that the archaeological record reveals a continuum between these poles. An aggregated population can be better
prepared to withstand environmental stress because there may be access to shared resources (Rautman 1993). Large coresident settlements are also more defensible against invading groups (LeBlanc 1999:56-63). In the wake of a natural disaster, social unrest and violence can occur (Blong 1984:159-162) and an aggregated population is in a better position to protect resources from raiding and looting. After a disaster, a dense population also has the benefit of shared labor for reconstruction activities (Kohler and Sebastian 1996).

However, it is not entirely beneficial to live in an aggregated settlement in times of stress. While food sharing can occur, a dense population places greater pressure on remaining wild resources (Kelly 1995:220). Also, aggregated societies can be more susceptible to disease, which can exacerbate stresses brought on by disaster. An aggregated population is highly inter-reliant. This dependence on the group results in reduced mobility for individuals (Cameron 1995). Reduced mobility is a hindrance to evacuation and may make the population more likely to remain in place during disaster.

A dispersed population has its own advantages and disadvantages. A major benefit of a dispersed settlement pattern is the possibility that an environmental hazard could affect only a portion of the group. A low density population places less stress on wild resources and so may be able to rely on those when crops are damaged or destroyed. Also, when a population is widely dispersed, decision-making is less centralized and is based at the household level (Waggoner 1992). For example, in modern volcanic disasters, it has been found that populations typically evacuate damaged areas as family
units (Blong 1984:149; Landry et al. 2007). If evacuation becomes necessary, a dispersed population may be capable of migration in a more efficient manner.

Conversely, a low-density population has less support for recovery efforts in rebuilding habitations and rehabilitating fields. They are also more vulnerable to crop failure without communal stored surplus (Anderson et al. 1995). Dispersed populations are also not as defensible against raiding groups who might take advantage of the disaster.

The vulnerability of a population to environmental hazards is also affected by the frequency of the event (Clark 1985) and thus the level of the population’s experience with hazard conditions. Human groups have little prior experience with low-frequency processes and are more familiar with high-frequency processes (Dean et al. 1985). Prior experience with a hazard can have positive and negative consequences. If a group has experienced similar stress in the past, it is more likely to know when and how to react (Gillespie and Streeter 1987). Prior experience may have inspired an evacuation or contingency plan. Similarly, if hazard conditions are frequent, religious or political institutions may be in place to aid the population in coping with changed conditions.

A disadvantage of prior experience may be the under- or overreaction to an event based on the nature of previous occurrences. The population may react excessively to a hazard that is not as damaging as expected or underprepare for a large catastrophe because previous experience was with smaller events. One major disadvantage of having no prior experience with a hazard is that infrequent events are often perceived to have
low risks (Greene et al. 1981:53). This could leave a population unprepared for potential disasters or catastrophes.

The third determinant of a population’s vulnerability is sociopolitical complexity. Complexity is closely related to population density (Wills and Windes 1989) and so can have some of the same effects on disaster responsiveness. A society with low complexity may retain organizational flexibility that allows it to adapt more easily to changed conditions (Perry and Lindell 2003; Smithers and Smit 1997).

However, a less complex society might have less technology available to aid in adaptation or response to environmental stress. This kind of group might also be expected to have less contact with distant groups, those outside the zone of destruction, to go to for food or housing.

A population with high sociopolitical complexity, on the other hand, may have institutions of authority in place to organize groups of people for the purpose of evacuation or reconstruction. They may have distant trade or ceremonial partners with whom they can find food, shelter, and protection, if evacuation and migration become necessary. A complex society may also have a ritual infrastructure in place to facilitate cultural recovery and maintain social cohesion.

Sociopolitical complexity could be a disadvantage. Communities with strict hierarchies can have disorganized responses because of multiple levels of decision-making (Leroy 2006; Tobey 1992). Also, in historic disasters, those people with wealth that depends on the community are reluctant to evacuate (Nolan 1979), putting them at greater risk of death or injury. Finally, political or religious prohibitions that can
accompany complex social systems can result in inefficient responses to changed environmental conditions (Kelly and Adger 2000; Leroy 2006; Oliver-Smith 1996).

Responses

A population’s responsiveness to an environmental hazard can be influenced by many factors, but those that are most visible archaeologically have the greatest utility in studying responses to prehistoric events. Likewise, a dendrochronological investigation is best suited to characterize aspects of an environmental hazard that are recorded by trees. Therefore, in developing a model of human responses to natural disasters, density of the settlement, level of prior experience with similar events, and relative sociopolitical complexity are used as criteria to evaluate the vulnerability of the population. Timing of onset, duration, and extent of a hazard as recorded in tree rings are used to characterize environmental hazard. If the vulnerability of the population and the nature of the environmental hazard are understood, the most likely response can be predicted by evaluating the pressures placed on that population.

At a basic level, there are only two responses available to a population faced with environmental stress. They can choose to remain in the original location or move away from it. This dichotomy is a vast oversimplification of actual human behavior (Dillehay and Kolata 2004), but to be functional, a model must maintain generality that makes it applicable to diverse conditions and circumstances. In this case, two more responses are considered. In addition to the options to stay or leave, a population can choose to adapt
to changed conditions and stay or depart and adapt to the environmental or social conditions of a different locality. These four general responses are used in the model.

Migration

A migration is a long-term residential relocation beyond community boundaries by one or more discrete social units as the result of a perceived decrease in benefits of remaining residentially stable or a perceived increase in benefits of relocating to prospective destinations (Clark 2001:2). Human migrations have occurred on many scales and for many different reasons. For the purpose of examining the ways in which migration can be used as a response to environmental disaster, migration theory is summarized in three parts. First, the causes of migration are reviewed. Second, the nature of migration and the migration end points are evaluated based on examples from Southwest archaeology. Finally, the integration of immigrants into the destination location is addressed with special attention placed on aggregated populations.

Migration in prehistory has been alternately a popular focus of archaeology and a passé theory receiving little attention (Cameron 1995). Because of its long history of varying popularity, migration has been addressed from a variety of theoretical perspectives (Childe 1950; Haury 1958; Mills 1998; Reid 1989). The result is a more comprehensive understanding of its causes and functions. According to resilience theory, borrowed from ecology, migration/abandonment is a part of a repeated cycle of growth, release, reorganization, and conservation (Gunderson and Holling 2002). Each of these phases is seen as variation in the diversity of social and ecological units and functions.
migration is a part of the reorganization phase that can take place at any level of a society from the household to the entire community. From another perspective, migration can occur during the regular cycles of mobility in a seasonally mobile population (Nelson and Schachner 2002). This kind of short-term, short-distance migration is not relevant to disaster responsiveness except in that it emphasizes the mobility and flexibility of some populations. The kind of migration of interest here is that which proceeds from an unique or sudden event, such as environmental disaster or catastrophe.

Population relocation can be a response to environmental changes or stresses (Reid et al. 1996). These changes are most disruptive when they occur with low frequency (Dean et al. 1985). Unlike high-frequency events such as forest fires or ten-year floods, which can be anticipated and for which responses can be planned, low-frequency events are typically unexpected. This can result in an inability to adjust to changed conditions that force the population to relocate (Lekson and Cameron 1995). Panicked evacuations are historically rare (Blong 1984:151), and it seems more likely that prehistoric abandonments and migrations were processes rather than abrupt events (Oliver-Smith 1996; Schiffer 1987:89) that took place with varying degrees of organization. Abandonment of one area and migration into another requires consideration of the negative effects of remaining in a given location (push factors) and the positive effects of relocating to a given location (pull factors) (Dorigo and Tobler 1983). In an environmental disaster, push factors might include destruction of homes or livelihood,
inability to obtain resources, or hazardous conditions. Pull factors might include safety, available food and water, or kin with whom to reside.

Southwestern population dislocations are best described in terms of scale and destination. Movements can be divided into short-distance and long-distance (Anthony 1990). A short-distance migration is one that occurs within a sphere of social groups with habitual interaction and is considered small in scale. Change of residence after marriage is an example of this kind of migration (Cameron 1995). A long-distance migration is one that crosses an ecological or cultural boundary and takes place on a larger scale. The movement of Athapaskans into the Southwest is an example of long-distance migration (Iverson 2002). These migrations typically involve a larger number of individuals and may include social units from the family to the entire community (Anthony 1990).

Long-distance migration may take place over predetermined routes constructed between distant kin groups or trade partners (Cameron 1995). Migration can also take place in a less stream-like manner in which groups move and settle along a trajectory leading to a final destination. Long-distance migrations can take place in the opposite direction as well, returning to the source location. Intercommunity and regional movement dynamics are determined by ethnic identity, long-term social interactions, and short-term social contacts (such as violence or warfare) (Cameron 1995). A degree of mobility is assumed for prehistoric populations as they interact with and respond to environmental and social conditions. This kind of movement may prove subtle archaeologically (Stark et al. 1995). Fortunately, large-scale, long-distance movements
such as might be expected in response to major environmental change (i.e., volcanic eruptions) are visible and are not without precedent in the Southwest.

Migration is visible archaeologically in two ways. First, a depopulation or abandonment episode is evident at the source location for a migrating population. Second, an immigrant population is recognized by an increase in local population, a complex of traits intrusive into or incongruent with traits commonly found in the location, or both. The second source provides information on the relationship of a migrant community with a destination location. Intrusive traits can include ceramic style, architectural style, food preferences, or mode of burial (Clark 2001; Cordell 1995; Elson et al. 1995). Because integration often takes place between migrant and native groups, evidence of migrating populations is most visible archaeologically when the group is newly arrived (Stark et al. 1995). Integration can occur through cultural or religious mechanisms. For example, the Katsina religion may have provided a motivation for groups to aggregate in order to participate in shared rituals (Adams 1991). Likewise, ballcourts and other features may be architectural indicators of ritually integrative behavior (Wilcox and Sternberg 1983). Very rarely, an immigrant group is seen to persist over several generations in the archaeological record, retaining a suite of traits from the source locations (Haury 1958). More often, traits are mixed. Modern pueblos are probably combinations of diverse prehistoric groups (Cordell 1995) and a direct historical investigation of migration is impossible.

The type of movement postulated in this model is one in which the population is faced with environmental stress and feels pressure to leave the affected area. The model
does not predict the manner of the evacuation nor the destination location; it merely reflects the decision to move. Archaeological interpretation of specific hazard conditions will determine whether and how migration takes place. The response option, “Move,” in the model means that a group will move out of the affected area and will retain most or all cultural traits in the destination area. The presence of a natural disaster does not dictate that the population must leave. This model acknowledges the option to “stay” in the affected area and maintain original social and technological patterns and not take part in any of the activities detailed above. The choice to move or stay represents the first two response options in the model.

