AN ABSTRACT OF THE THESIS OF

Stephan Edward Matz for the degree of Master of Arts in Interdisciplinary Studies in the co-departments of Anthropology, Geology, and Soil Science presented on May 28, 1987.

Title: The Effects of the Mazama Tephra-Falls: A Geoarchaeological Approach

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About 7,000 years ago two major tephra-falls blanketed the Pacific Northwest in volcanic ash. These two tephra-falls, identified as the Llao and climatic tephra-falls, were a part of the eruptive events that led up to the collapse of Mount Mazama to form Crater Lake in the southern Oregon Cascades. The tephra-falls occurred about 200 years apart at around 7,000 years B.P. and 6,800 years B.P. for the Llao and climatic eruptions respectively. The effects of the tephra-falls on the flora, fauna, and people of the period have been characterized by different researchers as ranging from minimal to catastrophic.

In an attempt to better understand the affects of these two events on the flora, fauna, and people, a model is presented to help organize the various lines of research into a coherent whole and to suggest profitable areas of research which have not yet been completed. The model is based on ecological and anthropological theory with a

strong reliance on analogy with modern ecosystems and volcanic hazards research.

The model makes use of the ecosystem concept as the framework for the interaction of the abiotic, or nonliving habitat, with the biotic, or living system. The biotic organisms are adapted to the characteristics of the abiotic habitat and in many respects the composition, frequencies, and distributions of biotic organisms are determined by their tolorance levels to these characteristics. Tephra-falls act as environmental disturbances which change the abiotic habitat of the ecosystem. Therefore, any changes caused by such a disturbance in the abiotic characteristics that are not optimal or are outside of the tolorance limits of the biotic (flora and fauna) components should cause changes in the composition, distribution, and frequency of organisms within the ecosystem. The changes brought about by the tephra-falls may be described by successional and evolutionary processes through analysis of pollen and faunal remains, population demography as described by mortality profiles, and research into the reaction of specific flora and fauna within adaptational types to the properties of tephra-falls and the tephra as a soil body.

The state factors used to describe the abiotic component of the ecosystem are: time, distribution, material properties, climate, and geomorphology. The state factor of time involves the determination of the occurrence in time of the event(s), the duration of the event(s), the season of occurrence of the event(s), and the residence time of tephra in the ecosystem. This state factor is used to define the specific point in time and duration of the effects of the tephra-

fall(s) for individual ecosystems. The state factor of distribution describes the aerial extent and thickness of the air-fall deposits. This state factor determines the extent of the initial disturbance. The state factor of climate describes the specific components of rainfall, wind, and temperature which control ecosystem composition and development, and the changes to the climate which may have occurred due to volcanic aerosols associated with the eruption. The state factor of geomorphology describes the location of tephra and nontephra bodies across the landscape and through time as the tephra is reworked by wind, water, and gravity from the initial air-fall positions. The determination of the long term distribution of the tephra is important in determining post-event influences on ecosystems as described by the material properties of the tephra.

It is argued that most people were not greatly harmed by the Mazama tephra-fall events themselves, but instead may have been greatly affected by a loss of food resources during and after the events. Changes in food resource availability and exploitation locations due to the tephra-falls may have resulted in changes in both settlement and subsistence activities. Changes in settlement and subsistence activities may be seen in a corresponding change in differential frequencies of functional tool types across space and time. The kind and amount of expected changes in settlement and subsistence systems are linked to distance from the source of the tephra, the stability and compostion of pre-disturbance ecosystems, the types and intensity of resource exploitation, and the amount of variability in subsistence and settlement traits which were available to the sociocultural system.

# The Effects of the Mazama Tephra-Falls: A Geoarchaeological Approach

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# THE EFFECTS OF THE MAZAMA TEPHRA-FALLS:

# A GEOARCHAEOLOGICAL APPROACH

## I. INTRODUCTION

About 7000 years ago a series of volcanic eruptions began on Mount Mazama, a stratovolcano, which stood at the present site of Crater Lake in southwestern Oregon (Figure 1). Over a period of approximately 200 years a series of eruptions sent lava-flows, mud-flows, and ash-flows sweeping down the mountain's flanks. At least two of these eruptions, the Llao and climatic phases, resulted in a blanket of tephra (fragmental volcanic debris) spread across the Pacific Northwest (Bacon 1983).

The climatic eruption which resulted in the collapse of Mount Mazama to form the caldera which is now Crater Lake has been given a Volcanic Explosivity Index or VEI (Newhall and Self 1982) of 6 (Simkin et al. 1981:86). For comparison, Mount St. Helens was rated at a 5 and Krakatau (Krakatoa) was rated as a 6 (Newhall and Self 1982). The VEI indicates that the closing phases of the Mazama climactic eruptions were of an Ultra-Plinian (Walker 1980) nature. An Ultra-Plinian eruption is marked by extreme violence, a high eruptive column (> 25 km above sea level), a relatively long eruption (> 12 hours), a substantial injection of fragmental debris into both the troposphere and the stratosphere (Newhall and Self 1982), and deposits consisting of extensive sheets of fragmental air-fall materials (Walker 1981b). The minimum area that is covered

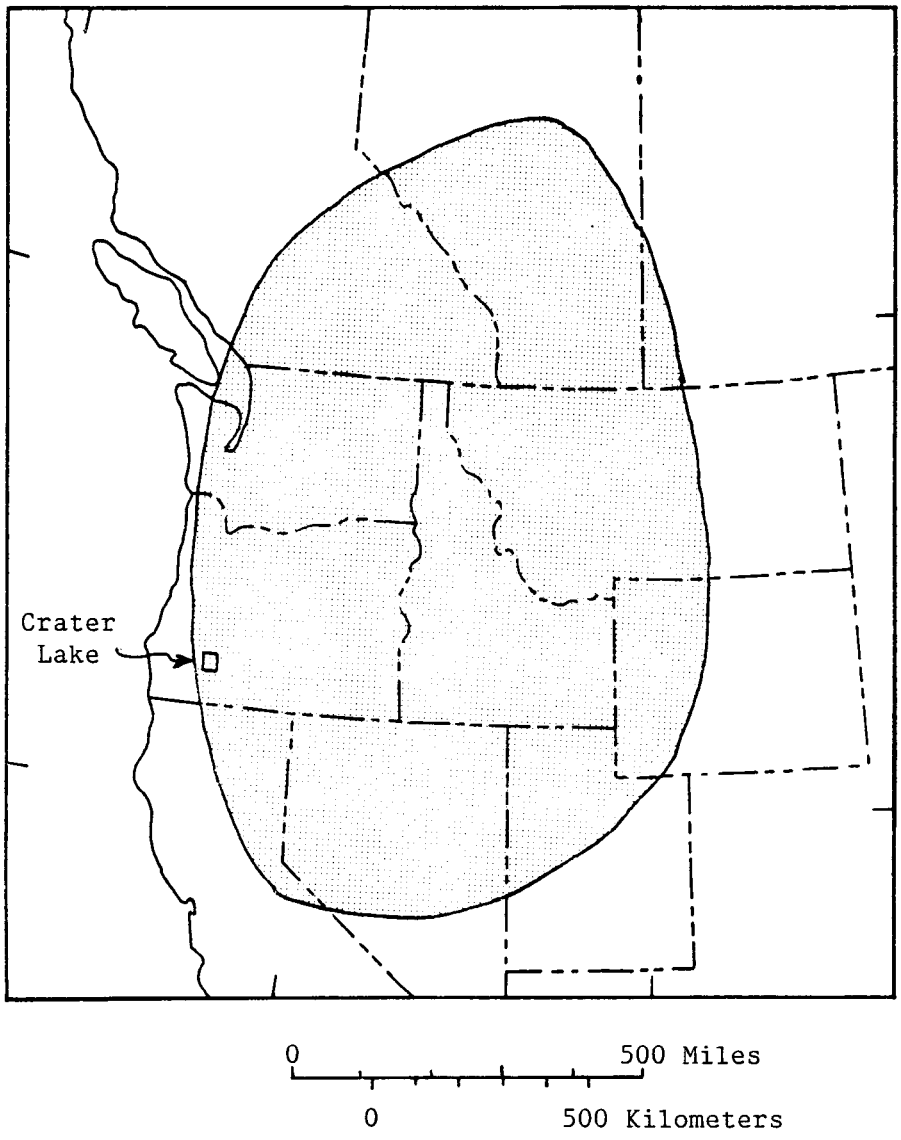


Figure 1. Location of Mount Mazama (Crater Lake) and minimum extent (1 cm isopach) of the Mazama tephras (after Sarna-Wojcicki et al. 1983:Figure 5.9).

by ash from the Mazama eruptions is 1.7 million km2 (Sarna-Wojcicki et al. 1983:68) and estimates of the total volume of fragmental material (corrected to original magmatic volume) that was erupted range from 30 to 64 km3 (Williams and Goles 1968; Lidstrom 1972).

Howell Williams (1941,1942) was one of the pioneers in the study of the cataclysm that produced Crater Lake. He described the initial eruptions that lead to the collapse of Mount Mazama to form Crater Lake in such vivid terms that his words no doubt inspired others (eg. Fryxell 1963:11-13; Malde 1964:10-11 among others) to wonder at the effects such an eruption may have had on the Pacific Northwest.

> Suddenly there was an ominous rumble underground, and a moment later a plume of steam rose from the crater. The slumbering mountain had awakened. Within a few moments the plume over the summit assumed a globular form and then with alarming speed, expanded into a giant cloud shaped like a cauliflower. The billowy mass rose miles into the upper air, and there the wind drew it out into fleecy banks that drifted to the east...
>
> Day after day, night after night, the eruption continued. There were brief intervals of comparative calm, but each was brought to a close by an outburst more violent than the one preceding. It was now exceedingly difficult to see what was happening on the mountain. Fine dust and the smoke from forest fires permeated the air. The hot, acid fumes were suffocating. As the activity grew in strength, the winds veered toward the northeast... Over thousands of square miles the air was so charged with dust that the days were darker than the blackest night. Far off, on the plateau to the east, small bands of Indians gathered in dumb horror about their campfires, too bewildered to flee for safety (Williams 1941:29-30).

Since the time that Williams wrote these words researchers in various disciplines have suggested the possible effects that this

eruption may have had on the flora, fauna, and people of the Pacific Northwest. Hansen (1942a, 1942b), through the use of pollen data, maintained that the forests immediately adjacent to the mountain were destroyed outright by the eruption while the forests further away were destroyed or changed by changing edaphic conditions brought about by the tephra-fall. More recent pollen data, from lakes and bogs in eastern Oregon and Washington, and western Montana suggest that grass production increased after the tephra-fall which may mean that herbaceous vegetation was significantly affected for at least several years (Blinman 1978; Blinman et al. 1979; Mehringer 1986; Mehringer et al. 1977; Aikens et al. 1982). Fryxell (1963) suggested the ash from the eruption covered wildlife forage, fouling all but the largest streams and water holes and caused people to abandon Marmes Rockshelter in eastern Washington for several hundred years. Malde (1964), argued that the effects of the eruption were widespread and catastrophic on plants, animals, and people.

Bedwell (1973) in his study of the Fort Rock area of eastern Oregon believed that the ash from the eruption had a drastic influence on the local human population and may have caused a temporary abandonment of the valley. Snyder (1981), found evidence for a change in tool types that she attributed to the Mazama tephra-falls at a site on the western crest of the southern Cascade Mountains of Oregon.

On the Lower Snake River, Galm (1975) identified the Mazama tephra-falls as one possible environmental stress that was responsible for culture change during the Cascade phase, and in the

Mid-Columbia region, he suggested that the tephra-falls contributed to a change in the settlement and subsistence patterns of the Vantage phase (Galm et al. 1981). Hammett (1976:181-182) agreed that the tephra-falls were an important catalyst to culture change along the Lower Snake River but believed that the effects were minimal and short lived. Shiner (1961), in the mid-Columbia region, compared the effects of the Mazama eruptions with those at Katmai in Alaska and concluded that the area was abandoned by people for several years until a return to normal conditions. Brauner (1975; 1976:306-307) concluded that the major effects of the tephra-falls on the Lower Snake occurred about 3000 years after the Mazama eruptions had ended when increased precipitation and down-cutting of the river systems caused the ash along with other sediments, to be reactivated thus ruining the salmon runs and thereby forcing a shift in settlement and subsistence during the Tucannon phase.

Other researchers contend that there is little or no evidence of widespread and catastrophic implications for the Mazama tephra-falls. Bense (1972), in a detailed analysis of lithic artifacts for 13 archaeological sites on the Lower Snake River, suggested that there was little or no influence on settlement and subsistence systems during the Cascade phase. In the Blue Mountains of Oregon, Brauner (1985; Brauner et al. 1983) postulated that a shift in tool technologies and settlement patterns were a result of the stress that the tephra-falls placed on the local peoples but could find no evidence for such a shift in the tool assemblages. Lyman (1980:125) found that the bivalve molluscs of the Columbia Basin showed no

stress due to ash in the river systems. Grayson (1979) found no evidence for abandonment of the Fort Rock area of south-central Oregon by fauna due to the tephra-falls, except for pikas.

## THE ERUPTIVE HISTORY OF MOUNT MAZAMA

The eruptive history of Mount Mazama has been studied by Diller and Patten (1902), Moore (1934), Williams (1941, 1942), McBirney (1968), Fisher (1964a, 1964b), Williams and Goles (1968), Lidstrom (1972), Mullineaux and Wilcox (1980), Bacon (1983), and others. Bacon (1983) does an excellent job of discussing the timing of the eruptions, the products of the eruptions, and the extent of the individual eruptions. For this reason Bacon's (1983) research will be used to give a brief sketch of the eruptions which led up to the collapse of Mount Mazama.

Mount Mazama began with the construction of Phantom Cone about 400,000 years ago and continued with episodic eruptions of mafic andesite, andesite, and dacite. About 22,000 to 15,000 years ago the magma chamber which would feed the eruptions leading to the collapse of the caldera and the emplacement of at least two regional pyroclastic deposits began. The eruptions of this period can be divided into two distinct phases, the pre-caldera collapse or preclimactic eruptions, and the caldera collapse or climactic eruptions. The preclimactic eruptions began as early as 7200 years ago with the Redcloud eruptive center.

The Redcloud eruptive center was located just east of the present caldera wall. The eruption may have begun as early as 7200

years ago or as late as about 7000 years ago. The eruption consisted of a small pumice-fall to the east of the mountain followed by a 100 meter thick rhyodacite lava flow with a minimum volume of 0.2 $km^3$.

The Llao Rock eruptive center is located in the present caldera wall. The eruption is dated at about 7015 +/- 45 years B.P.. The eruption began with the emplacement of a widespread air-fall deposit mostly to the east of the mountain which was followed by a rhyodacite flow. An ash that has been correlated with the Llao ash-fall has been found in northern and southeastern Washington, southeastern Oregon, and in western Nevada.

The Grouse Hill lava flow and dome are older than the climactic eruption and younger than the lower pumice-fall. The dome and flow are of limited extent around the mountain and have a combined volume of at least 0.5 $km^3$

The Cleetwood eruptive center produced a rhyodacitic flow which can be seen in the caldera wall. The climactic eruption occurred so soon after the Cleetwood eruption that material from both were mixed at the interface. A small volume of air-fall material created a ring around the mountain locally. The minimum amount of lava that was deposited was about 0.6 $km^3$.

The climactic eruption can be divided into two phases, the single vent phase and the ring vent phase. The collapse of the caldera may have caused the change from one phase to the other. The single vent phase consisted of two units erupted successively from the same vent. The first unit emplaced was the climactic pumice-

fall and the second unit was the Wineglass Welded Tuff. The ring vent phase consisted of ash flows deposited over the Wineglass unit.

The single vent phase began with the eruption of a plinian column and emplacement of the climactic pumice-fall. This material fell mainly to the northeast of the mountain and was at least 20 meters thick at the caldera rim and as much as one centimeter thick in southwestern Saskatchewan. The Wineglass Welded Tuff was emplaced almost immediately afterward, probably from the collapse of the eruptive column. At the caldera rim the tuff was up to 10 meters thick and in canyon mouths, 11 km to the east, it was a few meters thick. All of the juvenile single vent materials were of an identical rhyodacite composition.

The ring vent phase started as the mountain began to collapse to form the present caldera. A large amount of welded tuff was deposited locally with some fine ash being scattered much farther to the east. The deposits of this phase can be divided laterally into proximal, medial, and distal facies. The proximal facies consisted mostly of ash-flows up to 20 meters thick that graded into the medial facies at 2-11 kilometers from the caldera. The medial facies consisted of three compositional zones and a number of flow units which were emplaced up to 20 km from the caldera. In the deepest valleys these deposits were in excess of 100 meters thick. The distal facies mostly consisted of nonwelded ash-flow deposits correlated with zone 1 of the medial facies. These deposits were emplaced as far as 60 kilometers from the caldera. Ash-cloud deposits tend to overlie and extend beyond the ash-flow deposits.

See Figure 2 for a diagrammatic representation of the major deposits.

The climactic single vent phase and ring vent phases occurred about 6800 years ago. The ring vent phase probably followed the single vent phase by no more than a few days.

## OBJECTIVES AND RATIONALE

As can be seen from the brief discussion above there is a good deal of interest in the possible effects of the Mazama tephra-falls and some controversy as to just what influence the event may have had on flora, fauna, and people. The study of the Mazama tephra-falls offers a chance to study how an event of extreme magnitude and possibly of far reaching ecological consequences affected the flora, fauna, and human populations of the Pacific Northwest. Such a complex study has unique needs and must be approached from a multidisciplinary aspect. An assessment of the problem and research needs should be undertaken to determine what is actually known and what needs to be known of the physical manifestations of the event.

The major objective of this thesis is to review what is known of the physical aspects of the Mazama tephra-falls within a model which should help clarify how the flora, fauna, and people of the Pacific Northwest may have been influenced. Besides detailing what is known about the event such a model can be used as a research design that should help to direct the study of the event.

This approach is important for a number of reasons. There has never been an in-depth synthesis of the events and physical

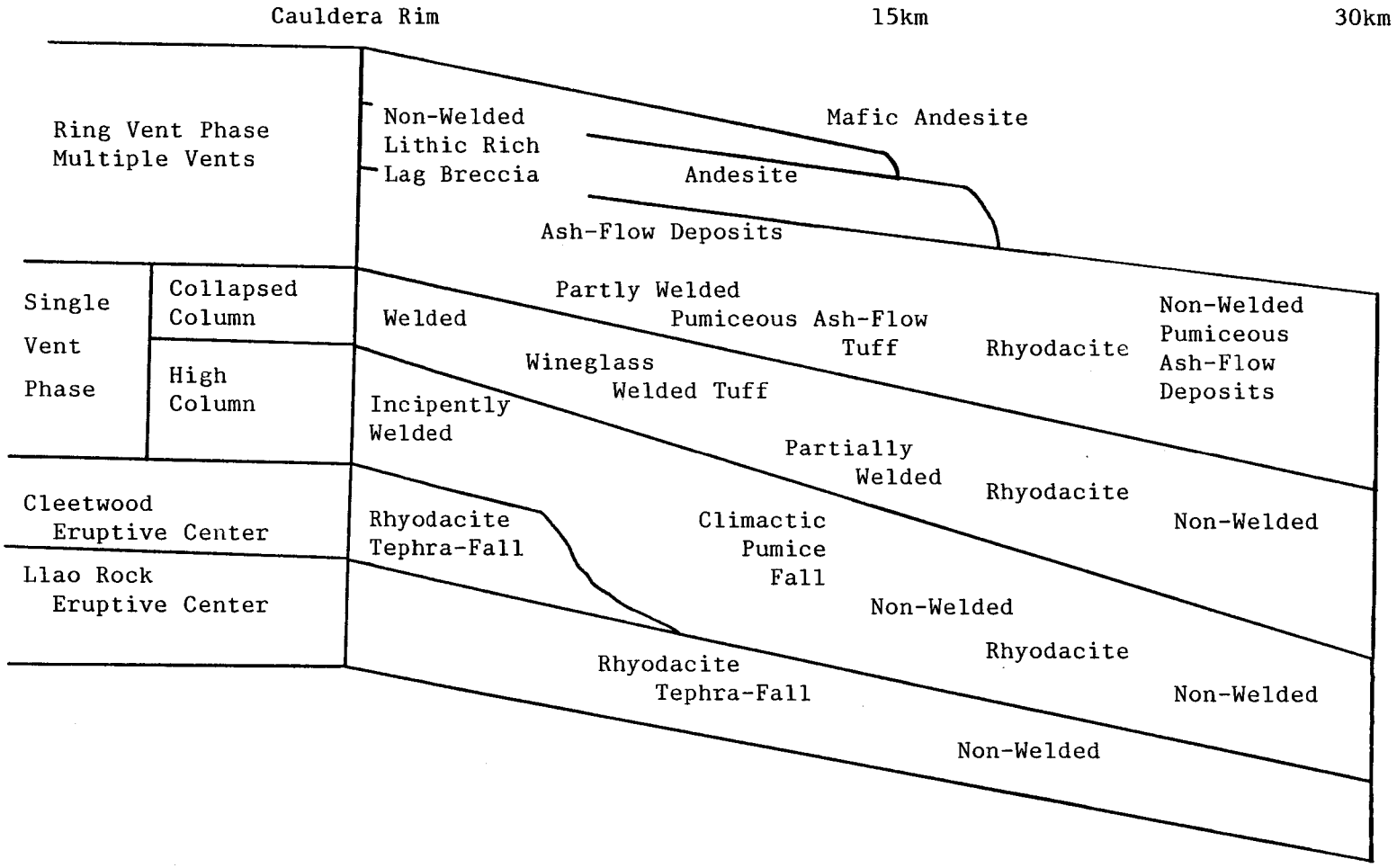


Figure 2. Diagrammatic representation of pre-climactic air-fall deposits and the proximal climactic deposits. Thickness not to scale. Adapted from Bacon (1983).

manifestations of the Mazama eruptions and the subsequent influences on the plant, animal, and human relationships of the Pacific Northwest. This thesis brings together the studies of human ecology and volcanic hazards through the fields of geology, soils, biology, and archaeology to investigate these questions and so is of a multidisciplinary nature which is needed in the study of such a complex issue. The multidisciplinary nature of this thesis allows it to be used as a starting point for a more intense study of many of the questions concerning the effects of the Mazama eruptions. Valuable archaeological and biological data about the Mazama tephra-falls can be lost due to an inadequate understanding of what is needed to answer questions pertaining to the effects of the Mazama tephra-falls. A research design which can be used to answer these questions can correct this problem. Studies of past volcanoes and their effects may help to direct future research or provide answers to modern volcanic hazards research.

## THE SCOPE AND ORGANIZATION

While the proximal lava and ash-flows were no doubt devastating to the surrounding ecosystems (See Blong 1984 for a discussion of the hazards associated with these types of events) they were of limited scope, no more than 30 to 60 km to the northeast of the mountain. It has been the ash-falls that have been of interest to archaeologists due to their widespread occurrence.

The Llao and climactic phases have produced widespread blankets of tephra. Tephra consists of three main sizes, blocks and

bombs, lapilli, and ash which are 64mm and above, 2 to 64mm, and less than 2mm in size respectively. Blocks and bombs are deposited close to the vent due to their size, while lapilli and ash may be carried for great distances on the wind. Therefore, for the purpose of this thesis, the Llao and climactic tephras consisting of mostly lapilli and ash size particles will be the prime focus of research.

The known distribution of the Mazama tephra-falls is given in Figure 3. The tephra-fall covers a minimum area of nearly 1.7 million km2 (Sarna-Wojcicki et al. 1983:68) across the western United States and southern Canada and so in order to make this discussion more manageable the area to the east of the Cascade mountains in Oregon and Washington will be the major focus, since this is the area that received the heaviest Mazama tephra-falls.

In Chapter II the model of the effects of the Mazama tephra-falls on ecosystems, flora, fauna, and humans is outlined. Within Chapters III through VII the state factors which are introduced in Chapter II are discussed with reference to what is known about the Mazama eruptions and how the components of each state factor interact. The purpose of each chapter is to detail the physical manifestations of the tephra-falls within a model which will give the general principles of how tephra-falls may affect flora, fauna, and people. Chapter VIII will summarize the model of the effects of the tephra-falls on the ecosystems of the Pacific Northwest and identify specific questions that need more research or that have not yet been addressed.

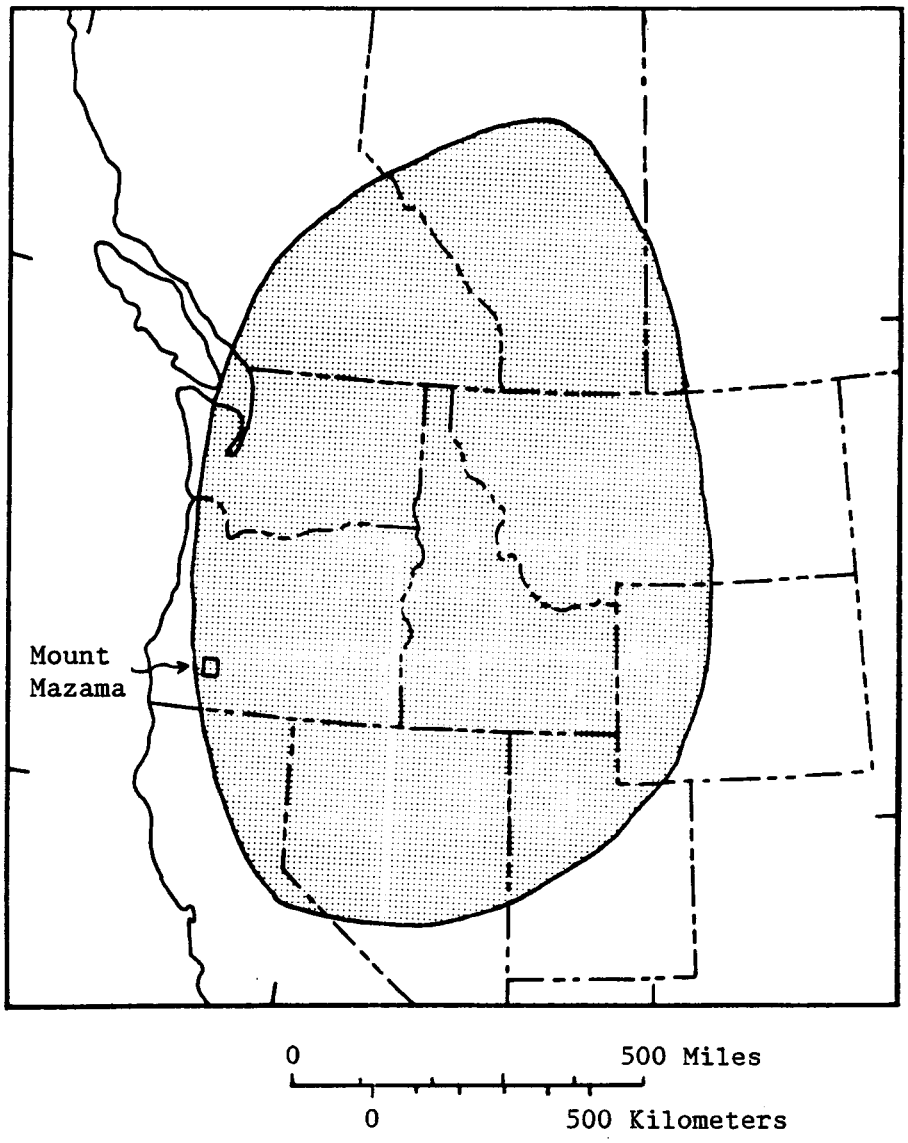


Figure 3. Minimum extent of the Mazama tephras within a 1 cm isopach (after Sarna-Wojcicki et al. 1983:Figure 5.9).

# II. THE MODEL

## INTRODUCTION

In this chapter a description of the model and a discussion of the concepts which will be used is presented. A brief discussion of the model building process is included at the beginning. The major ecological concepts are presented next which are based on systems theory, ecological theory, and evolutionary theory. These concepts should provide a background and a framework by which the effects of the Mazama tephra-falls may be better understood. The model of ecological interactions will be presented after discussion of the concepts. Then a discussion of the concepts as they apply to human systems will be presented. The model will help to organize and make the discussion in the chapters to follow more easily understood.

## THE MODEL BUILDING PROCESS

Both Clarke (1972) and Gibbon (1984) provide discussions of model building which have been adapted for this discussion. Models are heuristic devices which can be used to structure observations or play with ideas so that conclusions may be drawn. By modeling it is possible to take complex situations, pick out the relevant or important variables and arrange these variables into an approximation of reality. The model can be tested against the real world and if found lacking, the variables may be deleted,

rearranged, emphasized or deemphasized, and tested again. Models are important in the scientific method because they may lead to the construction of theory and almost surely will help to make complex situations more easily understood (Clarke 1972; Gibbon 1984).

## DISCUSSION OF PERTINENT ECOLOGICAL CONCEPTS

In this section the concepts that will be used in the chapters to follow will be discussed. These concepts are the basic theoretical underpinnings of the model and will help to make sense of the material in an explanatory way and to identify research needs. There will be seven subsections. The first includes a discussion of systems theory which is important as a structural device for explaining how complex systems work. The second defines the components of natural ecosystems. The third deals with adaptation and discusses the major ways in which organisms interact with the environment. The fourth and fifth (evolution and ecological succession respectively) discusses change in natural ecosystems and explores the two major ways in which natural ecosystems change. The sixth section deals with stability in ecosystems which is important for understanding under what conditions ecosystems may change. The seventh section discusses the measure of population demography as a way of understanding and testing assumptions about past population dynamics. These sections are just brief overviews and so it is suggested that for more indepth discussions the cited references should be referred to.

## Systems Theory

Systems are an interrelated network of attributes or entities that form a complex whole. This complex whole is made up of a set of components or subsystems with states or values that change sequentially with space or time or both. This means that the component attributes or entities are interrelated in such a way that a change in one may trigger a change in another. These changes or transformations take place in space and in time from one state to another state along a specific path called a trajectory. These changes may be stimulated by the external world acting on the system (Clarke 1978).

Systems work by unidirectional stimulus as well as positive and negative feedback loops. The connections between attributes or entities within a system may be of a unidirectional nature where entity one ($E_1$) stimulates entity two ($E_2$) with no feedback to $E_1$ from $E_2$. The connections may also be joined in a feedback loop where the $E_1$ transforms $E_2$ and at the same time is transformed itself. Negative feedback occurs when the transformation back to $E_1$ from $E_2$ causes the output of $E_1$ to diminish. Positive feedback is the opposite transformation, where feedback from $E_2$ causes the output of $E_1$ to increase (Clarke 1978). The feedback process is important in establishing equilibrium in systems (Forman and Godron 1986).

## Ecosystems

The word ecosystem dates from Tansley (1935) but the idea of an ecosystem has a much longer history (Major 1969). The term ecosystem generally refers to the interaction of living organisms (biotic component) with their nonliving (abiotic component) habitat (Tansley 1935; Evans 1956; Major 1969; Odum 1969; Kormandy 1976). The fundamental unit of study for the biotic portion of an ecosystem is variously given as the individual or organism, the species which is a group of similar kinds of individuals (Ricklefs 1979), the population or all the individuals of a given species in an ecosystem, the community or all of the populations in an ecosystem (Clapham 1983), and the biome or a group of interrelated communities (Evans 1956, King and Graham 1981). Each of these units is important to different kinds of studies or different research questions and strategies.

The abiotic portion of the ecosystem consists of a "physio-chemical setting" or "sets of environmental substances and gradients" (Kormandy 1976). This physio-chemical setting consists of inorganic substances and compounds, organic compounds, and physical factors and gradients which can generally be lumped into the geomorphology, soils, and climate of a specific landscape. The geomorphology describes the long history of the landscape from a geologic perspective on which the ecosystem exists (cf. Swanson 1980). The soil describes the various physical and chemical properties of the thin mantel in which plants grow and animals

depend (cf. Jenny 1980). The climate describes the factors of moisture and temperature and their general overall availability (Forman and Godron 1986).

The biotic portion of the ecosystem can be characterized as consisting of floral and faunal organisms, species, populations, and as interacting groups of communities or biomes. The major source of interdependence for the biotic component is the search for energy. This search results in what can be referred to as the food chain. The food chain is a very simple model for showing the flow of energy and materials through the community. The grazing food chain consists of the uptake of energy through photosynthesis and chemical nutrients by plants, the consumption of the plants by herbivores, and the consumption of herbivores by carnivores. Each step of the chain passes on a portion of the energy and nutrients to the next step (Clapham 1983). Change in one link of the chain may cause changes in other parts of the chain.

Through the food chain the biotic component responds to the abiotic component in the ecosystem according to each individual's physical requirements. That is, each individual, or considered as a collection of individuals, each population, has specific abiotic requirements. If one or more of the essential abiotic requirements are outside of the tolerance of the organism it will not be able to survive. If the abiotic requirements are fulfilled at a minimal level, the organism will not reproduce at as great a potential as if the requirements were at an optimal level. Therefore, the organism, to exist or thrive in an ecosystem, needs to have these physio-

chemical factors to be within it's tolerance, even though none of them have to be at an optimum level (Clapham 1983).

Ecosystems then consist of two major components or subsystems which are the biotic and abiotic. The state of each is the result of interactions within the individual subsystem and between subsystems. The biotic subsystem can be thought of as consisting of floral (fl) and faunal (fa) subsystems. The abiotic subsystem can be thought of as consisting of the climate (c), geomorphology (g), and soils (s).

The concept of the ecosystem plays the role of the main structure within which the components interact. A disturbance, such as a volcanic tephra-fall, must be viewed as acting on this framework and not just on the individual organism, population, or community. A tephra-fall can shift the characteristics of the abiotic component of the ecosystem out of the tolerance range of individual species. In this case the organism will become locally extinct. In many cases however, the tephra-fall will cause a change in the abiotic system to a less than favorable, but nonlethal state for the organism. This causes the frequencies of individuals for a certain habitat to change but does not necessarily change the composition of the biotic component. As the "lower" species in the food chain increase or decline in numbers so do the "higher" species that depend on them for sustenance. Species which are not directly affected by an environmental stress, such as a tephra-fall, may be affected indirectly through their dependence on other species. For

this reason it is important to ascertain these ecosystem interactions.

## Adaptation

The tolerance range within the actual environment or ecosystem is referred to as the organism's ecological niche. That is, the unique morphological, physiological, and behavioral attributes that the individual has within the ecosystem (Kormandy 1976). The ecological niche corresponds to the individual's role in the ecosystem or its adaptation.

Growth forms of plants are their functional adaptive types and can be a key to the plant's niche. They include such features as stratification, type of branching, periodicity, and leaf type (Clapham 1983). Table 1 shows the major growth forms for terrestrial plants.

Adaptive types of animals are analogous to growth forms in plants. Adaptive types include place in the food chain, position within the stratification of the community, means of locomotion, size, and certain behavioral characteristics (Clapham 1983). Table 2 gives the major adaptive types for land vertebrates.

These adaptive types or growth forms reflect the influence of both the biotic and abiotic components of the system, but in many ways it is the abiotic component which limits the range of a population. This concept provides a means by which the possible effects of a tephra-fall on individuals and populations can be identified without considering each individual. Specific species

Table 1 . Major Growth Forms for Terrestrial Plants (After Clapham 1983:Table 8.3).

Trees: Larger woody plants, mostly well above 3 m. in height, inhabiting canopy and understory layers
- Needle-leaved, mainly conifers
- Broadleaved evergreen, mainly tropical and subtropical forms, most of which have medium sized leaves
- Evergreen-sclerophyll, with small, tough, evergreen leaves
- Broadleaved deciduous, shedding leaves in tropical dry season or temperate-zone winter
- *Thorn-trees, armed with spines, in many cases compound deciduous leaves
- *Rosette trees, unbranched, with a crown of large leaves as in palms and tree ferns

*Lianas: Woody climbers or vines

Epiphytes: Plants growing wholly above the ground surface, on other plants

Shrubs: Smaller woody plants, mostly below 3 m. tall
- Broadleaved deciduous
- Evergreen-sclerophyll
- *Rosette shrubs
- Stem succulents, such as the cacti
- Thorn shrubs
- Semishrubs, with the upper parts of stems and branches dying back in unfavorable seasons
- Shrubs or dwarf shrubs, spreading near the ground surface, less than 25 cm. high

Herbs: Plants without perennial above-ground woody stems
- Ferns
- Graminoids, the grasses, sedges, and other grasslike plants
- Forbs, herbs other than ferns and graminoids

Thalloid plants: Very low nonvascular plants with an encrusting habit
- Lichens
- Mosses
- Liverworts
- Algae

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* Not found or rare in study area

Table 2. Major Adaptive Types for Terrestrial Vertebrates (After Clapham 1983:Table 8.4).

- Herbivores
  - Ground-dwelling
    - Running
      - Large narrow-hooved ungulates of the grasslands
      - Large broad-hooved ungulates of moist forests
      - Large running birds: ostrich, rhea, emu, etc.
    - Jumping
      - Small gnawing animals: rodents, rabbits, wallabies
      - Large fast-moving animals: kangaroos
    - Heavy
      - Armored slow-moving animals: armadillos, turtles
      - Unarmored exclusively terrestrial animals: elephants
      - Unarmored amphibious animals: hippopotami
    - Digging
      - Small, gregarious animals: prarie dogs, etc.
  - Tree-Dwelling
    - Small gnawing nut-and-leaf eaters: squirrels, etc.
    - Large fruit-and-leaf eaters: monkeys, oppossums, etc.
  - Flying
    - Large fruit-eaters: bats
    - Small nut-eaters: birds
    - Small nectar-drinkers: hummingbirds
    - Small parachuters and gliders: flying squirrels, etc.
    - Water and shore birds
- Carnivores
  - Ground-dwelling
    - Large cursorial carnivores: wolves, varanid lizards
    - Small cursorial carnivores: weasels, civets, lizards
    - Large springing carnivores: cats
    - Omnivores: racoons, bears
    - Legless carnivores and insectivores: snakes
    - Large insectivores: anteaters
    - Small insectivores: toads, lizards, salamanders
    - Carrion feeders: hyaenas, etc.
  - Digging
    - Large fossorial carnivores: badgers, etc.
    - Small fossorial carnivores: ferrets, some snakes
  - Aerial
    - Small insectivores: some birds, bats
    - Carrion feeders: vultures, buzzards, condors
    - Large raptors: hawks, owls, eagles
  - Amphibious
    - Large armored carnivores: alligators
    - Small insectovores: frogs

may be grouped into adaptive types which may be treated in a general sense as equivalent in their response to a tephra-fall. This provides a way of discussing the effects of a tephra-fall on the large numbers of species in a diverse habitat within a manageable framework. For more precise applications or unusual situations individual species should still be considered.