Adaptation

To accommodate a wider range of human behavior into the model, adaptation is also considered as a response option. In addition to pressures to migrate out of or remain in hazard-affected areas, the population may also be pressured to adapt to changed environmental or social conditions. When the environment is altered such that prior methods of subsistence or resource procurement are no longer viable, adaptation may be made that allows habitation or utilization of the affected area to continue (Dean 2006). This may include the development of new technologies and methods or the incorporation of existing methods into new situations.

An example of technological and subsistence adaptation in response to changed conditions is the adoption of the deer skin trade by the protohistoric Creek in the southeastern United States (Knight 1994). European colonists in the Southeast
constricted traditional hunting territories thereby stressing the resource procurement abilities of the indigenous peoples. European infectious diseases decimated prehistoric populations (Reff 1990). No longer able to subsist using traditional methods, the Creek faced pressure to leave the region, fight the Europeans, or adapt to changed conditions. The deer skin trade provided a means of remaining in traditional territories by allowing survival through trade with Europeans for food resources and raw materials (Pavao-Zuckerman 2007).

Social reorganization is another means of adapting to changed environmental or social conditions brought about by a natural hazard. Ancestral Puebloan response to the Great Drought (Dean and Robinson 1977) and other environmental hazards at the end of the 13th century is an example of both migration and adaptation following environmental disaster. Environmental deterioration spurred regional abandonment and migration into other areas. Centralization and aggregation of populations appear to be prevalent throughout the region (Cordell 1997) and are centered on the Hopi mesas, Zuni, Acoma, Laguna, and the Rio Grande Valley (Adams and Duff 2004). The social structure of these communities likely underwent changes in order to accommodate a new density of habitation and new kinds of resource distributions. The appearance of the Katsina religion after AD 1300 may be evidence of social adaptation (Adams 1991:185). It attracted people to the population centers, and it also was a source of cohesion for the multiethnic communities that the largest pueblos had become.

The model incorporates both technological and social changes into the term “adaptations” in recognition that these processes rarely occur entirely independently of
one another. The response option, “move with adaptations,” reflects a scenario in which a population moves away from the affected area and also adopts new traits in the form of settlement pattern, material culture, technology, or ritual behavior. These adaptations are the result of changed environmental or social conditions. The fourth response option for a population faced with environmental stress is to “stay with adaptations.” This option reflects the choice to remain in the affected area, and adapt to changed social or environmental conditions resulting from the disaster.

Model Construction

This model is intended as an organizational device that can aid in understanding the complex pressures placed on a population during environmental disasters. It is not an exhaustive review of all the ways a population can act, nor does it mandate that a population must respond in a predictable manner. Each response option reflects the decision of surviving members of a population and does not take into account disaster mortality. For the sake of simplicity, only initial responses are included and return migration is not given as a possible option.

In constructing the model, it was determined which of the responses was most likely for each of the social criteria (population density, prior experience, sociopolitical complexity) and each disaster criterion (onset, duration, extent). These responses were based on modern disaster theory and archaeological interpretations of prehistoric environmental disasters detailed above. The determinations are as follows:
Social Criteria:

**Aggregated Population**: Likely to stay or stay with adaptations. Higher density populations are better able to withstand brief food shortages and other stresses because of shared resources. A large labor force for reconstruction makes staying a workable option.

**Dispersed Population**: Might either migrate or stay depending on the severity of the event, but would be unlikely to adopt significant adaptations because of already flexible mobility.

**No Prior Experience**: Would mean that a population would most likely migrate because of lack of preparation enabling them to stay and adapt.

**Prior Experience**: A population with prior experience might have means of adapting in the face of stress and so would stay with adaptations or migrate, depending on the severity of the disaster.

**Low Complexity**: A population with little social, political, or physical hierarchical infrastructure has a variety of response options. Increased flexibility and decreased dependence on specific resources might enable them to stay and adapt or migrate and adapt. It might also be possible for a population with low complexity to withstand environmental stress without migration or adaptation.

**High Complexity**: A highly complex population has a sociopolitical infrastructure in place that, due to its nested or hierarchical nature, is more likely to be preserved or maintained during periods of environmental stress. Disaster severity would determine whether a highly complex society would migrate or stay.
**Disaster or Catastrophe Criteria:**

Disaster criteria do not take into account social characteristics and so adaptation is not included as a response. The response given for each criterion represents the dominant pressure that would be placed on a population undergoing a disaster with that characteristic.

- **Rapid Onset** - Little time to adjust, would result in pressure to move.
- **Slow Onset** - Population likely to stay.
- **Long Duration** - A long event indicates lasting effects of the disaster, pressuring the population to move.
- **Short Duration** - Disaster effects are brief and the population probably would stay.
- **Widespread Extent** - The disaster is severe and affects the majority of the settlement area, pressuring the population to move.
- **Limited Extent** - The disaster affects a smaller area and the population is likely to stay in the affected area.

Each possible combination of social and hazard criteria is given in the model, though some scenarios are highly unlikely in reality. In each combination, the responses for each criterion are noted and the most commonly appearing response is listed in the table. This response represents the greatest pressure placed on a population with a given combination of social characteristics. When more than one response is dominant, both are listed. In some cases, all four criteria ranked equally, indicating a situation in which a
simple model cannot be used to describe human behavior. Archaeological and dendrochronological evidence provides insight into how the population in fact responded. These situations are particularly interesting as they represent instances in which the population is faced with equal pressures and the ultimate response to disaster may stem from other factors. Table 2 displays the predicted response for each combination of social vulnerability and hazard severity. The boxes outlined in red represent the predicted response for the case study, Sunset Crater.
Table 2. A model for human response to environmental hazard. Outlined boxes indicate projected responses to Sunset Crater eruption event.

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Population Density, Degree of Prior Experience, Sociopolitical Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aggregated, prior experience, low complexity</td>
</tr>
<tr>
<td>Rapid Onset, Long Duration, widespread</td>
<td>Move, Move with Adaptations</td>
</tr>
<tr>
<td>Rapid Onset, Short Duration, Widespread</td>
<td>Stay with Adaptations</td>
</tr>
<tr>
<td>Rapid Onset, Short Duration, Limited Extent</td>
<td>Stay, Stay with Adaptations</td>
</tr>
<tr>
<td>Slow Onset, Long Duration, Widespread</td>
<td>Move, stay with Adaptations</td>
</tr>
<tr>
<td>Slow Onset, Long Duration, Limited Extent</td>
<td>Stay, Stay with Adaptations</td>
</tr>
<tr>
<td>Slow Onset, Short Duration, Widespread</td>
<td>Stay, Stay with Adaptations</td>
</tr>
<tr>
<td>Slow Onset, Short Duration, Limited Extent</td>
<td>Stay, Stay with Adaptations</td>
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</table>
CHAPTER FOUR: SUNSET CRATER AS CASE STUDY

To test this model of population response to natural hazard, it is beneficial to apply the model to an archaeological situation. The eruption of Sunset Crater in northern Arizona provides an appropriate case study. First, the environmental characteristics of Sunset Crater are examined. Dating the event is reviewed in order to establish the onset and the duration of the eruption. The extent of disruption from the volcano is derived from modern maps and archaeological data. Next, societal characteristics of the population that would have been affected by the eruption are examined including the density of the pre-eruption and post eruption population. Then, the degree of prior experience with environmental disturbance is evaluated using dendrochronological reconstructions of paleoclimate, particularly temperature and precipitation. Finally, the relative sociopolitical complexity of the population before and after the eruption is assessed. This information comes largely from archaeological survey data from the U.S. 89 archaeological project (Elson 2006a) and Wupatki National Monument (Anderson 1990).

Environmental Setting

The area around Flagstaff, Arizona, is a volcanic landscape. The San Francisco volcanic field extends over 1,800 mi² and includes more than 600 volcanos (Priest et al. 2001). Humphreys Peak, Arizona’s highest point, at 3,852 m, stands within the volcanic field and is itself an extinct stratovolcano (Priest et al. 2001). Sunset Crater, a cinder
cone volcano, is northeast of Flagstaff at an elevation of approximately 2,100 m (Figure 2).

The groundcover surrounding Sunset Crater is largely deep, coarse, very well drained cinders (Miller et al. 1992). The local tree population is largely ponderosa pine (*Pinus ponderosa*) with occasional pinyon (*Pinus edulis*) and juniper (*Juniperus* spp.). Douglas-fir (*Pseudotsuga menziesii*) is found at higher elevations (Elson et al. 2006a).

The San Francisco volcanic field rests atop the Moenkopi sandstone and is at the southern edge of the Colorado Plateau.

Sunset Crater is the youngest volcano in the San Francisco volcanic field. Like other cinder cone volcanos, Sunset Crater erupted from a fissure in the earth’s surface that spewed ash, lava, and cinders (Colton 1937). Sunset Crater is an example of a scoria cone. The scoria from the eruption built up during the eruptive sequence creating a 300-m-high mound of cinders with a distinctive crater shape at the top (Elson et al. 2002). The cinders have oxidized, giving the volcano a reddish hue said to resemble the setting sun (Colton 1960:4).

**Eruption Date and Determination of Onset, Duration, and Extent**

An interdisciplinary team from the University of Arizona, Northern Arizona University, and Desert Archaeology, Inc., is collaborating to learn as much as possible about the eruption of Sunset Crater. Palaeomagnetism and geomorphology are being used to characterize the nature and duration of the eruption sequence. The long-established eruption date of AD 1064 is being evaluated. Existing archaeological wood
and charcoal samples from the Flagstaff area are being re-examined for any dendromorphological signals other than that at AD 1064 that may have been missed in prior studies. Comparative dendrochemical studies are being conducted to see if Sunset Crater’s eruption introduced chemically distinct soils that are reflected in the rings. Alternative explanations for the 1064 ring suppression are also being explored, including wind events, insect damage, and fungal root colonies (Sheppard, Ort, Anderson, and Elson 2005). The palaeomagnetic, geomorphologic, and dendrochronological projects detailed below combine to form a more complete picture of the eruption of Sunset Crater, i.e., its onset, duration, and extent.