## Evolution

Ecosystems are dynamic and constantly changing in both space and time due to the interactions of the abiotic and biotic components. Fundamental change at the organism level or within a population is referred to as evolutionary change or evolution. Evolution, through the process of natural selection, acts upon variability within the genetic material of the organism and in many instances changes the organism so that it is better adapted to existing or new conditions. The organism that is more fit in a reproductive sense will be selected for in relation to the other members of the population. That is, the individual which can survive to reproduce will pass down more genetic traits than one that does not reproduce (see Williams 1966 and Sober 1984 and the references contained therein for excellent discussions of evolution).

Both evolution and adaptation are dependant on the process of natural selection. Evolution describes the manner in which organisms become adapted to changing environments. In this context, evolution may play an important part in the long term state of the

ecosystem after a dramatic disturbance event, such as a large tephra-fall, has occurred. This is especially true for new types of habitats created by especially disastrous tephra-falls where new species may be created through evolutionary change to fill a new niche. Evolution may also play a role in bringing about more subtle changes in an organism. For instance, at Mount St. Helens, where eruptive periods are separated by only 100 to 500 years within the last 3,500 years some Douglas fir forests northeast of the volcano may have become genetically adapted to repeated tephra-falls (Means and Winjun 1983).

Due to the relatively slow rate of evolutionary change and the diversity of species available to colonize even drastically altered terrains, the development of entirely new or significantly altered forms by evolution is not considered an important factor for this study. Instead, a different approach to change is needed, one which explains how frequencies of preadapted organisms adjust in response to the changing abiotic habitat.

## Ecological Succession

In contrast to a strict interpretation of evolutionary change, community change through ecological succession is defined as the cyclic change or reaction of the community to the progressive development in regional environmental factors (Clapham 1983:146). Succession can be thought of as the oscillation of the parameters of the ecosystem around a central tendency. The central tendency is the path that a stable biotic community follows in its development

under stable abiotic conditions. As the abiotic conditions change, the biotic system responds by changing species composition or population densities to meet the new requirements demanded by the abiotic habitat.

Ecological succession therefore is involved in predictable change due to minor perturbations in the environment or the natural tendency toward equilibration within the existing environment. A tephra-fall is one source of disturbance which can cause a change in the ongoing successional process. The results of such a disturbance can range from no effect on succession to a completely new successional pattern, depending on how much disturbance is caused to the ecosystem. In the case of a catastrophic tephra-fall event a new successional pattern may emerge which could be significantly different from the old pattern. At the very least, the successional cycle will be reset and the vegetative and associated faunal patterns will be disrupted. How much disruption is caused by the event is determined by the severity of the tephra-fall and by the stability of the ecosystem.

## Ecosystem Stability

Stability is an important concept for understanding the dynamics of an ecosystem over time and space as well as under stress. The following discussion of ecosystem stability is adapted from Forman and Godron (1986).

Variation curves describe the changes in a landscape as a function of time. They can be characterized by three independent

parameters: 1) the general tendency of change, that is whether the trend is increasing, decreasing, or level; 2) the relative amplitude of oscillation around the general tendency, that is whether the oscillation is large or small; 3) the rhythm of the oscillation, whether it is regular or irregular. These three parameters can be combined to create 12 different patterns of variation. These are presented in Forman and Godron (1986:Figure 12.3).

Of the above patterns, variation curves with a level tendency and small or regular oscillations are stable. This is true because biological stability is actually a state of metastability or equilibrium where oscillations occur around a central position. The ecosystem can deviate from this stability or equilibrium but in doing so tends to seek a new stability. A system is unstable if a small environmental change can divert the system from its metastable state. The fluctuations in a stable system are statistically predictable while the fluctuations in an unstable system are not.

Resistance is the ability of the system to withstand variation when subjected to an environmental stress. Resilience is the ability of the system to return to the prior equilibrium conditions.

Most ecosystems follow a long term tendency to increase in biomass, the total weight of living things in an area, over time and several successions. A model of a metastable system is presented in Figure 4 that shows the relationship between biomass and time. The following five ecological patterns are derived from this model: 1) The ecosystem developes along points A to B to C to D, so that biomass progressively increases if nothing disturbs it and as the

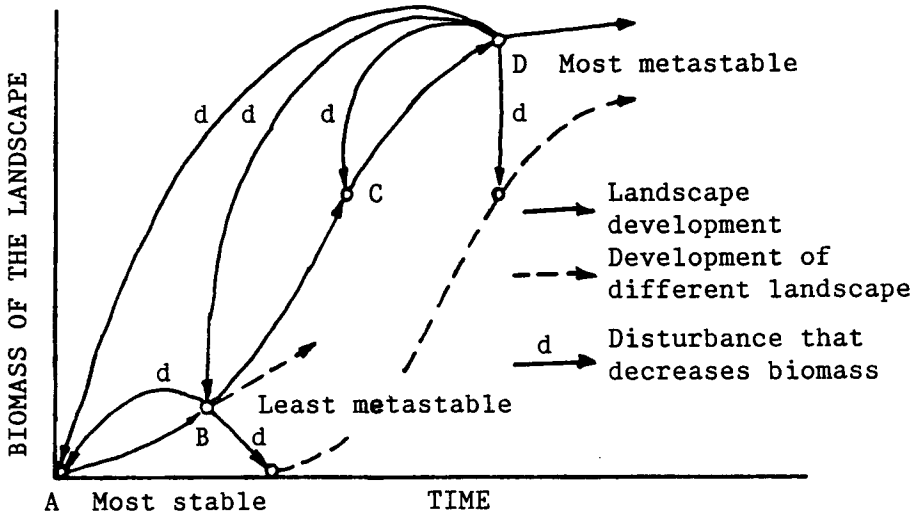



Figure 4. Metastability model of an ecosystem. Biomass increases through successional changes. Most disturbances decrease biomass. As metastability increases, greater environmental changes are needed to disturb the system. The effects of a tephra-fall may range from very little disturbance to the creation of an entirely new successional pattern depending on the metastability of the ecosystem and the violence of the eruption. Points A, B, and D represent the three basic types of metastability (after Forman and Godron 1986:Figure 12.6).

ecosystem reaches its maximum biomass the biomass levels off in a sigmoid fashion; 2) Disturbances such as heavy tephra-falls may decrease biomass or if the blanket is thin it may increase biomass; 3) "Most-stable", that is "barren" physical or mineralogical systems cannot lose biomass, but they may change rapidly to a low metastable ecosystem by landscape development (biomass accumulation), biomass-increasing disturbance, or they may remain unchanged; 4) "Low-metastable" systems have little resistance to biomass-increasing or biomass-decreasing disturbance, but may recover rapidly from biomass-decreasing disturbance if seeds or sprouts are abundant; 5) "High-metastable" systems have high resistance to many different disturbances but usually do not recover very quickly if at all, because their feedback loops are destroyed or considerable biomass is lost.

Within the Pacific Northwest, the concept of metastability models outlined above can be used to understand the consequences of an event such as the Mazama tephra-falls on various ecosystems. Stable ecosystems are essentially barren and include rock outcrops, barren talus slopes, unstable sand dunes, unvegetated river bars, and etc. Low metastable systems consist of numerous high production, short lived species such as found in grasslands and deserts. High metastable systems consist of long lived, low production species such as found in forests.

The stability of an ecosystem, is an important concept in understanding how an ecosystem may change when subjected to stress. An understanding of the different effects of stress (amount of force

over a specific area) on an ecosystem gives some clue to the levels of strain (amount of change) on an ecosystem.

Varying amounts of stress can cause varying levels of strain from very little to complete change. A low level stress produces an oscillation around a central position so that change takes place but the whole is still in equilibrium over time. A light dusting of volcanic ash may cause some plants to be killed, but by the next season more are established due to increased nutrients. Moderate stress causes the ecosystem to return to the prior equilibrium state after the disturbance has occurred. In this case a few centimeters of ash causes the death of a number of plants across the landscape but within the next few years the ash is incorporated into the soil and the old landscape is reestablished. Severe disturbance results in a new landscape equilibrium. An example of such a disturbance can be seen on the pumice plain of central Oregon where the thick mantle of pumice deterred much of the former herbaceous vegetation from being reestablished even though the major tree species could continue to exist (Dyrness and Youngberg 1966). A drastic or cataclysmic disturbance causes landscape replacement so that the old ecosystem disappears and is replaced with a new one. The proximal portion of the blast zone at Mount St. Helens (Lipman and Mullineaux 1981) is an example of where the entire landscape has been changed and a new ecosystem will replace the old.

## Demography of Populations

Demography is the study of the birth and death processes which determine the age structure of populations and rate of change in population size (Ricklefs 1979:423). The basic statistics of demography involve the determination of the probability of an individual's death and the fecundity of an individual at any age within the population. The statistics for determining these probabilities are discussed and example of their use is found in Ricklefs (1979) in general for both plants and animals, in Silvertown (1982) for plants, in Tanner (1978) for animals in general, and Caughley (1966) for mammals.

The life table is a summary of the survival and reproductive performance of a population under specific conditions (Ricklefs (1979:432). The major statistics include age (x), survival ($l_x$), fecundity ($b_x$), expected offspring ($l_x b_x$), and product of age and expected offspring ($x l_x b_x$). From this table the population growth rate and the expected age composition may be determined for any period within the life cycle of the population.

The use of such a table for both plants and animals could be important in establishing the dynamics of natural and stressed populations under various conditions of tephra-falls. Mortality profiles, that is a profile derived from the life table, describes the fraction of the population of the same age (cohort) that dies during the interval (X, X+1) (Caughley 1966). Mortality profiles can be used to determine whether the population died under natural

attrition or by catastrophic mortality conditions (Deevey 1947) and with some limitations can be used on past populations (Caughley 1966; Voorhies 1969; Klein and Cruz-Uribe 1984; Lyman 1987). "Attritional" mortality profiles show a "U-shaped" pattern due to an over representation of very young and very old individuals because of greater rates of mortality than reproductively active individuals under normal conditions. "Catastrophic" profiles that are "L-shaped" show a synchronic view of the population because of the relatively instantaneous death of the population as a group. In this case, virtually all age groups are represented in the profile in the same proportions that they occurred in while living (Lyman 1987). These two profiles are shown in Figure 5.

Life tables for species, along with experimentation and analogy, can be an important tool in understanding the effects of the Mazama tephra-fall. They can provide insight into general population growth and parameters and so help model how certain species might be affected by tephra-falls. They can also act as sources of data for testing insights about past populations as they are found in archaeological and paleontological sites.

## EFFECTS OF TEPHRA-FALLS ON ECOSYSTEMS

There have been many studies of the effects of tephra-falls from volcanic eruptions on various ecosystems which provide analogies to the effects of the Mazama eruptions on past ecosystems. Unfortunately, many of these studies are not directly comparable to the Pacific Northwest and the Mazama tephra-falls. Many studies are

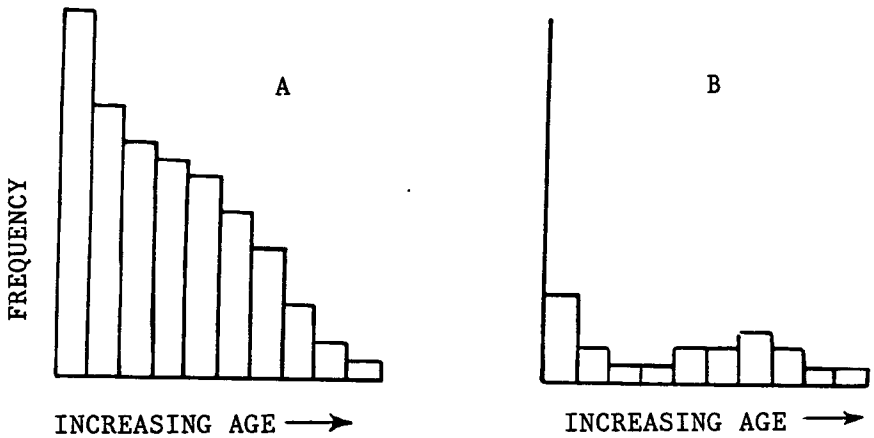



Figure 5. Examples of catastrophic mortality profile (A) and attritional mortality profile (B) (after Lyman 1987:Figure 1).

of volcanic systems which are essentially different in composition, such as the basaltic tephra of Iceland (eg. Thorarinsson 1979), have a different type of eruptive character, such as the lateral blast at Mount St. Helens (eg. Lipman and Mullineaux 1981; Keller 1982), or are of a much smaller magnitude, which includes almost every other volcanic eruption of historic times. Many studies are in different ecosystems than those of the Pacific Northwest, for instance Paricutin is surrounded by a subtropical ecosystem (Eggler 1948, 1959, 1963, 1967; Rees 1970, 1979). Many studies deal with agricultural plants (eg. Gough et al. 1981) and domestic animals (eg. Preston et al. 1982). Most of the studies on people deal with modern societies and their responses, although some notable exceptions do exist (cf. Sheets and Grayson 1979). Even though these studies are not directly comparable they should help to identify many of the generally applicable factors in understanding the effects on past ecosystems.

## Volcanic Hazards Due to Tephra-Fall

According to Blong (1984) the major hazards produced by tephra-fall are due to accumulation of the deposit, which is described by the thickness of the tephra-fall deposit, hot tephra particles which may burn organisms or start fires, and the extreme darkness caused by the falling tephra. These hazards should decrease exponentially as the distance from the source increases.

Gases and acid rains are also a source of hazard which can accompany tephra-falls (Blong 1984). Gases may be spread as acid

aerosols, as compounds absorbed onto particles, and as salt particles (Thorarinsson 1979:142). The amount of gases that are transported in an eruptive column is proportional to the explosivity of the eruptive episode (Oskarsson 1980), and amount and chemistry of the magma.

Climate and Tephra-Falls

Volcanic eruptions can influence climate through the injection into the stratosphere of volcanic aerosols from high eruption columns, from ignimbrite deposition, and from degassing of near-surface non-eruptive magma bodies. Major plinian columns can reach into the stratosphere and inject volcanic aerosols to form layers. Ignimbrite emplacement can also be a major contributor of volcanic aerosols to the stratosphere as the clouds of fine ash and dust, referred to as co-ignimbrite clouds, are caught up in powerful thermals (Walker 1981a). Degassing of near-surface non-erupted magma bodies may also play an important role in adding to the aerosols in the stratosphere (Rose et al. 1983).

The major aerosol components are fine ash and dust, sulfur and chlorine gases. The fine ash and dust which is pushed into the stratosphere by an eruptive plume or ignimbrite emplacement can build up as a layer which heats up the stratosphere through absorption of thermal radiation (Baldwin et al. 1976; Hansen et al. 1978; as cited in Hammer et al. 1981). Much of these particles may be scrubbed out of the atmosphere almost immediately by aggregation and accompanying loss of velocity (Sorem 1982; Carey and Siggurdson

1982) and by rainfall (Walker 1981a) or they may travel around the globe in the stratosphere, finally settling out in a few months (Mossop 1964; Pollock et al. 1976 as cited in Hammer et al. 1981). Sulfuric gases, mostly through injection into the stratosphere, tend to build up in a layer becoming the dominant aerosol and staying in the stratosphere for several years (Rose et al. 1983). Chlorine, mainly from the degassing of near-surface non-eruptive magma bodies, is almost as important in the ozone layer as sulfur aerosols (Lazrus et al. 1979 as cited in Rose et al 1983). The Cl is produced from the interaction of HCl with OH radicals which ultimately can catalyze ozone decomposition (Rose et al. 1983). A limiting mechanism seems to exist so that after a certain amount of aerosols are injected into the atmosphere further amounts have no more influence (Self et al. 1981; Rampino and Self 1982).

The major effect of volcanic aerosols seems to be a lowering of the temperature. Frequent and violent periods of volcanic activity have been correlated with cold climate conditions such as the Pleistocene glaciations and Holocene neoglaciations (Flohn 1979; Porter 1981; Papp 1983). Large scale eruptions, such as Krakatau, and even smaller eruptions, such as Agung in 1963, produce a small but consistent decrease in temperature of 0.2 to 0.5 degrees C on a hemispheric scale for periods of one to five years (Self et al. 1981).

Flora and Tephra-Fall

Damage to plants is due to four major reasons: 1) complete burial of the plant; 2) partial burial that restricts oxygen access to roots; 3) defoliation and prolonged absence of leaves; and 4) "tephra covering foliage surfaces, clogging stomata and blocking out sunlight" (Rees 1970:17 cited in Blong 1984:315-316). According to Miller and Lee (1966, cited in Blong 1984:316) the retention of tephra on foliage is a function of leaf surface area; the "foliage density per unit area of ground surface"; "the shape, size and orientation of individual leaves"; "leaf surface characteristics such as roughness and the presence of fibers and oils"; "the tephra particle size and volume"; "the velocity of the air through the canopy"; and the relative humidity especially if it is above 90 percent. Limbs and leaves may be damaged by loading and perforation due to tephra and ballistic projectiles or by tephra abrading the plants as it is blown across the surface (Griggs 1918; Blong 1984).

Gases and acid rains accompanying tephra-falls may weaken or kill plants (Blong 1984). These effects are especially evident in association with basaltic tephra (Thorarinsson 1979) and less so with increasing silica content.

The stage of growth and the life form of the plant is also an important factor in understanding the effects of a tephra-fall and gases on plants (Harrison 1982; Antos and Zobel 1984a, 1984b; Blong 1984). The portion of an individual plant's life cycle that it is in can determine whether it will live or die, and whether it will

leave any offspring. The life form, that is whether the plant is a low growing grass or a tall tree, plays a role in the severity of the above mentioned effects.

The major hazards associated with thickness result from burial and overloading of the plants. Taller plants are less likely to be buried and so will more likely survive. As leaf surface increases, the plant holds more tephra which causes loss of photosynthesis potential and overloading that leads to the breakage of stems and branches. According to Blong (1984) at depths of over one meter of tephra most vegetation is killed and recovery is difficult. At 10-15 cm, overloading of some plants can still occur and even at several centimeters some loss of plants, foliage, or fruit will be evident. At Mount St. Helens, in forested habitats, huckleberries, other shrubs, herbs, and small trees were killed by 8 inches of tephra deposition (Means and Winjun 1983). In his study of the effects of tephra-falls in Alaska, Wilcox (1959) determined that greater than 2 inches of tephra smothers most grasses and low shrubs and at 1 inch or less and with good rainfall vegetation can continue to live and grow or at most revegetation takes only a couple of years.

Antos and Zobel (1984), described the revegetation of plants in tephra from the Mount St. Helens eruptions which may be of use here. They found that various plants had certain morphological plasticity that allowed differential survivability of individual species which may be generalized to adaptive types. All species of shrubs developed adventitious roots systems above the old soil that

penetrated the tephra although most shrubs had very poorly developed adventitious root systems. Shrubs with rhizomes could also use these features to grow from the old soil surface upward into the tephra although only a few species could use such an adaptation to any great extent. Herbaceous plants could also respond in this manner and 11 morphological types could be identified based on the ability to respond to burial by tephra (Table 3). Figure 6 shows how plants were able to move upward into the tephra from the soil below. Many plants could penetrate up to 12 cm of tephra, while fewer could penetrate 15 cm, and almost none could penetrate much deeper deposits. While the studies cited above are not directly applicable to all of the plant types or climates of the Pacific Northwest they show some interesting trends.

There are a number of studies of Mazama tephra which suggest that the properties of coarse tephra soils may not be as conducive to plant growth as other mineral soils (Youngberg and Dyrness 1964; Cochran 1966; Cochran et al. 1967; Doak 1972; Dingus 1974). The studies suggest that in coarser pumice, plant water availability may be low due to packing of the grains and high vesicularity of individual grains. Some plant roots may not be able to penetrate the pumice mantle. Fertility status is low compared to other mineral soils (Youngberg and Dyrness 1964) and the high concentration of phosphorus may be a problem for some plants (Dingus 1974). The pumice soils are also colder than other mineral soils, causing problems with plant growth (Cochran 1966; Cochran et al. 1967). In the pumice plain of central Oregon, the Mazama tephra has

Table 3. Key to morphological types of herbs with respect to penetration of tephra (after Antos and Zobel 1984a:Table 2).*

A. Perennating buds above ground; often partially woody
  B. Long stolon .....stoloniferous
  B. Nonstoloniferous .....subshrubs
A. Perennating buds at surface or below; all herbaceous
  C. Buds seldom produced in tephra
    D. Plant dies back to buried soil surface .....dies back
    D. Slight upward movement of perrenating bud .....mostly dies back
  C. Buds commonly produced in tephra
    E. Plants with long rhizomes
      F. Upward movement through rhizomes only .....long rhizomes
      F. Upward movement through rhizomes and normal aerial shoots
        G. Upward movement through culms (Graminoids) .....culms
        G. Upward movement not by culms .....long rhizomes and shoots
    E. Plants with crown, caudex, or short rhizomes
      H. New crown, short rhizome, etc., formed in tephra
        I. Crown from culm (Graminoids) .....culms
        I. Crown not from culm
          J. many roots in tephra .....crown and roots
          J. Few or no roots in tephra .....crown
      H. No eveident crown, etc. in tephra
        K. Many roots in tephra .....no crown but roots
        K. Few or no roots in tephra no crown

* Refer to citation for a list of plant species and their assigned morphological type.

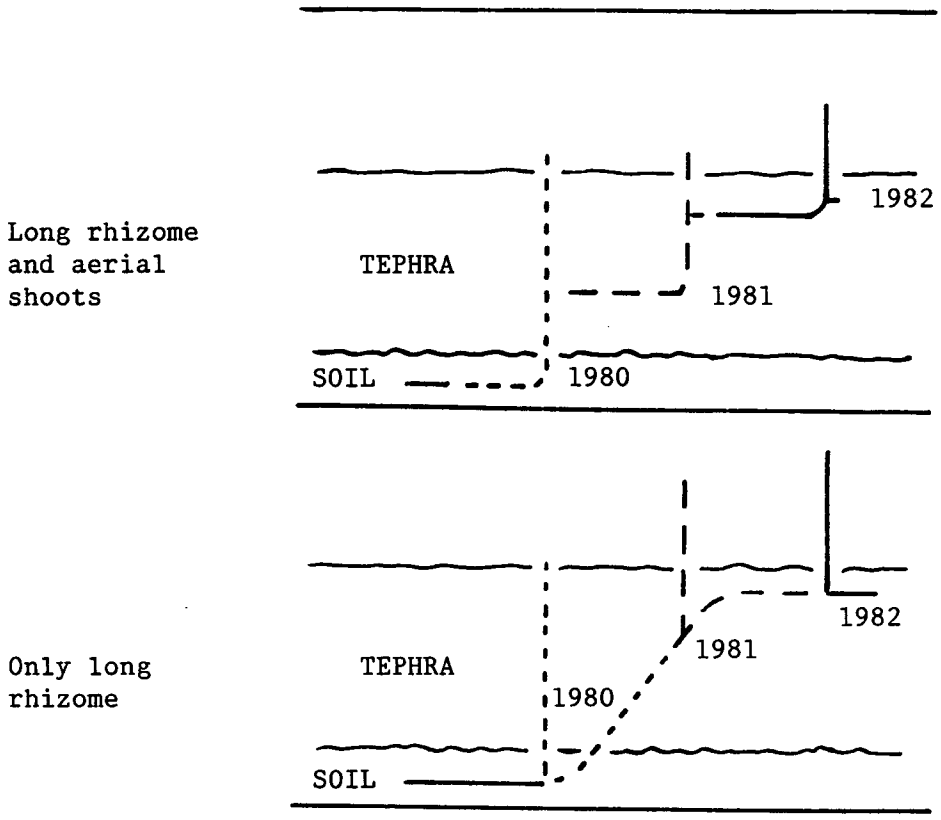



Figure 6. The two methods of upward movement in plants with long rhizomes. At top both the long rhizomes (horizontal) and the aerial shoots (vertical) contribute to the upward movement of plants through tephra. Bottom shows movement of plant by use of long rhizome alone (vertical lines are annual shoots) (after Antos and Zobel 1984a:Figure 1).

created a physical environment which has limited the growth of many types of plant species (Dyrness and Youngberg 1966). Germination and seedling establishment on tephra may be difficult for many plants (Radwan and Campbell 1981).

Much of the plant growth in especially hard hit areas is from pre-existing plants which push through the tephra layer from buried regenerative portions (Griggs 1918; Adams and Adams 1982; Antos and Zobel 1984a, 1984b). For this reason the buried mineral soil is the key to plant establishment (Means et al. 1982). Regeneration from the buried soil can be helped by the stripping of the tephra or the establishment of rills and gullies in the tephra mantle (Means and Winjun 1982; Franklin et al. 1985).

From the above discussion, a set of factors which are important to determining how a plant species or adaptive type will respond to tephra can be constructed. Those plant species that are taller, have deeper root systems, have smaller leaf surfaces, have a greater range of nutrient and water tolerances, reproduce from regenerative portions, and have higher reproductive rates will recover from disturbance better than those that do not.

Fauna and Tephra-Fall

Land mammals are affected in numerous ways from tephra-falls (Huggins 1902; Martin 1913; Griggs 1922; Wilcox 1959; Erskine 1962; Horton and McCaldin 1964; Rees 1970; Bolt et al. 1975; Trowbridge 1976; McReynolds et al. 1980; Cook et al. 1981; Preston et al. 1982) and associated gases (Nielson 1937; Coleman 1946; Mullens 1977;

Thorarinsson 1979). Gases, especially fluorine, can cause immediate death, and long term or short term disease or disfigurement. In relatively heavy tephra-fall conditions animals can die almost immediately due to asphyxiation. Over a period of time, tephra within the environment may cause weakening and possible death due to: (1) chronic respiratory problems, (2) toxicity of elemental and gaseous components, (3) increased tooth wear due to grinding of tooth surfaces when ash laden plants are chewed, and (4) destruction of plant foods and resulting starvation. Generally, the larger animals are not as severely affected by tephra-falls as the smaller animals and juveniles.

Aquatic life are generally affected by "increased acidity, increased turbidity, changed temperature or changes in food supply" (Blong 1984:335). The effects of these factors have been documented by Ball (1914), Eicher and Rounsefell (1957), Wilcox (1959), Erskine (1962), Martin (1913), Bardsdate and Dugdale (1972), Thorarinsson (1979), Fish and Wildlife Service (1980), Phinney (1982), and Stober et al. (1982).

For fish, suspended solids can directly cause death, increase susceptibility to disease, reduce rate of growth, modify normal movements, reduce the number of suitable spawning locations, and kill developing eggs. Rainbow trout (Salmo gairdnerii) can survive one day at 80,000 mg/l of silt, needing concentrations of 160,000 mg/l to kill them within this period. At 90 mg/l of kaolin and diotamaceous earth, rainbow trout can survive for long periods with only slightly increased mortality rates. In several Oregon streams,

brook trout and salmon will travel through natural concentrations of 137-395 mg/l of suspended solids without apparent harm (Alabaster and LLoyd 1982). Particle size requirements for Chinook salmon (Oncorhynchus tschwaytscha) spawning beds in selected Idaho streams were mainly between 7.0 to 20 mm in geometric mean diameter (Platts et al. 1979). Ash size particles (< 2 mm) would certainly not be appropriate for spawning. Spawning beds that are covered with silt after eggs have been laid suffer high rates of mortality to the eggs. Some fish, such as cutthroat trout (Salmo clarkii), will not spawn in silt covered gravels. Some rivers with heavy suspended loads of glacial solids when periodically cleared of silt by heavy rains support large populations of Pacific Salmon (Oncorhynchus). In general, healthy fish populations are found in streams with less than 100 mg/l of suspended sediments where silica mining, gravel washing, and natural sediments occur (Alabaster and LLoyd 1982).

After the 1980 eruptions at Mount St. Helens, Stober et al. (1982) studied the tolerance of Coho to suspended sediment. Live box bioassays of presmolt Coho salmon found that in 2,022 mg/l mortality was 100 percent in 3 hours, at 11,429 mg/l mortality was 100 percent in 30 minutes, and at 1,217 mg/l in 96 hours mortality was less than 10 percent. Adult Coho could stand increased levels of sediment so that of the four fish kept at 1,600 mg/l, one died after 4 days, another after 6 days, and the two remaining fish died at 8 days. At 1,425 mg/l one ripe Coho female died on the second day, another Coho died on the ninth day, with the 2 remaining Coho, two male chinook salmon, and 2 steelhead lived.

Birdlife have had their migration, roosting, flying abilities, and feeding activities affected by tephra-falls (Blong 1984). These effects may be due to asphyxiation by gases, confusion by darkness and blinding brought on by the thick tephra-fall, and feathers being clogged by ash so individuals could not fly. Tephra-falls with a thickness of as little as a few millimeters can kill some of the local bird population with the smaller birds being the most vulnerable. Nests in high accumulations of tephra or where grasses are loaded down from the tephra may be buried, while in lighter areas of accumulation eggs may be dug out by birds and new nests built (Hayward et al. 1982). The decimation of local insect populations can cause later starvation for many birds.

Tephra-falls are the most important aspect of volcanic eruptions affecting insect populations (Blong 1984). This is mostly because tephra-falls can cover such a wide area. The timing of the tephra-fall with relation to the stage of growth of the insect is very important. Cook et al. (1981 as cited in Blong 1984) suggests that abrasion by ash particles of the epicuticular layer causes death due to desiccation in a short time and ash on their bodies causes problems in flying.

The major factors which determine the survivability of an individual is size, food and other habitat requirements, range or ability to migrate out of the impacted area, means of locomotion, ability to compete, and physiology. As well, the ability of a species to recover from the tephra-fall is based on the available food resources and recruitment rates for juveniles. Those species

which have wider tolerances and more diversified food tastes will be able to survive and compete better than those that do not. Those species with higher birth and recruitment rates will recover from the effects quicker than those with lower birth and recruitment rates.

Ecosystems and Tephra-Fall

Recovery of ecosystems from tephra-falls may be quite rapid even for fairly heavily devastated areas (Ball 1914; Griggs 1918; Wilcox 1959; Adams and Adams 1982; Means et al. 1982; Means and Winjun 1983; Blong 1984; Franklin et al. 1985). This is due to tephra compacting quickly and the development of a surface crust which inhibits infiltration and increases runnoff. Of course the eroded tephra must be deposited elsewhere and these areas will continue to be affected by the tephra over time. Those ecosystems which are adapted to frequent disturbance (eg. wildfire, flooding, high winds) may be able to absorb more of the stress caused by a tephra-fall without fundamental change if the pre-adaptation is appropriate for the new conditions. In some cases, such as severe events, fragile habitats, or ecosystems which are already under stress from other factors, a new community succession may replace the old.

The discussion above shows that there are a number of factors which can be considered important to the study of a tephra-fall on an ecosystem. These are the effects of climate (c) on the properties of the tephra-fall and the effects of tephra-falls on

climate; the distribution and thickness (d) of the tephra blanket; and the material properties (m) of the tephra. Since the tephra blanket becomes the new soil medium (s) the distribution and thickness (d) and the material properties (m) of the tephra blanket describes the soil system of the ecosystem. The erosion and redeposition of tephra or the landform it is stable on is reflected in a the local geomorphology (g).

## A MODEL OF THE EFFECTS OF TEPHRA ON NATURAL ECOSYSTEMS

What we begin to see is a set of relationships characterized by specific processes of change. Ecosystems are made up of biotic components which can be grouped into floral (fl) and faunal (fa) systems which not only interact with each other as a community but also interact with the abiotic habitat. The abiotic habitat consists of numerous factors which can be grouped into the major categories of climate (c), geomorphology (g), distribution and thickness (d), and material properties (m). Another factor is time (t), since change in the ecosystem occurs over a period of time and the structure of an ecosystem can be detailed for a specific point in time. In a sense, the amount and kind of change or the effect on biotic factors (E) is a function (f) of the abiotic factors (T,D,M,C,G). Of course the opposite is also true but for this model the biotic factors will be considered to be of little consequence.

In the short term this assumption is probably fairly accurate, but as time continues and the biotic realm becomes adapted to the changing abiotic realm through feedback mechanisms the effect by the

biotic component on the abiotic habitat will be much stronger (Clapham 1983). This is especially true if we consider the effects of an event such as a volcanic eruption on the biotic system. As a devastated area is recolonize the biotic component begins to bring the abiotic component into a new equilibrium until the once sterile tephra is covered by a new soil and biotic community.

To understand the effects of volcanic tephra on an ecosystem, a model of state factors is developed much as Jenny (1941,1980) has done for soil systems. This state factor analysis is not a quantitative, but a qualitative and descriptive model of the factors that are important to an understanding of the effects a volcanic tephra-fall may have on an ecosystem. The equation is as follows:

$$E_{fl,fa,} = f(T,D,M,C,G,...)$$

Where E stands for the effects on an ecosystem made up of floral (fl) and faunal (fa) subsystems. The effects on the ecosystem (E) are a function (f) of the state factors time (T), distribution of the tephra (D), material properties of the tephra (M), climate (C), geomorphology (G), and possibly some as yet undetermined factors (...).

The left hand side of the equation is made up of various properties and interactions within the ecosystem where the major subsystems that are of interest here are the floral and faunal. These subsystems in any combination or the entire ecosystem can be the focus of this research. For instance, the floral or faunal subsystems within the ecosystem can be investigated separately ($E_{fl}$, $E_{fa}$), or in combination ($E_{fl,fa}$).

The right hand side of the equation gives the state factors as a function (f) of their influence on the biotic ecosystem properties (E). The state factors represent a related set of processes or components which interact to affect the ecosystem in various ways. Each of these state factors, separately or in concert, play a role in determining the effects on the properties of the ecosystem and the subsystems. The effect of a single state factor on the ecosystem can be investigated by holding the others constant. It is possible to investigate the effect of time: E=f(T,d,m,c,g,...), distribution of the tephra: E=f(D,t,m,c,g,...), material properties of the tephra: E=f(M,t,d,c,g,...), climate: E=f(C,t,d,m,g,...), geomorphology: E=f(G,t,d,m,c,...), or of some as of yet undetermined factors: E=f(...,t,d,m,c,g) on the ecosystem or any of the subsystems. Of course it is not possible to completely isolate the effects of the state factors from each other and so, for instance, time will have an effect on the material properties of the tephra just as it will on the constituents of the ecosystem. Where this occurs it will be noted and the relationships explained.

The actual relationships between the state factors are too complex to give any single mathematical relationship to them. The relation of each individual state factor to another or to the ecosystem will have to be described in detail. In this sense the model is no more than an organizational device for identifying important ecological factors and relationships, and the orderly and logical explanation of the simplified system being studied. The

state factors detailed above were chosen because they are readily resolvable by the methods available to the natural sciences.

The model at this stage, takes into account the effects of a tephra-fall on a natural ecosystem. Human beings are also affected by tephra-falls and so must be considered.

## THE HUMAN INFLUENCE

We have considered the ecosystem to be made up of biotic and abiotic components. The biotic components consist of floral and faunal systems. For an anthropological and ultimately an archaeological perspective it is necessary to consider the effect of tephra-falls on human beings as well.

### Volcanic Hazards and Human Beings

Human beings are subject to many of the same effects from tephra-falls as plants and other animals. These effects become more important as one nears the source and as eruptive violence increases. Generally, few humans die from tephra-falls even when the tephra is quite thick, unless noxious fumes accompany the tephra. Most hazards for humans that are related to tephra involve acute or chronic medical problems from inhaling ash or noxious fumes. The most important problems for a large proportion of the people impacted by tephra-falls result from post-eruption changes to the ecosystem. About 40 percent of the deaths associated with tephra-falls from the period of 1692 to 1982 were due to disease and starvation indirectly related to the eruptions; the remaining 60

percent generally occurred in a few extremely violent eruptions and in areas located near the source (Blong 1984). This points out that a lack of food resources due to ecosystem disruption may be an important factor in determining the effects of tephra-falls on human populations.

## Culture and Sociocultural Systems

Culture can be thought of as the framework within which people may be studied. Culture can be defined in many ways (cf. Kroeber and Kluckhohn 1952), but archaeologists need a definition or manner of considering culture which fits with their research questions. Gibbon (1984) discusses culture by borrowing the distinction from Popper (1972:106-190) that the world is composed of three distinct but real realms. These are culture, mind, and physical environment. The dichotomy between biotic and abiotic components as seen in the ecosystem concept is also useful here, in that the physical environment has some influence on the mind and culture.

> These realms interact with and influence one another. For instance, culture in this ideational sense clearly influences one's thoughts and dreams, and, through the intended and unintended consequences of culturally informed activity, the physical environment. Changes in the physical environment, such as glacial surges or overpopulation, nearly always lead to the creation of new thoughts that affect the content of culture. And human thought processes may eventuate new conceptions of the physical environment and lead to the invention of new tools, myths, and rules of behavior; these thoughts elaborate and change the content of culture and, therefore, the patterned actions of individuals (Gibbon 1984:16).

To again distinguish between the realm of culture and the physical realm the concept of culture can be distinguished from a sociocultural system (Keesing 1974:81-83 cited in Gibbon 1984:17-18).

> Culture in this conceptualization refers to ideational designs for living, patterns of shared meanings, and systems of knowledge and belief. Sociocultural systems, on the other hand, "represent the social realizations or enactments of [these] ideational designs-for-living in particular environments" (Gibbon 1984:17).

This brings us from an abstract, nonphysical view of culture to objective, empirical sociocultural systems which can be studied by the methods of the natural sciences (Gibbon 1984:18). It also brings us to a view of culture as a system that can interact with the other environmental systems we have already discussed. Therefore, the biotic portion of the ecosystem can be thought of as consisting of the interrelated floral (fl), faunal (fa), and sociocultural (sc) systems.

## Cultural Ecology

The relationships between the sociocultural system and the floral and faunal systems can be investigated through the use of cultural ecology. Cultural ecology assumes that:

> "sociocultural systems are adapted for exploiting particular portions of their environment through the use of certain technologies, and that the form of a sociocultural system is in large part determined by the ecological conditions to which it is adjusted" (Gibbon 1984:7).

From this it may be assumed that the people of the Mazama period, through their sociocultural systems, gained their subsistence from a specific set of plant and animal species drawn from the total range of locally available plant and animal species. They did this through a specific technology which was appropriate to harvesting certain plants and animals. That is, the Mazama period people, through their sociocultural systems, were adapted to a specific niche within the total environment (see Kirch 1982 and Bettinger 1982 for a discussion of adaptation in archaeological applications).

Since this model is being applied to the Mazama tephra-falls we are generally considering the sociocultural systems of hunters and gatherers as being representative of these past lifeways.

> Of all the peoples studied by anthropologists, hunter-gatherers are the most likely to be considered in ecological terms. Their relationship to their physical environment is so direct, since they depend on naturally occurring plants and animals for daily food, that it seems obvious to view subsistence techniques as largely conditioning their way of life (Netting 1977:8).

To simplify assumptions and make this model more appropriate for archaeological study, the technoeconomic sphere of the sociocultural system (Gibbon 1984) is assumed to be the most important component of the sociocultural system even though other components of the sociocultural system may also play a role in the effects of tephra-falls on people (cf. Nolan 1979; Blong 1984). From an archaeological viewpoint, economic principles are more readily usable and are paramount among the different subsystems of the overall sociocultural system (Gibbon 1984). Within this view,

the floral and faunal subsystems are only important as food larders for the people of the past and so it is important to understand the subsistence portion of the sociocultural subsystem to be able to determine the effect that the Mazama tephra-falls may have had on prehistoric populations. That is, in what way did the Mazama ash-fall affect the economic plants and animals that people relied upon for their food resources and how might changes in the floral and faunal subsystems have affected their sociocultural systems.

Within subsistence technology the traits or behaviors which are important for study are the use of tools and the use of space. Tools which are used to process plants and animals can have specific shapes or use-wear patterns which correspond to how they are used (cf. Hayden 1979; Keeley 1980). These shapes and use-wear patterns may then indicate the function of a tool. Since tools may be discarded after use, the location of a tool or group of functionally related tools may indicate specific subsistence activities which took place at a specific location (Dunnell 1978).

It is also important to understand what resources were available, in what proportions they may have been available, and what limitations the available resources may have had on the human populations. The floral and faunal remains in archaeological sites indicate the economically important species and to some extent the quantities of each species that were used for food (Ford 1982; Lyman 1982; Grayson 1984). Models of hunter-gatherer foraging strategies can be used to determine how resources may have been exploited (Jochim 1976).

## Evolution

If the character of a human population's niche changes in any fundamental way, say that certain plants or animals decrease in numbers or die out altogether, then the form of the subsistence technology within the sociocultural system would have to change to become adapted to the new set of conditions. The process by which this change occurs is evolution.

Darwinian evolution as a process of change is accomplished through the mechanism of natural selection acting upon a portion of the total available traits or behaviors within a sociocultural system thus causing those traits or behaviors which confer fitness on the individual or group to increase in frequency through time and those traits or behaviors which do not confer fitness to be dropped or decreased in frequency through time (Dunnell 1982). That is, to adapt to the new conditions certain subsistence oriented traits or behaviors that confer fitness will increase in frequency (be selected for) and those that do not confer fitness will be decreased in frequency or even disappear (be selected against). By examining the frequencies of specific functional tool types through time and space it should be possible to see evolutionary changes within the technological realm of the sociocultural system being studied (Dunnell 1982).

If change can be correlated with a specific stress on the environment, for instance the Mazama tephra-falls, and if a reasonable argument can be given that the stated stress was the

cause, then it may be taken that the change was due to the stated stress (Salmon 1982; Salmon and Salmon 1979). For this reason it is important that the physical aspects of the event be ascertained with as much detail and accuracy as possible. The effect of the event on the species that were important to the subsistence activities of the sociocultural system need to be detailed. The subsistence technology of the sociocultural systems involved must be examined through time so that any change can be seen. Archaeology is uniquely suited to investigate these past adaptations. The material portion of the subsistence technology (the tools) and the spatial distribution of the technological traits should give an indication of the state of the subsistence technologies when correlated with available floral and faunal remains at any period in time.

## Ecological Crises and Change in Sociocultural Systems

Raup (1981) proposes that the definition of a crisis has three elements. These are: 1) a crisis is an "event" in the sense of it being of relatively short duration compared to the total time under consideration; 2) a crisis is unpredictable, or at least not specifically predictable by the participants; and 3) a crisis results in fundamental change in the natural order of a system. This definition states that a fundamental change in the structure of the system is significant. Fundamental change, according to Raup (1981), means that the conditions following the crisis are altered either permanently or for a long period of time after the event. Changes in long term (e.g. slowly shifting climatic conditions) or

cyclic (e.g. seasonal weather patterns or even periodic wildfire in grasslands or forests) environmental factors, can be specifically adapted to by organisms. In the case of short term and unexpected variation in environmental factors, organisms must rely on fortuitous adaptation to exist in post crisis environments.

Sociocultural systems must also rely on a wide range of variability in traits and behaviors for adaptation to crisis events. Variability is important because it allows a range of behaviors or traits to exist from which a portion of these may be selected out to confer fitness to the individual, and in total, to the system. The greater the variability of traits or behaviors within the system (the more general or diffuse the adaptation) the more likely the system will not change in any significant way under selective pressure. Conversely, more highly specialized (or focal) adaptations have a smaller amount of variability within their technoeconomic systems and under intense selection pressure the system will tend to change drastically (Dobzhansky 1968; Cleland 1976).

Variability in traits and behaviors is important as a reservoir from which the various traits and behaviors which are not at present being used, or being used only peripherally, may be selected to meet new and or changing environmental conditions (Kirch 1982). This means that as change occurs there will be a differential preservation of variability within subsequent states (Dunnell 1978). The transmission of variability is accomplished through information networks (Clarke 1978). Differential

representation of traits can be measured through the frequencies of specific traits before, during, and after a change takes place in the system. These frequencies of traits can be represented by similarity and variance indices (Bense 1972; Thomas 1976; Beck 1984; Gibbon 1984).

Adaptation of a system occurs in response to specific environments and specific selection pressures. The kinds of selection pressures which change the system are dependant on whether the environment is stable, changing, homogeneous, or heterogeneous and to what extent the population has already adapted to the environment (Kirch 1982). In a stable environment traits or behaviors which are used infrequently except under stress will be eliminated. In a changing environment formerly peripheral traits or behaviors will be selected to allow the system to become adapted to the new conditions. In a homogeneous environment only a small selection of traits or behaviors is needed to cope and peripheral traits or behaviors will be eliminated. In a diversified environment a large number of traits will be needed to cope and two or more adaptive norms may be seen in the same environment.

Various types of system change will result from specific selection pressures (Kirch 1982). Cyclic change can result from seasonal variation and gives rise to a greater range of overall behavioral variation in the sociocultural system. Unidirectional and continued change can result from major shifts in climatic patterns and involves an initial cultural change which is just enough to keep pace with environmental change, but which continues

to grow as the environmental change becomes more drastic. Minnis (1985), has postulated that as such environmental change occurs the cultural response would involve increasing reliance on larger social networks. Where environmental change is drastic, such as the disappearance of a habitat, the result will be a greater range of variability within the system as the sociocultural system seeks to become adapted to the change. This last type of change is called revolutionary change and may reflect how a catastrophic tephra-fall may affect a sociocultural system..

The rate of adaptational change for a sociocultural system is dependant on whether the sociocultural system is adapted to the environment and whether the environment is stable or changing (Kirch 1982). If the sociocultural system is adapted to a stable environment the rate of change will be slow. For a population which is not adapted to a stable environment, such as a pioneering population, the rate of change will be high at first and then become slower as the population becomes increasingly adapted to the environment. Within a changing environment the rate of system change will tend to keep pace with the environmental change although some lag will exist between the environment and the system. Figure 7 shows the relationship between the rate of sociocultural change and environment. Since the effects of a tephra-fall will be manifested on a very short time scale and may create new or significantly altered habitats we might expect the model for a pioneering population to be an appropriate one in the case of a catastrophic tephra-fall event. This means that change will be

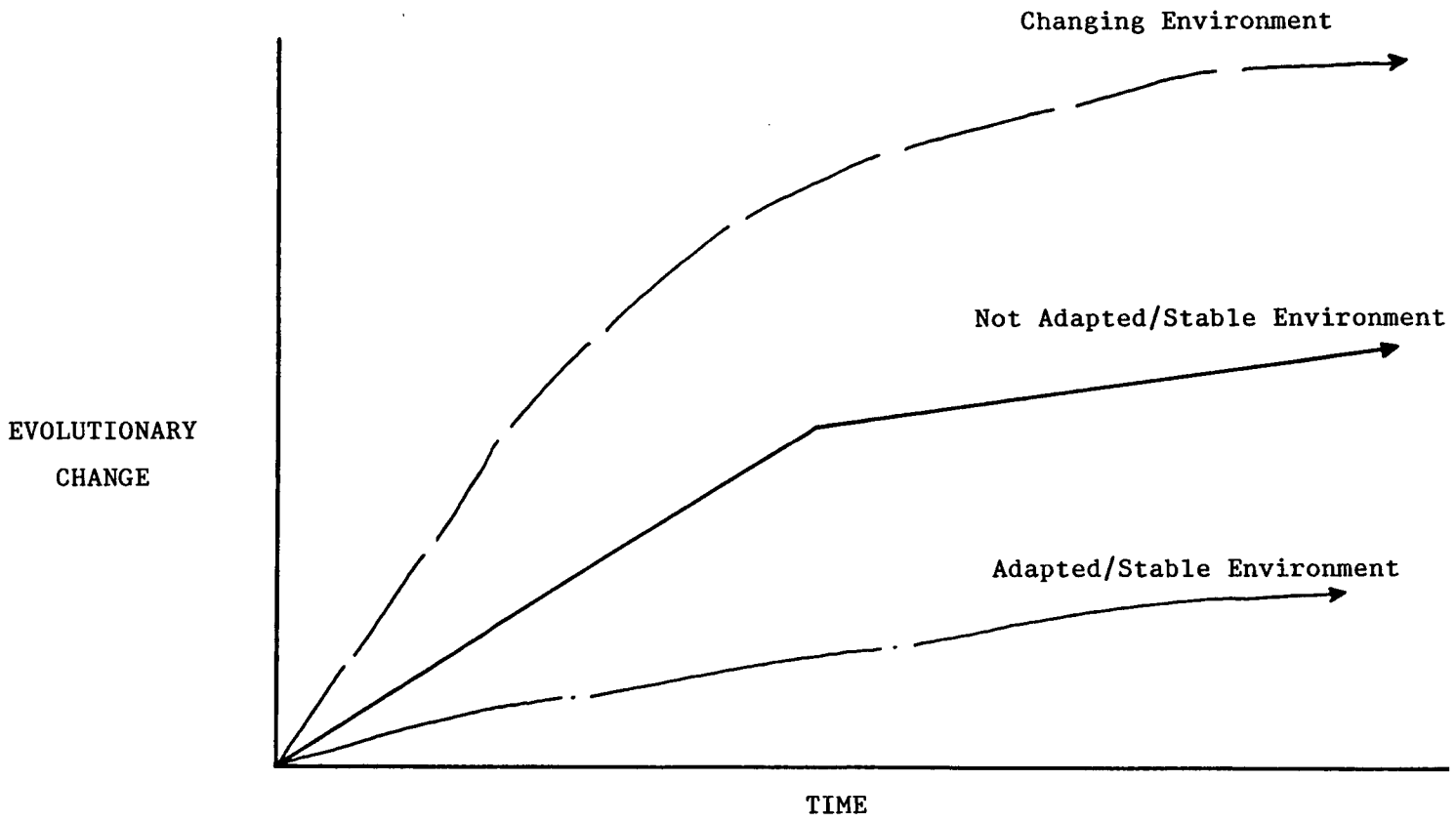



Figure 7. Hypothetical change in sociocultural systems as a function of time and environment (after Kirch 1982:Figure 3.6). The rate of evolutionary change is dependant on whether the sociocultural system is adapted to the environment and the stability of the environment.

rapid at first and then become slower as the population reaches a state of equilibrium with the environment.

According to Sahlins and Service (1968), once sociocultural systems become adapted to a specific environment they tend to resist change until forced to by some external stress. This concept is stated as the "Principle of Stabilization, that a culture at rest tends to remain at rest" (pg. 54). An associated corollary of the "Principle of Stabilization" is stated as: "When acted upon by external forces a culture will, if necessary, undergo specific changes only to the extent of and with the effect of preserving unchanged its fundamental structure and character." (pg 54 emphasis in original). This resistance to change has important philosophical implications which must be taken into account for determining the effects of a ecological stress on a sociocultural system. If it is true that people resist change within the sociocultural system, any fundamental change within the structure of the sociocultural system may be significant.

As in natural ecosystems varying levels of stress can cause varying amounts of strain to sociocultural systems. Stress can be minor and cause very little strain to the system so that the trajectory of the system may vary little, if at all. Stress can also be so great that the strain to the disturbed sociocultural system causes the old system to be replaced by a new one. Within this continuum, the point of fundamental change where a pre-existing system can no longer be considered to exist and a new system takes

the place of the old must be determined if we are to ever answer the question of the significance of the Mazama tephra-falls.

If fundamental change in the structure of the sociocultural system is the result of a catastrophic ecological event, then what represents fundamental change? From the discussion thus far, it is asserted that variability within the sociocultural system is an important natural part of the system and signals an ability to resist fundamental change. Therefore, a sociocultural system with a wide range of available traits (subsistence patterns and technological variables) that uses these traits within a long established pattern to resist structural change can not be said to have undergone any more than a normal and expected response to environmental stress. For instance, the use of starvation foods or those resources which would not normally be eaten except during times of stress could not be considered a fundamental change in the system. Therefore, the use of a tool or subsistence pattern that indicates such stress would not necessarily signal fundamental change. However, if the pattern of occasional use should become one of habitual use over a longer period of time than would be expected (months or years?) the change could signal a fundamental shift within the system. The inclusion of entirely new behavioral traits within the system (such as a new weapons system or processing and storage of foods) might also indicate a fundamental change due to environmental stress.

This does not mean that every such change seen in the sociocultural system can be linked to environmental stress. Such a

view is ecological determinism which would result in oversimplifying the reasons for change in cultural systems. As stated before, some causal linkage must be established to indicate that the stated environmental stress was responsible for the change.

It is possible from the previous discussion to hypothesize, in a very general way, about the results of various intensities of tephra-fall events on a sociocultural system. Each case is extremely simplified and individual responses would certainly be much more complex. Three separate scenarios are hypothesized for varying ecological situations.

1) A minor amount of tephra from a fallout event would have little effect on natural ecosystems except to cause minor fluctuations in the ecosystem variables. People could absorb such changes with little or no change in their own system.

2) A moderate amount of tephra might cause some change in equilibrium to the ecosystem but this change would be short lived and the ecosystem would soon come back to its original state or nearly so. Human populations in both focal and diffuse adaptations would be able to absorb much of this change in the ecosystem. Diffuse systems would change in minor ways (e.g. use peripheral traits such as starvation foods) while focal systems would be stressed but would not change unless already under stress from some other source, or unless their adaptation was significantly affected by moderate amounts of tephra.

3) A major amount of tephra would certainly cause significant changes in both the ecosystem and the sociocultural system. If the sociocultural system could not absorb the change in the ecosystem through incorporation of peripheral traits or

behaviors, new behaviors or traits would have to be developed. Diffuse systems would be able to absorb fundamental change more readily while focal systems would be more likely to be stressed past the breaking point. Since the effects on the ecosystem of such a disturbance would be long term, the sociocultural system would have to be able to resist change for a long term as well, or people would have to make a fundamental change in their system to cope with the new conditions.

## SUMMARY

In summary, the effects of the Mazama tephra-fall can be understood through analysis of how natural ecosystems are influenced by the event, and the subsequent effects on human sociocultural systems as people attempt to cope with stress. A model of such an interaction is represented in Figure 8. The arrows represent the major flow of the output of the system component. Most of these interactions should be in the form of feedback loops (double arrows), but only the most important are considered as such here.

The sociocultural subsystem (sc) within the ecosystem can be stressed by an environmental event such as a tephra-fall through changes in the plant and animal populations which are relied upon for subsistence. The people, through the technoeconomic subsystem of the sociocultural system, attempt to reduce the impact of the stress by changing their adaptive pattern. This is reflected both in their utilization of space for hunting and gathering of food stuffs and in their tools which are used for subsistence activities. If such a change is correlated to expected changes in the local

Figure 8. Interactions between components of the model.

Culture, at least in part is conditioned by the environment through the interaction of the technoeconomic portion of the sociocultural system with specific ecosystems. Land use, that is, the combined components of subsistence and settlement traits, gives rise to an assortment of possible functional tool types and settlement locations. Out of all of these, certain ones are selected for depending on their fitness for a specific environment. The major factor in determining the selection of traits within an environment is the food species which are relied on by people for their sustenance. The availability of these food species is dependent on many interactions within the floral, faunal, and physical realm which makes up the ecosystem. Each of these food resources has specific environmental needs, termed their niche, which are realized in their growth forms or adaptive types.

Under an environmental stress, such as the Mazama tephra-fall, food species will adjust themselves to the stress either by successional or evolutionary processes depending on the type of stress and the amount of stress. The type and amount of stress may be measured by the physical attributes of the system. These attributes are represented by time (T), distribution of the tephra (D), material properties of the tephra (M), climate (C), and geomorphology (G). The prehistoric sociocultural systems will react to the change in food resources by: 1) no change, 2) using peripheral traits or behaviors, or 3) creating new traits or behaviors. The response, in large measure, depends on the type and severity of the stress on food resources.

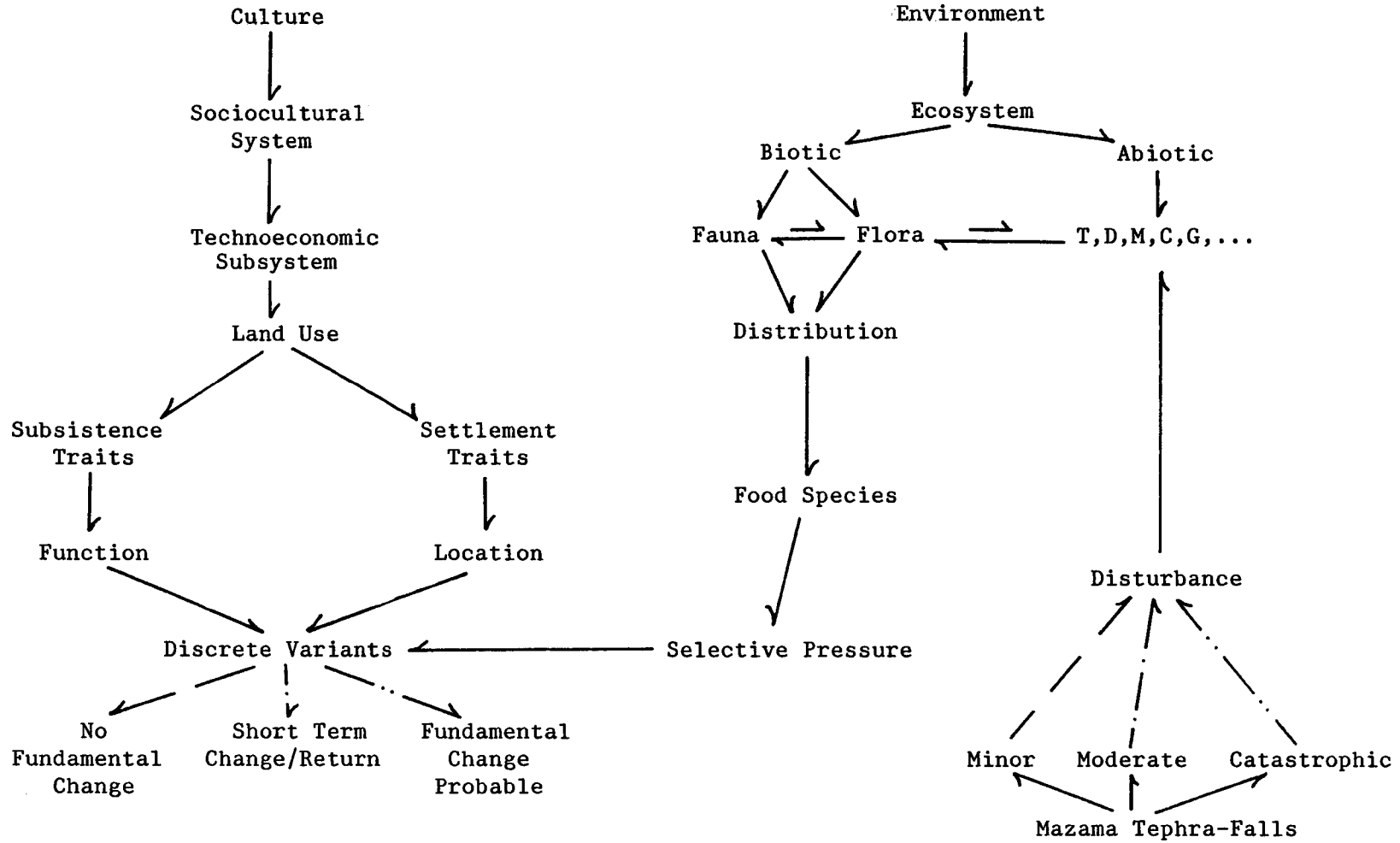



Figure 8. Interactions between components of the model.

ecosystem due to the environmental stress, the changes in the sociocultural system may be due to the environmental stress. Of course this supposes that the environmental stress will have a profound enough effect on the sociocultural system to overcome the built in resiliency of the system.

# III. THE STATE FACTOR OF TIME

## INTRODUCTION

The state factor time, E=f(T,d,m,c,g,...), has a number of components which include: the point in time that the event or events occurred, the duration of the event, the season of the event, and the residence time of the tephra within a given ecosystem. These components define the period of study and elapse time since the event, the length of the event or events, the time of year that the event or events occurred, and the length of time that the tephra may affect a given ecosystem, respectively.

### Time-Stratigraphic Nomenclature

Since time is the topic in this chapter, this is an appropriate place to define the time-stratigraphic nomenclature that will be used for the eruptive events and products. An eruptive period is defined as "clusters of eruptions distinguished by close association in time, by similar rock types, or both" (Mullineaux and Crandell 1981:6). For example, the Mazama eruptive period includes all of the eruptive activity associated with the collapse of the cauldera from the initial eruptions of the Redcloud center (between 7200 and 7000 years ago) to the end of the ring vent phase (about 6800 years ago). The eruptive products of the Mazama period will be referred to as the Mazama series and for this thesis will denote the

tephra-fall deposits that were emplaced during the Mazama eruptive period.

An eruptive phase is defined as that portion of the eruptive period that is distinct from another portion of the period in its products or occurrences. For instance, the pre-climactic phase and the climactic phase are the two portions of the Mazama eruptive period which are noted by Bacon (1983). Each of these phases can be split into various subphases as noted in the introduction. For this thesis, only tephra-falls are important and so the subphases include the Redcloud, Llao, single vent, and ring vent. Since the Redcloud tephra-fall was so localized (see Chapter I) it will not be considered further. Each subphase can be represented by a single layer of tephra or a set of tephra deposits depending on the eruptive conditions. The deposition of a single layer of tephra or a set of layers within a subphase or phase will be referred to as an eruptive event or simply as an event.

## COMPONENTS OF THE STATE FACTOR

### Occurrence in Time of the Mazama Eruptive Period

The timing of the Mazama eruptive period is an important aspect for determining the state of the ecosystem. By defining a specific point in time for the Mazama eruptive period a correlation can be given for biotic and abiotic properties of the ecosystem. This aspect of time gives a reference point by which the specific components of the ecosystem can be identified and measured. In this

sense, the state factor of time, also allows a measurement of the time that has elapsed between the occurrence of the events within the Mazama eruptive period and the time when the properties of the event and\or ecosystem are studied. Since ecosystems can be quite dynamic, the importance of changes in the properties that are investigated should not be overlooked.

Bacon (1983:104-105) cites a number of radiocarbon ages for the two major tephra-falls. The Llao or lower tephra-fall is dated by radiocarbon analysis on twigs that rest in a soil immediately below and mixed with the Llao tephra. The date for the deposition of this tephra is 7015+\-45 radiocarbon years before the present. The climactic tephra-fall is dated by the weighted mean age of four charcoal samples at 6845+\-50 radiocarbon years ago. With these dates in mind and by defining the extent of individual eruption events, it is possible to identify specific ecosystems in time that may have been affected by the tephra-fall.

## Duration of the Tephra-Fall Events

The duration of a tephra-fall event is defined as the period of time that tephra is being deposited during the eruptive event. It does not include any secondary redeposition. The duration of the event may be defined for a single shower or pulse that deposits a discrete layer of tephra, a series of showers within an individual eruptive event, or a series of eruptive events that took place so close in time that they can not be separated.

Historic eruptions of tephra have generally been of short duration with the greatest production of tephra occurring in short, intense bursts (Kittleman 1979:57) as pressure is released with the unplugging of the vent. Various examples are found in Minakami (1942), Wilcox (1959), Bullard (1962) Thorarinsson (1979), MacDonald (1972), Ledbetter (1977), and Walker (1981b) where the eruptions cited lasted for far less than a year and the major deposition of tephra occurred during a few hours or a few days. At Mount St. Helens, Washington the climactic eruption lasted for only nine hours with later magmatic eruptions lasting for a few hours each (Christiansen and Peterson 1981). The present eruptive period at Mount St. Helens has continued for seven years and in the dome building phase may go on for many more. Like the historic eruptions cited above, the eruptions of the Llao subphase and climactic phase probably followed a trend of short intense bursts of tephra over a period of a few years.

At Lost Trail Pass bog in Montana, Mazama ash deposits were subjected to pollen analysis (Mehringer et al. 1977, Blinman 1978, Blinman et al. 1979). By using pollen influx data it was determined that there were three periods of rapid ash deposition during a three year time span. The radiocarbon dates of 6700 +/- 100 years ago from above the ash and 6720 +/- 120 years ago from below the ash would indicate that these ash-falls coincide with the climactic eruptions. While there is evidence for short showers of ash within the major eruption, 23 graded laminations at Lost Trail Pass (Mehringer 1977:257), the appropriate techniques for determining the

duration of these pulses are not available. From the historic sources cited above it would seem reasonable that each tephra-fall event lasted for no more than a few hours or days.

Other pollen columns have not yielded information about the length of the Llao tephra-fall, but Bacon (1983) suggests the wide distribution of the ash indicates that the eruption lasted for at least several days (it would have taken at least several days for differing wind directions to give such a wide distribution). Dudas (1973) found evidence for as many as three eruptive events in a lower Mazama tephra in eastern Oregon based on stratigraphic and chemical analyses. If this tephra corresponds to the Llao tephra (see Chapter IV for a discussion of correlation), several eruptive events would suggest at least several days to possibly a year or more were needed for the deposition of the Llao tephra set.

## The Season of the Tephra-Fall Events

The season of a tephra-fall event is defined as the three month period within the year (spring, summer, fall, or winter) that the deposition of tephra takes place. This may be resolved by use of pollen data where indicator species are present (Blinman 1978; Blinman et al. 1979). Indicator species only pollenate during specific seasons and so those indicator pollens which are deposited with the tephra give a clue as to the season of tephra deposition.

The season of the tephra-falls for the climactic eruption has been outlined in Mehringer et al. (1977), Blinman (1978), Blinman et al. (1979), and Mehringer (1986) from sediments in a bog at Lost

Trail Pass, Montana. This study indicates that an initial ash-fall occurred in the autumn, another ash-fall occurred one year later in the autumn, and the final ash-fall occurred in the following spring or summer. There is no pollen evidence for the season of deposition for the Llao tephra-fall.

Ames et al. (1981) believe that the tephra-fall event occurred in the winter based on the morphology of the tephra deposits. "Coarse white ash in the openwork of fan gravels, infilled krotovina and localized plugs of clean ash in tributaries all point to primary fallout on firm snow and frozen ground" (pg. 51). They suggest that deposition of the tephra on ice and a delay of deposition until the thaw, instead of directly on the water surface during the season indicated by pollen data, may invalidate the use of pollen as an indicator of the season of the deposition.

Studies of the deposition of Mount St. Helens tephra on snow indicate that the thickness of the tephra blanket has some effect on the rate of snow melt. A relatively thick covering of ash on snow may insulate the snow and result in a later than normal snow melt (Tangborn and Lattenmaier 1982). Driedger (1981) found that 2 and 5 mm ash thicknesses increased melt rates, while thicknesses over 24 mm decreased melt rates.

## The Residence Time of the Tephra in an Ecosystem

The residence time of tephra in a specific ecosystem is defined as the period when the tephra is in contact with the ecosystem and may likely, but not necessarily, have some influence

on it. This period may be considered to have begun when the tephra first falls or is transported into the system by other means. The period will have ended when the tephra is removed from contact with the ecosystem either by removal or by burial. The effects that the tephra may have on a system can change within a specific period of time as the relationship of the ash with the ecosystem changes. For instance, the nutrients in a small quantity of ash laying on the surface will have little affect on plants until the ash is mixed with the root zone where nutrients can be used; but blowing ash can be very abrasive to that portion of the plant which is above ground and may destroy leaves (Griggs 1918; Wilcox 1959).

Pollen influx data from upland bogs has been used to quantify the period of redeposition for the Mazama tephra-falls (Mehringer et al. 1977; Blinman 1978; Blinman et al. 1979; Mehringer 1986). At Lost Trail Pass Bog in Montana, a 2 hectar bog and meadow surrounded by forest in the Bitteroot Mountains, 80 years of ash redeposition occurred after the fall of the climactic ash. At Wildcat Lake in eastern Washington, within a depression surrounded by Agropyron-Festuca grassland, about 17 years of ash redeposition occurred after the lower ash-fall (Llao tephra?). About 142 years after the first ash-fall a second ash (climactic tephra?) was deposited. Following this event both ashes were redeposited until 5380 radiocarbon years ago. At Wildhorse Lake in southeastern Oregon, situated in a glacial cirque surrounded by alpine grassland, a prolonged but undetermined period of redeposition occurred after two ashes were initially deposited.

Geomorphic studies have also helped to define residence times. In the Lower Snake River canyon, Hammett (1976) found that over primary deposits, a mixed ash horizon and an ash-rich loess were deposited over a period of approximately 2000 years before the ash was stabilized. Thin lenses of pure ash are also found in later alluvial sediments dated at 4,000 to 2,500 years b.p. and in eolian sands dated at 1,500 to 800 years b.p.. Primary Mazama tephra is still found below a thin A horizon in northeastern Oregon on broad ridge tops and the upper portions of northern slopes in heavily forested areas (Rai 1972).

These five examples show some of the complexity of this subject. It would seem likely that the residence time of a tephra in an ecosystem is dependant on the rate of burial and\or the rate of removal. The major factors in determining the residence time would be climate, vegetation, and geomorphology.

Climate plays a role by determining the amount and character of the transport processes and the amount and character of vegetation for stabilization of the tephra. Rain or wind transport are the major climatically controlled processes for removal of tephra. High rainfall areas will of course be subject to relatively greater water transport processes, while areas of low rainfall amounts will have a relatively greater amount of eolian transport of tephra. High rainfall areas will have greater vegetative cover than areas of low rainfall, and will therefore have increased rates of stabilization and burial through accumulation of decaying plant remains. Areas of low rainfall (and low plant densities), but

intense seasonal storms cause periodic flushing of tephra, possibly in relatively pure form.

The landform type and the associated vegetation play an important role in determining whether the tephra will remain stable. Stable geomorphic positions (those not subject to excessive erosion) and locations of long term, dense vegetation will tend to trap tephra and retain it on site, thus allowing longer residence times. Locations of long term, dense vegetation and positions of heavy sediment deposition will cause quick burial of tephra, which leads to short surface residence times and differing times of subsurface contact depending on the rate of burial. Areas that are subjected to wind and water movement tend to have low residence times due to erosion. For the most part, the residence time of tephra in an ecosystem is shorter as distance from the source increases (all other factors being equal) due to the lesser thickness of the tephra layers. See the chapter on geomorphology (VI) for more specific processes and locations.

# IV. THE STATE FACTOR OF DISTRIBUTION

## INTRODUCTION

The state factor of distribution, E=f(D,t,m,c,g,...), consists of the following components: the areal extent of the tephra and the thickness of the tephra. The areal distribution of the tephra determines the area that is affected by the initial air-fall event(s), while the thickness gives an indication of the impact for any one area within the total areal distribution. Each of these components will be discussed in this chapter for the Mazama eruptive period and the eruptive phases.

Both the areal distribution and the thickness of the Mazama eruptive series deposits are confounded by the various tephra layers deposited during the Mazama eruptive period and by other tephras from various sources that have been deposited within the last 20,000 years. For this reason the correlation of the various tephra-falls in the Pacific Northwest and the tephra units within the Mazama series must be discussed.

### Correlation of Tephra-Falls Within the Study Area

Kittleman (1979:77) has identified nine separate ways to correlate volcanic ashes. These are color in aggregate, thickness of the deposit, grain-size, proportions of vitric, crystal, and lithic fragments, mineral abundances of enclosed and free crystals,

morphology of shards, optical properties of minerals, refractive index of glass, and chemical composition of a bulk sample and of the glass fraction. It is also possible to correlate tephra deposits by the pore volume of pumice (Doak 1969) and by their age.

Most of the correlational research has been focused on discrimination of the products of different volcanoes from one another or of different eruptive periods for the same volcano (cf. Crandell et al. 1962; Powers and Wilcox 1964; Wilcox 1965; Randle et al. 1971; Mullineaux 1974; Smith et al. 1977; Smith and Westgate 1969; Kittleman 1973; Mack 1980; Mullineaux and Wilcox 1980; Westgate and Gorton 1981). Sarna-Wojcicki et al. (1983) have reviewed the literature on the tephra units of the American West and have identified 15 tephra units from Mount St. Helens, Newberry Volcano, Crater Lake (Mount Mazama), and Glacier Peak. Each of these tephra units is widespread in extent in various portions of eastern Oregon and Washington, although the Mazama tephra has the largest areal extent and is the only tephra to cover the entire study area. The Mount St. Helens and Glacier Peak tephras are confined to portions of eastern Washington and northeastern Oregon, while the Newberry tephra is confined to central Oregon. Each unit is discernible from the others based on characteristic mineralogical and chemical suites and abundances.

## Correlation of the Mazama Tephras

Correlation of the Mazama tephra deposits with specific time-stratigraphic units allows the thickness and distribution of

deposits from separate eruptive events to be considered instead of just a total tephra thickness for the Mazama eruptive period. From studies of the proximal deposits it is certain that there were four eruptive events that produced ash-fall deposits. These are the Redcloud phase (only proximal deposits), the Llao phase, and the climactic single vent and climactic ring vent subphases. The problem is correlating the distal ash deposits with these proximal deposits when it is not possible to trace them out continuously from their source.

Correlation is especially confusing when one considers the complicating factors in the development of tephra stratigraphy. A tephra layer may be developed due to a single eruption depositing a single layer of tephra. It is possible that an eruptive phase may consist of a number of pulses or showers that each deposit a discrete layer of tephra within a very short time to create a set of tephra layers. It is also possible that an ongoing eruptive period will have a series of phases, where each phase corresponds to a discrete tephra layer or set of tephra layers with some period of time elapse between depositional layers. Within any of these occurrences, changes in intensity of the eruption, the products of the eruption, or shifts in wind direction with time and altitude can cause even more depositional layers to be seen. Therefore a series of methods of correlating ash deposits would be the safest approach to identification (cf. Kittleman 1979; Westgate and Gorton 1981; Sarna-Wojcicki et al. 1983).

The deposits of two major Mazama eruptions have been found across the Pacific Northwest; a stratigraphically lower ash correlated to the Llao Rock eruption center has been found in northern Washington (Mack et al. 1979a, 1979b; Bacon 1983), in southeastern Washington and southeastern Oregon (Mehringer 1977; Blinman 1978; Blinman et al. 1979; Bacon 1983; Mehringer 1986), and in western Nevada (Bacon 1983; Davis 1978, 1985) and a stratigraphically higher ash covering the entire Pacific Northwest which is correlated to the climactic phase (Bacon 1983). Pollen data (Mehringer et al. 1977; Blinman 1978; Blinman et al. 1979; Mehringer 1986) and radiocarbon dates suggest that these eruptions occurred about 60 to 200 years apart (Bacon 1983). Evidence also suggests that three ashes were deposited over a three year period in a bog in Montana (Mehringer et al. 1977; Blinman 1978; Blinman et al. 1979; Mehringer 1986) that correspond to the climactic eruption (Bacon 1983).

Studies in central and northeastern Oregon have helped to interpret the tephra-fall distributions of the Mazama eruptions (Chichester 1967; Chichester et al. 1969; Harward and Youngberg 1969; Rai 1971; Dudas 1973; and Dingus 1974). A fairly consistent A1-AC-C1-C2 soil profile over a buried soil has been found in this area and correlated to the Mazama eruptive series (Borchardt 1970; Borchardt et al. 1971). The C1 horizon consists of a massive, fine Mazama tephra. The C2 horizon is a much coarser Mazama tephra that has as many as seven distinct layers which may represent three different pulses or showers within the same eruptive phase based on

chemical differences in plagioclase crystals (Dudas 1973). Rai (1971) studying the stratigraphic relationships of the two horizons in northeastern Oregon found that the C2 horizon was not always found with the C1 and attributed this fact to erosion of the C2 before the deposition of the C1. Based on this evidence it was suggested that the C1/C2 horizons represent different eruptive events where the C1 horizon occurred as a single depositional episode and the C2 horizon occurred as a series of tephra showers with quiescent periods between successive depositions. Later work by Mack et al. (1979a), suggests that there is indeed two separate tephra-falls represented at Bonaparte Meadows in northeastern Washington. The two tephra units have the same size characteristics as the C1/C2 horizons in eastern Oregon and are separated by 50 cm of peat. The radiocarbon dates, while statistically within the same range, are progressively older and within the expected range for both eruptions. This evidence seems to indicate that both the climatic and Llao eruptions are represented by the C1 and C2 horizons, respectively.