**Palaeomagnetism and Geomorphology**

The first focus of the team was determining the duration of Sunset Crater’s eruption. When Shoemaker and Champion conducted palaeomagnetic studies of Sunset Crater eruptive material and determined that the eruption took place over a 100-200 year time span (Champion 1980), the report was widely accepted. This long eruption period was included in archaeological interpretations of human responses to the volcano (e.g., Downum 1988; Pilles 1979; Sullivan and Downum 1991). However, it is very unusual for cinder cone eruptions to last more than one year, let alone more than one century. This aspect of the dating of Sunset Crater, therefore, deserves renewed research.

In June 2001, Michael Ort, Duane Champion, and Mark Elson conducted field work to collect additional samples for palaeomagnetic dating. Thirteen new sampling locations were added to the seventeen used by Champion (Ort et al. 2002). These were
combined with the older data for a total of 106 samples. According to established paleomagnetic field methods (Eighmy and Sternberg 1990), each sample was oriented in situ according to modern magnetic directions and then removed for analysis at the U.S. Geological Survey office in Menlo Park, CA (Ort et al. 2002). The mean magnetization of each sample was plotted against the most recent archaeomagnetic curve for the southwest (Lengyel and Eighmy 2002). Palaeomagnetic dates for each of the Sunset Crater flows ranged between AD 1020 and 1170. The error ranges associated with each date and the nature of the secular variation curve during this time interval necessitate additional interpretation of these results.

The Southeast Fissure of Sunset Crater produced a date of AD 1030-1165. The earliest dates for the Kana’a Flow are between AD 1047 and 1075. The Bonito Flow suggests a date between AD 1045 and 1170. A study by Holm and Moore (1987) determined that the South East Fissure and the Kana’a Flow were geologically contemporaneous. Combining their palaeomagnetic age ranges means that the earliest possible deposition date for these two flows is AD 1047 (Ort et al. 2002). This brings them close to the age range for the Bonito Flow. A short duration for the eruption is supported by the work of Amos (1986), who found that there are at least 8 cinder deposition strata and Ort et al. (2008), who found little or no erosion between cinder units. In a location as windy as Sunset Crater (see below), this would suggest that very little time passed between cinder strata depositions, lasting at most one to two years (Amos 1986). Based on these data, Ort et al. (2002) concluded that Sunset Crater erupted some time between AD 1040 and 1100 and lasted no longer than a few years.
Smiley’s AD 1064 eruption date falls within this range and cannot be discounted using palaeomagnetic information. However, these new data present a strong case against the traditional interpretation of a centuries-long eruption sequence for Sunset Crater (Champion 1980). A one- or two-year eruption would have a different effect on human populations living and farming in the area than a very long eruption. A shorter eruption span means that archaeological interpretations of human response and adaptation must be re-evaluated.

Tree-Ring Studies

Dendrochronology has been an integral part of Sunset Crater research since the early 1930s when an archaeological expedition from the Museum of Northern Arizona (MNA) discovered archaeological remains beneath Sunset Crater cinders, making it obvious that the volcano erupted during the prehistoric occupation (Colton 1932). Knowing what a massive impact this would have had on Sinagua farmers, Harold S. Colton and his staff of Katharine Bartlett, Lyndon L. Hargrave, and John C. McGregor set about trying to determine when the eruption took place and how local prehistoric populations were affected by it (Downum 1988). An effort was made to determine whether sites were occupied before or after the eruption. The use of tree-ring analysis to date archaeological ruins was already established (Douglass 1921). Colton enlisted the aid of A. E. Douglass at the University of Arizona, and he and John C. McGregor began dating wood and charcoal material from Flagstaff area sites. The expeditions continued from 1930 to 1935 (McGregor 1936).
The results of the expeditions were twofold. First, a great number of archaeological sites were dated. This enriched the Flagstaff chronology and enabled calendar dates to be assigned to the existing relative ceramic chronology. Second, a major advantage of having absolute dates for ceramic types and architectural material was that sites found both above and below volcanic deposits could be dated. In this way, Colton was able to narrow down the possible eruption date of Sunset Crater to between AD 700-875 (Colton 1932). This placed the eruption firmly in the Rio de Flag phase of the Sinagua chronology and the Pueblo I phase of the Anasazi chronology (Pilless 1978). With this information, Colton was able to examine the effects of the volcano on the local prehistoric population. Because the eruption of Sunset Crater is so important to Flagstaff area archaeology, the evaluation of the eruption date continued to be an important task.

The eruption date continued to be corrected and refined as new evidence emerged (Breternitz 1963; Colton 1945; McGregor 1936; Smiley 1958). In the 1950s, Terah Smiley of the University of Arizona began to examine archaeological wood samples from the eruptive period, looking for a physical reaction of the trees to the eruption. Smiley found a small group of Douglas-fir and ponderosa pine samples with significant suppression of growth combined with ring-width complacency beginning with the 1065 ring and continuing for the remaining life of the trees (Figure 2) (Smiley 1958). These samples were all recovered from the posteruptive site of Wupatki Pueblo located approximately 20 km northeast of the volcano.
Figure 2. AD 1065 growth suppression and complacency in Wupatki wood. (from Sheppard, May, Ort, Anderson, and Elson 2005)

Because Wupatki postdates the eruption, any trees felled to build Wupatki presumably would have survived Sunset Crater’s eruption and thus potentially recorded its effects in their annual growth. Smiley believed he had found a smoking gun in these suppressed and complacent trees. An eruption date of AD 1064 was soon published (Smiley 1958). The Museum of Northern Arizona and the National Park Service adopted this date and no significant alteration has since taken place (though Breternitz [1963] proposed an eruption date of AD 1066).

Another important aspect of Sunset Crater’s eruption that would have affected local populations is its duration. Most cinder cone eruptions last under a year (Vespermann and Schmincke 2000). However, early paleomagnetic work at Sunset Crater suggested that the eruption lasted much longer than this, perhaps as long as 100-200 years (Shoemaker and Champion 1977). These data have been incorporated into the
scientific literature (Holm and Moore 1987; Pilles 1979) as well as public interpretation materials (Houk 1992).

When these data are examined more closely, it becomes apparent that there is still room for interpretation (Boston 1995; Elson et al. 2002). The physiologic response of Smiley’s Wupatki samples seems convincing indeed. This sample group, however, contains several duplicates and in fact represents only three different trees (Elson et al. 2007; Ort et al. 2008). This much smaller sample consists of two Douglas-firs and one ponderosa pine. Wupatki lies within a saltbush desert climatic zone (Stanislawski 1963:13) that does not support the growth of pine or Douglas-fir now or in the prehistoric past (Elson et al. 2006a). The closest sources for these trees are at least 20-30 km south and west of Wupatki Pueblo (Elson 2006b) in higher elevations either near Sunset Crater or in the San Francisco Mountains (Figure 1). The tephra fallout from Sunset Crater covered an area of at least 2,000 km² and varied with elevation. Because the exact provenance of Wupatki wood is unknown, and not all high elevation sites experienced volcanic deposition (Ort et al. 2002), it is possible that Smiley’s sample trees did not grow in areas affected by Sunset Crater, and the observed growth suppression may have an unrelated cause.

In addition to being of unknown origin, Smiley’s Wupatki trees show a suppression signal that is poorly replicated. Of the 155 tree-ring dates obtained from Wupatki Pueblo (Robinson et al. 1975), only the three trees sampled by Smiley (1958) show evidence of the 1064 reaction. To date, no other tree from the Flagstaff area has been found to share the particular characteristics of the AD 1064 reaction. One would
expect that an event as regionally devastating as Sunset Crater would have a more widespread effect. Furthermore, there are a number of processes, other than volcanos, that can cause trees to grow abnormally. The established AD 1064 date for the eruption is thus based on an inadequate sample size of trees of ambiguous origin showing a regionally unique reaction that could be caused by other events. It deserves further scrutiny. This evaluation of prior research is not intended to debase its proponents, but rather to understand as precisely as possible an event that took place in the past. This work builds upon the fundamental research of others.

Other sources of growth disturbances in trees were researched in order to assess the validity of the AD 1064 signal so that a reliable onset date for the eruption might be determined. Ring suppression can be caused by a multitude of natural and unnatural events in the life of a tree (Boston 1995; Sheppard, May, Ort, Anderson, and Elson 2005):

- Root pathogens tend to affect trees in several ways (Cherubini et al. 2002). Roots are damaged, limiting their ability to take up water or nutrients from the soil. In this way, the pathogens can damage a tree over a long period of time, resulting in decreased ring growth before tree death. Similarly, the pathogens can temporarily impair a tree, causing suppressed ring growth from which the tree eventually recovers. This response to a pathogen could look like the observed Wupatki response.
• Defoliators and insect outbreaks also influence ring growth (Hogg 1999). When a tree canopy or bark is damaged by insects, the tree does not receive the necessary sunlight or nutrients to produce the same amount of ring growth (Swetnam et al. 1985). An insect outbreak might appear as a period of suppressed rings during the infestation and ensuing tree recovery period. This kind of insect outbreak is not uncommon in the Southwest today (Sánchez-Martínez and Wagner 2002). The Flagstaff region’s propensity for insect outbreaks has been established in the present day and it is possible that a similar outbreak happened in 1064 and caused a period of suppressed rings in the Wupatki samples.

• Trees show reaction wood (increased growth) or decreased ring growth after a mass movement event such as a debris flow, landslide, gully erosion, earthquake, or river movement (Lang et al. 1999; Sheppard and Jacoby 1989; Stefanini 2004; Winchester and Harrison 2000; Yoshida et al. 1997). All of these events can disturb the growth of a tree and cause it to lose limbs resulting in reduced ring growth. These movements can also cause reaction wood to form in a tree that has been partially uprooted or had its vertical axis altered by changing ground surface dynamics. Though they do not exhibit reaction wood, the trees used in the construction of Wupatki Pueblo have an unknown origin, and until their source can be identified, the possibility that they were affected by a localized landslide or erosion event cannot be ruled out.

• Tornados and catastrophic winds can damage the crown, limbs, or root system of a tree and cause the tree to die or decrease its ability to produce normal rings
Sheppard, May, Ort, Anderson, Elson 2005). Trees are damaged to varying degrees in a wind or tornado incident (Dunham and Cameron 2000). Depending on soil conditions and tree age/size, trees are killed, heavily damaged with disruption in ring widths, are tilted and produce reaction wood, or show no response to tornadoes.