Contrary to the view of multiple eruptions, Doak (1969:46), using porosity of the tephra, suggested that the C1/C2 discontinuity represents a single eruption with an increase in violence and a change of wind direction. In further support of Doak's conclusions, Borchardt (1970) found that within the analytical error of neutron activation analysis of the volcanic glass fraction of the tephra there was no resolvable chemical difference between the C1 and C2 horizons.

Davis (1978, 1985) found that by using an electron microprobe he could distinguish the Llao tephra from the climactic tephra. A similarity coefficient (Borchardt et al. 1972) was used by Davis to correlate tephra beds at Crater Lake (Llao pumice and climactic pumice beds) to the Tsoyawata tephra bed (Llao ash) in northern Nevada and the surface tephra mantle (climactic ash) at Summer Lake in southeastern Oregon. Both Davis (1985) and Sarna-Wojcicki et al. (1980) have found through multiple analyses on the same ash beds that a similarity coefficient of greater than 95 (100 is perfect) generally means a good correlation.

To determine if the C1 and C2 horizons from four different soils in eastern Oregon had a correlation coefficient less than 95, which may suggest that they were deposited from different eruptions within the Mazama eruptive series, the data from Borchardt (1970:22) was analyzed for correlation by the methods outlined in Borchardt et al. (1972). Correlation coefficients for the C1 and C2 layers from Huckleberry Spring (H.C1, H.C2), Antelope Unit (A.C1, A.C2), Walker Rim (W.C1, W.C2), and Royce Mountain (R.C1, R.C2) are displayed as a matrix in Table 4.

None of the coefficients between different C1 or C2 layers is above 95 and so using Davis' (1985) and Sarna-Wojcicki's et al. (1980) criteria, not only do the C1/C2 horizons not correlate but a specific C1 (C2) horizon at one location does not correlate with a C1 (C2) horizon at another location. Since these deposits have a consistently higher correlation by instrumental neutron activation analyses (INAA) to the Mazama eruptive series than to other tephras

Table 4. Correlation coefficients for C1 and C2 horizons of soils from a transect through eastern Oregon.

| | H.C1 | A.C1 | W.C1 | R.C1 | H.C2 | A.C2 | W.C2 | R.C2 |
|---|---|---|---|---|---|---|---|---|
| H.C1 | 100 | 86 | 86 | 85 | 87 | 88 | 91 | 83 |
| A.C1 | | 100 | 92 | 92 | 88 | 87 | 88 | 90 |
| W.C1 | | | 100 | 91 | 87 | 89 | 89 | 93 |
| R.C1 | | | | 100 | 88 | 89 | 88 | 88 |
| H.C2 | | | | | 100 | 91 | 86 | 89 |
| A.C2 | | | | | | 100 | 89 | 88 |
| W.C2 | | | | | | | 100 | 85 |
| R.C2 | | | | | | | | 100 |

(Borchardt 1970; Borchardt et al. 1971) the C1 (C2) horizon at one location should show a correlation coefficient of 95 or greater when compared to the other C1 (C2) of another location.

The following explanations are offered as to why these correlations do not occur. The chemical analyses were done by two different methods and may not yeild strictly comparable results. Davis (1985) used an electron microprobe on the glass fraction and converted the numbers to weight percent of oxide for Si, Al, Fe, Mg, Mn, Ca, Ba, Ti, Na, K, and Cl. To eliminate analytical error he did not use concentrations of less than 0.10% of the oxide in the calculations. The electron microprobe by being able to analyze single shards of volcanic glass is not as prone to biases due to contamination as the INAA analyses are (Westgate and Gorton 1981). Borchardt (1970) used INAA on the glass fraction to determine the concentrations in ppm. of Rb, Cs, Ba, La, Ce, Nd, Sm, Eu, Tb, Yb, Lu, Th, Hf, Ta, Co, Sc, Cr, and concentrations in weight percentages of Na and Fe. To reduce the effects of analytical error he built in a weighting factor to the calculation of the coefficients which allowed less precisely determined concentrations to be used without unduely influencing the coefficients. It is entirely possible that the mixing of the expectations from the one method with the results of the other method is not reasonable. It is also possible that Davis' (1985) technique is particularly sensitive to differences which are insignificant and/or that Borchardt's (Borchardt et al. 1972) technique is not sensitive enough to differences that exist between the tephras.

Other complications arise when the descriptions of tephra layers at various sites are compared. In eastern Oregon, the C1 layer is characterized by a massive tephra while the C2 has a number of layers which may represent three different eruptive events (Dudas 1973). At Lost Trail Pass bog in Montana, there are 23 graded laminations which may have been deposited over three years time in three separate episodes (Mehringer et al. 1977; Blinman 1978; Blinman et al. 1979). This same type of pattern is seen in the proximal air-fall deposits from May 18th and later at Mount St. Helens where a number of discrete tephra layers can be identified that were deposited in a matter of only a few hours (Waitt and Dzurisin 1981; Waitt et al. 1981). By stratigraphic morphology and number of eruptive events it would seem that the Lost Trail Pass (Blinman et al. 1979) and the C2 layers correlate. The Lost Trail Pass tephra is constrained in time by radiocarbon dates corresponding to the climactic eruptive phase (see Chapter III). This would mean that the C2 tephra would correlate to the single vent eruptive subphase and the C1 tephra would have to be correlated to a late portion of the single vent subphase or to the ring vent subphase of the climatic eruptions and that the Llao tephra does not exist or has not been found in this area.

At this time it is not possible to correlate the C1 and C2 horizons with any certainty to either the Llao subphase or the climactic phase. It seems reasonable to assume that if both the Llao and climactic tephras are documented across the Pacific Northwest, then the C1 and C2 horizons would be good candidates for

the deposits of these eruptions. The pollen influx data from Wildcat Lake, radiocarbon dates and stratigraphy from a bog at Bonaparte Meadows in eastern Washington (Mack et al. 1979), particle size data, chemical analysis of the plagioclase crystals, and erosional discontinuity of the deposits can be used to argue that the C1 horizon represents the climactic tephra deposits and the C2 horizon represents the Llao tephra deposits. The porosity data, C1/C2 stratigraphic morphology, Lost Trail Pass pollen and radiocarbon data, and INNA data support the hypothesis that both horizons represent changing conditions within a single eruptive phase. Chemical analysis by electron microprobe on the C1 and C2 horizons using Davis' (1985) technique may help define which portion of the Mazama eruptive series that these units represent.

## THE COMPONENTS OF THE STATE FACTOR

### The Areal Distribution and Thickness of the Tephra

The areal extent of the ash is defined as the surface area which is covered by the ash at the time of original deposition. This factor defines the original extent of the ash for a given eruption before it has been retransported by wind, water, or gravity. The thickness of the ash-fall can be defined as either the primary (original) or the secondary (redeposited) thickness.

The Mazama eruptive plume and subsequent tephra-fall should follow the model proposed by Carey and Sparks (1986) for a convective eruption column. The column consists of a bouyant

convecting mass of pyroclastic materials which rises to a height ($H_T$) where the column density equals that of the atmosphere. The column rises further to height ($H_B$) due to excess momentum of the particles. Between $H_T$ and $H_B$ the column is forced laterally into the upper atmosphere forming an upper umbrella region. The thickness and distribution of an ash-fall depends on the altitude that the ash particles leave the eruptive column, the horizontal wind velocity, the rate at which the particles fall, the wind direction, and other characteristics of the eruptive column (Kittleman 1979:58; Sarna-Wojcicki 1981:598; Walker 1981b; Carey and Sparks 1986). The tephra sheet that is deposited from a high eruptive column usually takes the shape of a gentle wedge or fan that systematically thins along an axis at distance and laterally from the source (Fisher and Schmincke 1984).

The thickness and distribution of the Mazama tephra-falls have been studied by Moore (1934), Williams (1942), Williams and Goles (1968), and Lidstrom (1972) to determine the volume of material ejected from the mountain during the climactic phase. Fisher (1964a:344) has combined the isopach maps from Moore (1934) and Williams (1942) into one map of the thickness of the proximal air-fall deposit (Figure 9). The isopachs show a northeast and a southeast trending lobe. In the references cited above the researchers treated the thickness of the distal Mazama tephra as representing only the tephra from the climactic phase.

In the late 1970's at least two layers of tephra were noted in wetlands scattered across the Northwest which have been correlated

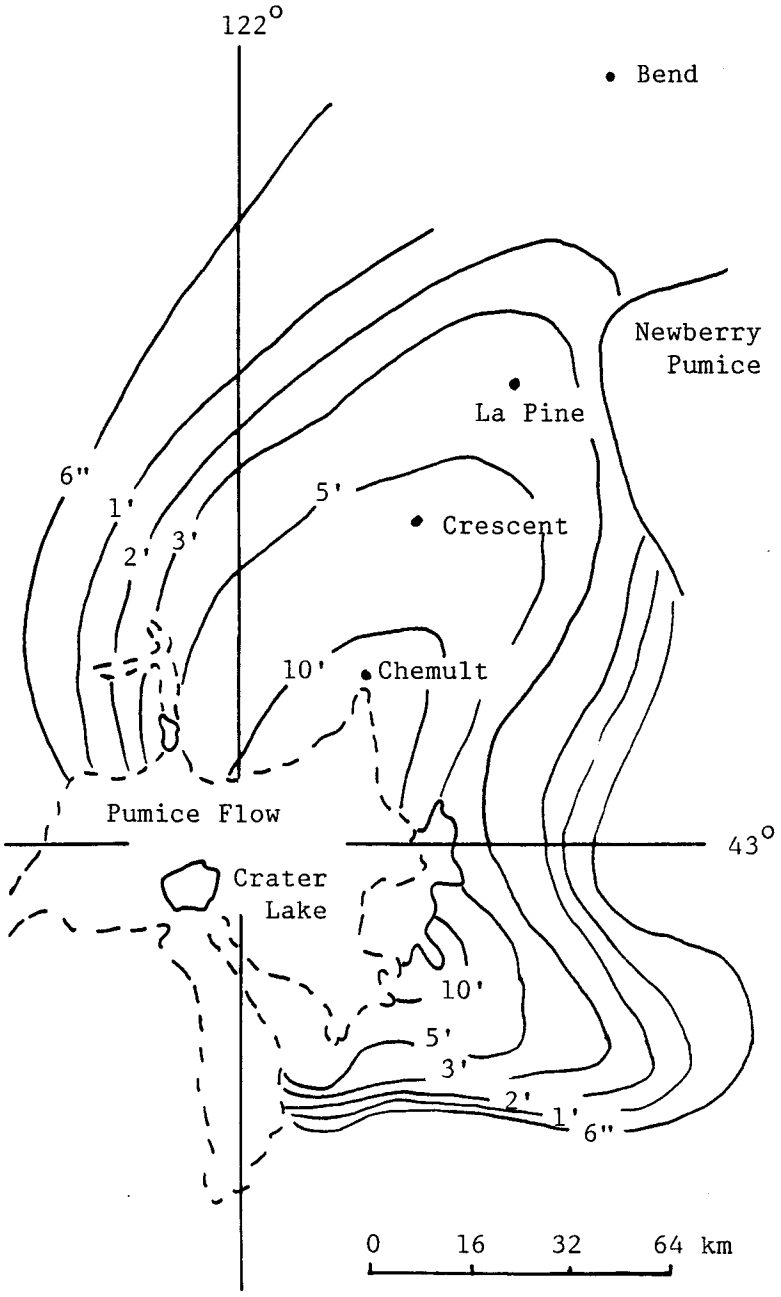



Figure 9. Isopach map of total proximal air-fall deposits in the Crater Lake vicinity. Note the lobes to the northeast and southeast. (Adapted from Fisher 1964:Figure 3).

to the earlier Llao Rock eruption and the later climactic eruptions (Bacon 1983). In an attempt to show the distribution and thicknesses of both tephra-falls a survey of the pollen literature was undertaken to find published locations and thicknesses of Mazama tephra. Many pollen studies are done in wetlands because the pollen is well preserved and because pollen strata are not usually removed by erosional episodes. Wetlands are also ideal locations for the study of tephra distribution and thicknesses since the primary tephra-fall deposits are preserved from erosion, are usually laid down in a horizontal layer which may be measured and corrected to give original upland thickness estimates (Rai 1971: Lidstrom 1972), and because primary air-fall tephra can be isolated from redeposited tephra by a low pollen content due to the rapid deposition of air-fall tephra (Mehringer 1977; Blinman et al. 1979). Well controlled studies of upland sites of tephra accumulation were also used to document thickness totals where they were available.

The data are presented in Tables 5 and 6. Table 5 gives the location of the site and up to four references. Table 6 shows the assigned thicknesses of the lower (C2) and upper (C1) tephras at each location, the location's position, and the manner of identification of the tephra. The location of each site reported in the tables are shown on Figure 10.

From the data in Table 6 a number of maps have been drawn that show interpolated thickness isopachs of the tephra-falls as recreated from the reported sites (Figures 11 through 15). Figure 11 shows the total tephra distribution and thickness for the Mazama

Table 5. Mazama tephra locations and selected references.*

| # | Location | State | Reference | Date | Reference | Date | Reference | Date | Reference | Date |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Banff | Alb. | Westgate and Dreimanis | 1967 | Lidstrom | 1972 | | | | |
| 2 | Lofty Lake | Alb. | Lichti-Federovich | 1970 | | | | | | |
| 3 | Jesmond Bog | B.C. | Williams and Goles | 1968 | Lidstrom | 1972 | | | | |
| 4 | Osgood Swamp | Ca. | Adam | 1967 | | | | | | |
| 5 | Hager Pond | Id. | Mack et al. | 1978a | | | | | | |
| 6 | Middle Butte Cave | Id. | Bright and Davis | 1982 | | | | | | |
| 7 | Moscow | Id. | Garber | 1970 | Lidstrom | 1972 | | | | |
| 8 | Rattlesnake Cave | Id. | Bright and Davis | 1982 | | | | | | |
| 9 | Lost Trail Pass Bog | Mt. | Blinman | 1978 | Blinman et al. | 1979 | | | | |
| 10 | Tepee Lake | Mt. | Mack et al. | 1983 | | | | | | |
| 11 | Lake Lahonton | Nv. | Davis | 1978 | Davis | 1983 | | | | |
| 12 | Antelope Unit | Or. | Harward and Youngberg | 1969 | Chichester | 1967 | Lidstrom | 1972 | | |
| 13 | Anthony Lake Meadows | Or. | Harward and Youngberg | 1969 | Lidstrom | 1972 | | | | |
| 14 | Bend | Or. | Hansen | 1947a | | | | | | |
| 15 | Day Creek | Or. | Doak | 1969 | Rai | 1971 | Lidstrom | 1972 | Dingus | 1974 |
| 16 | Diamond Pond, Malheur Maar | Or. | Aikens et al. | 1982 | | | | | | |
| 17 | Dick Springs | Or. | Doak | 1969 | Rai | 1971 | | | | |
| 18 | Fish Lake | Or. | Aikens et al. | 1982 | | | | | | |

* # column refers to locations on Figure 10.

Table 5. (cont.)

| # | Location | State | Reference | Date | Reference | Date | Reference | Date | Reference | Date |
|---|---|---|---|---|---|---|---|---|---|---|
| 19 | Huckleberry Springs | Or. | Doak | 1969 | Doak | 1972 | Harward and Youngberg | 1969 | Lidstrom | 1972 |
| 20 | Hurricane Creek | Or. | Harward and Youngberg | 1969 | Lidstrom | 1972 | | | | |
| 21 | Meadowood | Or. | Rai | 1971 | Dingus | 1974 | | | | |
| 22 | North Ochoco Butte | Or. | Rai | 1971 | | | | | | |
| 23 | Ochoco Butte | Or. | Rai | 1971 | Dingus | 1974 | | | | |
| 24 | Royce Mountain | Or. | Chichester | 1967 | | | | | | |
| 25 | Simpson Place Bog | Or. | Harward and Youngberg | 1969 | Lidstrom | 1972 | | | | |
| 26 | Skull Creek Dunes | Or. | Mehringer and Wigand | 1986 | | | | | | |
| 27 | South Ice Cave | Or. | Doak | 1969 | Harward and Youngberg | 1969 | Lidstrom | 1972 | | |
| 28 | South Ochoco Butte | Or. | Doak | 1969 | Rai | 1971 | | | | |
| 29 | Summer Lake | Or. | Davis | 1985 | | | | | | |
| 30 | Tollgate Pass Bog | Or. | Rai | 1971 | Lidstrom | 1972 | | | | |
| 31 | Walker Rim | Or. | Chichester | 1967 | | | | | | |
| 32 | Wildhorse Lake | Or. | Blinman | 1978 | Blinman et al. | 1979 | | | | |
| 33 | Western Saskatchewan | Sas. | David | 1970 | Lidstrom | 1972 | | | | |
| 34 | Curelom Cirque | Ut. | Mehringer et al. | 1973 | | | | | | |
| 35 | Great Salt Lake, Bird Is. | Ut. | Spencer et al. | 1984 | | | | | | |

Table 5. (cont.)

| # | Location | State | Reference | Date | Reference | Date |
|---|---|---|---|---|---|---|
| 36 | Great Salt Lake, S. Arm | Ut. | Spencer et al. | 1984 | | |
| 37 | Snowbird Bog | Ut. | Madsen and Currey | 1979 | | |
| 38 | Big Meadow | Wa. | Mack et al. | 1978b | | |
| 39 | Bonaparte Meadows | Wa. | Mack et al. | 1979b | Mack et al. | 1979a |
| 40 | Carp Lake | Wa. | Barnosky | 1984 | Barnosky | 1985 |
| 41 | Creston Bog (Wilber) | Wa. | Mack et al. | 1976 | | |
| 42 | Davis Lake | Wa. | Barnosky | 1981 | | |
| 43 | Goose Lake | Wa. | Nickmann and Leopold | 1985 | | |
| 44 | Hoh Valley | Wa. | Heusser | 1974 | | |
| 45 | Lake Washington | Wa. | Leopold et al. | 1982 | | |
| 46 | Mount Rainer | Wa. | Mullineaux | 1974 | Lidstrom | 1972 |
| 47 | Mud Lake | Wa. | Mack et al. | 1979 | | |
| 48 | Newman Lake | Wa. | Lidstrom | 1972 | | |
| 49 | Panghorn Bog | Wa. | Hanson and Easterbrook | 1974 | | |
| 50 | Simpson Flats | Wa. | Mack et al. | 1978c | | |
| 51 | Wildcat Lake | Wa. | Blinman | 1978 | Blinman et al | 1979 |
| 52 | Williams Lake Fen | Wa. | Nickmann | 1979 | | |
| 53 | Buckbean Fen | Wy. | Baker | 1970 | Baker and Richmond | 1978 |
| 54 | Cub Creek Pond | Wy. | Waddington and Wright | 1974 | | |

Table 6. Thicknesses, positions, and manner of identification for Mazama tephra locations.

Each location is given a number which is noted in the # column. The numbers in the table correspond to map locations shown on Figure 10. If only one tephra layer was noted it was designated as the upper tephra (C1). If two tephras were noted the lower tephra was designated C2. Table 6 also gives the position of the site as "w" for wetland and "u" for upland. This is important since the wetland sites tend to have about one half of the thickness of upland sites due to compaction under wet conditions (Rai 1971; Lidstrom 1972). The thickness columns show both the uncorrected wet thicknesses in parentheses and the corrected wet thicknesses outside of the parentheses. The "~" symbol means that the thickness is only an approximation by the author or is measured from a printed pollen column from within the cited reference. The "P" in the thickness columns refers to a case where the tephra was present, but no thickness was given within the reference. The final column, "Manner of ID", gives the method of identification of the tephra where "n" is no reference to manner of identification was cited, "d" is where the tephra was identified according to its relationship with a radiocarbon date, "ir" is where the ash was identified by polarizing microscope according to its index of refraction, "ch" is where an unspecified chemical method was used, and "emp" is where an electron microprobe was used to characterize the tephra. With as many different tephras as exist in the Pacific Northwest (cf. Wilcox 1965; Randle et al. 1971; Sarna-Wojcicki et al. 1983) it seems wise to confirm tephra identifications by as many different ways as possible.

Table 6. Thicknesses, positions, and manner of identification for Mazama tephra locations.

| # | Location | State | Thickness C1 (cm) | Thickness C2 (cm) | Pos. | Manner of ID. |
|---|---|---|---|---|---|---|
| 1 | Banff | Alb. | p | 0 | ? | n |
| 2 | Lofty Lake | Alb. | (0.1) 0.2 | 0 | w | ir,emp |
| 3 | Jesmond Bog | B.C. | (0.5) 1 | 0 | w | n |
| 4 | Osgood Swamp | Ca. | (~2) 4 | 0 | w | ir,d |
| 5 | Hager Pond | Id. | (~10) 20 | 0 | w | d |
| 6 | Middle Butte Cave | Id. | 0 | 0 | u | n |
| 7 | Moscow | Id. | 30 | 0 | u | n |
| 8 | Rattlesnake Cave | Id. | 6 | 0 | u | n |
| 9 | Lost Trail Pass Bog | Mt. | (7) 14 | 0 | w | n |
| 10 | Tepee Lake | Mt. | (~6) 12 | 0 | w | n |
| 11 | Lake Lahonton | Nv. | 0 | p | w | emp |
| 12 | Antelope Unit | Or. | 43 | 64 | u | n |
| 13 | Anthony Lake Meadows | Or. | (18) 36 | 0 | w | n |
| 14 | Bend | Or. | 10-30 | 0 | u? | ir |
| 15 | Day Creek | Or. | 15 | 12-17 | u | ir,ch |
| 16 | Diamond Pond, Malheur Maar | Or. | p | p | w | n |
| 17 | Dick Springs | Or. | 12 | 15 | u | ir,ch |
| 18 | Fish Lake | Or. | p | p | w | d |
| 19 | Huckleberry Springs | Or. | 61-63.5 | 147-150 | u | n |
| 20 | Hurricane Creek | Or. | (12.5) 25 | 0 | w | n |
| 21 | Meadowood | Or. | 12-15 | 12-15 | u | ir,ch |
| 22 | North Ochoco Butte | Or. | 15 | 15 | u | ir,ch |
| 23 | Ochoco Butte | Or. | 38-48 | 20-30 | u | ir,ch |
| 24 | Royce Mountain | Or. | 64 | 50 | u | ir,ch |
| 25 | Simpson Place Bog | Or. | (30) 60 | 0 | w | n |
| 26 | Skull Creek Dunes | Or. | 2.5 | 2.5 | u | n |
| 27 | South Ice Cave | Or. | 10 | 28 | u | n |
| 28 | South Ochoco Butte | Or. | 23 | 17 | u | ir,ch |
| 29 | Summer Lake | Or. | p | 0 | w | emp |
| 30 | Tollgate Pass Bog | Or. | (18.5) 37 | 0 | w | n |

Table 6. (cont.)

| # | Location | State | Thickness C1 (cm) | Thickness C2 (cm) | Pos. | Manner of ID. |
|---|---|---|---|---|---|---|
| 31 | Walker Rim | Or. | 118 | 138 | u | ir,ch |
| 32 | Wildhorse Lake | Or. | (2) 4 | (0.1) 0.2 | w | n |
| 33 | Western Saskatchewan | Sas. | p | 0 | ? | n |
| 34 | Curelom Cirque | Ut. | (~2) 4 | 0 | w | emp |
| 35 | Great Salt Lake, Bird Is. | Ut. | (0.5) 1 | 0 | w | emp |
| 36 | Great Salt Lake, S. Arm | Ut. | p | 0 | w | ch |
| 37 | Snowbird Bog | Ut. | 0 | 0 | w | n |
| 38 | Big Meadow | Wa. | (19) 38 | (17r) 34 | w | n |
| 39 | Bonaparte Meadows | Wa. | (14) 28 | (8) 16 | w | d,ir |
| 40 | Carp Lake | Wa. | (3) 6 | 0 | w | n |
| 41 | Creston Bog (Wilber) | Wa. | (~5) 10 | (~5) 10 | w | n |
| 42 | Davis Lake | Wa. | (6) | 0 | w | d |
| 43 | Goose Lake | Wa. | (~6) 12 | (~6) 12 | w | ir |
| 44 | Hoh Valley | Wa. | 0.1 | 0 | u | d |
| 45 | Lake Washington | Wa. | p | 0 | w | d |
| 46 | Mount Rainer | Wa. | 5 | 0 | u | n |
| 47 | Mud Lake | Wa. | (~40) 80 | 0 | w | n |
| 48 | Newman Lake | Wa. | (15-30) 30 | 0 | w? | n |
| 49 | Panghorn Bog | Wa. | (2.5) 5 | 0 | w | d |
| 50 | Simpson Flats | Wa. | (~25) 50 | 0 | w | n |
| 51 | Wildcat Lake | Wa. | (1) 2 | (<1) <2 | w | n |
| 52 | Williams Lake Fen | Wa. | (3,2.5) 11 | (0.8) 1.6 | w | ir |
| 53 | Buckbean Fen | Wy. | 0 | 0 | w | n |
| 54 | Cub Creek Pond | Wy. | (1?) | 0 | w | ir |

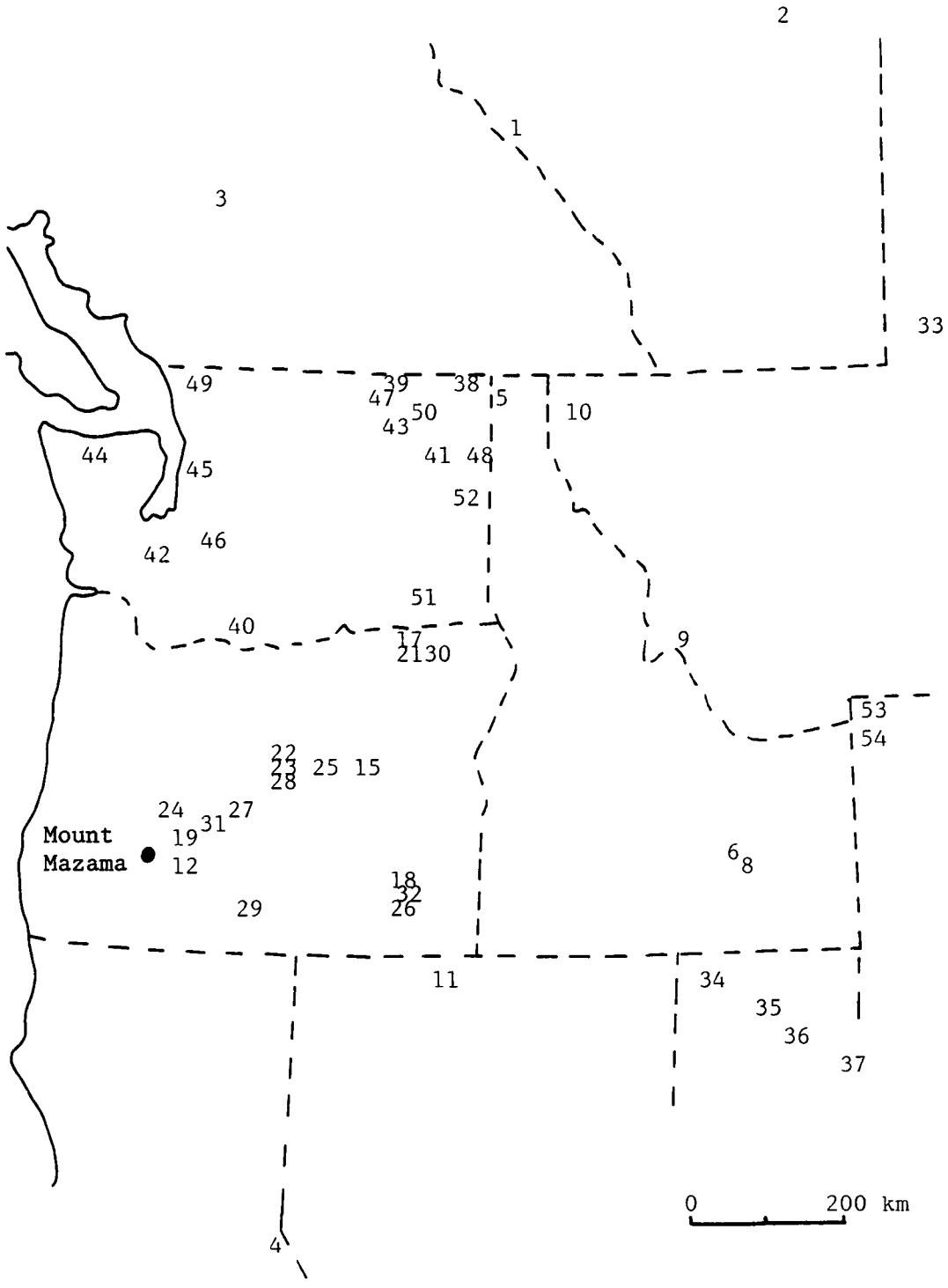



Figure 10. Location of sites reported in Tables 5 and 6.

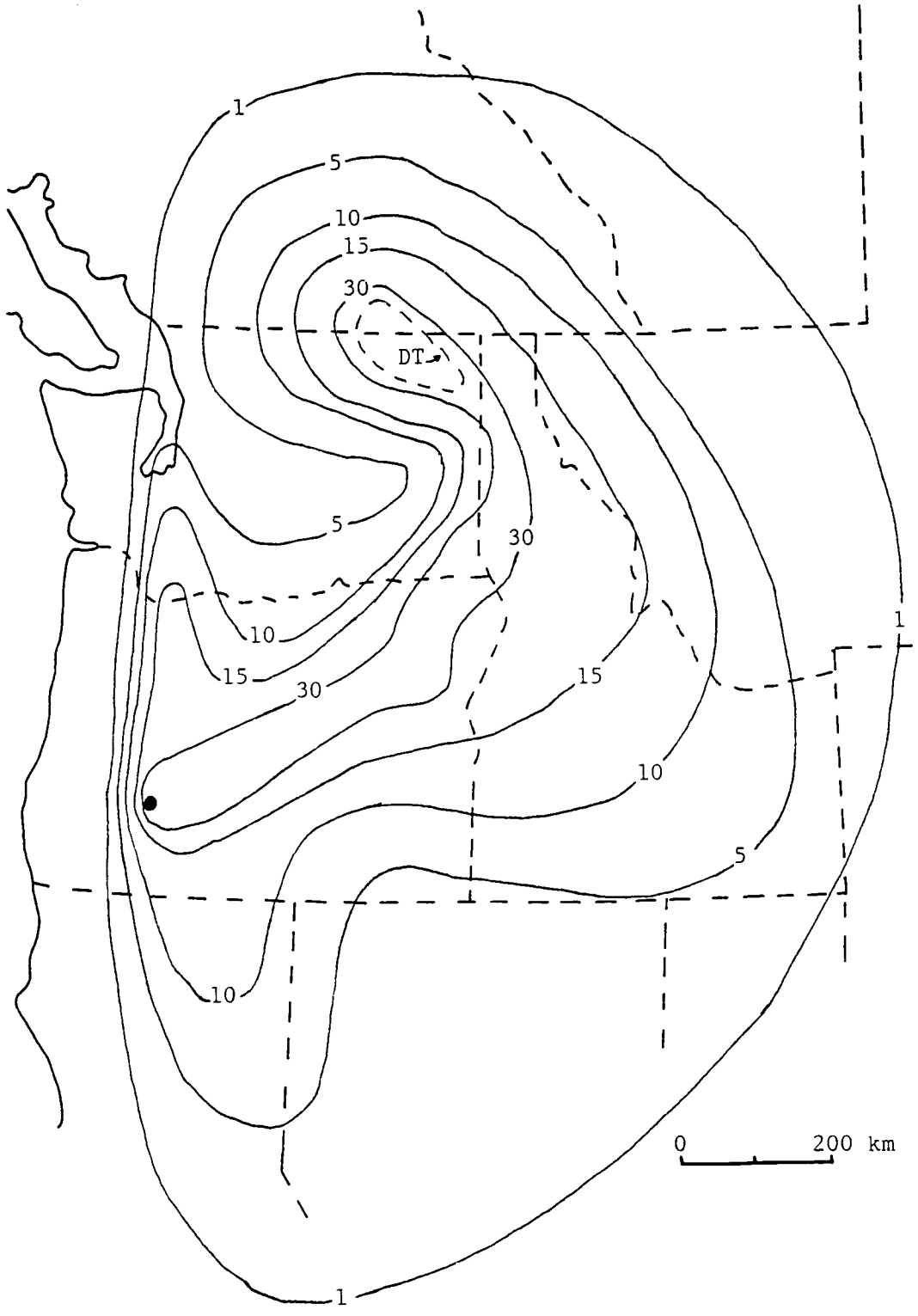



Figure 11. Tephra thickness by isopach in centimeters for combined C1 and C2 layers as derived from Table 6. DT refers to postulated distal thickening as discussed in text.

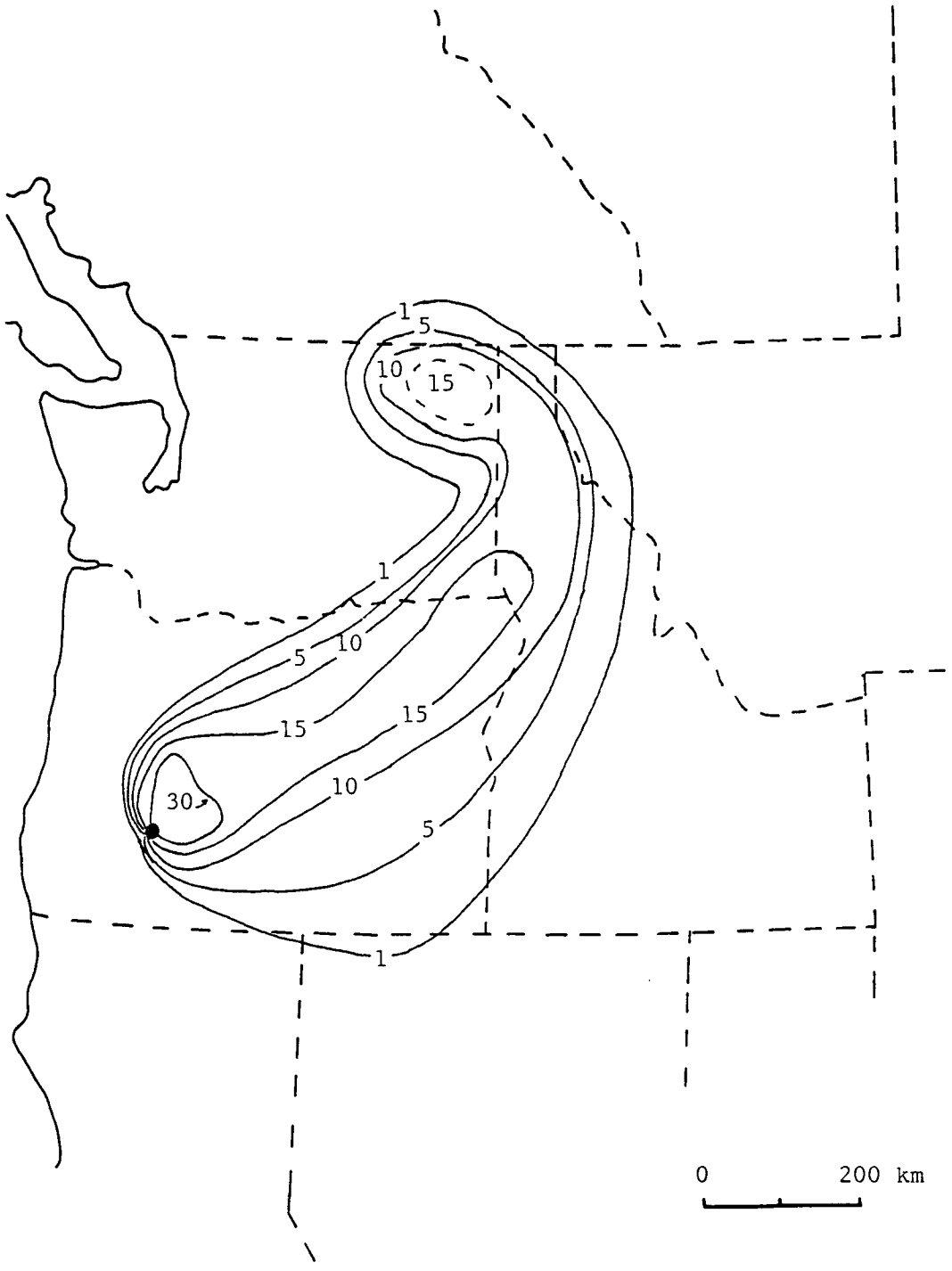



Figure 12. Tephra thickness by isopach in centimeters for the lower (C2) unit as derived from Table 6.

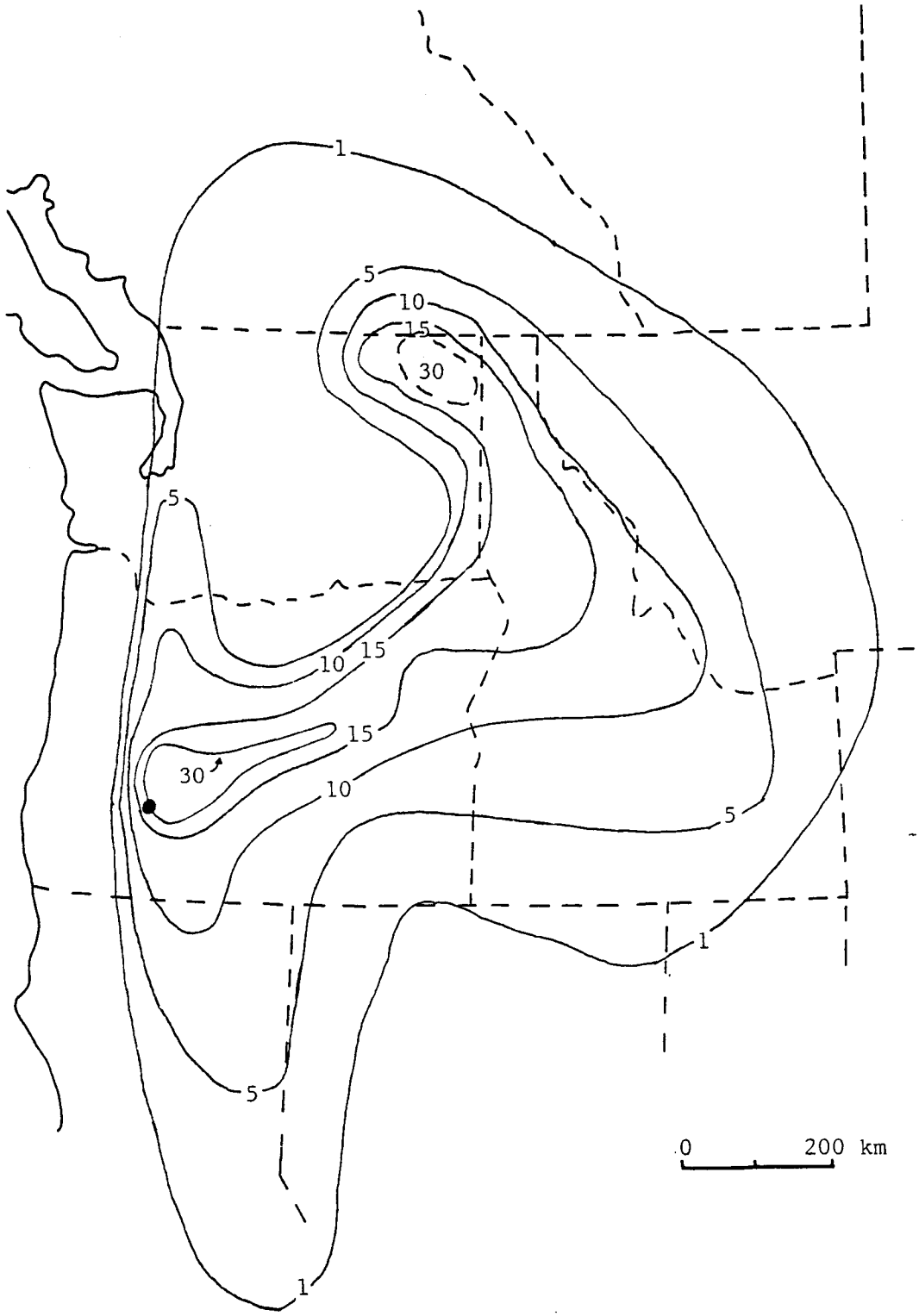



Figure 13. Tephra thickness by isopach in centimeters for the upper (C1) unit as derived from Table 6.

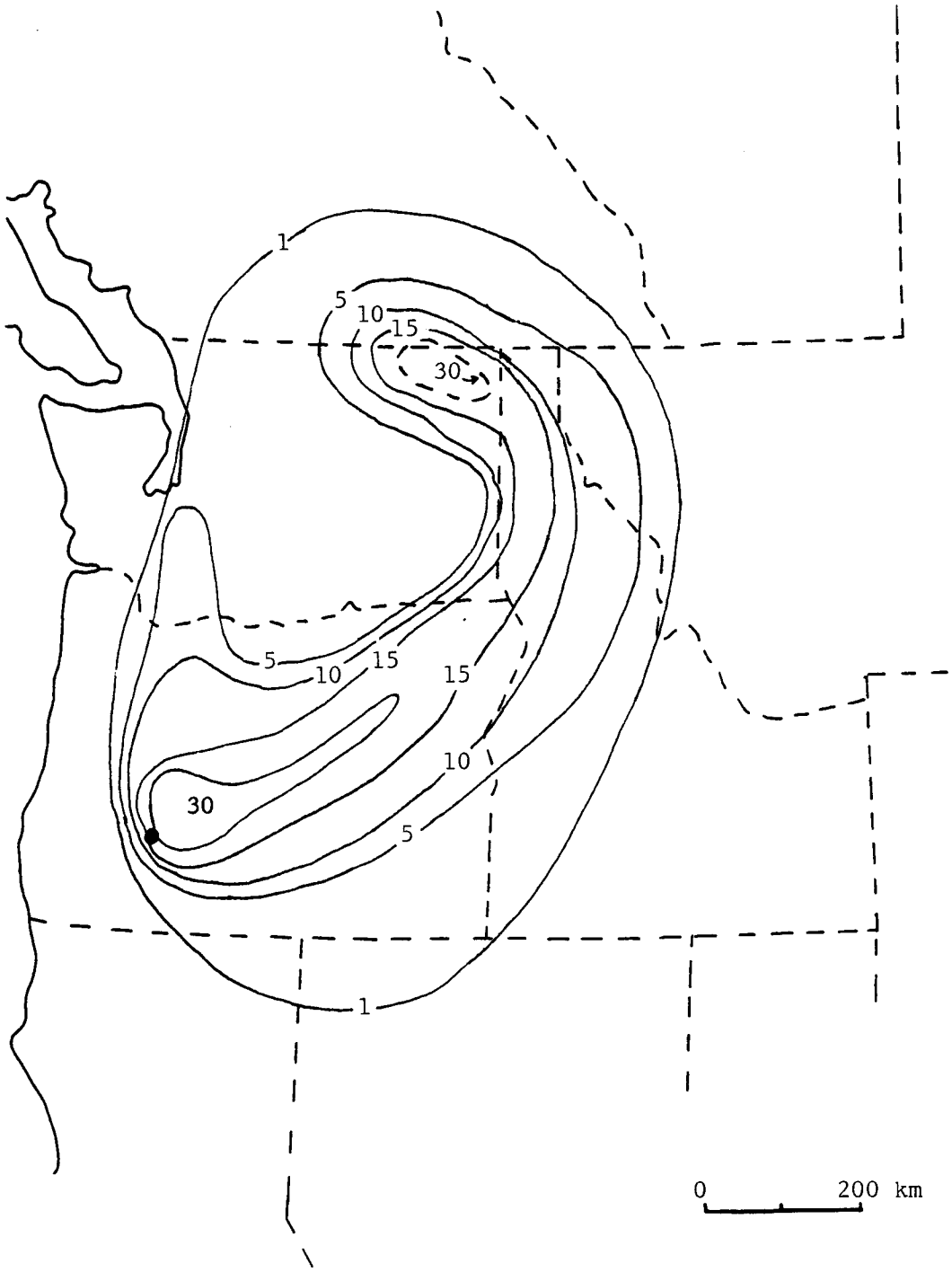



Figure 14. Recalculated tephra thickness by isopach in centimeters for the lower (C2) unit. These isopachs were derived by subtracting half of the thicknesses in the C1 column where only one tephra layer was reported and adding that amount to the C2 layer for the site. Where two tephras were reported the thicknesses noted in each column were used.

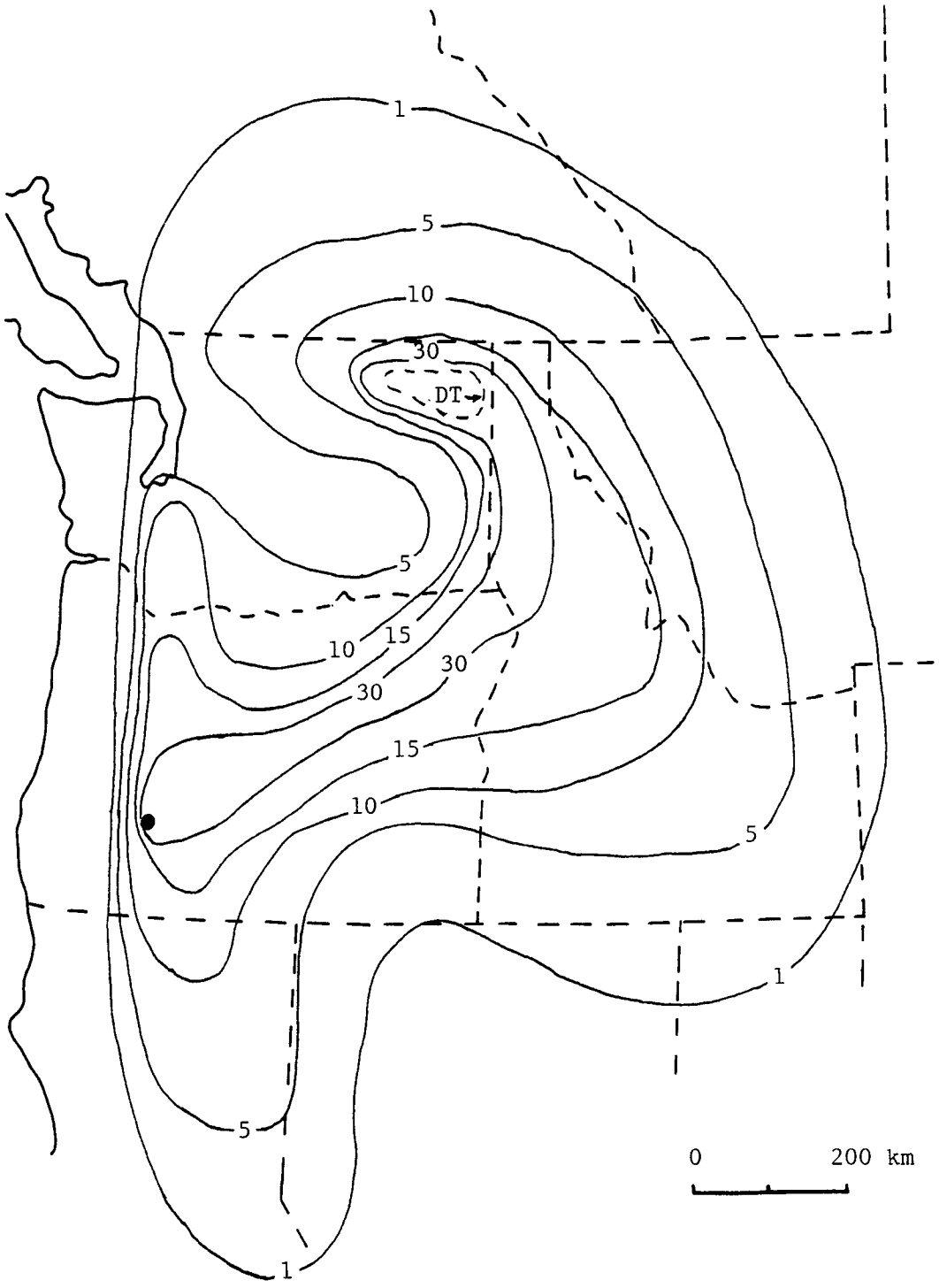



Figure 15. Recalculated tephra thickness by isopach in centimeters for the upper (C1) unit. These isopachs were derived by subtracting one half of the thickness of the C1 unit at those sites where only one tephra was noted. Where two tephras were reported the noted thicknesses were used. Isopachs derived from Table 6. DT refers to distal thickening as discussed in the text.

period. Figures 12 and 13 show the isopachs for the lower (C2) and upper (C1) tephras respectively. Figures 14 and 15 show the interpolated isopachs of the lower (C2) and upper (C1) tephra deposits respectively, where the tephra thickness at a site where only one layer is reported has one half of the total thickness assigned to the lower and one half to the upper tephra-falls. These last two maps may give a more reasonable ash thickness if in fact two tephra-falls are present. With more controlled studies a better method of interpolating the thickness of the tephra deposits at various locations may be developed.

The lower tephra unit (Figure 12) is widespread but of a lesser extent than the upper tephra unit (Figure 13). The 1980 Mount St. Helens eruptions (Sarna-Wojcicki et al. 1981) have shown that a wide distribution of ash can occur in a single eruption due to divergent wind directions at various altitudes. It is also possible to see such a distribution from a succession of eruptions where wind directions have changed over an extended period of time (Fisher 1964a; Bacon 1983).

Both the lower and upper tephras show a distribution to the east and north of the mountain with the main lobe to the northeast and a curl to the northwest. This type of curl pattern was well represented at St. Helens (Sarna-Wojcicki et al. 1981) and was due to the plume being caught in a changing wind pattern. The upper tephra-fall unit seems to be more lobate than the lower tephra deposits. These lobes could represent changing wind patterns during successive pulses of the same eruption or differing wind patterns,

possibly during different seasons, for successive eruptions (Sarna-Wojcicki et al. 1981). The lobes may also represent sampling bias either in the reported thickness of the ash or in the location of the sites. Fisher (1964a) in a study of the proximal air-fall deposits used the median diameters of the tephra particles to show that three lobes are present instead of the two that his thickness measurements indicated (Figure 16). Since these lobes are present in nearly all the grade sizes indicates that they did not result solely from vertical wind shear acting on a cloud in which there are variations in the grain size distribution with elevation, but may be due to differences in eruptive intensity over time or to different eruptive events (Fisher 1964a:345). These lobes correspond to the northern, northeastern, and southeastern lobes seen in the isopach maps in this study. Fisher's work may then support the conclusion that these lobes are real and not due to some bias. As well, Wilcox (Sarna-Wojcicki et al. 1983) reports finding four distinct lobes at some distance from Crater Lake.

Both tephra units show a distal thickening in north central Washington which may be due to the same mechanisms seen at St. Helens (Sarna-Wojcicki et al. 1981). It was found that the maximum ash thickness near Mount St. Helens was due to material being erupted below the layer of maximum wind velocity, an area of lower ash thicknesses near Yakima was due to ash being picked up by the high velocity wind layer causing it to by-pass the area, and an area of greater thickness distally from the mountain in the Ritzville area was due to a fall-out of the finer ash from above the high

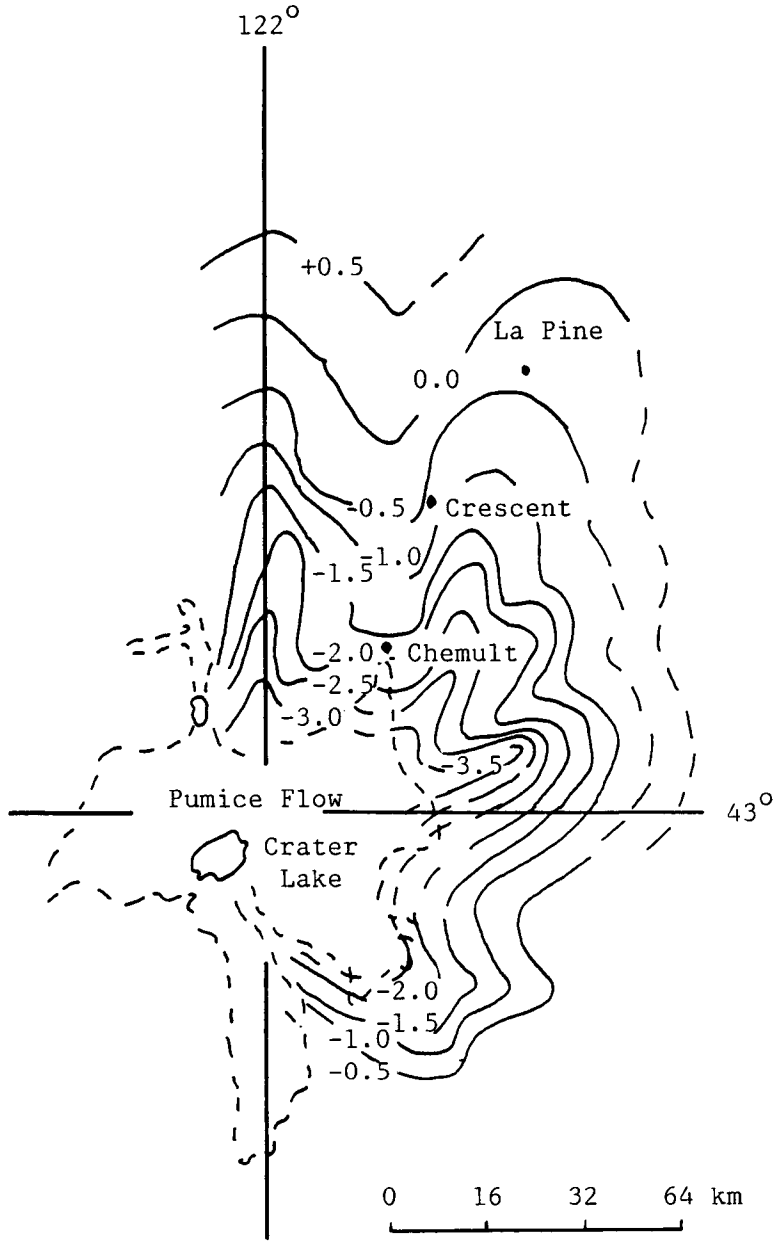



Figure 16. Isomedian map, Crater Lake proximal air-fall. Contours of median size values (in phi units). Note lobes to the north, northeast, and southeast. (Adapted from Fisher 1964a: Figure 6).

velocity layer (Sarna-Wojcicki et al. 1981). This pattern, as seen in the Mazama tephra units, may also be due to sampling bias in the sites chosen or to problems in the reported thicknesses, such as combining more than one tephra unit or combining primary and secondary tephra thicknesses.

Figures 14 and 15 show various manipulations which for the most part only change the thickness of the ash for a specific location and leave the major patterns the same. An exception is the northern lobe which was added to the lower tephra unit distribution (Figure 14) and which needs to be verified through increased sample size.

A more thorough investigation of Mazama sites is needed, using careful coring and measuring techniques and pollen influx data (Mehringer et al. 1977; Blinman 1978; Blinman et al. 1979) and the chemical correlation of stratigraphic layers to their respective eruptive episodes (Davis 1985), to more accurately assess the validity and assignment to specific events of these distributions.

# V. THE STATE FACTOR OF MATERIAL PROPERTIES

## INTRODUCTION

The state factor of material properties, E=f(M,t,d,c,g,...), includes the following components: particle size distribution of the tephra, vesicularity of the tephra, chemical composition and mineralogy of the tephra, and gases that may adhere to the tephra. Each of these components are interrelated so that they especially affect plant growth through moisture, heat retention, and fertility characteristics. Animals and humans also are affected either directly, by such factors as grain size, chemical elements and gases present, or indirectly through their dependence on the plants.

The particle size and vesicularity of the deposits is important for determining drainage and heat retention characteristics of the deposits. Drainage characteristics, particle size, particle vesicularity, as well as the chemistry and mineralogy of the deposit will have an effect on the types of elements which are available to an ecosystem (Youngberg and Dyrness 1964; Cochran 1966; Cochran et al. 1967). Gases can adhere to ash particles and may be taken up into the environment in some cases proving quite harmful (Kittleman 1979; Thorarinsson 1979).

## COMPONENTS OF THE STATE FACTOR

### The Grain Size Distribution and Porosity of the Tephra

The grain size distribution and porosity of Mazama tephra is an important factor contributing to the cation exchange capacity, ionic diffusion through pumice particles, mass transport of solutes by displacement, and equilibration between internal pores and external solutions (Doak 1972), availability of moisture for plants (Youngberg and Dyrness 1964; Cochran 1966), heat retention and heat conductivity (Cochran 1966; Cochran et al. 1967), and weathering rates and development of clay and amorphous materials (Borchardt 1970; Dudas 1973; Dingus 1974). In other words, the particle size and porosity of the Mazama tephra has an important bearing on many properties of the tephra, especially for plant growth.

Variation of grain sizes of tephra deposits with respect to distance from the source is due to eruptive conditions such as viscosity, gas content, and explosivity due to magma composition that determine the size, shape, and density of the tephra fragments as well as the angle and height of the eruptive column. The tephra is then acted upon by external variables such as air density, pressure, humidity, wind velocity, direction, and turbulence to give specific distributions of particle sizes across the landscape (Fisher 1964a). The vesicularity of the tephra is related to the viscosity and gas content of the magma as pressure is released. Under adequate pressures below the Earth's surface, the gases remain

dissolved in the magma, but under eruption conditions (approaching atmospheric pressure) the gases expand and form cavities or vesicles in the quickly cooling and hardening tephra.

At Mount Mazama, Fisher (1964a) determined that the median diameters of tephra decrease with increasing distance from the source and that the deposits become better sorted with increasing distance from the mountain. Kittleman (1979), has plotted the median grain size of the ash versus distance from the mountain for deposits up to 200 km away (see Figure 17). This chart shows that ash size particles (<2mm) are predominant at distances of greater than 20 km, although Fisher's (1964:346) grain size isopachs show that fragments larger than ash (lapilli, 2-64mm) are still significant portions of the deposit as far as 100 km from the mountain.

There is also a difference in grain size between the C1 and C2 horizons. Chichester (1967), Rai (1971), and Dudas (1973) have found that the C1 horizon is coarser while the C2 horizon is much finer with neither strata showing any significant gradation in size. The mean weight diameters as a function of distance from the mountain for the C1 and C2 horizons are given in Figure 18.

One way of expressing the vesicularity or porosity of the tephra is through particle density and bulk density. The measurement of the particle density versus bulk density gives an indication of the amount of air space in the whole soil. Youngberg and Dyrness (1964) examined 12 samples from Mazama tephra in central Oregon for particle and bulk densities. The average particle

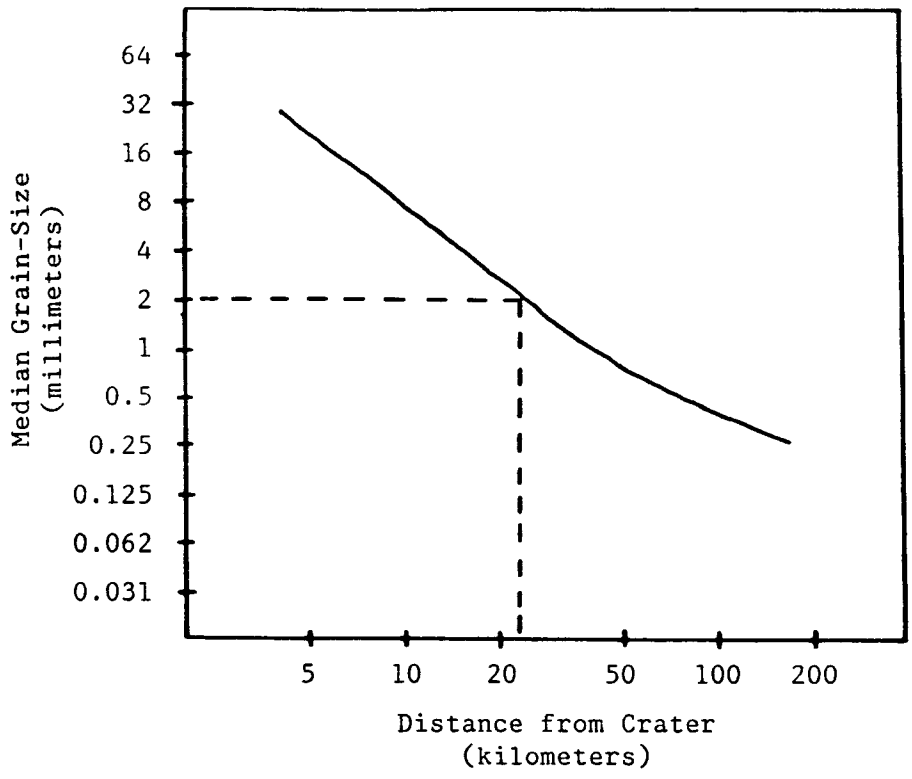



Figure 17. Variation in grain size of tephra with distance from Crater Lake (after Kittleman 1979:Figure 3.6). Dashed line shows the distance at which ash becomes the predominant size fraction in deposits.

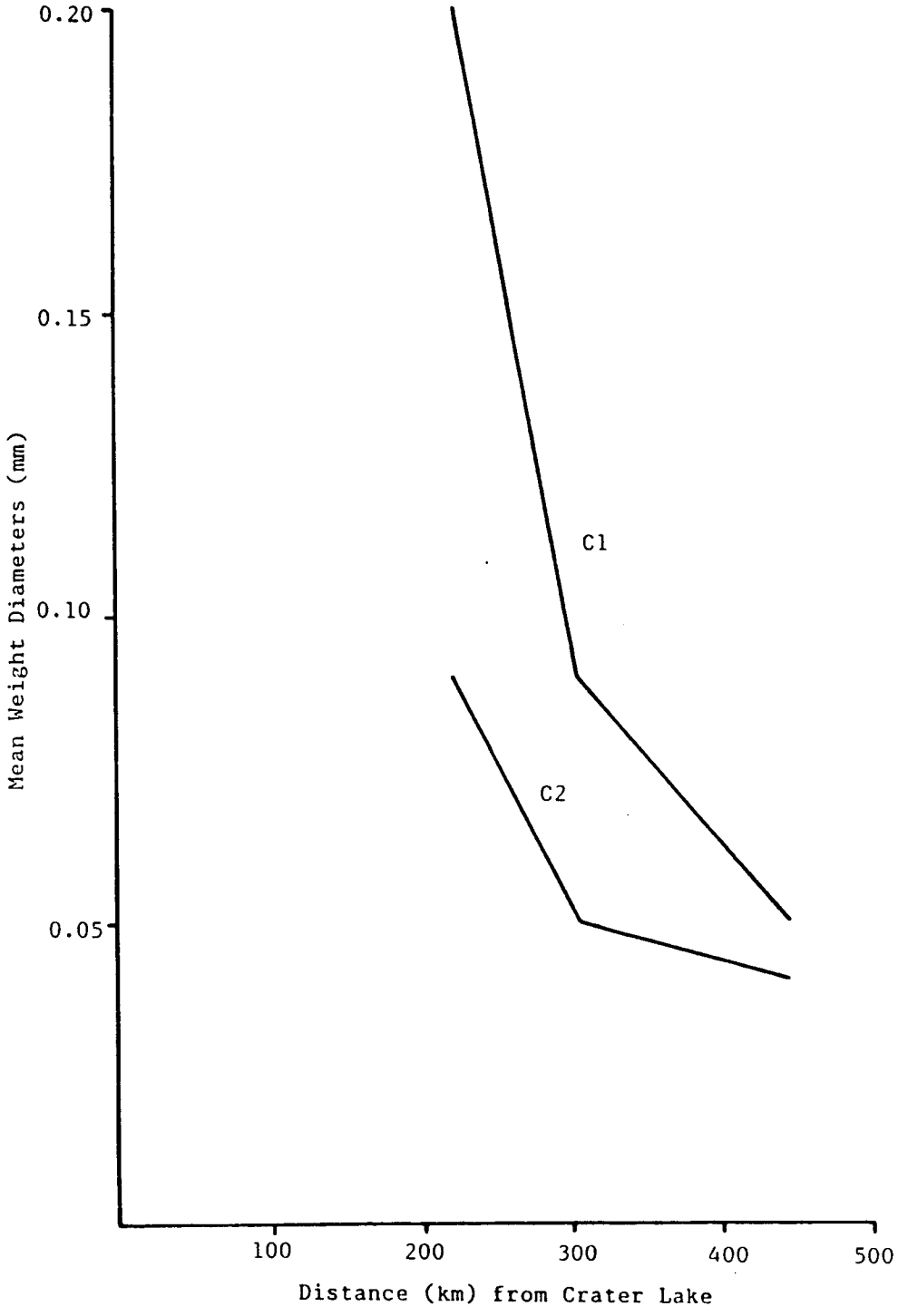



Figure 18. Changes in particle size for the C1 and C2 horizons with distance from Crater Lake (after Rai 1971:Figure 18).

density, ranging in particle size from silt loam to coarse gravel, was 2.61 g/cc with a range of 2.35 to 2.83 g/cc. The average bulk density for the Mazama tephra was 0.7 g/cc with a range of 0.5 to 0.9 g/cc. The lower figures for the bulk density are mainly due to pore space in the whole pumice. From these figures the total porosity is calculated as 73 percent for an average pumice soil.

Doak (1969) studied the particle porosity of Mazama ash by mercury intrusion methods (see also Borchardt 1970; Borchardt et al. 1968) across a transect of the deposits in eastern Oregon. In his study he noted the following characteristics with respect to porosity:

1. The characteristic porosity of a given particle size does not change with distance.
2. As particle size increases so does the percent of pore space between 30.0 and 0.2 microns.
3. All particle sizes have a percentage of total volume between the above pore diameters of 80 to 95 percent.
4. Larger particles are more vesicular.
5. The range of vesicularity for all particle sizes is 0.8 to 2.0 ml/gm.
6. Median pore diameters, no matter what the particle size, are between 4 and 10 microns.

Soil temperature is one of the primary controls of growth and distribution of plants; rate of growth, multiplication, and activity of soil microorganisms; and physical and chemical properties in soils (Carson 1961). The thermal properties of soils that are derived from tephra are directly related to the grain size,

porosity, and moisture content of the soil. The C1 and C2 horizons of a Lapine soil in central Oregon have very low heat conductivities, low heat capacities by volume, and low heat diffusivities. This means that these horizons are not able to store as much heat as more dense materials and so soils which consist of these materials will have much greater frost hazard potential than denser mineral soils (Cochran 1966; Cochran et al. 1967).

The moisture content of soils derived from tephra is directly affected by the grain size and porosity of the soil. The C1 and C2 horizons of a Lapine soil in central Oregon have shown that moisture characteristics for Mazama tephra are not as conducive to plant growth as non-tephra soils (Cochran 1966). The following generalizations can be made for soils derived from Mazama tephra:

1. The C1 and C2 horizons have slow unsaturated flow rates and may limit the rate of water flowing through the profile.
2. Field capacities for the C1 and C2 horizons exist at suctions of less than 0.06 bars and a large percentage of available moisture is stored between 0.05 and 2 bars suction.
3. Larger pumice particles release more moisture than the < 1.5mm size fractions on a weight basis, but the rate of release is low.

Even though there may be enough moisture in these soils for plants it may not be available for use. This is due to the slow unsaturated flow conditions, the tephra is not a good medium for plant root growth, and the contact between the roots and particles

is low thus impeding the moisture flow to the roots from the particles (Cochran 1966).

## Chemical Composition and Mineralogy of the Tephra

Chemical composition studies have been undertaken for correlational work (Williams 1942; McBirney 1968; Powers and Wilcox 1964; Borchardt 1970; Borchardt et al. 1971; Mack 1980; Cormie et al. 1981; Westgate and Gorton 1981; Sarna-Wojcicki et al. 1983; Davis 1978, 1983, 1985), but these data are also useful in determining the potential nutrient pool of the Mazama tephra. To determine the actual nutrient pool, the mineralogy of the tephra must be considered because the elements within the tephra are locked up into the minerals and volcanic glass in such a way that each element is not available to plants unless released by weathering of the minerals and glass. The elements are released upon weathering of the minerals and glass as a function of the weathering properties of the minerals and glass (cf. Dinauer 1977; and the references contained within).

About 75 chemical elements are found in volcanic rocks in significant quantities of which ten are major elements, in abundances of 0.1 percent or more, and many trace elements, in abundances of less than 0.1 percent (Kittleman 1979:72). The elements which have been identified in the Mazama tephra are Al, Ba, Ca, Ce, Cl, Co, Cr, Cs, Eu, Fe, H, Hf, K, La, Lu, Mg, Mn, Na, Nd, O, P, Rb, Sc, Si, Sm, Ta, Tb, Th, Ti, U, and Yb. The concentrations of

individual elements are listed in the original references cited above.

The mineralogy of the Mazama tephra series is characteristic of a dacitic composition. The minerals include plagioclase (72.9 +/- 5.3%), hypersthene (9.4 +/- 0.5%), hornblende (3.9 +/- 0.4%), clinopyroxene (2.8 +/- 0.3%), and magnetite (10.2 +/- 1.1%) (Kittleman 1973). These compositions and frequencies generally agree with other studies (Randle et al. 1971; Powers and Wilcox 1964) except for apatite which was found in the Tsoyawata tephra beds of Davis (1978) and biotite which was found in the C1 and C2 layers in eastern Oregon (Rai 1971).

The major component of the Mazama tephra is not a mineral, but volcanic glass which makes up about 77 to 90 percent by count of the total fragments in the silt size fraction (Rai 1971). Volcanic glass comes in all sizes from the larger pumice which is made up of frothy, highly vesicular volcanic glass to ash size particles which consist of the fragments of the bubble walls of pumice that are broken up in the explosive process leading to the eruption of the tephra (Fisher and Schmincke 1984). The mineral grains can be enclosed in pumice or they can be free grains mixed with the glass shards in ash (Kittleman 1979; Fisher and Schmincke 1984).

Rai (1971) has studied the mineral composition of Mazama tephra at four sites in central and northeastern Oregon to determine the mineralogical composition of the C1 and C2 layers mentioned in the preceding chapters. These compositions and frequencies are shown in Table 7.

Table 7. Mineralogical compositions and frequencies of Mazama tephra from the C1 and C2 horizons (after Rai 1971).

| Constituent | C1 Horizon Ave. % | Range | C2 Horizon Ave. % | Range |
|---|---|---|---|---|
| Glass | 77.05 | 70.01-82.2 | 90.45 | 85.0-94.4 |
| Plagioclase | 11.6 | 6.3-18.2 | 5.05 | 3.3-7.3 |
| Pyroxene | 2.6 | 1.1-5.3 | 1.2 | 0.4-2.3 |
| Hornblende | 0.48 | trace-1.3 | 0.05 | 0-1.3 |
| Biotite | 0.75 | trace-2.0 | 0.05 | 0-0.3 |
| Magnetite | 0.35 | trace-1.1 | 0.22 | 0-0.4 |
| Other | 6.72 | | 2.08 | |
| Total | 100.00 | | 100.00 | |

The data cited above are based on present day studies of events that occurred about 7000 years ago. Since that time there have been a number of chemical and mineralogical changes that have taken place in the tephra deposits. The major changes are in selective enrichment and depletion of certain elements, the introduction of clay minerals and the formation of amorphous colloids from weathering processes.

Chemical data from the Mazama series shows that silica is being selectively leached from the system, while aluminum is being retained. The molar ratio of $SiO_2$:$Al_2O_3$ for authogenic clay is between 1 and 2, while the unweathered pumice has a ratio of 8.2 (Dingus 1974). Borchardt (1970; Borchardt et al. 1971) found an enrichment of trace elements in the upper horizons which he felt was due to weathering of the volcanic glass; but Dudas (1973) showed that this enrichment, at least in part, is due to contaminants and not to weathering.

The amorphous colloids developed in Mazama tephra include halloysite, allophane, and imogolite (Dudas 1973), while crystalline clays include chlorite, chloritic intergrades, mica, smectites, and vermiculite (Chichester 1967; Rai 1971; Dudas 1973). Halloysite is found in both wet and dry sites with less feldspar and more volcanic glass. Imogolite was predominantly found where sites are poorly drained and there is an abundance of volcanic glass. Allophane is predominantly found in drier sites where silica and aluminum are present. Within poorly drained sites up to 20 percent clay was formed from weathering of the tephra. Chichester (1967) suggested

that crystal lattice clays were formed from the weathering of the tephra; but Dudas (1973) showed that they were derived from mixing of non-ash materials with the tephra.

For the most part, the Mazama series tephra has not undergone much transformation due to weathering. This is true for elemental enrichments and clay development although exceptions can be found in the continuously saturated tephra profiles. For the most part, the material properties of the tephra should be about the same at the present as they were in the past.

As mentioned above, the mineralogical and chemical characteristics of the Mazama tephra play an important part in the nutrient pool that is available to an ecosystem. This is reflected in a number of measures of fertility. Among these measures are amounts of exchangable cations, cation exchange capacity (CEC), pH, available phosphorus, percent nitrogen, and percent organic matter. The values for each of these measures is given in Table 8 for three different soil types in eastern Oregon that are derived from Mazama tephra. The Lapine and Steiger soils, developed from coarse pumice, are found in central Oregon. The Tolo series is developed from a much finer Mazama ash and is found in northeastern Oregon and into southeastern Washington.

The major exchangable cations are $K^{+}$, $Ca^{++}$, and $Mg^{++}$. These cations can be deposited or picked up from exchange sites on amorphous clays in tephra from soil solutions. Since these cations are important to plant growth and viability their quantity in a soil may help in understanding soil fertility. The quantity of a

Table 8. Fertility status for some representative soil profiles in eastern Oregon that are developed on Mazama tephra (after Youngberg and Dyrness 1964:Table 6).
* Determinations for pumice gravels 2 to 6 mm in size; all other values are for whole soil, including pumice gravels.

| Horizon | Depth | pH | P | K | Ca | Mg | CEC | Total N | O.M. |
|---|---|---|---|---|---|---|---|---|---|
| | in. | | ppm. | me./100 g. | | | | % | |
| **Lapine loamy coarse sand** | | | | | | | | | |
| A1 | 0-2 | 6.6 | 21.5 | 0.68 | 4.25 | 1.17 | 11.87 | 0.15 | 6.48 |
| AC | 2-9 | 6.75 | 12.2 | 0.51 | 4.40 | 1.32 | 9.66 | 0.05 | 1.34 |
| C1 | 9-16 | 6.75 | 2.7 | 0.24 | 1.20 | 0.79 | 6.04 | | |
| C1* | 9-16 | -- | 2.7 | 0.40 | 1.45 | 1.00 | 21.54 | | |
| C2 | 16-23 | 6.70 | 2.2 | 0.26 | 0.95 | 0.75 | 6.28 | | |
| C2* | 16-23 | -- | 2.3 | 0.35 | 1.70 | 1.17 | 13.21 | | |
| **Steiger coarse sandy loam** | | | | | | | | | |
| A1 | 0-2 | 6.0 | 12.0 | 0.50 | 5.2 | 0.78 | -- | 0.13 | 5.46 |
| AC | 2-8 | 6.0 | 14.0 | 0.43 | 2.4 | 0.60 | -- | 0.06 | 2.59 |
| C | 8-24 | 6.2 | 8.0 | 0.66 | 3.7 | 0.80 | -- | 0.03 | 0.76 |
| **Tolo silt loam** | | | | | | | | | |
| A1 | 0-4 | 6.15 | 27.8 | 1.90 | 10.40 | 3.42 | 18.45 | 0.19 | 9.17 |
| AC | 4-10 | 6.35 | 20.7 | 1.68 | 9.40 | 2.96 | 15.51 | 0.06 | 1.41 |
| C | 10-18 | 6.50 | 12.5 | 1.27 | 8.35 | 3.12 | 14.02 | 0.04 | 0.83 |

specific exchangable cation can change over time and under differing conditions and so these factors must be controlled for. The types of clay, pH, organic matter content, as well as the quantity of solutions perculating through the soil and the exchangable ions which are dissolved in the solution can affect the amounts of exchangable cations in a specific profile.