In order to positively identify the 1064 signal as that of Sunset Crater’s eruption, it must be established that the signal could not have been caused by any of the above phenomena. To eliminate potential sources of disturbance in tree rings, it is helpful to begin with known events. Responses to these events can be directly observed in living trees and compared to responses in other trees where that cause is unknown. Though a volcanic eruption in Flagstaff cannot be recreated, it is possible to observe other events in local tree rings. If another event can be found to cause similar responses to those seen in the three trees used in the construction of Wupatki, even greater doubt would be cast on the postulated 1064 eruption date. Likewise, tree growth responses can be recorded for other events so that they can be identified in the past as well.

In northern Arizona, the events that are likely to cause damage, and thus response, in trees include fire, frost, drought, high winds, and insect outbreaks. The responses of trees to fire (Baisan and Swetnam 1990; Chambers et al. 1997; Lageard et al. 2000) and frost (Hallman et al. 2006; LaMarche and Hirschboeck 1984), are well known, and neither closely resembles the 1064 signal and so are not appropriate for comparison here. Drought is also well studied in the Southwest (Cook et al. 1999; Grissino-Mayer 1996)
and does not cause the kind of reaction found in Smiley’s trees. Though drought can cause reduced ring growth, it is a more widespread phenomenon that would be apparent in the majority of local trees rather than an isolated few.

Tornado Study

A high-wind event, contrastingly, could be localized enough to affect only some trees in a resource area. The Flagstaff area is notably windy. The area north and east of Flagstaff has a wind power class of 3 (Acker et al. 2007), meaning that typical wind speeds vary between 14.1 and 15.7 mph with increased intensity and frequency in the winter months. This level of wind is not likely to damage a tree in such a way as to cause growth suppression for several decades. This would require a more severe event. In October of 1992, a rare, but not unprecedented, tornado swept through Sunset Crater National Monument (Crisp 1996), 25 km northeast of Flagstaff. The tornado touched down in several places, uprooting trees and breaking limbs in its path. In those trees that were not destroyed, wind damage that might be visible in the tree rings is expected.

In the summer and fall of 2004, field work was undertaken to determine the effect of the tornado on local trees. Of eighty-three sampled trees, forty-seven (or 57%) demonstrate at least one response to the 1992 tornado (Sheppard, May, Ort, Anderson, and Elson 2005). Responses were varied and some trees exhibited more than one of the following patterns. The most widespread response was a growth release beginning with the 1993 ring. This occurred in 57% of the responsive trees. The most likely cause of the growth release is the phenomenon of thigmomorphogenesis: the physiologic response of
trees to short-term mechanical disturbance such as high-wind events (Telewski and Jaffe 1981).

The high wind associated with the tornado is also responsible for the second most common response to the tornado; a thin latewood in the 1993 ring. In 45% of the trees that responded to the tornado, the latewood in the year following the event was reduced in size by as much as half (Sheppard, May, Ort, Anderson, and Elson 2005). In some trees, the 1993 latewood was also fainter in color than those in rings immediately before or after. Latwood can be more sensitive to effects of defoliation than the earlywood (Krause and Morin 1995) and though the ponderosa pines at Sunset Crater were not obviously defoliated by the tornado, they may have been subjected to damage that reduced the efficacy of their needles. During the tornado, airborne coarse angular cinders may have impacted the trees and needles at high velocity causing damage that, while perhaps not noticeable, may have been sufficient to hinder respiration (Van Gardingen et al. 1991). Similar damage may have occurred during the eruption of Sunset Crater when newly formed, angular, hot ash and cinders impacted needles, though decreased latewood has yet to be observed in 11th century wood from the area.

A third way in which Sunset Crater area trees responded to the tornado is in the addition of reaction wood in the rings following 1992. Twenty-five percent of tornado response trees showed evidence of this response. Reaction wood occurs when the main stem of a tree is displaced from vertical (Dadswell and Wardrop 1949; Scurfield 1973).

The final response noted in the tornado study was a suppression of growth resulting in small ring widths in 6% of the responsive trees. The duration of suppression
ranged from four years to the life of the tree (to 2004) (Sheppard, May, Ort, Anderson, and Elson 2005). Growth suppression is of particular interest to this project because it resembles the 1064 signal. The suppression of growth in Sunset Crater trees in response to the tornado is not on the same scale as the 11th century suppression, but it does include greatly reduced ring growth and a reduction in ring-width variability. Due to limited evidence, growth suppression should not be interpreted as the dominant marker of tornado activity.

The investigation of the dendrochronological response of ponderosa pine to a tornado had two important results. First, characterizing the effects of a tornado on tree-ring growth will make it possible to identify evidence of tornados in other areas. Climatologists can employ these data in studies of tornado severity, frequency, and range.

The second result is the one most relevant to the study of the eruption of Sunset Crater. Based on the responses noted in 47 trees known to have experienced the 1992 tornado, it can be conclusively stated that the event that caused the 1064 suppression signal was not a tornado. None of the dominant responses to the tornado (Figure 3) closely resemble the 1064 signal. This study eliminates a possible candidate for that disturbance and reveals additional material that will be useful for future study.
Interestingly, during sampling, five trees were found to have significant growth suppression that was not associated with the tornado. These trees show a stark reduction in growth and interannual variability from which they have not yet recovered. The five trees are still living, though they are not growing at a normal rate in comparison with neighboring trees. There is no exterior indication that these trees are under stress. Each of them supports foliage and a relatively normal-looking crown. Onset of growth suppression occurs at different dates in each of the five trees, and they are not growing next to one another. It appears that an isolated malady is affecting these trees that does not affect all neighboring trees. Because decades-long suppression (like that of 1064) is precisely the signal that the team is seeking to reproduce, it is important to note that it can occur independently of a volcanic eruption.
Dendromorphological Responses

A survey of wood samples collected from Wupatki pueblo and other archaeological contexts in the Flagstaff area was conducted with two major goals (Dean et al. 2006; Elson et al. 2008). The first was to find replication for the AD 1064 signal (Smiley 1958). The second goal was to closely examine a sample of low elevation and high elevation wood in search of a morphological response at any time other than the AD 1064 date. This second objective is to provide evidence for the onset of the eruption and its duration.

Thirty-nine samples from the Flagstaff area were examined. Within the sample set, the earliest ring dates to AD 983 and the latest is AD 1195. Every one of the samples contains rings that fall within the AD 1050-1100 expected eruption range (Ort et al. 2002; Ort et al. 2008). Each sample has been measured and crossdated at the Laboratory of Tree-Ring Research at the University of Arizona. Of these samples, thirty-five, or 90%, exhibit at least one period of reduced ring growth. The earliest example of reduced ring growth occurs in only one sample. It begins in AD 1037 and persists for seven rings. The next period of reduced ring growth is also evident only in one sample, beginning in AD 1046. This tree does not resume normal growth before its outside ring, AD 1116. Another sample shows a gradual and variable reduction in growth at AD 1052 that continues until the outside ring, AD 1135.

The first major pattern of narrow rings among the sample set occurs in the AD 1060s, with twelve trees (31%) showing a response (Figure 4). Of these, two (5%) show
reduced growth starting in AD 1064, three (8%) in AD 1065, six (15%) in AD 1066 and one (3%) in AD 1067.

![Graph showing reduced ring-width in AD 1060s](image)

Figure 4. Trees showing reduced ring-width in AD 1060s.

The second major instance of reduced ring growth occurs in the AD 1080s and 1090s, with twenty-two (56%) trees responding (Figure 5). Ten trees (26%) show reduced growth starting in AD 1085, six (15%) have reduced growth beginning in AD 1088, three (8%) begin reduced growth in 1089, another two (5%) begin in AD 1090, and one (3%) begins in AD 1091. This second pattern of narrow rings is more pronounced than those occurring in the AD 1060s (David Street, personal communication 2007).
These patterns indicate that there are at least two events in the late 11th century that affected the growth of local trees. The first pattern, in the AD 1060s evokes the proposed AD 1064 date for the eruption of Sunset Crater (Smiley 1958). However, in Flagstaff and other regional chronologies, AD 1067 stands out as an extremely dry year, producing a narrow ring that is not related to the eruption of the volcano (Salzer 2000:88-90). This leaves the strong AD 1080s and 1090s signal as a possible morphological response to the volcano. Here too, regional chronologies reveal a pattern of heat and drought in the AD 1080s and 1090-91 that extends beyond the influences of Sunset Crater (Salzer 2000:90). This suggests the second major pattern found in the sample set may also be due to regional climatic conditions rather than to volcanic effects. Because many trees spanning the suspected eruption period have been examined and no obvious eruption year is apparent, it may be that the eruption did not affect the trees in a way that reduced ring growth.
Though morphological responses have largely been ruled out, the eruption may have introduced new materials into the soils around living trees, causing a change in the chemical composition of the rings after the eruption year (Pearson et al. 2005; Sheppard, Ort, Speakman, Anderson, and Elson 2005). Though the conditions following the eruption of Sunset Crater cannot be replicated exactly, similar conditions were probably present at two other well-dated cinder cone eruptions. Cinder Cone at Lassen volcano erupted in AD 1666 (Finch 1937) in what is now northern California. This eruption is dated by historic account and verified using dendrochronology. Living trees and dead wood at the site span the eruption period and provide samples for chemical research (Sheppard, Ort, Anderson, Clynne, and May 2008). Volcán Parícutin, in Michoacán, Mexico began erupting in early AD 1943 and continued to erupt until 1952 (Luhr and Simkin 1993). This eruption was well documented popularly as well as scientifically. It provides an ideal laboratory for the study of cinder cone eruptions (Sheppard, Ort, Anderson, Elson, Vázquez, Selem, Clemens, Little, and Speakman 2008).

At Lassen, living and dead wood was collected and crossdated. Samples spanning the mid 17th century were measured for many elements using inductively coupled plasma mass spectrometry (ICPMS). Two responses were noted. There was a reduction in ring width followed by a release in width in the years following the eruption. Also, there was an increase in sulfur, phosphorous, and sodium in some, but not all of the trees (Sheppard, Ort, Anderson, Clynne, and May 2008). Similarly, trees surrounding Volcán Parícutin were also sampled looking for a physical and chemical response to the eruption.
ICPMS measurements at Parícutin indicate that there was a similar increase in sulfur and phosphorous at the time of the eruption (Sheppard, Ort, Anderson, Elson, Vázquez, Selem, Clemens, Little, and Speakman 2008). Sodium does not appear to change significantly at Parícutin, though this may be due to the specific chemical composition of each cinder cone.