The cation exchange capacity (CEC) is the amount of exchangable cations per unit weight of dry soil and is measured in milliequivalents of cations per 100 grams of soil (Donahue et al. 1983:99). Soils derived from tephra tend to have very large CEC values due to the amounts of amorphous colloids in weathered tephra, high humus contents (Donahue et al. 1983), and from the trapping of ammonium salts in the pores of the pumice gravels instead of on exchange sites (Youngberg and Dyrness 1964; Doak 1972). When CEC values are separated from the effects of salt trapping in pores they are a good deal lower than for normal mineral soils. These salts are trapped by continued wetting and drying cycles. Under saturated conditions with a hydraulic gradient, soil solutions can readily flow through pores in the pumice, but as the soil dries out the solutions remain in the pores due to very slow diffusion rates. As drying continues air pockets can block these pores causing the salts to be trapped in concentrated amounts. These cations are not readily available to plants due to the roots not being able to reach into the pores. Therefore, even though CEC values are remarkable high, fertility is relatively low for tephra materials. This

phenomena is less important as the size of the particle deceases due to decreasing pore space in the smaller particles (Doak 1972).

Dingus (1974:77) found that phosphorus was absorbed by clays in large amounts. He warns that in sites where clays are especially prevalent large amounts of an insoluble mineral phase between the clays and the phosphorus may be formed, causing fertility problems.

The pH, total available nitrogen, and organic matter concentrations are influenced by the plant communities which live in and on the soil, and as such, are not actually a part of the material properties of the tephra even though they do give an indication of fertility.

## Volcanic Gases Associated with the Tephra

Volcanoes erupt large quantities of gases which have implications for volcanic hazards close to the volcano itself and also at great distances. Chlorine, fluorine, carbon dioxide, carbon monoxide, hydrogen sulfide, and sulfur dioxide are the major gases that can be emitted from volcanoes. These gases can be poisonous and some may be absorbed onto tephra and carried great distances away from the volcano (Rose 1977; Kittleman 1979; Thorarinsson 1979).

There has been little or no research done on the gases which may have accompanied the tephra depositions of the Mazama series. Some residual gases have been analyzed as a byproduct of the research into the chemical composition for the Mazama tephra. The two gases measured in this manner are chlorine and water vapor.

Dacitic magmas such as occur at Mount Mazama and form the bulk of tephra deposits do not show the types of effects as seen with more mafic sources (e.g. Anderson 1974a, 1974b, 1975; Carmichael et al. 1974; White and Waring 1963; Johnston 1980; Burnham 1979). Therefore the hazards from gases associated with the Mazama tephra-falls most likely would have been minimal with chlorine and sulfer gases playing a greater role fairly close to the mountain.

# VI. THE STATE FACTOR OF CLIMATE

## INTRODUCTION

The state factor of climate, E=f(C,t,d,m,g,...), can be thought of as a dynamic system which includes the effects of climate on tephra properties (Youngberg and Dyrness 1964; Harward and Youngberg 1969; Borchardt 1970; Borhcardt et al. 1971; Doak 1972; Dudas 1973; Dingus 1974) as well as the effects of tephra on climate (Flohn 1979; Hammer et al. 1981; Kyle et al. 1981; Newell 1981; Porter 1981; Robock 1981; Self et al. 1981; Thompson and Mosley-Thompson 1981; Walker 1981a; Rampino and Self 1982; Papp 1983; Rose et al. 1983). The climatic system consists of those properties and processes that are responsible for the climate and its variations. There are four system properties: the thermal, the kinetic, the aqueous, and the static properties. The thermal properties consist of the temperature of the air, water, ice, and land. The kinetic properties include the wind and ocean currents, with the associated vertical motions, and movement of the ice masses. The aqueous properties include the air's moisture or humidity, the cloudiness and cloud water content, ground water, lake levels, and the water content of the snow and of land and sea ice. The static properties include the pressure and density of the atmosphere and ocean, the composition of the dry air, the oceanic salinity, and the geometric boundaries and physical constants of the climatic system. Each of

these properties are interconnected by the physical processes that occur within the system. The physical processes include precipitation and evaporation, radiation, and the transfer of heat and momentum by advection, convection, and turbulence. (United States Committee for the Global Atmospheric Research Program 1975:13).

The system components consist of the atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere. Changes in any one of these system parts can produce change in either short term or long term climate states (The United States Committee for the Global Atmospheric Research Program 1975).

A practical definition of climate is referred to as a climate state or:

> ...the average (together with the variability and other statistics) of the complete set of atmospheric, hydrospheric, and cryospheric variables over a specified period of time in a specific domain of the earth-atmosphere system. The time interval is understood to be considerably longer than the life span of individual synoptic weather systems (of the order of several days) and longer than the theoretical time limit over which the behavior of the atmosphere can be locally predicted (of the order of several weeks). (United States Committee for the Global Atmospheric Research Program 1975:19).

A macro-climate state can then be used to refer to a climate state applied to a large region, such as the western United States or the Columbia Plateau. A micro-climate state is used to refer to a climate state on a much smaller scale, for instance, the Lower Snake River region or the riparian zone of the river. The

micro-climate state will tend to have a more homogeneous climate than the macro-climate due to its reduced size.

Changes in the climatic state can occur over any period of time. Climatic variation, the difference between climatic states of the same kind, can be described for the same month in two separate years, the same season in two separate years, the same year for two separate decades, and as in this thesis at much longer cycles.

Climatic variability and anomaly are two important concepts to understand. Climatic variability involves the variance of climate states of the same kind, while climatic anomaly is the deviation of a particular climate state from the average of climate states of the same kind. (United States Committee for the Global Atmospheric Research Program 1975:19).

It is important for this thesis to detail the climatic state, that is the long term general state, that existed during the Mazama eruptive period. Paleoclimates, or past climates, can not be measured directly by instruments, but must be inferred through a series of indirect methods. These methods, for the most part, give relative climatic conditions which must be referenced against the present climatic conditions to be meaningful. In other words, how past climatic conditions vary from the present conditions. Since these methods do not generally give quantitative data it is necessary to broaden the period of the climatic state so that long term trends are used instead of short term variation. Therefore, for this thesis, the time period used to define the climatic states will be based on longterm fluctuations in climate that occur due to

changes in the properties, processes, or components of the climatic system. This means that a climatic period that shares the same qualities of properties, processes, and components will be included in the same climatic state.

The sources for reconstructing the paleoclimate include tree rings, fossil pollen, mountain glacier and ice sheet terminal positions, ancient soils, lake levels within closed basins, and varve thicknesses in lakes (United States Committee for the Global Atmospheric Research Program:Table A1), as well as volcanic tephra-fall distributions, faunal remains from paleontological and archaeological sites (Grayson 1981), and deposition of various sediments (Antevs 1955; Fryxell and Daugherty 1962).

This chapter will be concerned with the macro-climate for eastern Oregon and Washington. The macro-climate will give a baseline by which general principles can be discussed for the area of the Mazama tephra-falls, while the micro-climate will be useful in discussing the specific effects on the tephra, plants, animals, and humans of specific locals. As well, both the effects that tephra-falls may have on climate and how climate may affect the distribution and properties of tephra-falls will be discussed.

## MACRO-CLIMATE

The weather conditions for the Pacific Northwest during the present are discussed by Jackson (1985). The Pacific Northwest climate is distinguished by distinctive seasonal changes in temperature and precipitation. These seasonal differences are due

in part to the cyclonic storm belt, oceanic and continental influences, and surface form and elevation. These factors contribute to relatively dry, warm summers and wetter, cooler winters. The Cascade Mountains, due to their shadowing effect, cause greater seasonal temperature ranges and less precipitation to the east of the mountains than to the west. East of the Cascades, average precipitation totals range from 10 to 20 inches to as much as 30 inches at higher elevations. During the winter, precipitation tends to fall as snow which averages 10 to 30 inches depending on elevation and exposure. July daytime temperatures are commonly in the 80's and 90's while nightime temperatures are in the mid-50's. January mean temperatures average 20 to 30 degrees Fahrenhite, but may drop to -20 and -30 degrees. Strong winter winds are common.

If the climatic states of the past are of similar to the present climate, the climate of the Mazama period may be recreated by using the present climate as a baseline for understanding any climate variability and anomalies of the past. The position and height of the Cascade Mountains, which causes a major rain shadow for eastern Oregon and Washington, has not changed in the last 10,000 years. Another major factor in the weather of the Northwest, is the cyclonic storms which sweep in from the ocean and out of the arctic. If these cyclonic storm patterns were the same during the Mazama eruptive period as today the same sorts of wind and precipitation patterns would be in effect as today. There is some indication that this is so.

The cryonic component of the climate system, the position of the ice caps and alpine glaciers, plays an important role in the position of the mid-latitude cyclonic storm belts in the Pacific Northwest. During the Pleistocene, the position of the ice caps forced the cyclonic storm systems farther to the south and coupled with the effects of alpine glaciers caused greater effective precipitation to occur. Since the end of the Pleistocene, except for minor fluctuations in alpine glaciers (Table 9), the position and size of the northern ice cap has remained relatively stable. There have not been any of the large scale southern movements of the ice position as seen prior to about 10,000 years ago (Flint 1971). If the neoglaciations that have occurred in the mountain areas are of minor consequence to the patterns of cyclonic storm systems, it should be expected that during the Mazama period wind and storm patterns were essentially the same as today with only minor variations.

Wind patterns can be recreated by the distribution of the various tephra-falls. Since the distribution of a tephra-blanket depends on the patterns of wind at the time of deposition (Kittleman 1979; Walker 1981a; Carey and Sparks 1986), the recreated distribution of the Mazama tephra-falls should show the wind patterns of 7000 years ago. Since the factors which determine wind patterns are generally the same now as for 7000 years ago (e.g. position of the Pacific Ocean, Cascade Mountains, and etc.) then it may be possible to determine the season of the wind patterns by comparing the general wind patterns of today with the distributions

Table 9. Glacial advances of the Holocene in the Cascades of Oregon and Washington, and the Wallowa Mountains (after Burke and Birkeland 1983).

| Years B.P. | Central Cascade Range, Oregon (Composite of Carver 1972; Scott 1977; Dethier 1980) | Mt. Rainier (Crandell 1969; Crandell and Miller 1964, 1974) | Dome Peak (Miller 1969) | Glacier Peak (Beget 1980) | Eastern Cascades Waitt et al. 1980) | Wallowa Mts. Oregon (Kiver 1974; Williams 1974; Burke 1978, and Unpublished) |
|---|---|---|---|---|---|---|
| 0 | Neoglaciation II | Garda Stade of Winthrop Creek Glaciation | Late Neoglac. | | Brynhild | Eagle Cap |
| 1000 | | | | | | Prospect Lake |
| 2000 | | Burroughs Mt. Stade of Winthrop Creek Glaciation | | | | Early Neoglaciation? |
| 3000 | Neoglaciation I | | | | | |
| 4000 | | | | | | |
| 5000 | | | Early Neoglac. | | | |
| 6000 | | | | | | |
| 7000 | | | | Unnamed Till | | |
| 8000 | | | | | Brisingamen | |
| 9000 | | | | | | Glacier Lake |
| 10,000 | Early Holocene Advance | McNeely Glac. | | | | |

of the Mazama tephra units. Figure 19 gives the distribution of the lower tephra-unit with the present day wind patterns overlaid on it while Figure 20 gives the distribution of the upper tephra unit overlaid by the present day wind patterns. The distributions for the northeasterly lobes for the lower and upper tephra units show a counter-clockwise pattern which may correspond to winter wind patterns. The southeasterly lobe of the upper tephra unit may correspond to summer wind patterns. While these patterns do not show conclusively that wind and storm patterns were the same 7000 years ago they at least do not necessarily contradict that interpretation. Pollen data, as discussed in the Chapter III, suggest that successive tephra-falls of the climactic phase occurred during the autumn, and then again during the autumn of the next year, and finally the spring or summer of the third year (Mehringer 1977; Blinman 1978; Blinman et al. 1979; Mehringer 1986). These seasons of deposition suggest that past wind patterns may have actually corresponded to present day patterns.

In another interpretation Fisher (1964b) suggests from stratigraphic and grain size evidence, that the various lobes could have been accounted for by changing wind patterns during a single eruption or at least closely spaced eruptions. The initial eruption began when the winds blew to the southeast and as the eruption grew in strength the winds shifted to the northeast. Grain size differences also indicate that during the emplacement of the northeasterly lobe, low level winds blew directly east, while high level winds blew to the northeast. The northern lobe, which is much

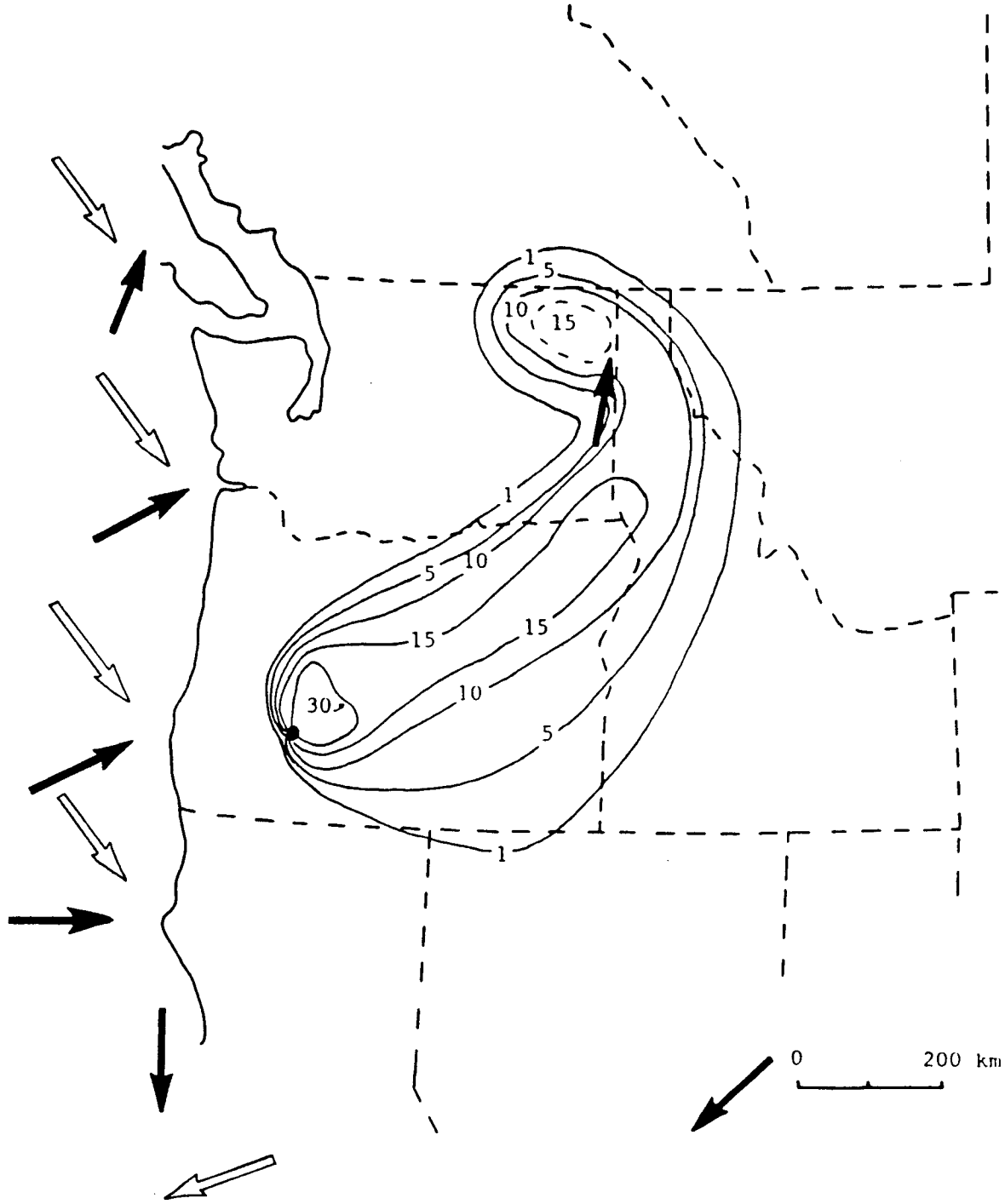



Figure 19. Present day general wind patterns overlaid on distribution of the lower tephra-fall. Black arrows represent January wind patterns; open arrows represent July wind patterns (Jackson 1985:49). Tephra isopachs in centimeters derived from Table 6.

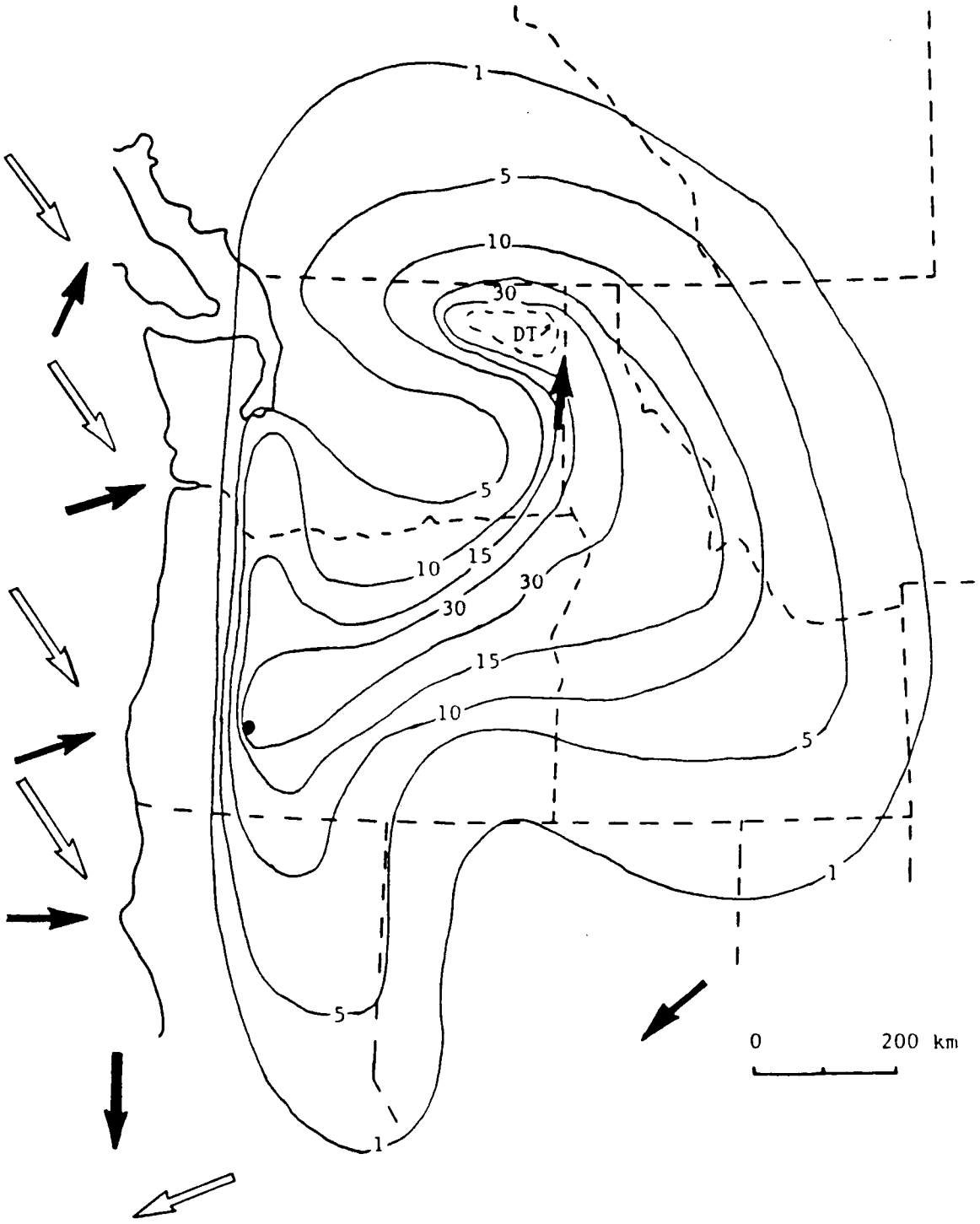



Figure 20. Present day generalized wind patterns overlaid on distribution of the upper tephra-fall. Black arrows represent January wind patterns; open arrows represent July wind patterns (Jackson 1985:49). Tephra isopachs in centimeters derived from Table 6.

smaller in size, was probably emplaced toward the waning stages of the eruption or somewhat later than the end of the major eruptions.

The macro-climate states for the Holocene or post glacial period in the western United States has been detailed in a tripartate scheme originally developed by Antevs (1948, 1955) and since reinterpreted and refined by others (Deevy and Flint 1957; Hansen 1947:Table 9; Fryxell and Daugherty 1962; Mehringer 1986:174; and others) (Table 10). The schemes are based on vegetation distributions developed through pollen analysis, various geologic methods such as periods of increased erosion or deposition, and other methods. As such, they indicate general moisture and temperature fluctuations for the region as a whole. To determine actual time periods or climactic conditions for any specific area each separate micro-climate state must be independently developed (Bryan and Gruhn 1964).

The Mazama tephra-falls occurred during the end of the Anathermal and the beginning of the Altithermal period. Conditions were becoming generally drier and hotter than they had previously been and than they are at the present. As time continued, conditions became more moist and cool than during the height of the Altithermal so that by the Medithermal, the climate was moister and cooler than today's conditions.

As discussed in Capter II, volcanic eruptions can have some effect on climate. The dacitic magma at Mount Mazama is not as high in sulfur or chlorine content as a basaltic source, but the size and violent nature of the eruptions may have caused less than a 1 degree

Table 10. Examples of some of the major climatic schemes that apply to the Pacific Northwest.

<table>
<tr><th>Years B.P.</th><th>Antevs (1955) Neothermal Sequence</th><th>Deevey and Flint (1957) Postglacial</th><th>Fryxell and Daugherty (1963) Postglacial</th><th>Hansen (1947) Postglacial</th><th>Mehringer (1986) Postglacial</th></tr>
<tr><td>0<br>1000<br>2000</td><td rowspan="2">Medithermal</td><td rowspan="2"></td><td rowspan="2">Present Climate</td><td rowspan="3">Cooler, Moister Than Prior Period</td><td rowspan="2">Present Day Climate</td></tr>
<tr><td>3000</td></tr>
<tr><td>4000</td><td>Transition to Cooler, Moister</td><td>Moister, Cooler Climate</td></tr>
<tr><td>5000</td><td rowspan="2">Altithermal</td><td rowspan="4">Hypsithermal</td><td rowspan="2">Period of Maximum Warmth and Drought</td><td rowspan="2">Maximum Warmth and Dryness</td><td>Slower Drying</td></tr>
<tr><td>6000</td><td rowspan="2">Height of Warmer, Dryer Period</td></tr>
<tr><td>7000</td><td rowspan="3">Anathermal</td><td rowspan="2">Warming, Drying Trend</td><td rowspan="3">Increasing Warmth and Dryness</td></tr>
<tr><td>8000</td><td rowspan="2">Increasing Warmer, Drier Period</td></tr>
<tr><td>9000</td><td rowspan="2">Cool, Moist Climate</td></tr>
<tr><td>10,000</td><td rowspan="2"></td><td rowspan="2">Cooler, Moister Period</td></tr>
<tr><td>11,000</td><td></td></tr>
</table>

C. drop in temperature for a few years. There does not seem to be any indication that the Mazama eruptions coincided with a major period of volcanic activity and so there would have been a minimal and short lived improvement in the Altithermal climate.

It should then be possible to talk about a macro-climate state for the Mazama eruptive period that coincides with the Altithermal. These drier and hotter conditions may have had some consequences for the deposition and subsequent physical properties of the tephra. The Mazama eruptive period was followed by the macro-climate state of the Medithermal where cooler and moister conditions may have had an influence on post depositional properties of the tephra as well.

# VII. THE STATE FACTOR OF GEOMORPHOLOGY

## INTRODUCTION

The state factor of geomorphology, E=f(G,t,d,m,c,...), defines the geomorphic landform on which the tephra is stable either as a primary or secondary deposit. The landscape positions which hold tephra are locations of ecosystems which have been most heavily affected by longterm contact with the tephra.

Within this context, it is important to define the agents of transport and deposition of the tephra because this will give clues as to which landforms the tephra can be preserved on as a primary deposit or where it may be trapped as a secondary deposit. It is possible to define these positions by theoretical considerations of the properties of the tephra and the forces which may act to transport or trap tephra. Analogous situations where modern day eruptive deposits can be studied to learn about the past deposits (cf. Lisle et al. 1983; Swanson et al. 1983) may give hints as to how tephra deposits may differ from other materials in their transport and storage properties. It is also possible to study the present day positions of the Mazama tephra bodies to help understand past dynamics. These studies have been conducted as a primary research question (e.g. Rai 1971), as a part of archaeological research (e.g. Hammett 1976), and as a result of soils survey activities (e.g. Wenzel 1979; Carlson 1974; Carlson 1979; Ehmer

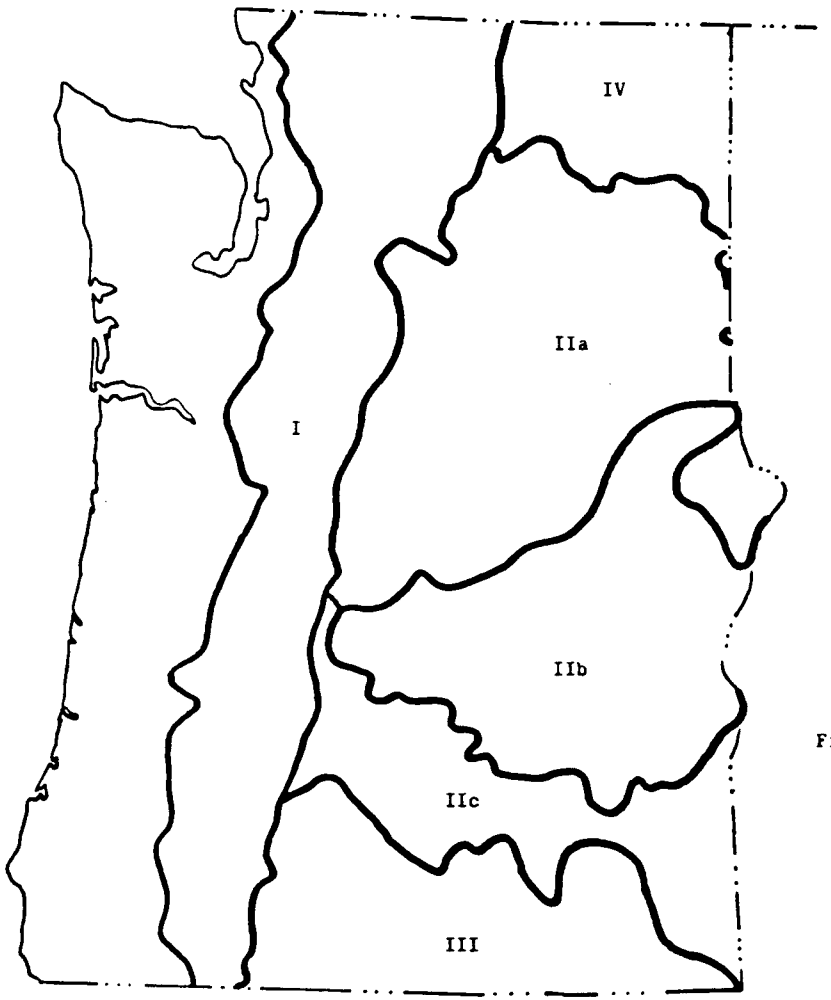
n.d.). Each of these sources adds knowledge about the dynamics of secondary tephra transport and deposition.

## Regional Geology and Landforms

The three major provinces in the study area are the Cascade Mountains Province, the Columbia Intermontane Province, and the northern Basin and Range Province as defined by Rosenfeld (1985). These provinces are shown on Figure 21.

The Oregon and southern Washington portion of the Cascades Mountains consists of a broad upwarp composed of the lower most early Tertiary tuffs, breccias, lavas, and mudflows found in the Columbia Gorge and other deep valleys which underlie a thick middle section of tertiary basalts exposed on the western Cascades and an upper section of Tertiary and Quaternary andesites and basalts that make up the crest of the mountains at elevations of 4000 to 6000 feet. A series of composite volcanoes rise above the upper platform. The northern half of the Cascades in Washington consist of dissected uplands underlain by folded and faulted Paleozoic sediments that have been intruded by granites. The highest ridges are at elevations of 6000 to 8000 feet with Mt. Baker and Glacier Peak rising above them (Rosenfeld 1985).

The Columbia Intermontane Province consists of the Columbia Basin, Central Mountains, Harney High Lava Plains, Malheur-Owyhee Upland, and the Snake River Lava Plain to the east of the study area. The Columbia Basin is an irregular structural basin consisting of Tertiary basalt flows that are covered by fluvial,




KEY

I. Cascade Mountains
II. Columbia Intermontane
  a. Columbia Basin (Plateau)
  b. Central Mountains
  C. High Lava Plains
III. Basin and Range
IV. Rocky Mountains

Figure 21. Landform regions within the study area (after Rosenfeld 1985:40).

lacustrine, eolian, and glacial sediments. The Central Mountains consist of complexly folded and faulted uplifts that rise 2000 to 5000 feet above their surroundings. These mountains are quite dissected and the higher portions have been glaciated. The Harney High Lava Plains are a fairly flat region of recent lavas at about 4000 to 5000 feet in elevation. The Malheur-Owyhee Upland is a partly dissected, partly warped plateau consisting of Cenezoic lava flows, tuffs, and lakebeds. This last province is about 4000 to 8000 feet above sea level (Rosenfeld 1985).

The Basin and Range Province consists of a high lava plain that is interupted by north to south trending fault block ridges and troughs. The fault block ridges include Steens Mountain, Hart Mountain, Abert Rim, Winter Ridge and others. The troughs include Alvord Basin, Warner Valley, Abert Lake basin, Summer Lake basin, Goose Lake basin and Klamath Lake basin (Rosenfeld 1985).

## COMPONENTS OF THE STATE FACTOR

### Secondary Transport and Deposition of Tephra

Retransport of volcanic tephra can occur through the action of water, wind, and gravity. Retransport of tephra by water can occur through fluvial processes or by surface wash. Each of these factors can greatly change the original distribution of tephra deposits and therefore the possible longterm effects of the tephra on individual ecosystems.

Fluvial transport includes retransport of tephra by streams and rivers. Material may be transported as bedload, that is along the bottom of the channel, or as suspended load. The manner and extent of transport is based on the flow characteristics and energy supplied by the fluvial system to the particles. The transportability of the particles depends on the size, shape, and density of the material being transported (Morisawa 1968; Reineck and Singh 1980; Richards 1982).

Fluvial deposition is due to loss of capacity or competence because of a decrease in gradient, decrease in volume, increased caliber of load, or the damming of the channel. A decrease in gradient can occur due to changes in rock type, increase in stream length with the same vertical fall (i.e. a meander), or the stream drops onto a level plain or still body of water. A decrease in volume can occur due to changes in vegetation that promote infiltration and retention of rainwater, a change in climate to drier conditions, or by diversion of water by another stream. The change in competency or capacity is often seen in glacial outwash situations or in denuded water sheds (Morisawa 1968). The major areas of deposition in a fluvial system are floodplains, deltas, and alluvial fans (See Reineck and Singh 1980 for an excellent treatment of depositional environments for each of the above systems).

Near Mount St. Helens, areas which were subjected to air-fall deposition only, showed little channel adjustment, while the areas that received both blast and air-fall deposits had localized channel modification. Stream systems subjected to only air-fall deposits

did not undergo heavy transport and sedimentation of tephra, due to the large grain size of the tephra. In contrast, the blowdown areas where blast deposits and air-fall material were found showed significant localized transport and sedimentation. Steep, upper tributaries were quickly cleared of most of the tephra and the major sediment storage occurred in the middle order streams from slope wash and sediments delivered from upstream (Lisle et al. 1983).

The factors which define the amount of erosion by overland flow are slope length, slope steepness, slope shape, amount and type of vegetation, climate, and the type of soil materials (Smith and Wischmeier 1957; Young and Mutchler 1969; Carson 1972; Young 1972; Clark and Small 1982). Erosion occurs through the process of raindrop splash, which may detach particles and move them down slope, or by sheet wash, a fairly uniform sheet of water moving downslope, and rilling, the concentration of water into microchannels. Surface wash and rill wash occur when the rate of water application to the surface is greater than the rate of inflow to the subsurface strata. The moving stream of water down slope is a good transport mechanism though it has little erosive power especially at the top of the slope. Raindrop impact is a much more effective erosive agent. The energy derived by the force of the raindrop striking a particle is enough to detach and even throw the particle into the air and downslope. Raindrop splash coupled with transport by sheet and rill wash are very effective in moving soil materials downslope. On bare soil raindrop impact is a more effective erosion agent than surface wash and unlike surface wash,

its power is not affected by the position on the slope or the slope angle (Young 1972). Saturated overland flow is most common at the base of slopes where excess water may gather (Young 1972:62). Surface wash is most effective at transporting particles on higher slope angles and toward the bottom of the slope. The effects of raindrop impact also include sealing the soil through dispersion of fine particles and clogging of pores to give increased runnoff, deterioration of soil structure, removal of finer particles and relative enrichment of sand.

Sheetwash tends to deposit material in the lowest topographic positions due to the water sheet loosing momentum or energy. These positions can occur at the break of a slope where the slope angle approaches horizontal or in depressions without surface drainage. Vegetation and other natural blockages on slopes trap sediment as well. Slope wash is also an important factor in delivering sediments to stream and river systems (Morisawa 1968). The larger particles will tend to be deposited first with succeedingly smaller sizes deposited further downslope. If the particles reach stream or river systems they may be transported long distances, but slope wash can be considered a short distance transport process in most cases.

Swanson et al. (1983) have discussed the erosion of tephra from hillslopes for Paricutin (Mexico), Irazu (Costa Rica), Vulcan (New Guinea), and Mount St. Helens (Washington). They found that steeper slopes, thicker deposits, finer textured deposits, and lesser amounts of vegetation and organic debris favor higher rates of sheet and rill erosion. As well, increased amounts of rainfall

and rainfall intensity will cause higher erosion rates. A factor which increases sheet and rill erosion is the development of an impermeable crust on the surface of the tephra deposits caused by an accumulation of fine particles in the surface pores that causes an increase in saturated overland flow (Segerstrom 1950 cited in Swanson et al. 1983) due mostly to cementation by a precipitation of salts (Waldron 1967 cited in Swanson et al. 1983) or compaction by raindrop splash (Young 1972).

The rate of rill erosion tends to peak and then decline after the first few years or sooner. In areas of killed and living vegetation forest litter falling on the tephra surface is mixed with the tephra by raindrop splash and other processes to form a protective barrier that inhibits erosion. At Mount St. Helens, in mature conifer forest stands where tephra was less than a few centimeters thick, the deposits were quickly incorporated into the forest floor. In areas where deposits are thin enough to leave downed logs uncovered, downslope transport is inhibited by these barriers (Swanson et al. 1983).

The effectiveness of wind in transporting particles is dependent on the size, shape, and density of the material being transported, as well as the velocity of the wind (Bagnold 1954; Reineck and Singh 1980). Silt and clay size particles (generally up to 0.05 mm) can be kept in suspension for longer periods than larger particles. The larger particles are moved by rolling and saltation (bumping along the surface). Particles up to 1 mm in size may be moved by saltation, while rolling or surface creep can move

particles up to 2 mm. The particles which are larger than 2 mm in size generally are moved by the pushing impact of saltating grains. Thus wind can effectively separate poorly sorted deposits into dust, sand, and gravel deposits through the process of winnowing (Reineck and Singh 1980). Deposition of the material can be accomplished through the disturbance of air currents causing a turbulent flow condition. This could happen when opposing or cross currents of wind meet or when obstacles such as vegetation or rocks stick up into the wind flow. At Paricutin (Segerstrom 1966), wide spread erosion and deposition by eolian processes was apparent by the formation of tephra dunes and the infilling of the heads of rills during the dry season.

Gravity generally works with rain and water to move the particles downhill but may also work on its own to transfer material short distances through three processes. These are: "1) shallow, rapid mass movements (debris slides, avalanches and flows of Varnes (1978)), 2) deeper-seated, slow moving (mm to mm/yr) slumps and earth flows (Varnes 1978), and creep which occurs at slow rates and without the development of a discrete failure surface" (Swanson et al. 1983). Except close to the mountain, in thick deposits and bared slopes, mass movement is not likely to be of significance. Farther from the mountain air-fall deposits on steep slopes usually seek more stable positions at the toe of the slope, resting at a smaller angle of repose.

Volcanic particles, due primarily to their high vesicularity, have unique hydrodynamic properties. According to Whitham and

Sparks (1986) cold pumice can stay afloat for over one and one half years, while hot pumice may sink immediately. This means that hot pumice nearer to the source may sink rapidly in rivers and in lakes. Pumice particles may be transported by wind and water more easily and therefore farther than denser rock fragments of the same size and composition under the same transport conditions.

## Landforms of Tephra Storage

In an attempt to define the landforms on which the Mazama tephra is stable, either as primary or secondary deposits, those landforms on which Mazama tephra is presently found are discussed. Primary deposits are recognized by airfall stratigraphy and lack of contaminents, while secondary deposits are recognized by bedding from eolian or alluvial processes and foreign materials include in the tephra deposits (Rai 1971; Dudas 1973). While this approach does not necessarily indicate how long the tephra has been stored on the landform it is appropriate for general modeling. Radiocarbon dating and climatic correlations are needed for determining the periods of redeposition for specific deposits. Extensive radiocarbon dating is not available and so correlation with climatic periods that have a potential for transport processes must be used to determine peak transport periods (See the section on residences times in Chapter III).

The National Forests have long had a program of soil survey on their lands which can give useful information about the landforms which are potential storage places for Mazama tephra. Since the

National Forests are situated in upland terrains for the most part, a strict reliance on these sources will give a skewed picture. Soil surveys for individual counties have been or are in the process of being completed by the USDA Soil Conservation Service. These surveys should provide information for lower elevation lands. Moreover, in certain instances geomorphic studies have been undertaken which also provide useful information for this study and will be used where appropriate.

Winema National Forest is located to the northeast, east, and southeast of Crater Lake National Park. On the West side of the Forest are the Cascade Mountains and on the east is the fault block basins of the Basin and Range Province. This area, like the rest of central and eastern Oregon has a climate characterized by warm, dry summers and wet, moderately cold winters. Precipitation ranges from a high of 60 inches near the Crest of the Cascades to a low of 20 inches in the basins to the east. Snow is the predominant form of precipitation in the winter. Prevailing winds are from the west and southwest with severe wind storms being common (Carlson 1979).

About 75 percent of the soils in the Winema National Forest are derived from Mazama tephra, while the other 25 percent have had minimal influence by tephra and so resemble typical mineral soils. There are eight Soil Groups on Winema National Forest which include those that are derived from air-fall tephra (Soil Groups A and B), those which are derived from glowing avalanche and associated deposits (Soil Groups C and D), those which are derived from the more basaltic composition materials deposited near the end of the

climatic eruption (Soil Group E), those which are derived from reworked tephra deposits in concave drainage positions (Soil Group G), and the more typical mineral soils with little tephra influence (Soil Groups H, R, and X). Soils which are heavily influenced by air-fall tephra (Soil Groups A and B) are found on most landforms in the northeastern and eastern portions of the Forest. To the southeast they give way to Soil Group H with distance from Crater Lake and to the south are not of any magnitude. From Table 11 it can be seen that many different landforms, all aspects, and all elevations are represented by ash-derived soils. Slopes range up to 70 percent but the average slope is somewhere less than 35 percent. The tephra deposits are quite influential in the local ecosystems due to close proximity to Crater Lake.

To the east and adjacent of Winema National Forest is the Fremont National Forest. Most of the Forest lies within the Basin and Range Physiographic Province at elevations from 4000 to less than 8500 feet above sea level. The drainage systems consist mostly of short streams that flow into low lakes or playas with no outlets. The Sprague and Sycan Rivers are the only ones to have outlets outside of the Forest. The general topography consists of flat to gently rolling lava plateaus and tablelands to some highly dissected landforms, with most slopes being less than 40%. Precipitation ranges from 15 to 30 inches per year most of which falls during the fall, winter, and spring months. Prevailing winds are from the west and southwest (Wenzel 1979).

Table 11. Landform Characteristics of Air-Fall Derived Soils on Winema National Forest (After Carlson 1979).

| Land-Type | Slope % | Aspect | Elevation feet | Landform |
|---|---|---|---|---|
| A1 | 0-10 | varies | 4000-5500 | Upland flats |
| A2 | 0-15 | varies | 4000-5500 | Concave toe slopes and valley bottoms |
| A3 | 0-15 | varies | 5000-5800 | Concave toe slopes and valley bottoms |
| A4 | 0-35 | varies | 4000-5500 | Convex ridges and side slopes |
| A5 | 0-35 | varies | 5000-5800 | Convex ridges and side slopes |
| A6 | 0-35 | varies | 4000-5500 | Convex ridges and side slopes |
| A8 | 0-10 | varies | 4000-5500 | Broad flats and basins |
| A10 | 0-10 | varies | 4000-5500 | Broad flats and basins |
| A11 | 0-35 | varies | 5000-6000 | Convex ridges and side slopes |
| A12 | 0-35 | S | 5000-6000 | Convex ridges and side slopes |
| A13 | 0-35 | E | 6000-7000 | Concave glacial troughs |
| A14 | 10-70 | varies | 6000-7500 | Convex glacial carved ridges and side slopes |
| A15 | 0-50 | N | 5000-6000 | Convex ridges and side slopes |
| A16 | 0-35 | E | 5000-6000 | Concave glacial troughs |
| A17 | 0-35 | varies | 5000-6000 | Convex ridge tops and side slopes |
| A18 | 0-15 | varies | 5000-6000 | Concave toe slopes and valley bottoms |
| A19 | 35-70 | varies | 5000-6000 | Convex side slopes |
| B1 | 0-10 | varies | 4000-5500 | Upland flats |
| B2 | 0-15 | varies | 4500-5500 | Concave toe slopes and drainage ways |
| B3 | 0-15 | varies | 5000-6500 | Concave toe slopes and drainage ways |
| B4 | 0-35 | varies | 4000-5500 | Convex ridges and side slopes |
| B5 | 0-35 | varies | 5000-6500 | Convex ridges and side slopes |
| B6 | 35-70 | varies | 4000-6500 | Very steep side slopes |
| B7 | 0-35 | varies | 4000-5500 | Convex ridges and side slopes |
| B8 | 0-10 | varies | 4000-5500 | Broad flats and basins |
| G1 | 0-5 | varies | 4200-5500 | Valley bottoms |
| G2 | 0-5 | varies | 4200-5500 | Valley bottoms |
| G3 | 0-5 | varies | 4200-5500 | Valley bottoms |
| 3 | 0-5 | varies | 4200-4800 | Flat river bottoms with oxbows along Williamson and Sprague River bottoms |
| 6 | 0-20 | varies | 4500-5500 | Pumice and ash mantled sand dunes |
| 20 | 20-60 | varies | 4500-5500 | Pumice and ash mantled side slopes of cinder cones |
| 21 | 20-60 | varies | 5500-6000 | Pumice and ash mantled side slopes of cinder cones |

Soils derived from Mazama tephra for the most part are considered to be of eolian origin (Mapping Units 77-99) by Wenzel (1979), although some are found as primary and secondary deposits in old lake beds (Mapping Units 13 and 14), and as colluvial and/or alluvial deposits in steep canyons along major drainages (Mapping Unit 2). Most of these eolian derived soils are found on the west and northern parts of the Forest with thicknesses increasing to the north (Wenzel 1979). Table 12 gives the landform characteristics for various ash-derived soils within the Forest. Slopes range from 0 to 80%, but most seem to be less than 20%. The tephra can be found on all aspects, at all elevations, and on all types of landforms. These patterns may be due to the heavy covering of the tephra blanket across the landforms, little transport, short distances of transport, or even eolian retransport and deposition of the tephra from elsewhere.

The buried profiles in Fremont National Forest (Table 12) are mostly residual and colluvial materials with some valley fill, and one instance of alluvial deposits (Mapping Unit 90). The type of buried profile may indicate the process responsible for retransport or storage of at least some of the tephra besides eolian processes which may act across any landscape. For instance, residual buried profiles could indicate stable positions where primary tephra profiles may be found. Colluvial buried profiles would indicate sheet wash and gravity transport processes may have deposited the tephra there. Valley fill buried profiles indicate either

Table 12. Landform Characteristics of Ash Derived Soils on Fremont National Forest (After Wenzel 1979).

| Mapping Unit | Slope % | Aspect | Elevation feet | Buried Profile* | Landform/position |
|---|---|---|---|---|---|
| 2 | 30-80 | varies | -- | -- | Steep and narrow canyon types along major drainages |
| 8 | 0-70 | varies | 6400-8400 | -- | Subalpine lands |
| 10 | varies | varies | -- | -- | Cinder cones |
| 77a | 0-15 | all | 4800-6200 | R | Gently sloping narrow ridges or side slopes on dome-shaped uplifts |
| 77b | 16-40 | all | 5000-6400 | R | Moderately steep side slopes on dome-shaped uplifts |
| 78 | 25-70 | S | 5000-6400 | R | Steep side slopes on dome-shaped uplifts |
| 79 | 10-40 | all | 6000-8000 | R | Gentle to moderately steep side slopes on eruptive centers |
| 80a | 0-15 | all | 6000-7500 | R | Upland tablelands |
| 80b | 16-40 | all | 6200-7800 | R&C | Moderately steep slopes on tablelands |
| 81 | 0-15 | all | 4500-5800 | R | Gently rolling lava tablelands and plateaus |
| 82 | 0-10 | all | 4500-5500 | VF | Broad basins |
| 83 | 0-5 | all | 4500-6200 | VF | Broad basins |
| 84 | 0-10 | all | 4500-5800 | R | Gently rolling lava plateaus and tablelands |
| 85 | 0-10 | all | 4800-6200 | R | Gently rolling lava tablelands and plateaus |
| 86 | 0-10 | all | 5800-7000 | R | Gently sloping lava tablelands |
| 87 | 5-30 | S | 4800-5800 | R | Gently to moderately sloping ridges and sideslopes |
| 88a | 0-15 | all | 5400-7400 | R&C | Gently rolling lava tablelands and plateaus |
| 88b | 16-40 | all | 5500-7400 | R&C | Moderately steep slopes on basaltic eruptive centers, shield volcanoes, and block faults |
| 88c | 40+ | all | 5800-7800 | R&C | Steep slopes on basaltic eruptive centers, shield volcanoes, and block faults |
| 89a | 0-15 | all | 5800-7800 | R&C | Gently rolling tablelands, plateaus, and basins |
| 89b | 16-40 | all | 5800-7800 | R&C | Moderately steep slopes on basaltic eruptive centers, block faults, and shield volcanoes |
| 89c | 40+ | all | 5800-7800 | R&C | Steep slopes on basaltic eruptive centers, block faults, and shield volcanoes |

* R refers to residual material, C refers to colluvial material, and VF refers to valley fill material.

Table 12. (continued)

| Mapping Unit | Slope % | Aspect | Elevation feet | Buried Profile* | Landform/Position |
|---|---|---|---|---|---|
| 90 | 5-20 | all | 5600-7600 | C&A | High elevation foot slopes, basins, and valleys |
| 91 | 0-15 | all | 5800-7000 | R | Gently sloping uplifted tablelands |
| 92 | 5-50 | N | 6800-8000 | R&C | High elevation moderatly steep to steep side slopes |
| 93a | 0-15 | all | 4600-5600 | R | Gently rolling lava tablelands and plateaus |
| 93b | 16-40 | all | 4600-5700 | R&C | Moderately steep slopes on block faults, eruptive centers, and drainages |
| 94a | 0-15 | all | 4700-6000 | R | Gently rolling lava tablelands and plateaus |
| 94b | 16-40 | all | 4800-6000 | R&C | Moderately steep sideslopes on eruptive centers, drainages, and block faults |
| 95 | 0-6 | N.A. | 4500-6000 | VF | Gently sloping basins and foot slopes |
| 96a | 0-15 | all | 4800-6000 | R | Gently rolling lava tablelands and plateaus |
| 96b | 16-40 | all | 4800-6000 | R&C | Moderately steep side slopes on block faults, eruptive centers and drainages |
| 97a | 0-15 | all | 5400-6600 | R | Gently sloping lava tablelands and side slopes |
| 97b | 16-40 | all | 5400-6600 | R&C | Moderately steep side slopes on eruptive centers, block faults, and drainages |
| 98 | 0-25 | all | 5900-7800 | R | High elevation upland flats, plateaus, and tablelands |
| 99 | 0-8 | N.A. | 4800-5200 | VF | Wide, gently sloping basins |

* R refers to residual materials, C refers to colluvial materials, A refers to alluvial materials, and VF to valley fill materials.

colluvial, eolian, or alluvial processes. Alluvial buried profiles indicate river or stream transport and deposition processes.

Malheur National Forest is located about 150 to 210 miles to the northeast of Crater Lake National Park. The Forest is in the Central Mountains of the Columbia Intermontane Province as previously discussed. The climate is characterized by low to moderate annual precipitation and high summer temperatures. Precipitation ranges from 15 to 45 inches a year depending on elevation. Torrential rainstorms can occur during the spring and summer causing both erosion and flooding. Heavy winds are noted at any time of the year which can cause drifting of snow or erosion of the soil (Carlson 1974).

Erosional processes have removed much of the tephra from the lower southern aspects, while upper elevations and north aspects have 18 to 24 inches of ash remaining, and east and west aspects have 8 to 12 inches of ash remaining (Carlson 1974). The landforms that have ash-derived soils on them are given in Table 13. The tephra is preserved on slopes of 0 to 70%; although 0 to 30 percent is probably closer to the average. The tephra may be found at all elevations. Landforms include depressional areas, flats, terraces and glacial outwash areas, glacial troughs, side slopes, and ridge tops. It seems that even at this distance the tephra is still a major part of many soils.

Umatilla National Forest is located approximately 200 to 300 miles northeast of Crater Lake National Park. The Forest belongs to the Central Mountains of the Columbia Intermontane Province as

Table 13. Landform Characteristics of Ash Derived Soils on Malheur National Forest (After Carlson 1974).

| Mapping Unit | Slope % | Aspect | Elevation feet | Ash Thickness inches | Landform/Position |
|---|---|---|---|---|---|
| 5 | 0-15 | varies | 3200-6000 | 15-24 | Meadow areas, in depression or basin like areas, and along stream bottoms |
| 9 | 15-100 | varies | 3200-6800 | 8-12 | Slopes |
| 10 | 15-100 | N | 3600-7500 | 15-24 | Slopes |
| 14 | 5-30 | varies | 4500-5500 | -- | Terrace and glacial outwash areas |
| 17 | 10-70 | varies | 7500-9000 | -- | Ridge tops and side slopes |
| 19 | 10-50 | varies | 7500-8500 | -- | Glacial troughs |
| 32 | 30-70 | varies | 4000-6000 | 6-12 | Steep side slopes |
| 36 | 30-70 | N | 4000-6000 | 12-18 | Steep side slopes |
| 42 | 0-30 | varies | 3600-6500 | 6-12 | Upland flats and side slopes |
| 48 | 30-70 | varies | 3600-6500 | 6-12 | Steep side slopes |
| 58 | 0-30 | varies | 4000-6500 | 15-24 | Upland flats and side slopes |
| 59 | 30-70 | N | 4000-6500 | 12-24 | Steep side slopes |
| 63 | 5-50 | N | 4500-6500 | 15-24 | Upland flats and side slopes |
| 65 | 5-50 | varies | 4500-6500 | 8-12 | Upland flats and side slopes |
| 75 | 0-30 | varies | 4500-6000 | 6-10 | Upland flats |
| 82 | 0-30 | varies | 3500-6200 | 6-12 | Upland flats, side slopes, and toe slopes |
| 83 | 0-40 | N | 4000-6500 | 12-18 | Upland flats and north facing side slopes |
| 86 | 30-70 | varies | 3500-6200 | 6-12 | Steep side slopes |
| 94 | 10-40 | N | 5500-7500 | 10-18 | Ridge tops and side slopes |
| 95 | 0-30 | varies | 3500-7000 | 4-10 | Ridge tops and side slopes |

Table 13. (continued)

| Mapping Unit | Slope % | Aspect | Elevation feet | Ash Thickness inches | Landform/Position |
|---|---|---|---|---|---|
| 114 | 5-50 | varies | 6000-7500 | -- | Glacial troughs and outwash |
| 122 | 30-70 | varies | 3500-6000 | 6-12 | Steep side slopes |
| 124 | 0-30 | varies | 3500-6000 | 6-12 | Ridge tops and side slopes |
| 126 | 30-70 | N | 4000-6200 | 12-18 | Steep side slopes |
| 127 | 0-30 | varies | 4000-6200 | 12-18 | Upland flats and north facing side slopes |
| 132 | 30-70 | varies | 4500-5500 | 6-10 | Steep side slopes |
| 142 | 0-30 | varies | 4500-7000 | -- | Upland flats and side slopes |
| 148 | 0-30 | varies | 4500-7000 | -- | Steep side slopes |
| 159 | 30-70 | N | 4500-7000 | -- | Steep side slopes |
| 162 | 30-70 | varies | 5000-7000 | -- | Steep side slopes |
| 164 | 0-30 | varies | 5000-7000 | -- | Upland flats and side slopes |
| 166 | 30-70 | N | 5500-7000 | -- | Steep side slopes |
| 172 | 5-50 | varies | 4500-6500 | -- | Side slopes |
| 176 | 5-50 | N | 5000-7000 | -- | Upland flats and north facing side slopes |
| 182 | 0-30 | varies | 3600-6200 | -- | Side slopes and toe slopes |
| 183 | 0-30 | N | 4500-6200 | -- | Side slopes and toe slopes |
| 186 | 30-70 | varies | 3600-6200 | -- | Steep side slopes |
| 189 | 30-70 | N | 4500-6200 | -- | Steep side slopes |

described earlier. Specifically, the Forest is found in the southern Blue Mountains of Oregon, a large assymetrical anticline with a gently sloping south flank (Ehmer n.d.) that has been folded and faulted into a fairly rugged terrain. The climate is temperate and semi-arid with pronounced differences in temperature and precipitation with elevation. Winters are comparatively mild at lower elevations and much more severe at higher elevations. Precipitation averages about 20 inches in the lower elevations and about 55 inches at the higher elevations. Most of the precipitation falls between November and March with average snowfall for the upper elevations averaging 100 inches per year (Ehmer n.d.).

Mazama tephra is found on all types of landforms within the Forest (See Table 14). Tephra seems to be found more often on north aspects than any other. Tephra thickness ranges from 4 to 50 inches with 20 to 30 inches being about average. All bedrock profiles are considered as being either residual or colluvial. While Mazama tephra is still a large part of the ecosystems of the Forest, at this distance more changes can be seen in its post depositional characteristics than closer to Crater Lake.

In northeastern Oregon, Rai (1971) found that generally the soil profiles on broad, flat ridge tops and northern slopes under vegetative cover had significant portions of primary Mazama tephra. The ash was generally missing on southern slopes and was found as colluvial and alluvial ash fans along streams and canyons.

Soil surveys published for various counties in Oregon and Washington can give some useful information about the landforms that

Table 14. Landform Characteristics of Ash Derived Soils on Umatilla National Forest (After Ehmer n.d.).

| Mapping Unit | Slope % | Aspect | Ash Thickness inches | Buried Profile* | Landform/Position |
|---|---|---|---|---|---|
| 2 | 2-10 | all | 10-16 | R | Mesa and tablelands, gentle bench slopes |
| 7 | 5-35 | N | 20-36 | R | Gentle plateau, protected slopes along drainages |
| 10 | 1-30 | N | 20-40 | R | Gentle side slope and toe slope |
| 11 | 25-60 | N | 16-30 | C | Steep side slopes, faulted ridges |
| 12 | 25-65 | E, W | 4-18 | C | Steep ridge side slopes, colluvial side slopes |
| 13 | 1-35 | all | 20-34 | R | Undulating ridge top |
| 14 | 25-60 | N | 18-30 | C | Steep ridge side slope |
| 15 | 2-25 | N | 20-30 | R | Gentle north slope on ridge top or crest |
| 16 | 1-35 | all | 20-34 | R | Toe slope to gentle side slope |
| 18 | 2-25 | all | 14-40 | R | Cool ridge tops and uplands, gentle side slopes |
| 19 | 25-65 | E, W | 12-30 | C | Steep upper ridge slopes |
| 21 | 2-30 | N | 20-40 | R | Gentle ridge tops and gentle side slopes |
| 22 | 25-60 | N | 20-40 | C | Steep ridge side slopes |
| 41 | 5-30 | N | 30-50 | R | Toe and lower slopes |
| 42 | 30-70 | N | 18-30 | R | High elevations - upper ridge side slopes |
| 48 | 20-60 | N | 20-30 | R | Protected steep ridge slopes |
| 49 | 2-35 | N | 12-22 | R | Lower side slopes and toe slopes |
| 51 | 25-60 | N | 8-18 | C | Upper ridge side slopes |
| 53 | 5-30 | E, W | 6-20 | R | Ridge crest and upper ridge side slopes |
| 57 | 25-60 | E, W | 10-24 | C | Steep colluvial side slopes |
| 58 | 25-70 | N | 20-36 | R | V shaped drainways and side canyon; steep |
| 66 | 5-35 | N | 20-40 | R | Ridge and fault scarp side slope, toe slope |
| 67 | 25-65 | N | 12-26 | C | Side slopes to large slumps and steep ridge side slopes, geologic breaks |

* R refers to residual and C refers to colluvial materials.

Table 14. (continued)

| Mapping Unit | Slope % | Aspect | Ash Thickness inches | Buried Profile* | Landform/Position |
|---|---|---|---|---|---|
| 72 | 2-30 | N | 12-30 | R | Concave toe slope positions |
| 74 | 2-35 | N | 14-30 | R | Slump trough, hung valley side slopes |
| 75 | 2-30 | all | 10-28 | R | Slump basin gently rolling to undulating |
| 76 | 25-60 | N | 14-28 | C | Slump scarps, concave position, rolling relief |
| 81 | 2-20 | all | 14-24 | R | Undulating ridge crest and gentle side slopes |
| 82 | 2-10 | all | 18-30 | R | Swales and trapped basins |
| 83 | 2-35 | all | 20-30 | R | Benches, undulating to gently rolling |
| 84 | 25-64 | N | 14-26 | C | Ridge or steep side slopes |
| 85 | 5-35 | N | 20-30 | R | Undulating to gently rolling plateau |
| 86 | 2-30 | E, W | 14-20 | R | Gentle side slopes adjacent to meadows |
| 87 | 2-30 | E, W | 18-34 | R | Toe slopes and concave positions along drainageways |
| 88 | 2-35 | S | 10-30 | R | Undulating side slopes |
| 89 | 5-40 | all | 12-30 | R | Gently sloping anticlinal ridge, gently rolling |

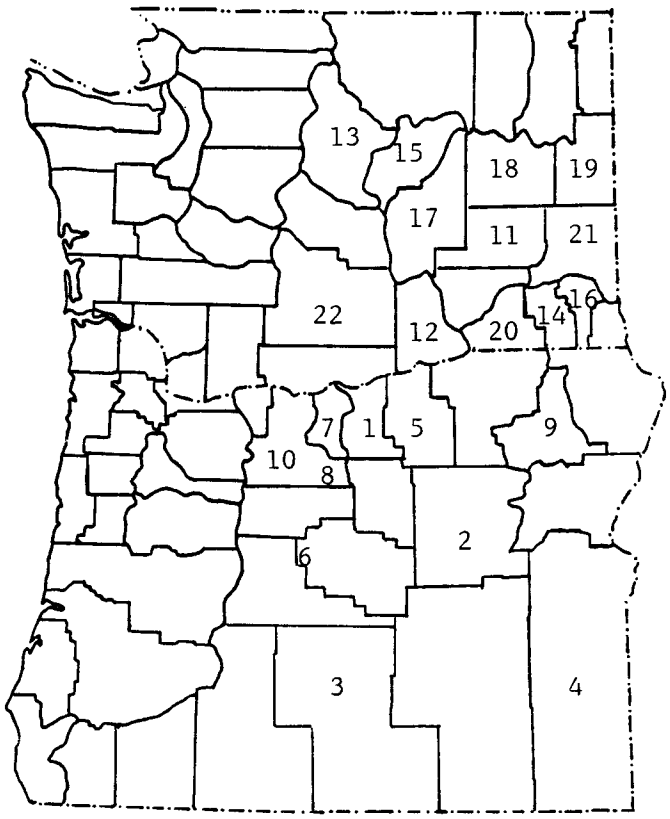
* R refers to residual and C to colluvial materials.

tephra is trapped on in the lower areas outside of forest lands. Figure 22 shows the soil surveys by county and reference used in this discussion. Table 14 gives the landforms of ash-derived soils in the Oregon counties, while Table 15 gives them for the Washington counties.

Most of these counties have little or no predominantly ash-derived soils in them. The percentages of soil series in this category for the each county is generally less than 10 percent. Only uplands, fans, bottom lands, stream terraces, or lakebeds have these soils. This may be due to many factors including erosion and transport of the materials by streams and winds, rapid burial in high sedimentation areas, and mixing of thinner deposits with mineral soils by farming and other human disturbances.

An example of an excellent study of the location of primary and secondary Mazama tephra within the lower Granite Reservoir in the Snake River Canyon has been described by Hammett (1976). The major geomorphic features and stratigraphy of the deposits with special emphasis on the Mazama tephra will be discussed in this section.

There are four major geomorphic surfaces in the Lower Snake River canyon (Figure 23). The valley fill terraces, eddy bars, and flood bars were formed by the Scabland or Bretz flood episodes during the late Pleistocene. The point bar deposits were formed after the Bretz floods (Bretz 1969; Bretz et al. 1956) from alluvial processes associated with the Snake River channel. The valley fill terraces and eddy bars exist in the tributary canyons to the main




KEY

| Oregon Soil Surveys | | | Washington Soil Surveys | | |
|---|---|---|---|---|---|
| # | County | Reference | # | County | Reference |
| 1 | Gilliam | Hosler 1984 | 11 | Adams | Lenfesty 1967 |
| 2 | Grant | Dyksterhuis 1981 | 12 | Benton | Rasmussen 1971 |
| 3 | Lake | Cahoon and Fergerson 1961 | 13 | Chelan Area | Beieler 1975 |
| | | | 14 | Columbia | **Eveard et al. 1973** |
| 4 | Malheur | Lovell 1980 | 15 | Douglas | Beieler 1981 |
| 5 | Morrow | Hosler 1983 | 16 | Garfield | Raver 1974 |
| 6 | Prinville Area | Mayko and Smith 1966 | 17 | Grant | Gentry 1984 |
| | | | 18 | Lincoln | Stockman 1981 |
| 7 | Sherman | Mayers 1964 | 19 | Spokane | Donaldson and Giese 1968 |
| 8 | Trout Cr.- Shanko Area | Green 1975 | 20 | Walla Walla | Eveard et al. 1964 |
| 9 | Union | Dyksterhuis and High 1985 | 21 | Whitman | Donaldson 1980 |
| | | | 22 | Yakima | Lenfesty and Reedy 1985 |
| 10 | Wasco | Green 1982 | | | |

Figure 22. Soil surveys by county and reference that are mentioned in the text. Numbers on map correspond survey numbers in the key.

Table 15. Landforms of Ash Derived Soils in Oregon.

| County<br>Series | Landform | Slope<br>% | % of<br>Co. |
|---|---|---|---|
| Gilliam Co. | none | | |
| Grant Co. | | | |
| Helter | Uplands | 3-60 | 2.2 |
| Lake Co. | | | |
| Shanahan | Fans and mountain slopes | 2-15 | -- |
| Malheur Co. | none | | |
| Morrow Co. | | | |
| Boardtree | North facing slopes | 7-40 | 1.1 |
| Helter | Ridge tops and north facing slopes in the Blue Mountains | 3-60 | 4.5 |
| Tolo | Ridge tops and north facing slopes in the Blue Mountains | 3-60 | 1.9 |
| Prineville area | | | |
| Forester | Low, nearly level terraces along the Crooked River | -- | 0.4 |
| Onkto | Bottom land on Mill and Ochocco Creeks | -- | 0.5 |
| Sherman Co. | | | |
| Walvan | Gently sloping north facing slopes near streams and depressions which were once ponds or small lakes | 2-10 | 0.2 |
| Trout Cr.-Shaniko area | none | | |
| Union Co. | | | |
| Helter | Irregularly shaped areas on mountainous uplands | 12-65 | 0.5 |
| Hooly | Old lake basins and valley floors | 0-2 | 0.7 |
| Olot | Ridge tops and mountainous uplands north and east slopes | 2-65 | 3.0 |
| Tolo | Mountainous uplands | 12-65 | 11.8 |
| Wolot | Uplands | 1-12 | 0.7 |
| Wasco | none | | |

Table 16. Landforms of Ash Derived Soils in Washington.

| County<br>Series | Landform | Slope<br>% | % of<br>Co. |
|---|---|---|---|
| Adams Co. | | | |
| Emdent | Nearly level depressions, basins, or potholes | 0-15 | 1.54 |
| Walvan | Undulating to hilly uplands | 0-65 | 0.02 |
| Benton Co. | None | -- | -- |
| Chelan Area | | | |
| Antilon | Low terraces near Lake Chelan | 0-25 | 0.7 |
| Chelan | Terraces in Lake Chelan area | 0-45 | 6.0 |
| Chiwawa | Terraces in Lake Wenatchee area | 0-3 | 0.4 |
| Jumpe | Mountainous uplands | 8-25 | 0.1 |
| Nevine | Mountainous uplands near Lake Wenatchee | 0-45 | 1.6 |
| Supplee | Terraces near Columbia River | 0-45 | 0.8 |
| Thow | Mountainous uplands | 0-45 | 2.5 |
| Columbia Co. | | | |
| Anatone | Open ridge tops, south and southwest facing slopes in the Blue Mountains | 30-65 | 1.7 |
| Tolo | Wide ridge tops and north facing areas in the Blue Mountains | 3-65 | 5.1 |
| Walvan | Strong sloping to steep hilly uplands | 15-40 | 0.1 |
| Douglas Co. | | | |
| Chelan | High terraces, terrace side slopes | 0-65 | 1.6 |
| Supplee | Terraces | 3-15 | 1.0 |
| Garfield Co. | | | |
| Tolo | Mountainous uplands, north or east slopes descending from basalt plateaus | 10-60 | 0.6 |
| Lincoln Co. | | | |
| Cocolalla | Bottom lands and basins in the channeled scablands | 0-3 | 0.4 |
| Emdent | Bottom lands and basins in the channeled scablands | 0-3 | 0.4 |
| Spokane Co. | | | |
| Bonner | Nearly level to moderately steep terraces | 0-20 | 2.0 |
| Cocolalla | Basins and potholes of channeled scablands | -- | 1.2 |
| Emdent | Basins and potholes of channeled scablands | -- | 0.1 |
| Hardesty | Slight depressions and nearly level areas along drainage ways | 0-5 | 0.5 |
| Laketon | Sloping outwash and reworked lake terraces | 0-20 | 0.5 |
| Moscow | Hilly to steep uplands | 0-55 | 6.1 |
| Peone | along drainage ways and streams | 0-5 | 0.2 |

Table 16. (continued)

| County<br>Series | Landform | Slope<br>% | % of<br>Co. |
|---|---|---|---|
| Walla Walla Co. | | | |
| Helmer | Gently sloping ridge tops and adjacent steep north slopes in the Blue Mts. | 3-60 | 1.8 |
| Ritzville[1] | Small valleys, heads of steep draws | 8-60 | 0.2 |
| Volcanic ash land | Small coves at heads of drainage ways, undulating to hilly areas | -- | 0.1 |
| Walvan | Bottom lands, small draws up north facing slopes, very steep north facing coves | 0-60 | 0.1 |
| Whitman Co. | | | |
| Emdent | Depressions, basins, and potholes | -- | 0.3 |
| Walvan | East and north facing side slopes of uplands | 7-25 | 0.1 |
| Yakima | | | |
| Aquic Cryandents | Swales on alluvial fans and stream terraces | 0-3 | 0.1 |
| Jumpe | Long broad mountain ridges, mountain sides, and canyons of north aspects | 0-3 | 6.1 |
| Naxing | Mountain tops and broad mountain ridges, and mountain sides | 5-65 | 2.4 |
| Saydab | Smooth mountain tops and broad ridge tops | 0-5 | 0.3 |

[1]Volcanic ash variant of the Ritzville series.

canyon. The valley fill terraces were cut by later alluvial action and filled with alluvial fans which contain thick deposits of Mazama ash. The flood bars are located in the main canyon along river curves and straight narrow stretches, slightly above the later point bars.

There are 13 point bars in the Granite Reservoir area. Figure 23 shows the geomorphic relationships and deposits of the point bars. Figure 24 gives the stratigraphic relationships and dates for the various deposits. The point bars are discontinous constructional bodies along the river channel which consist of basal river gravels that fine upwards into alluvial sands and silts referred to as the early alluvium. These deposits are overlain by pre-ash eolian sands. The point bars consist of an upper terrace, a lower terrace, and the active floodplain. The high terrace dates between 10,000 and 8,000 B.P., the lower terrace dates between 4000 and 2500 B.P., and the floodplain predates the historic period. On these major point bar surfaces interfan terraces, dunes, alluvial fans, and talus slopes can be found. The interfan terraces are located between the alluvial fans and above the terraces. Linear eolian dunes were formed locally on the higher terrace, which date to three separate phases of deposition in the last 8,000 years. One of the eolian deposits, the ash-rich loess, contains mainly Mazama ash and overlies redeposited eolian, sheetwash, and colluvial mixed ash deposits. Alluvial fans are found mainly on the upper terraces at the mouth of every tributary to the main canyon. Mazama ash can be found as thick plugs at the tops of the larger fans and as the

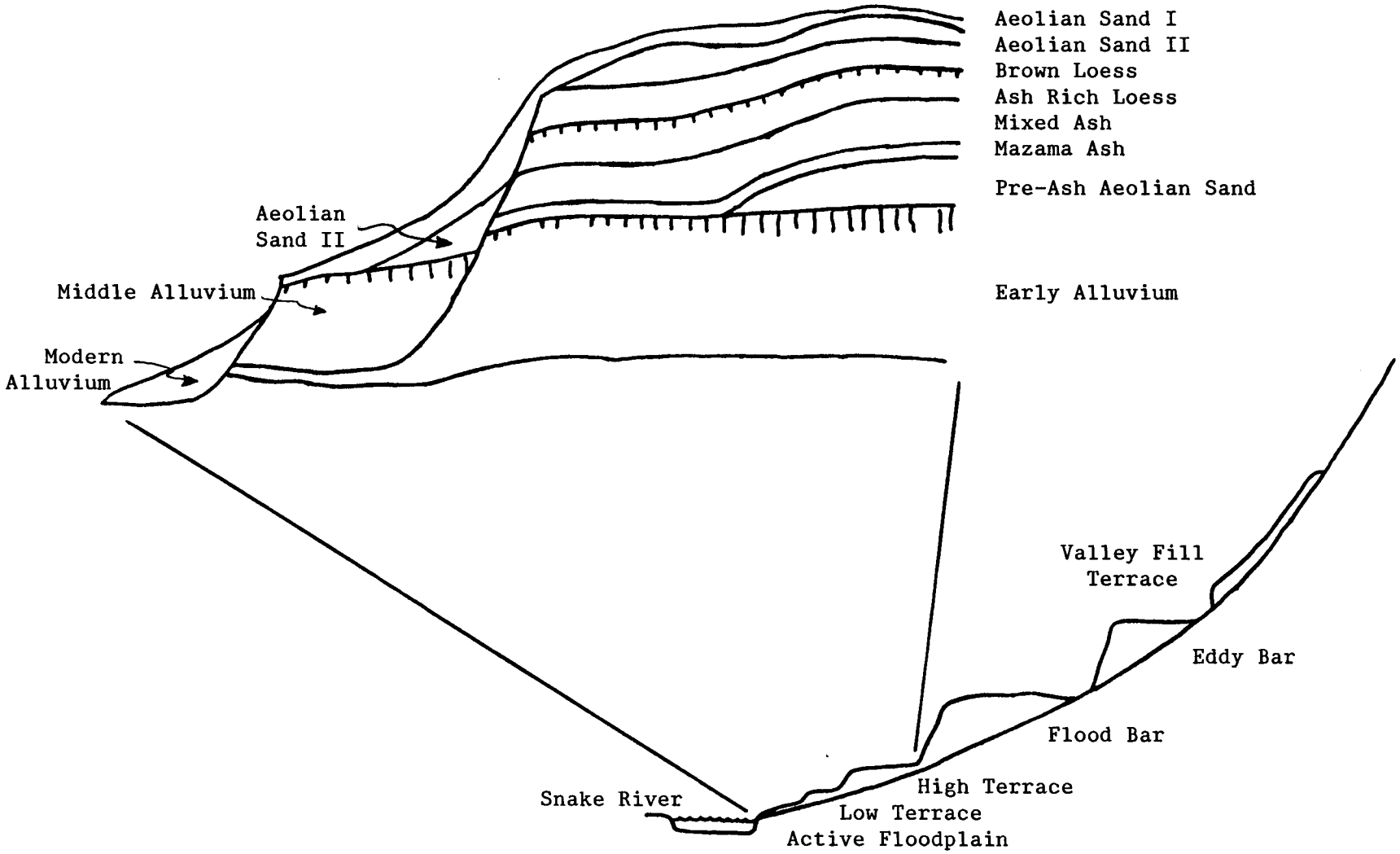



Figure 23. Geomorphic landforms and deposits of the Lower Snake River Canyon (after Hammett 1976:Figures 5 and 32).