These two eruptions of known age provide a test case for Sunset Crater. Because both Lassen and Parícutin show increases in sulfur and phosphorous in tree rings following the eruptions, these elements may be indicative of cinder cone eruptions. Archaeological wood samples from Wupatki pueblo have been measured using ICMPS for all elements, but with particular interest in sulfur, phosphorous, and sodium. Though results are preliminary, some of the Wupatki wood shows an increase in phosphorous beginning in AD 1085 and peaking at AD 1090. This falls within the suggested eruption range (Ort et al. 2002). It occurs at the same time as a period of decreased ring growth in Flagstaff area trees, though that response may be due to a regional decrease in precipitation (Salzer 2000:90).

Dendrochemical investigations of archaeological wood samples is ongoing, but comparison with other cinder cone eruptions indicates that a chemical response is possible and that that response may involve sulfur, phosphorous, sodium, or other elements. Early results may indicate a chemical response in the late AD 1080s, consistent with archaeomagnetic estimations and dendromorphological signals.
Summary of Eruption Evidence

Archaeomagnetic data, tree-ring studies, dendromorphological research, and dendrochemical work are combined to paint a more complete picture of the eruption of Sunset Crater. Each field of study looks at the event in a slightly different way, but together they provide an understanding of its onset and duration. The archaeomagnetic work suggests that Sunset Crater did not have a multicentury eruption, but was probably a more typical 1- or 2-year event (Amos 1986). This work also provides a range of dates in which the eruption most likely took place, AD 1040-1100 (Ort et al. 2002). Other tree-ring studies, including the investigation of a historic tornado, endeavor to find replication for the proposed AD 1064 eruption date (Smiley 1958) and also to eliminate other causes for that signal. Modern trees are identified with similar growth disturbances as the 11th century wood, proving that the signal is not unique to a volcanic episode (Sheppard, May, Ort, Anderson, and Elson 2005). A survey of other archaeological wood collected from the Flagstaff area reveals two periods of reduced growth, one in the AD 1060s and one the AD 1080s. Both fit into the archaeomagnetic eruption range, but both might also be due to climatic changes and not a volcanic eruption. Dendrochemical testing of the wood at Sunset Crater might support an AD 1080s eruption.

The combined evidence suggests that the onset of the eruption was rapid and probably took place in the late 11th century. The duration of the event was short, one or two years, though the effects of the eruption continue to be visible today. The extent of the eruptive effects is determined not with dendrochronology, but by observing and mapping modern distributions of ash and cinder deposits (Pilles 1979). The extent of the
hazard’s effects is relative to the group experiencing it. For the prehistoric Sinagua, Sunset Crater’s eruption had widespread effects.

Archaeological Evidence

Societal characteristics

In order to gauge the effect of Sunset Crater on human populations and to understand their responses, it is necessary to determine the characteristics of the population before and after the eruption. In both cases, the population density and sociopolitical complexity are evaluated. The experience level of the pre-eruptive population is also addressed. Any differences noted between pre- and posteruptive populations are discussed and their relevance to the volcano assessed.

Pre-Eruption

In the centuries preceding the eruption, human population was generally focused on high elevation sites near the location of the volcano at 2447 masl. This area features open ponderosa pine forests. Pit structures were the dominant architectural form, though these varied from circular to subrectangular (Bradley 1994).

Settlement patterns are difficult to determine precisely, because of the destruction and burial of many pre-eruptive sites by Sunset Crater, but excavation and survey suggest that the population was organized into scattered groups of extended family units living in small villages of two to five pithouses (Pilles 1978). Almost all pre-eruption habitation sites are pithouses without significant trash accumulation (McGregor 1936), though large pre-eruption pithouse villages are present (Elson 2006a). The Museum of Northern
Arizona categorized pre-eruptive pithouses into three groups. “Wooden” pithouses were typically deep with wooden supports, walls, and roofs (Colton 1946). These contained central firepits of various construction and east-oriented ventilators or entrances. Masonry pithouses were also deep, though these were lined with stones, shaped or unshaped (McGregor 1936). The third habitation type consists of shallow structures, sometimes with contiguous pit rooms. Alcove houses might also fit into this last category (Colton 1946).

Pre-eruptive sites are dated using tree rings or the dendrochronologically anchored ceramic chronology (McGregor 1938). Pre-eruptive assemblages are dominated by a ceramic assemblage that includes Kana’a’ Black-on-white, Lino Black on-gray, or Deadmans Black-on-red and Lino Gray, Kana’a’ Gray, Medicine Gray, Coconino Gray, or Rio de Flag Brown (Sullivan and Downum 1991). The immediate Sunset Crater area appears to have been populated by the Sinagua, though Kayenta and Cohonino influences are notable. The concept of a prehistoric “frontier” (King 1949) at Sunset Crater is not addressed here, though it may be important that there were more than one seemingly distinct group inhabiting the landscape.

**Population Density**

Population density is calculated in several ways. Because it is not possible to directly measure prehistoric populations, density of sites on the landscape, room counts, and density of features within a site are used as proxy measures for population density. The density of sites on a landscape and intrasite density are derived from the U.S.89 Archaeological Project (Elson 2006a pt1). The U.S.89 Archaeological Project database is
particularly appropriate for comparison of pre- and post-eruptive conditions because it is the largest archaeological project conducted near Flagstaff since the early work of Harold Colton (Elson 2006a), and it spans the relevant elevation zones and time periods. The Coconino National Forest (CNF) site files data are also used, largely for pre-eruptive data. Additional site information from Wupatki National Monument and other nearby areas are included to emphasize the patterns seen in the U.S.89 and CNF data.

To study the relevant pre-eruption population density, the area around Sunset Crater that is most likely to have been abandoned following the eruption is used as a test location. Work conducted by Desert Archaeology, Inc., shows that evacuation must have been necessary in areas with over 30 cm of ash deposits (Elson et al. 2007) (Figure 6) though even just 15-20 cm of ash are sufficient to disrupt agriculture and damage structures (Colton 1965; Maule 1963). Within this zone, locations between 6,200 and 7,200 ft usually receive sufficient precipitation and frost-free days to support maize agriculture (Elson 2006a).
The area above 6,200 ft in elevation, but under less than 30 cm of Sunset Crater tephra amounts to 265 km². According to CNF site files data, there is an average density of 10 sites/km² above 6,200 ft. This is likely an underestimate due to lack of full-coverage surveys and low visibility of subterranean house forms. Therefore, at a
minimum, 2,650 sites can be expected in the evacuation area. Not all sites represent habitation areas (Pilles 1978). According to data gathered during the US 89 Project, 58% of sites were residential (rather than fieldhouses or agricultural features). Using the same proportion, 1535 habitation sites can be expected (Elson, personal communication 2007). Again using the US 89 project area as a guide, 37% of the habitation sites, or 570 sites, were probably pre-eruption in date (Elson personal communication 2007). Sixty percent of these sites or 340 sites were likely occupied in the fifty years before the eruption, and if site duration was around 25 years (Ahlstrom 1985), then 170 residential sites were occupied in the generation before the eruption of Sunset Crater. In the 265 km$^2$ that were impacted by Sunset Crater ash, 170 sites would give a pre-eruption site density of 0.64 sites/km$^2$. Thus, the pre-eruption population at Sunset Crater can be said to have been sparse.

Wupatki National Monument, ranging in elevation from 4265-5580 ft, has been completely surveyed by archaeologists (Anderson 1990). In the 143 km$^2$ covered by the park, only two sites were found to be pre-eruption in date. This gives an extremely low site density of 0.014 sites/km$^2$. Insufficient precipitation for agriculture is more than likely the reason for such sparse occupation prior to the eruption of Sunset Crater.

Evidence for pre-eruption settlement patterns also comes from a 1990-1991 survey through the San Francisco Volcanic field for the Transwestern Pipeline Expansion Project. The survey covered an area known to have been occupied before the eruption, and 14 Sinagua sites were excavated (Bradley 1994). Pre-eruptive site structure is indicative of a dispersed settlement system more closely resembling Basketmaker III
(BMIII) sites elsewhere in the Puebloan world (Bradley 1994:352). Like the U.S.89 project, the Transwestern Pipeline Expansion Project may have underestimated pre-eruptive sites due to poor visibility (Bradley 1994). This is not surprising given the subterranean nature of early habitation sites and the significant deposition of ash during the Sunset Crater eruption.

The number of sites does not directly correlate with the density of population. To determine population density, the number of rooms per site is used to approximate density. In the U.S.89 Project, five pre-eruptive contexts are explored (Elson 2006a). Of these, four are small habitation sites and one is a large habitation site. Three sites have one residential room each, one has three, and the last has four rooms (Figure 7), giving an average room count of 2 rooms per site. In contrast, posteruptive residential sites had an average room count of 7.7 rooms per site. Total calculated room counts through time are shown in Figure 7. The sample size is much greater in posteruptive contexts (Table 3), and room counts per site increase (Figure 7). It may be concluded then, that the pre-eruptive population at Sunset Crater was small and dispersed in comparison with later occupation.
Sociopolitical Complexity

A social or political system consists of many independent and interactive parts that also interact with the environment. A society’s complexity is marked by the diversity of these parts and the degree of hierarchical structure among them (Lekson et al. 1994:16). To assess the degree of complexity of the pre-eruption social systems at Sunset Crater, three categories of data are combined to create a proxy measure. Site type diversity and site size diversity are used as measures of diversity of interactive parts and of hierarchical structure. The presence or absence of exotic trade goods is used both as a measure of the society’s interaction with distant groups and as possible evidence for
adherence to ritual regimes. Exotic goods procured from distant sources can indicate interaction within parts of a social or political system. The festival model of exchange and resource procurement suggests that festivals may have provided a venue for regional trade (Ford 1983). As with the Hohokam ballcourt system, regional exchange may have taken place according to a schedule of ritual or ceremonial events (Wilcox and Sternberg 1983).

US 89 Project Dated Sites

<table>
<thead>
<tr>
<th>Pre-Eruption</th>
<th>Elevation Zone</th>
<th>Date Estimate</th>
<th>Site type</th>
<th>Room count</th>
<th>Site Size (m$^2$)</th>
<th>Exotic trade goods</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA 20700 Locus B</td>
<td>5</td>
<td>400-700</td>
<td>Small habitation</td>
<td>3</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>NA 20700 Locus A</td>
<td>5</td>
<td>400-700</td>
<td>Small habitation</td>
<td>1</td>
<td>8915</td>
<td></td>
</tr>
<tr>
<td>NA 20700 Locus A</td>
<td>5</td>
<td>800-1025</td>
<td>Large habitation</td>
<td>8</td>
<td>6190</td>
<td></td>
</tr>
<tr>
<td>NA 21087</td>
<td>4</td>
<td>800-1025</td>
<td>Small habitation</td>
<td>1</td>
<td>2835</td>
<td>5pcs shell</td>
</tr>
<tr>
<td>NA 25779</td>
<td>5</td>
<td>930-1020</td>
<td>Small habitation</td>
<td>4</td>
<td>1075-1150</td>
<td>6pcs shell</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Post-Eruption</th>
<th>Elevation Zone</th>
<th>Date Estimate</th>
<th>Site type</th>
<th>Room count</th>
<th>Site Size (m$^2$)</th>
<th>Exotic trade goods</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA 181</td>
<td>2</td>
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<td>Large habitation</td>
<td>27</td>
<td>25770</td>
<td>6pcs shell</td>
</tr>
<tr>
<td>NA 18621</td>
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<td>13</td>
<td>2855</td>
<td></td>
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<tr>
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<td>Small habitation</td>
<td>6</td>
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<td></td>
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<td>NA 21090</td>
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<td>Activity area</td>
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<tr>
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<td>Large habitation</td>
<td>7</td>
<td>11260</td>
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<tr>
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<td>Special use/ ceremonial</td>
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<td>1075-1150</td>
<td>Limited Activity/ agricultural site</td>
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<td>Small habitation</td>
<td>3</td>
<td>6950</td>
<td>4pcs shell</td>
</tr>
</tbody>
</table>

Table 3: US89 project sites, room counts.

Both pre-eruption and posteruption sites were excavated during the US89 project (Table 3) (Elson 2006a). The pre-eruption sites are all habitation sites, though agricultural sites must have existed in the past. No separate ritual or other activity sites are noted for this period. These early sites are also all located exclusively in high
elevation contexts (Elson 2006a). There is some diversity in site size among pre-eruptive sites. They range from one room to eight rooms. Exotic trade goods (five pieces of shell) were found at only one pre-eruption site. Based on these data, pre-eruption sites have low site type diversity, limited site size diversity, and few exotic trade goods. Therefore, for the model proposed here, the pre-eruption society at Sunset Crater is characterized as having low sociopolitical complexity.

It is likely that decisions in pre-eruption sites were based at the household level. Architectural remains offer little evidence of overarching political or religious influence, though there are pre-eruptive structures that may be communal in function. For example, a large Cinder Park phase circular structure has been interpreted as a great kiva (Breternitz 1959:66) and other large pithouses may be community or ceremony related (Pilles 1979). Other than these, there is no evidence of social integration beyond the nuclear family in pre-eruptive contexts (Pilles 1979).

Prior Experience with Disaster

The population’s prior experience with disaster is a complicated determination to make. While it is probable that no other cinder cone eruption took place during the human occupation of the Sunset Crater region, other environmental phenomena might have exposed inhabitants to stress. A volcanic eruption is an episodic event unlikely to occur more than once in a human generation (Dean et al. 1985). In fact, the San Francisco volcanic field has a steady eruption cycle of approximately 1 volcano per 15 k.y. over the last 780 k.y. (Conway et al. 1998). Thus, the occurrence of a volcanic event
in the vicinity of Sunset Crater is too infrequent to promote adaptive behavior in humans. Therefore, the population had no prior experience with eruptions as an environmental hazard.

It may be that the pre-eruption inhabitants of the San Francisco Peaks recognized that they were living in the midst of a volcanic field and identified existing cinder deposits as belonging to earlier eruptions. The inhabitants of the area were clearly accustomed to volcanic debris from older eruptions, though they may have been unaware of the destructive potential of the cinder cones that formed familiar parts of the landscape. Like the Late Bronze Age inhabitants of Thera, the people of Sunset Crater may not have realized the destructive power of their landscape and may have underestimated the risk (McCoy and Heiken 2000).

The pre-eruption population was exposed to other sources of environmental variability that may have augmented their preparedness and response to the Sunset Crater eruption. Of these variables, those that could seriously disrupt agriculture would be the most analogous to the effects of a volcanic eruption. Adaptation to a high frequency of agricultural disturbance may be equated to the kind of experience necessary to cope with a volcanic disaster on the scale of Sunset Crater. In northern Arizona, the most likely sources of agricultural failure would have been excessively dry or wet conditions, intense heat or cold, and/or frost (Dean et al. 1994). Temperature, precipitation, and frost all affect the growth of trees and therefore are recorded in ring-width variation. As indicated by tree-ring chronologies, significant variability in temperature and precipitation is known for the Colorado Plateau in the centuries preceding the eruption (Salzer and
Temperature and precipitation variability are reviewed below to determine if they occurred with enough frequency to require adaptation or flexibility in subsistence practices.

Northern Arizona tree-ring chronologies and historic weather information are combined to reconstruct past climate conditions (Salzer 2000), allowing an evaluation of favorable and unfavorable growing conditions for the prehistoric period. The precipitation and temperature data developed by Salzer (2000) are used to determine the frequency of environmental disturbance experienced by pre-eruption inhabitants of the Sunset Crater area. Following the conventional interval of 25 years for a human generation (Dean et al. 1985), the pre-eruption period is divided into 25-year increments beginning with a conservative eruption date of AD 1100. The intervals AD 1051-1075 and AD 1076-1100 likely include the eruptive period (Elson et al. 2007; Smiley 1958). The debate concerning the eruption date and the need to provide evidence of additional environmental disturbance during the eruption period necessitate the consideration of time intervals that may or may not postdate the eruption (Table 4).

Extreme dry years and extreme wet years are listed in Table 4. Extreme dry years occurred with variable frequency. The years AD 901-1100 averaged more than one extreme dry period per human generation interval, making it a high frequency phenomenon. Likewise, very wet periods occurred with high frequency. A late spring frost is also a source of environmental disturbance that can be recorded in tree rings. Frost can cause failure in corn crops by preventing or stunting germination and can dramatically reduce crop yields (Woltz et al. 2006). By killing living plants as well as
stunting the viability of the seed crop, a widespread or severe frost could potentially deprive a population of immediate food resources and stored food. Table 4 includes all recorded frost rings for the Flagstaff region, separated into 25-year generational increments (Salzer 2000). In the eleven generations prior to the eruption, a frost occurred at least once. Between AD 876 and 976 frosts are even more frequent.

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<th>Interval</th>
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Table 4. Environmental disturbances in the Flagstaff region based on tree-ring reconstructions (based on Salzer 2000).

In addition to precipitation, temperature has an enormous impact on the success of corn agriculture, particularly at high elevations (Elson 2006a:20). However, temperature
reconstructions are appropriately examined in periods, rather than years, as this has more of an impact on local populations (Salzer 2000:63). Therefore, periods of high and low variability in reconstructed temperature are used in this study (Salzer 2000). Periods of high variability are considered to be environmental stressors, while low variability periods are not (Table 5). When the intervals of high or low variability span more than one generational increment, they are divided between them, though the variability may not span the entire period. The duration of the high or low variability period is noted in years in Table 5 for clarification.

<table>
<thead>
<tr>
<th>Interval</th>
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<td>Low Variability</td>
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Table 5. Temperature variability in the Flagstaff region based on tree-ring reconstructions (based on Salzer 2000).
The majority of the 15 generational intervals prior to the eruption of Sunset Crater are characterized by low temperature variability (Table 5). It can be confidently concluded that temperature variability was not an environmental stressor to the pre-eruption population and did not contribute to disaster preparedness.

Dendrochronological records reveal that precipitation variability and frost would have been a high-frequency disturbance to pre-eruption farming communities. This might have instilled in the inhabitants of Sunset Crater certain flexibility in subsistence practices, and they might have initiated storage practices as a safeguard against famine (Dean 2006). However, this kind of stress and response could not have been adequate preparation for a disaster on the order of the eruption of Sunset Crater. The population had never before seen such sudden destruction, nor could they have been familiar with landscape devastation on such a scale. Thus, despite variable environmental conditions and familiarity with a volcanic landscape, the population had no prior experience that could have influenced a response to the disaster at the end of the 11th century.

Eruptive Effects: The Eruption of Sunset Crater

Information on the eruption of Sunset Crater is drawn largely from tree rings and geomorphology, but it is also inferred from historic accounts of other cinder cone eruptions. Paricutin Volcano, which erupted between 1943 and 1952 in Michoacán, Mexico, is physically similar to Sunset Crater and so may provide a potential analog for the eruption and the response to it (Elson et al. 2002; Elson et al. 2007; Luhr and Simkin 1993; Ort et al. 2008; Pilles 1979). In addition, the written and photographic accounts of
the Parícutin eruption provide important information to model what the Sunset Crater population may have experienced prior to and during the eruption.

The most striking and ominous warning of the impending eruption was almost certainly a series of earthquakes, increasing in frequency and intensity over time. At Parícutin, pre-eruption earthquakes began 45 days before the eruption, the largest measuring 4.0 on the Mercalli scale, which would have felt like a “heavy truck striking [the] building” (Elson et al. 2002:122; Luhr and Simkin 1993). The earthquakes increased to 25 to 30 per day in the week before the eruption (Luhr and Simkin 1993:3). This would have alerted residents that something unusual and potentially harmful was occurring, possibly inspiring them to flee. The day before the eruption began, 300 earth tremors were felt. The local population may not have identified these events as an impending eruption, but the earthquakes, strange smells, and loud noises would have been an ominous sign and a significant disruption of daily life.

The Sunset Crater eruption likely began as a fissure in the earth from which smoke, fire, and lava were emitted. This rift may have occurred from the base of Janus Crater to Yaponcha Crater before centralizing into one focused vent (Colton 1937; Ort et al. 2008). Typical of a cinder cone eruption, Sunset Crater grew accretionally from ejected scoria (Holm and Moore 1987). Cinder cone volcanoes can grow quite quickly. Parícutin volcano reached 167 m in height in the first six days of eruption (Rees 1979:251). Sunset Crater reached an eventual height of 300 m in its probable one- to two-year eruption span. The two major lava flows, Kana’a and Bonito, burst laterally from the base of the growing crater (Ort et al. 2008). Though not explosive in the
manner of a stratovolcano, Sunset Crater and other cinder cones are capable of producing a fire fountain and expansive cloud of ash and smoke (Ort et al. 2008).

As terrifying as this must have been, the most destructive aspect of the eruption was the subsequent ashfall. Sunset Crater ash deposits covered a 2,300 km² area to varying depths from quite thick near the volcano to less than 10 cm in more distant locations, traces of which were recovered as far east as Kansas (Colton 1945). Damage to homes and fields was likely caused by burning and collapse from the tephra load (de Silva et al. 2000). In modern volcanoes, it has been found that 10 cm of tephra, particularly when wet, is the threshold for wooden roof collapse (Blong 1984:212). It is possible that Sinagua roofs collapsed under even lesser load. The tephra deposits had an equally destructive effect on farmland. Besides destroying current crops, the tephra precluded germination of future crops in the ashfall zone. Much of the arable higher elevation land exploited by the pre-eruptive population for its high annual rainfall was rendered unfarmable by Sunset Crater ash (Elson et al. 2007).
CHAPTER FIVE: EVALUATION OF SUNSET CRATER RESPONSE AND EFFICACY OF MODEL

Application of Model

To explore the human response to the eruption of Sunset Crater through the proposed model, posteruption conditions are reviewed with emphasis placed on possible population movements and social or technological adaptations. The predicted response is compared with the archaeological record to determine how well the model identifies the pressures an environmental disaster places upon a population. The pre-eruption and posteruption population density, settlement pattern, and subsistence technology are juxtaposed so that changes associated with disaster response can be discerned.

Pre-Eruption Population Density and Complexity

The pre-eruption population at Sunset Crater was dispersed, had no prior experience with environmental hazards on the scale of a volcanic eruption, and exhibited relatively low complexity. The experience designation is based on dendrochronological data for northern Arizona (Salzer 2000). Population density and complexity are based on archaeological measures of site density, room count data, and artifact assemblages (Anderson 1990; Elson 2006a). The population experienced an environmental disaster that had a rapid onset, enduring effects, and widespread damage, based on geomorphological and dendrochronological data (Ort et al. 2002; Dean et al. 2006; Elson et al. 2008). According to the proposed model (Table 2), it is predicted that a population with those characteristics faced with such a hazard would be most pressured to move, or
move with adaptations. If the disaster had a shorter duration, the model simply predicts move as a response.

It is clear that the immediate area around Sunset Crater became uninhabitable. The eruption would have made the area very dangerous, forcing initial evacuation. Resettlement did not occur because lava flow and the deep cinder cover prevented agriculture in previously occupied areas. Lower elevation areas such as those at Wupatki National Monument were largely unoccupied before the eruption and saw a significant growth in population after the eruption (Pilles 1979; Sullivan and Downum 1991). Occupation at most of those sites begins close to AD 1100 (Downum 1990). Sites at Walnut Canyon National Monument were founded as late as AD 1120 (Downum and Sullivan 1990). These dates are in accordance with the eruption estimation of AD 1050-1125 (Ort et al. 2008).

Post-eruption Population Density and Complexity

The posteruptive pattern at Sunset Crater is starkly different in both population density and complexity from what came before. With a large area of previously occupied land no longer open to habitation, it became necessary to relocate. Posteruptive sites are found outside the heaviest ash deposits, usually at lower elevations. For example, Wupatki National Monument, located approximately 20 km northeast of Sunset Crater, ranges in elevation from 1300-1700 masl and contains over 99% posteruptive sites (Downum and Sullivan 1990:5-13). These habitations are largely above-ground masonry structures, though pit structures are also found in posteruptive contexts. At Wupatki
National Monument, 8.5% of sites contained evidence of a pit structure (Downum and Sullivan 1990:5-25). In all contexts it is likely that pit structures are underestimated because they are subterranean and may not be visible in a surface survey. Data from the U.S.89 Project suggest that only 33% of pit structures leave visible surface depressions (Elson 2006a). Nevertheless, the lower elevation post-eruptive sites appear to exemplify the Pueblo II-III pattern found throughout the northern Southwest (Cordell 1997) in that they contain primarily above ground habitation structures with storage rooms, cists, or pits. Most of the sites have less than ten rooms each, but there are several sites with more than twenty rooms each that represent post-eruption population centers. For example, Citadel (51 rooms) and Wupatki Pueblo (102 rooms) are two of the largest residential structures in Wupatki National Monument (Anderson 1990). This architectural style and residential pattern is decidedly different from the scattered pithouse sites found in pre-eruptive contexts. U.S.89 Project data suggest that the number of sites and the number of rooms per site increases following the Sunset Crater eruption (Elson 2006a). There is an average of 7.7 rooms per habitation site after the eruption compared to an average of 2 rooms per site before. The settlement pattern after the eruption can be characterized as aggregated, though perhaps not as densely populated or as aggregated as later sites in the San Juan region (Cordell 1997).

Other changes accompany the shift in architectural style. Lower elevation sites exhibit a different approach to farming. Residents of higher elevations sites could rely on dry farming or floodwater farming because of higher annual precipitation. The lower elevation sites (below 1,890 masl), though they have a longer growing season at 180
days, receive only 250-300 mm of annual precipitation (Sullivan and Downum 1991). Most of this precipitation comes in the form of summer thunderstorms. This is not sufficient rainfall for the propagation of corn, making dry farming impossible (Elson 2006a). The posteruption population dealt with this challenge by creating or adopting a new technology. The cinders that blanketed so much of the region were found to be advantageous on agricultural fields in that they retained soil moisture by acting as lithic mulch (Colton 1965; Tejedor and Diaz 2003). Far from a simple solution, favorable grain size and cinder depth must be maintained in order for this technique to be successful (Tejedor and Diaz 2003). At Wupatki National Monument, it appears that the necessary 3-10 cm cinder level was maintained with the use of linear rock alignments that would have helped prevent loss of cinders due to runoff or high winds (Berlin et al. 1990; Elson et al. 2007). In addition, numerous “field houses” have been found in probable agricultural areas (Pilles 1979). These structures could have served as short-term habitations while farmers tended the fields. All of this is indicative of the adaptations that were made in order to grow crops at lower elevations.

The population at posteruption sites adapted in other ways as well. In the move from dispersed, family-based settlements to denser, more aggregated multiple household residences, individuals came to live in close proximity to other people with whom they did not share prior connections. This might have been both a source of security and a cause of stress. Providing food for an aggregated population in a marginal landscape necessitated cooperation between the entire community. Also, construction and maintenance of large residential structures would have required the work of many
individuals. There is evidence that the population may have facilitated cooperation and aggregation through the institution of integrative features. These include the ballcourts found at numerous posteruptive sites including Wupatki Pueblo and Winona Village (McGregor 1937). Though their exact function and derivation are unclear, it is presumed that ballcourts were used communally and that they attracted people for purposes of game playing, ritual, or trade (Wilcox and Sternberg 1983).

Three different groups have been identified in this part of northern Arizona largely based on distribution of pottery types (Colton 1940; Downum 1988; Samples 1990). The Kayenta Anasazi, Sinagua, and Cohonina are believed to have been living in close proximity to one another near Sunset Crater and were all likely affected by its eruption. Perhaps the immigrant population noted in Wupatki National Monument included a recombination of individuals from all three cultures (Downum and Sullivan 1990:5-52), heightening the need for integration. Kivas found at many posteruptive sites may be evidence of participation in an integrative religion or ritual regime. Ritual might have provided a means for coping with the stress of the natural disaster and the environmental and social changes that followed (Bode 1989). It has been noted that following volcanic disasters, survivors frequently suffer psychologically from bereavement, separation, social stress and depression, stress of relocation and crowded families, and frightened children (Blong 1984:139). Ritual is very often a means for alleviating such stress (Blong 1982; Nolan 1979). Archaeological evidence of prehistoric ritual response may be present in the Flagstaff area.
In excavations on the U.S.89 Project, 55 pieces of Sunset Crater basalt bearing the impressions of corn cobs were discovered at a site too distant from the volcano to have been the original location of the casts (Elson et al. 2002; Elson 2006b). These “corn rocks” were created by intentionally placing several different types of corn cobs at an hornito, or small spatter cone, where they were covered with spatter. The resulting impressions were recovered and removed to at least two sites away from the volcano where some of them were incorporated into architecture. The making of the corn rocks has been suggested to be ritual behavior perhaps as an offering to appease the volcano (Elson et al. 2002), as volcanos are often viewed as malevolent forces (Elson and Ort 2003). The incorporation of the corn rocks into later sites is a testament to the volcano’s lasting influence. Hopi tradition may also provide additional insight into the ritual response to the eruption of Sunset Crater.

There exists a tradition of the Kana’a katsina who married a young Hopi girl and caused the eruption of Sunset Crater (Malotki and Lomatuway’ma 1987; Nequatewa 1932). This young katsina brought forth a huge fire in a mountain (Sunset Crater) as a punishment for the Hopi people, a few of whom had tricked the katsina’s wife into adultery. Later, as a sign of reconciliation after years of drought, crop failure, and starvation, the katsina gave each surviving Hopi family an ear of corn to put in their storeroom, where overnight it magically multiplied and relieved their hunger. The relation of this story is important for several reasons. First, it is evidence of the long memory of the Hopi people as told through traditional histories and of the importance of Sunset Crater in their past. It also gives insight into how a natural disaster can be
incorporated into ritual. Though the katsina religion is not believed to have its origin until several hundred years after Sunset Crater’s eruption (Adams 1991), this story may stem from responses contemporary with the disaster. In fact, the corn rocks found in posteruptive structures may share some significance with the corn associated with the Kana’a katsina (Elson et al. 2002). Finally, and perhaps most importantly for this study, the survival of a supernatural interpretation of the eruption of Sunset Crater may be evidence of a shared ritual regime among the posterruption population.

As stated above, the degree of social complexity of the posteruptive population is evaluated based on diversity of site type, site size, and presence of exotic trade goods. These variables are used as measures of differential and hierarchical organization of social, political, and physical infrastructure. It has been shown that at least a portion of the posteruptive population lived in aggregated settlements of multiple households. These communities constructed masonry architecture and pithouses, ballcourts, and manipulated cinder-laden fields. The U.S.89 Project recovered data from a variety of site types. Small habitations, large habitations, activity areas, field houses, special use/ceremonial sites, and limited activity/agricultural sites were all identified along the U.S.89 corridor (Elson 2006a). Site size also became more diverse after the eruption. Post AD 1100 residential sites range from two rooms to 27 rooms. Six of the 16 post eruption sites contain exotic shell, which is evidence of trade contacts with outside groups. The population after the eruption shows evidence of a more complex social, political, and ritual organization than was in place before the eruption of Sunset Crater.
Complex social and political infrastructure is implied in the coresidence of nonrelated groups and in ritual spaces. Ballcourts were probably used for ritual and social interaction, both of which contribute to a higher degree of overall complexity for the posteruption population. Research in other areas has suggested that increased complexity can result from environmental stress (Sandweiss et al. 1999). In other volcanic disasters, dispersed populations quickly aggregate into massive settlements, accelerating social or political processes already underway (Plunket and Uruñuela 2005). This appears to be what occurred at Sunset Crater.

The model suggests that after the eruption of Sunset Crater, the population would be pressured to move and to adapt. The archaeological record indicates that the posteruption population moved to lower elevation sites and adopted new farming techniques, settlement patterns, and architectural styles. New ritual practices may also have been adopted. These changes are a modest confirmation of the model and suggest that it has potential for continued testing and investigation. It is significant in that it can identify catalytic moments in prehistory. Disaster or catastrophe conditions can create a break in the continuity of behavioral patterns in which new ideas or a reconstitution of the organizational system can be introduced. The volcano did not force the population at Sunset Crater to undergo dramatic alterations. The model suggests instead that disaster conditions pressured the population to make a break from earlier patterns during which reorganization and reconstitution may have taken place.
CHAPTER SIX: DISCUSSION AND CONCLUSIONS

The archaeological and dendrochronological data indicate that the eruption of Sunset Crater took place in the late 11th century, probably between A.D. 1050 and 1125 (Ort et al. 2008), and lasted no more than a few years. The eruption had a rapid onset and prolonged and widespread effects. The population living in the vicinity of the volcano was dispersed, had no prior experience with a natural disaster on the scale of a volcanic eruption, and had a relatively low degree of social complexity. Given these criteria, the model predicts that the population would migrate, or migrate and adopt adaptations.

Movement in response to Sunset Crater is seen in the abandonment of the affected area and subsequent occupation of previously vacant areas. Evidence of adaptation includes changes in architecture and community organization, changes in subsistence practices, innovations in soil and water control, and the adoption of ritual infrastructure in posteruption contexts. Though similar transformations occur in other areas of the Southwest (Cordell 1997), the eruption of Sunset Crater was a catalyst for these changes in the Flagstaff area of northern Arizona. The model accurately describes the type of response predicted for a population under environmental stress of this kind.

To be an effective and useful tool for interpretation, a model must apply to diverse situations and conditions. Here, the human response to three historic and prehistoric environmental hazards is compared with those predicted by the model. These represent three different classifications of hazard and three different classifications of societies. The Irish potato famine, the fire of London, and the 13th century drought in the American Southwest are used as test cases. The power of the model and its ability to
identify the most likely human response are strengthened with its application beyond the Sunset Crater case study for which it was derived.

Irish Potato Famine

The Irish potato famine of AD 1845-1850 is an example of an environmental hazard developing into a catastrophe through a combination of environmental and social factors. The potato crop of 1845 failed in Ireland and also other parts of Great Britain and Europe. The majority of the Irish population lived on very small pieces of land (i.e., 45% lived on less than five acres), and depended on agriculture (Green 1994). There was a nearly exclusive reliance on the potato as a food crop because of its high yield per acre. Because potatoes are grown from the eyes of other potatoes and not typically from seed, there was a low genetic diversity among 19th century Irish crops, making them vulnerable to disease.

A fungus, *Phytophthora infestans*, attacked the monocrop, destroying yields (Green 1994). Starvation and disease quickly followed. Public welfare systems were unable to, or otherwise did not, relieve the population. Potatoes cannot be stored for longer than one year, making storage in advance of famine impossible. With no stored food, and little reliable food or income, an estimated one million people left Ireland during the famine (Green 1994). Another one million likely succumbed to starvation or disease. Therefore, a third of the original 6.5 million inhabitants either died or moved away.
If the potato famine is examined using the model of human response to environmental hazard, it is classified as having a rapid onset, long duration, and widespread influence. The population experiencing the blight were aggregated in some places and dispersed in others (Moody 1994). They had prior experience with failed potato crops and with famine (Green 1994). Irish society in the 19th century was highly complex. Under these conditions, the model predicts that the population would be pressured to migrate, both with a dispersed or an aggregated population. Historically, the population acted on the pressure to migrate, corroborating the model’s predicted human response.

The Fire of London

In the early fall of AD 1666, the city of London was a densely packed urban center that included the ancient medieval walled city and extended across the river Thames (Hanson 2002). Despite improvement efforts and bans on overcrowding, many buildings in the city had thatched roofs and had overhanging upper stories called “jetties” such that buildings nearly touched one another across narrow streets. In the early morning of September 2, 1666, fire broke out in a bakery on one of these crowded streets, Pudding Lane (Porter 1996). In the dry and hot weather, the fire quickly spread from Thomas Farriner’s bakery to the rest of the street. Reaction was not quick, and houses were not pulled down in front of the fire, allowing it to spread throughout London (The London Gazette, 3-10 September, 1666). The fire was intense and destroyed much of the city until it was finally extinguished on September 5, 1666. When the smoke cleared,
88% of all homes in the city had been destroyed (Tinniswood 2003). The fire of London is an interesting test case for the model of human response because the fire was caused by human action and came to an end because of human intervention. This makes urban fires unique among environmental hazards.

The fire of London had a very rapid onset and a short duration. The fire was widespread with reference to the city of London. Before the fire, the population was aggregated. They had prior experience with fires, but not on the scale of the 1666 event (Hanson 2002). The organization of political and social life of the population was complex. According to the model, the dominant pressures facing Londoners were equally to migrate and to stay in the city. Though seemingly ambiguous model predictions, these mirror the behaviors of the population after the fire. Under pressure from King Charles II, some of the population left the city. Others remained and began reconstruction efforts. The important aspect of the model’s prediction, “migrate or stay” is that it does not include pressure to adapt. After the great fire, London officials were inspired to rebuild the city according to contemporary style, but instead, the city was reconstructed using largely the same plan as before the fire (Tinniswood 2003), and adaptations were not made.

Though in reality the fire of London cannot be fully understood without reference to class dynamics and the prevalence of bubonic plague, the model of human response effectively identifies the pressures that were placed on the population due to environmental conditions. This suggests that while human society is complicated and populations do not always act in predictable ways, it is possible to parse environmental
pressures and work toward understanding their influence on behavior. Testing the model on historical situations in which much is known about the political and social composition of a society lends credence to inferences drawn about archaeological cases in which fewer societal details are known or preserved.

The Great Drought

In the 13th century, the Colorado Plateau was occupied by farmers dependent on corn agriculture. Tree-ring records show that beginning in AD 1276, precipitation in this area was extremely low (Douglass 1929). This pattern continued until AD 1299. The Great Drought was accompanied by other related environmental conditions, including downgrading of the water table and variability in precipitation patterns (Dean 2006; Gumerman 1988). Drought conditions and abnormal precipitation were long lasting and extended over a regional scale. This meant that reliance on social networks or trade for relief may not have been possible (Cordell 1997; Rautman 1993). Unable to produce or store food, this environmental hazard was disastrous for the prehistoric population.

The Great Drought was an event with a rapid onset but a long duration. Its effects were widespread throughout the Four Corners and the greater Southwest. Because the drought affected many groups differently, it is necessary to test the model against one group’s response. The population living along the San Juan River in the Four Corners area was aggregated into Pueblo III style villages and cliff dwellings, some with more than fifty rooms (Adler 1996). Drought is not unusual in the arid Southwest, though the AD 1276-1299 event was more severe and perhaps compounded by other factors. The
The Pueblo population therefore can be seen as having prior experience with drought and environmental stress, but no prior experience with an event of this magnitude. Pueblo social organization at this time and in this area was complex. Given these characteristics, the predicted response is movement.

The Four Corners area was either largely vacated in the drought years or saw an extreme level of mortality (Cordell 1997). Drought and other environmental degradations alone were not enough to cause complete abandonment of the Four Corners area. However, they were powerful “push” factors that stimulated regional emigration (Dean and Van West 2002; Van West 1994). Evidence for emigration exists in the sudden increase in population and construction at other locations in the Southwest following the drought. For example, in the Grasshopper region, site densities increase dramatically starting in the 1280s (Reid et al. 1996; Dean and Robinson 1982). Similarly, population increased in the Taos and Santa Fe areas of New Mexico after the drought (Crown et al. 1996). This may be because drought conditions were less severe along the Rio Grande, southeast of the San Juan region (Rose et al. 1981). Though the Great Drought and the human response to it continue to be discussed in Southwest archaeology, this model supports the hypothesis that people abandoned the Four Corners and migrated into areas with more favorable conditions.

The three test cases above show that a generalized model of human response to natural hazard can be an effective interpretive tool in diverse social scenarios, geographic locations, and environmental hazards. This is not to say that human behavior can be simplified into a combination of four possible responses. On the contrary, this model
illustrates that one kind of environmental hazard can place vastly different stresses on human populations depending on their social organization and preparedness. Likewise, the exact nature of the environmental hazard determines how a population would be most pressured to respond.

This model attempts to clarify what may otherwise appear to be limitless and unpredictable behavior in the face of environmental stress. As an interpretive tool, this model is intended for use in two ways. First, as has been illustrated here, the model can be used to understand the archaeological record. This work relies on and fosters interdisciplinary cooperation so that environmental and societal conditions can be compared. This work may be used when the disaster and population are well understood, such as the eruption of Mt. Vesuvius in AD 79, to better understand why and how people responded as they did. It may also be used as a guide for future research when the response to an event is yet unknown.

The second intention of this work is for use in modern disaster studies. As global climate and environment continues to change, natural hazards may become more frequent (Mann et al. 1998; Webster et al. 2005). Additionally, as global populations increase, human settlements may begin to occupy areas more susceptible to hazards or abrupt changes. Understanding the pressures populations face in specific situations may enable more effective and comprehensive disaster response. For example, along the Gulf Coast of the southern United States, major hurricanes have caused significant disruption of regional and national economies (Brinkley 2006). Knowing that, according to this model, a hurricane is likely to have a rapid onset, short duration, and widespread effects,
the resident aggregated, high complexity society with prior experience is most pressured to migrate or to stay in a storm. Unlikely to adopt adaptations for future events, it is more prudent for emergency planners to facilitate migration (e.g., clear evacuation routes, efficient transportation) and to prepare for a population that will remain (e.g., stored resources, first aid protocols, and reconstruction plans) (Troy et al. 2008).

The study of the relationship between human populations and the environment is a science that belongs neither to the present nor to prehistory. Both may inform the other such that the experiences of past cultures may prevent the suffering of the present, and modern behavior may be used to understand the actions of those in the past.
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