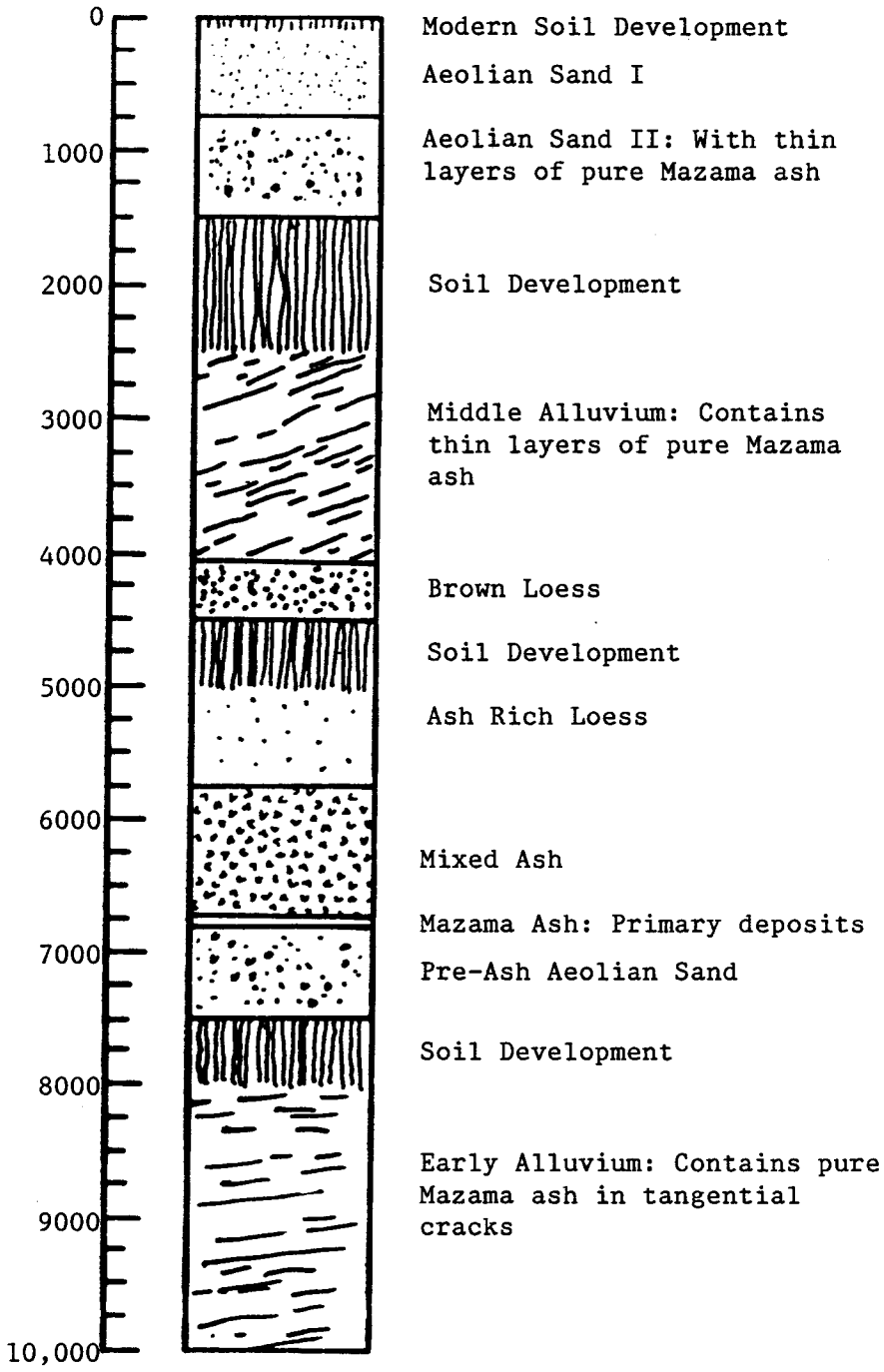



Figure 24. Stratigraphic column of post 10,000 year B.P. sediments of the point bars. Soils are shown as stratigraphic units. Adapted from Hammett (1976:Figure 31).

main constituent of the matrix within the smaller fans. Talus slopes are found next to the channel and on the upper terraces. Mazama ash appears just below the surface of individual talus slopes.

Mazama ash has been identified at various locations on the basis of the refractive index of the glass and by the characteristic mineral assemblage. Discontinous layers of pure white ash, which probably represent the primary depositional beds, vary from 5 to 15 cm in thickness and average 9.3 cm. Redeposited ash is as thick as several meters, especially at the toes of slopes and at tributary canyon mouths at the tops of alluvial fans. At all locations where the pure white ash exists, a less than 3 cm thick layer of pink (7.5YR 8/4 when dry) Mazama ash exists. Both of the layers have massive structure and are separated by an abrupt, smooth boundary suggesting air-fall deposition. The significance of the pink layer has not yet been established and further investigation is needed to determine its origin within the context of the discussion presented on correlation in Chapter IV.

Above the primary layers are deposits of mixed ash derived from eolian, colluvial, and sheetwash processes with an overlaying layer of ash rich loess. The mixed ash layer consists of ash and nonash materials of fine sand and silt with a maximum thickness of 50 cm. Mottles can be seen which are due to rodent activity. The mixed ash is found on point bars above layers of pure ash but sometimes directly overlying earlier deposits. The period of deposition for the mixed ash is limited by the tephra-fall events

for the intiation of redeposition and a radiocarbon date of 5245 +/- 200 years B.P. for stabilization. The ash rich loess is found above the mixed ash on the high terraces of point bars and interfan terraces. The ash rich loess consists of sets of eolian dunes and has a maximum thickness of 70 cm. The dunes date from the closing phases of the Altithermal at about 6000 to 5000 B.P.. The ash rich loess is capped by a paleosol which signals the stabilization of the ash filled dunes. This paleosol postdates the period of eolian activity which ended about 5000 B.P. and predates the middle alluvium at 4000 B.P.. The middle alluvium was deposited during the Medithermal when increased precipitation caused a downcutting episode in the canyon. The increased precipitation caused ash to be eroded by sheetwash and alluvial processes, especially from secondary positions such as the plugs at the tops of alluvial fans. Thin layers of almost pure ash are found in the middle alluvium dating at greater than 3000 years after the primary ash-fall. Ash is also found in the aeolian sand II dated at over 5000 years after the primary tephra-fall events occurred.

The initial, relatively uniform blanket of tephra would have been changed into a patchwork of primary and secondary tephra bodies across the landscape. Primary tephra bodies were quickly buried by mixed ash and eolian ash, or removed from the surface by erosion. A major period of tephra transport and redeposition occurred between the initial tephra-falls at 7000 B.P. until almost 5000 B.P.. About 5000 years ago the tephra dunes were stabilized by vegetation and buried by subsequent soil development. Increased affective moisture

during the Medithermal caused another period of retransport and deposition with thin ash layers deposited at before 4000 years ago. With relatively drier conditions returning, wind blown ash was redeposited before 2000 years ago. These periods of retransport and deposition allowed the tephra to continue to affect the local ecosystems for a significant time period after the initial depositional events.

The sequence found in the lower Palouse River canyon by Marshall (1971) is generally the same as for the Snake River. Five sets of alluvial terraces overlay gravel and slackwater deposits from the Bretz floods. Talus slopes, alluvial fans, and eolian dunes can be found on the terraces. Mazama ash occurs in the upper two terraces (I and II) as both primary and secondary deposits, but is absent from the later terraces. The ash is predated by a soil horizon formed in alluvium and postdated by another soil horizon formed in the upper portion of the ash itself. Ash occurs as lenses in the alluvial fans and dunes and as a portion of the matrix in talus slopes.

Large scale transport of the Mazama tephra out of the Columbia Basin is indicated by fairly thick ash deposits in the Astoria Canyon and fan off of the Oregon and Washington Coast. Ash deposits over 35 cm thick have been found at the mouth of the Astoria Canyon which is the structure formed by the outflow and downcutting of the Columbia River into the continental shelf and slope sediments of the Pacific Ocean and becomes progressively thinner in the Astoria channel and fan. The ash is found in the Cascadia abyssal plain as

part of the turbidite deposits, heavy, sediment-rich density currents which flowed down off of the continental shelf and slope, and out the Astoria fan. This same pattern is seen in Willapa canyon just to the north off the Washington coast, and in Blanco Valley adjacent to the Rogue River in southwest Oregon (Nelson et al. 1968).

# VIII. SUMMARY AND CONCLUSIONS

Within this chapter the implications for each of the state factors for flora, fauna, people and ecosystems are discussed. At this time a thorough understanding of the effects of the Mazama tephra-falls is impossible due to a lack of several kinds of data. Therefore, future research needs which will allow the effects of the Mazama tephra-falls to be better understood are addressed for each state factor. While these guidelines do not exhaust research potential, it is hoped that they will help to guide future researchers who may be interested in studying the effects of the Mazama tephra-falls on flora, fauna, ecosystems and prehistoric populations.

## IMPLICATIONS OF THE STATE FACTORS

### The State Factor of Time: E=f(T,d,m,c,g,...)

Each tephra-fall event occurred at a specific period in time which is resolvable by radiocarbon and relative dating methods. Regionally, significant air-fall events occurred at about 7000 and 6800 years ago. By identifying the Mazama eruptive period in time, the specific subsystems of an ecosystem may be identified or reconstructed for the period of the event through pollen, paleontological, zooarchaeological, and archaeological analysis. The conclusions drawn from such a reconstruction may vary in

robustness depending on the resolution of the method and the available data.

The duration of individual Mazama eruptive period events was fairly short and so the initial effects associated with the air-fall deposition would have been short lived as well. Periods of air-fall deposition were probably no longer than several hours to several days. Consequently flora, fauna, and people would not have suffered exceedingly long periods of tephra-fall or darkness. The Llao and climatic eruptive phases may have each lasted for a period of years and were probably characterized by a series of successive tephra showers punctuated by quiescent periods. Estimates of three years for the climatic phase have been proposed although there is some evidence for deposition within a single year. If successive eruptions occurred over a three year period there may have been an overlap in the effects of the individual events so that the effects of two succeeding events would have been greater than the effects of each individual event. The hiatus between the Llao and the climactic phases may have lasted from 60 to 200 years. Within most areas of tephra deposition, ecosystems may have recovered sufficiently to not have suffered any overlapping effects.

Individual tephra-fall events, since they were of short duration, would have occurred during specific seasons of the year. The climatic eruptions occurred during the autumn and spring/summer seasons although evidence exists for a single winter deposition. This would have had specific consequences on reproductive and food gathering schedules for individual organisms and populations.

Tephra-falls that occurred during periods of peak photosynthesis or pollination, such as the spring and summer, would have had a more drastic effect on plants and most insects than those that occurred during the late autumn or winter when most plants were dormant. Spring growth forms of plants could be severely affected by even light dustings of tephra. Perennial plants would have suffered greater risk of injury than annuals since perennials may decrease production during certain times of the year, but do not generally go completely dormant.

Fauna, depending on their breeding and birthing seasons would have also suffered differing effects due to the season of tephra-fall. Deep blankets of tephra would have restricted breeding behavior in animals during autumn and winter, thus leading to a decrease in the next seasons recruitment. Juveniles of all species are more susceptible to injury due to tephra and so spring and early summer tephra-falls could have caused increased juvenile mortality.

Early spring and autumn tephra-falls would have also acted to increase the period of winter food shortage for fauna and people. Especially after a hard winter, early spring is generally a period when both fauna and people have used up their fat and food reserves, while late summer and early autumn are critical times for putting on fat reserves or storing food for the upcoming winter. A tephra-fall which caused the spring or autumn plant growth to be decreased in any way could have added increased stress and possible mortality due to disease and starvation for faunal and human populations.

For people, the season of tephra deposition can have an effect on scheduling of resource exploitation and of travel for social occasions. A seasonal round of upland plant and animal exploitation and/or fishing during the summer may be restricted, due to an inability to reach the proper locals if tephra deposits are thick enough or if the tephra-falls cause specific seasonally exploited plants and animals to decrease in availability. Semipermanent and permanent villages or encampments with sufficient food stored away, would not have been as affected as highly mobile foragers and hunters dependant on fresh foods. People who relied on focal adaptive strategies based on seasonally restricted food sources, such as anadromous fish runs, would have suffered greater hardship than more diffuse adaptational sociocultural systems if a heavy tephra-fall occurred at a critical time.

The effects of even short term tephra-fall events continues past the end of the event itself, thus causing continued repercussions within the environment. The Mount Mazama tephra is a significant part of many present day ecosystems of eastern Oregon and Washington. Tephra carried by wind and water may be retransported for considerable periods of time depending on the distribution and local thickness of the tephra mantle. Wind blown tephra can cause abrasion to above ground plant parts, while eolian, colluvial, and alluvial transported tephra can bury plants. Increased sediment loads in streams can have a harmful effect on fish reproduction and survivorship. The material properties of the

tephra would have also have affected the ecosystems it was in contact with for long periods of time.

To more thoroughly understand the effects that the state factor of time has on flora, fauna, ecosystems, and people more specific data are needed. Such data consists of the determination of the duration of individual tephra-fall events and eruptive phases, the season(s) of the specific events, and residence times of the tephra at specific locations. The use of season specific pollen and radiocarbon dating can help tighten Mazama tephra-fall chronologies.

The State Factor of Distribution: E=f(D,t,m,c,g,...)

The Mazama eruptions deposited tephra across much of the Pacific Northwest, which affected almost all of the ecosystems in the region, to some extent. The impact of the tephra can be correlated to the primary thickness that was deposited at any one location. Since the thickness of each tephra deposit varies spatially, the effects on individual ecosystems will also vary depending on the location and tephra-fall event. Generally, the heaviest deposition occurred to the northeast of Mount Mazama with decreasing thickness as distance increased from the mountain and from the main axis of individual lobes. In addition to the main lobe to the northeast, lobes are also present to the north and southeast of the mountain. It is in these areas of heaviest deposition, located along the axes of the lobes, that the effects were greatest, where as with increasing distance from the mountain

and subsequently lighter deposition of tephra the effects were less. An area of greater than expected deposition is found in northern Washington which must be verified through a larger sample of sites and by detailed stratigraphic analysis of the deposits to determine if the deposits are over thickened by redeposited tephra.

Figures 25, 26, and 27 summarizes the hypothesized areas of impact for the Pacific Northwest based on tephra thicknesses. The thicknesses are for combined total Mazama period tephras (Figure 25), for the lower tephra (Figure 26), and for the upper tephra (Figure 27) as derived from Figures 11, 12, and 13, of this thesis, respectively. Figure 25 gives the total thickness of the tephra and therefore measures the greatest amount of stress possible, while Figures 26 and 27 measure the effects for their respective tephra-fall events. The impact to plants, animals, and humans will be briefly discussed for each zone.

If each of the tephra-falls were in the neighborhood of 1 to 5 cm thick there would have been a minor decrease in plant biomass which probably would have lasted less than a year or two. The effect on the animals and humans of the area would probably have been minimal. For humans, it is possible that the psychological effects associated with the tephra-fall event may have disrupted subsistence activities. Ray (1954) described such an occurrence for the people along the Columbia River when ash fell during the salmon harvest one summer in the late nineteenth or early twentieth century. The people quit fishing and prayed all summer, resulting

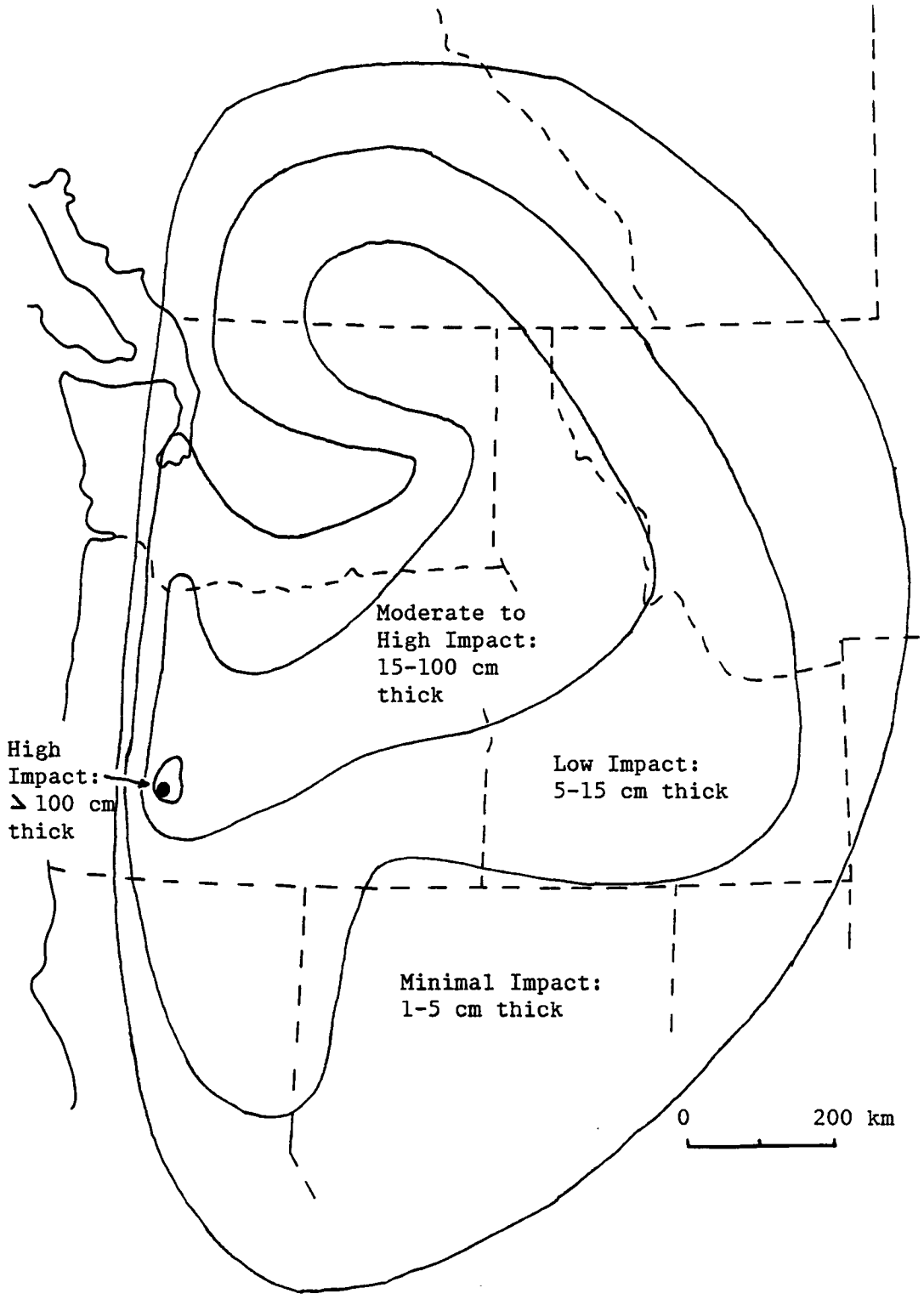



Figure 25. Hypothetical impact areas based on air-fall tephra thicknesses. Areas derived from total air-fall C1 and C2 layer thicknesses in Table 6.

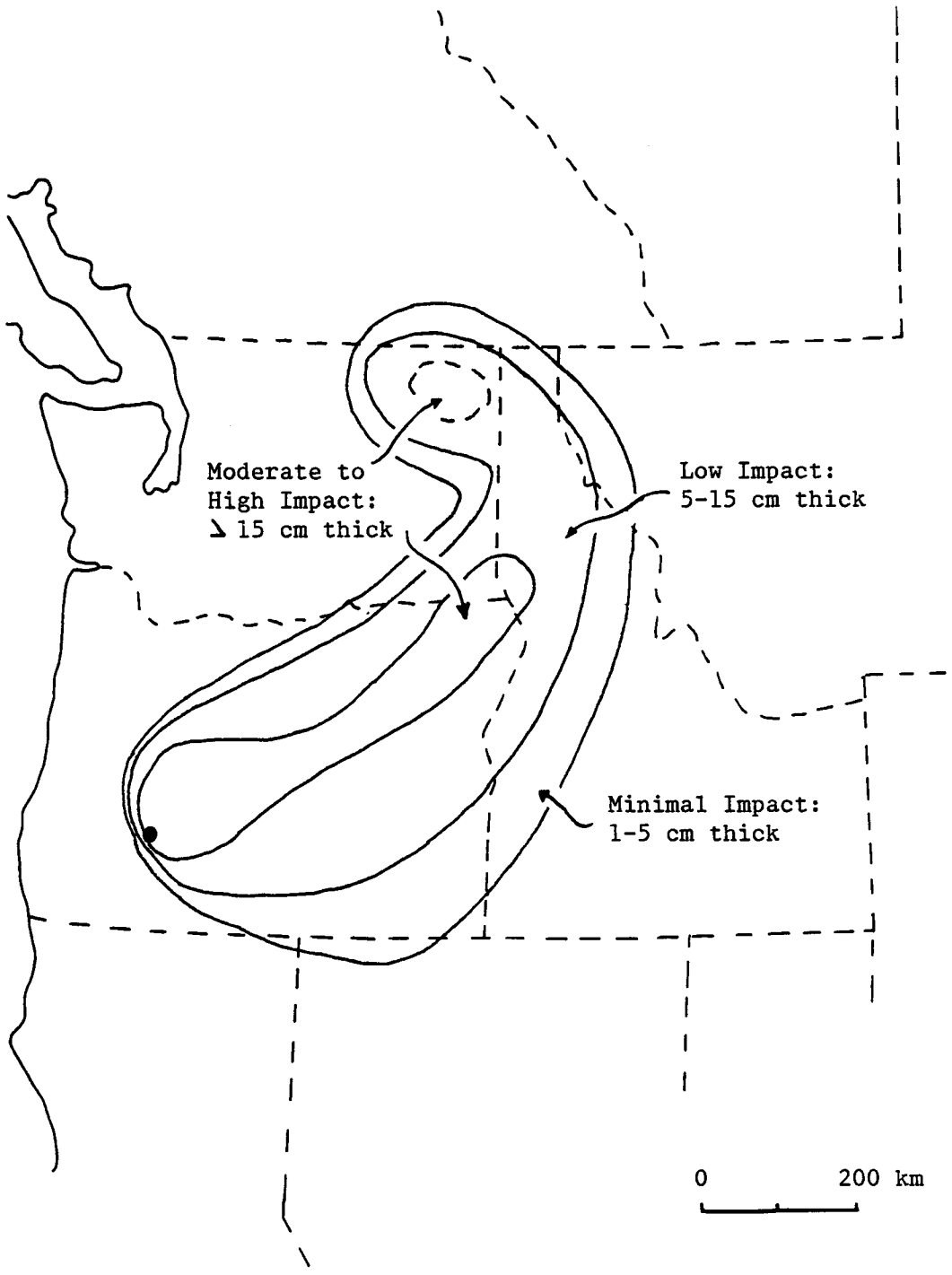



Figure 26. Hypothetical impact areas based on air-fall tephra thicknesses for the lower (C2) unit. Areas derived from Table 6.

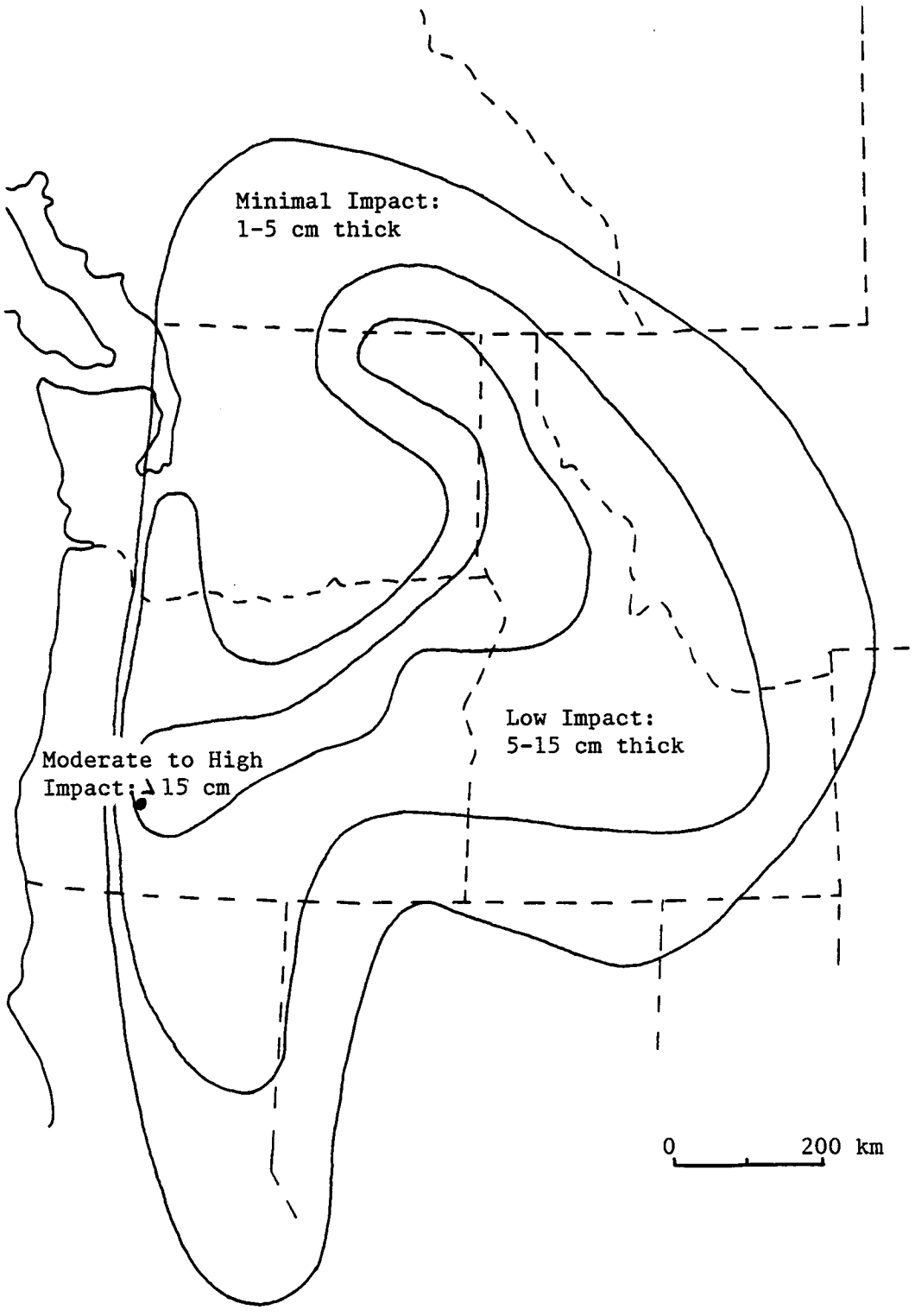



Figure 27. Hypothetical impact areas based on air-fall tephra thicknesses for the upper (C1) unit. Areas derived from Table 6.

in an inadequate food supply to last the winter. As a result many people starved to death that winter.

With thicknesses of 5 to 15 cm a loss of plant biomass and some loss of smaller animals would have occurred, but certainly not wholesale, long-term destruction of the ecosystem. A loss of branches and foliage on larger plants and complete loss of many of the smaller plants would have occurred. Reestablishment of herbaceous plants may have occurred within a few years for those plants that had viable underground regenerative parts (eg. rhizomes and/or stolons) and which could penetrate the tephra layer. Large animals would not have been significantly affected, however juveniles, small mammals, birds, some fish, and insects could have died in large numbers. Significant losses of large and small animals may have occurred during the winters following the tephra falls due to starvation. Some changes in subsistence activities probably occurred during this period as people adjusted to the loss of food resources. Within a few years, a return to predisturbance levels of resource availabilities woul allow settlement and subsistence traits to have also returned to a normal pattern. Changes in functional tool types or settlement locations would probably not be resolvable from the variability due to other types of periodic environmental stress.

At 15 cm to almost 1 m, a loss of almost all low herbaceous vegetation would have occurred, with many shrubs and trees dying, especially near 1 m depths. Significant problems for recolonization by vegetation would have been expected for: 1) those plants that

were not adapted to fertility limitations of tephra materials in which root systems were not deep enough to penetrate into the buried soil, 2) for plants that could not penetrate the tephra surface once seeds had germinated, and 3) for plants that regenerate from buried portions since most rhizomes and stolons would not have been able to successfully allow the plant to reach the surface at these tephra thicknesses. Therefore, most small to medium sized herbaceous plants that lived or recolonize the tephra, would not have been able to reach into buried soils with their root systems once germination of seeds occurred on top of the tephra or move upward into the tephra through rhizomes and stolons and so would have been restricted by the nutrient and moisture deficiencies of the tephra. Larger woody stemmed, deeply rooted plants, once reestablished in the soil below would not have been as stressed as the smaller herbaceous plants. Most large mammals would not have died outright, although juveniles, small mammals, birds, fish, and insect populations may have been drastically reduced as thicknesses of 30 cm or more were reached. Rates of ecosystem return of 5 to 10 years or more for many ecosystems could have occurred. In many cases the erosion of tephra from the ecosystem would have been the only way predisturbance vegetation could have been reestablished.

Subsistence technologies would have been drastically affected within the 15 cm to 1m zone. It is possible that abandonment of the worst hit areas near the axes of the lobes could have occurred. Shifts in resource exploitation were almost certain, as were shifts in functional tools and in subsistence activity locations. As

ecosystems returned to pre-ash conditions, subsistence activities could have also returned to pre-event patterns. While seemingly fundamental structural changes could have occurred in sociocultural systems, with a lessening of the stress the new or peripheral patterns of subsistence activities could have been abandoned for the predisturbance patterns. Only if the disturbance was of an exceptionally long occurrence or if the new patterns gave a much better adaptive advantage would the new pattern persist and thus be discoverable in the archaeological record. With the many factors that can obscure the relationships within the archaeological record (Schiffer 1976; Wood and Johnson 1981; Butzer 1982) and the margin of error within most dating techniques a specific pattern might have to remain in use for decades or centuries to be discernible.

At depths of one meter or more, almost all plants and most small animals, fish, birds, insects, and juveniles would have been killed. Recolonization by plants would have been difficult and recovery rates quite long. The area could have been abandoned for as little as a few years to many decades by animals and humans.

Due to the thickness of the tephra blanket becoming rapidly shallower away from the main axis of a lobe the effects on plants, animals, and people would have decreased as distance increased from the axis. These peripheral areas would have been refuges for populations to later recolonize interior locations.

The distribution and thickness of the Mazama tephra-falls can give important information about the expected effects of the event on the ecosystems of the Pacific Northwest. More work needs to be

done on correlation of individual sites to specific events and on the actual primary tephra thicknesses for the individual tephra-falls as represented at various sites. Special attention must be paid to the differences between primary and secondary tephra, grain size distributions for individual strata, and chemical composition of individual strata if the history of the eruptions is to be understood more thoroughly.

The State Factor of Material Properties: E=f(M,t,d,c,g,...)

The state factor of material properties has implications which are especially important for flora, as well as fauna and people. The effects associated with grain size and porosity varies with eruptive event, with increasing distance from the source, and to some extent as the material weathers, through time. The chemistry and mineralogy of the tephra varies insignificantly between individual eruptive events, but through time the chemistry and mineralogy of the tephra as a whole will begin to vary from the initial composition much more significantly as the material weathers. Presently, significant weathering of tephra materials is confined to poorly drained sites. Since grain size varies with increasing distance from the source and from the main axis of a lobe, the moisture and fertility characteristics will also vary.

The material properties of the pumice sized tephra found in central Oregon are not conducive to plant growth. The plant succession in this area has been greatly altered when compared to nonpumice soils. Herbaceous vegetation is greatly reduced in

density and species variety is limited on pumice soils within the understory of ponderosa pine associations (Dyrness and Youngberg 1966). The poor moisture availability and low fertility of the tephra materials, as well as the excessive thicknesses are responsible for the plant communities as they are seen today (Youngberg and Dyrness 1964; Dyrness and Youngberg 1966).

By northeastern Oregon, the tephra is mostly ash sized. Although fertility is low, it is higher than the larger pumice sized tephra. Water availability is high due to the many minute indentations on ash particles and infiltration rates of ash have little or no affect on water uptake of rangeland on soils with moderate to slow permeability and normal winter precipitation (Harrison 1982). Forest vegetation on eastern Oregon ash derived soils seems to be denser than on nonpumice soils due to the mulching effect of the ash (Simonson 1987, personal communication).

The crust which forms on ash size material could be a barrier to seeds becoming established in the fertile soil below the tephra and new shoots from buried plant remains may not be able to break through. Radwan and Cambell (1981) found that germination of most seeds tested was normal on volcanic ash, but that establishment of seedlings in the ash was difficult for some plants. Many seedlings would grow horizontally on the tephra instead of penetrating the surface. Plants that are intolerant of tephra properties can become established in the rills and gullies formed in the tephra layer by erosion (Griggs 1918; Means et al. 1982; Means and Winjun 1983; Franklin et al. 1985).

The fertility status of the ash is somewhat similar to the C horizon of the Tolo soil series (see Table 8) as it is found in the region today. The fertility of the tephra is fairly low compared to other mineral soils and individual species may not be able to become established within the tephra or once established will suffer from nutrient deficiencies. Means et al. (1982) found that seeded grasses and legumes showed signs of nutrient deficiency on Mount St. Helens tephra. Small plants, plants with shallow root systems, and seedlings would be affected the most by the fertility status of the tephra soils. Many of the existing larger, longer lived trees and shrubs would not have been especially affected by the fertility status of the tephra owing to a root system which would have been able to reach into the non-ash soil below. Over time, a more fertile A horizon has been developed within the region due to the colonization of the tephra by pioneering species of plants and essential microbial organisms, and the subsequent incorporation of decayed organic matter in the upper portions of the tephra.

Various trace elements occur in the Mazama tephra which are important for plant establishment and growth. Adriano (1986) discusses the nutrient and toxicity potential for five of these nutrients which have been analyzed for Mazama tephra. The availability of trace elements for plant uptake is dependant on a number of factors including oxidation state, pH, clay mineral species and content, competing ions, complexing agents, and other factors. Various trace elements have the potential of increasing

plant growth, reducing plant growth, or restricting the possibility of plant establishment (Adriano 1986).

The five elements in Mazama tephra which have information readily available, are barium (Ba), chromium (Cr), cobalt (Co), mangenese (Mn), and titanium (Ti). Others exist and may be important in a consideration of plant/tephra relationships but these will suffice as examples. It is important to realize that whole soil abundances of trace elements are poor indicators of nutrient availability or toxicity since much of the supply of individual elements in tephra are unavailable for plant uptake. As such, whole soil abundances would give a higher than actual indication of availability and should be treated accordingly.

Barium is found in Mazama glass at abundances of approximately 660 +/- 70 ppm which compares with mean abundances in general surface soils of around 500 ppm. Barium levels of around 2000 ppm may be considered toxic and so barium levels as seen in Mazama soils should not present any toxicity problems.

Chromium exists at abundances of about 1.6 +/- 0.6 ppm in Mazama glass compared with 25 to 85 ppm for most soils in the United States. Chromium is essential for plant nutrition but not for plant growth and under field conditions chromium would not be toxic to plants. With such low abundances in volcanic glass there may be some problems with plant establishment due to chromium deficiency, although this relationship is not certain.

Cobalt exists at abundances of 2.6 +/- 0.30 ppm in Mazama volcanic glass with most soils having Co levels of 2 to 40 ppm.

Cobalt is not essential for the growth of higher plants but it is essential for the fixation of $N_2$ by free-living bacteria, bluegreen algae, and symbiotic systems. The cobalt deficient tephra may be a limiting factor in the establishment of certain legumes.

Manganese exists at abundances of 0.03 to 0.04 ppm in Mazama volcanic glass with the arithmetic mean for surface soils in the United States at 560 ppm. Manganese is involved in the activation of many enzyme reactions involved in the metabolism of organic acids, phosphorus, and nitrogen, as well as photosynthesis and other important plant functions. Generally, for agricultural crops less than 20 ppm is considered deficient for good growth. A lack of Mn is responsible for discoloration of leaves, poor growth characteristics, and higher susceptibility of plants to diseases. The low amounts of Mn in Mazama tephra could play an important role in limiting plant establishment and growth.

Titanium exists at abundances of 0.25 ppm in Mazama volcanic glass and a mean abundance in United States soils of about 2400 ppm. Ti is not essential for plant growth but it plays a part in nitrogen fixation. It is not usually in concentrations of sufficient size to be toxic due to its poor solubility.

Gases associated with the tephra probably played a minor role in plant trauma. Fluorine is a relatively minor constituent of dacitic magmas. Chlorine could cause local plants to be stressed but it is difficult to know how much may have been present.

The ingestion of volcanic ash with plant foods may play a role in increased tooth wear and thus increased mortality for some

animals (Wilcox 1959), although no significant tooth wear was associated with domestic animals in eastern Washington as a result of the Mount St. Helens tephra-falls (Preston et al. 1982). These differing accounts may be due to grain size and depth differences between the Alaskan events and the St. Helens events.

One way of testing the effects of tephra ingestion on tooth wear would be to check archaeological fauna. This could be accomplished by comparing tooth crown heights versus incremental growth structures of teeth (Severinghaus 1949; Robinette et al. 1957; Low and Cohen 1963; Novakowski 1965; Rees et al. 1966; Hemming 1969; Keiss 1969; McCutcheon 1969; Kay 1974; Casteel 1976; Borque et al. 1978; Wilson 1978; Rice 1980; Klein and Cruz-Uribe 1984; Lyman 1987) for herbivores from pre-Mazama strata versus post-Mazama strata. If the crown heights of teeth from post Mazama strata for the same age individuals were lower than those for pre-Mazama strata then it is possible that the differences in wear were due to consumption of tephra with plant foods and the subsequent abrasion of tooth surfaces. Greatly increased wear on teeth could result in lower age classes being represented in post Mazama strata due to increased mortality from not being able to forage properly (Lyman 1985, personal communication). Sites such as Marmes Rockshelter (Gustafson 1972) may have sufficient faunal samples to test this hypothesis within fairly well dated contexts.

Ingestion of tephra with plants could in some circumstances lead to death or disease in animals (Wilcox 1959; Thorarinsson 1979). The elements such as chromium, mangenese, barium, cobalt,

and titanium have been reported within Mazama tephra and have data concerning their toxic effects (Preston et al. 1982; Adriano 1986). While other elements may be found in toxic levels, the above listed elements are not found in amounts which would be toxic to most animals. In fact, chromium and cobalt which are essential nutrients in animals (Adriano 1986) are found in very low amounts and so would be of little value nutritional value. Feeding experiments of up to 50 percent Mount St. Helens ash with feed had no toxic effect and did not block digestion in domestic animals (Preston et al. 1982).

Gases, such as fluorine and chlorine can cause death and disease in animals (Wilcox 1959; Thorarinsson 1979). They are relatively minor constituents of dacitic magmas and so were probably of little consequence to mortality for most animal populations of the Pacific Northwest.

For humans, it is possible that the constant exposure to blowing ash particles could have caused some chronic health problems. In a short term study of health problems experienced by loggers in contact with volcanic ash there was no statistically significant indication of respiratory problems although there is evidence that long term affects may be seen (Bernstien et al. 1982).

There is much experimental work which could be done to better understand the effects of tephra material properties on plants and animals. Probably of greatest significance would be a study of the responses of economically important plant species to moisture, toxicity, and fertility properties of various sizes of Mazama tephra. If it could be shown that these economically important

plants were adversely affected by tephra properties it could be argued that plant resource utilization by prehistoric peoples may also have been adversely affected. Further studies such as are occurring at Mount St. Helens, or wider application of material properties studies to more plant species would help to identify effects on a wider range of ecosystems than can presently be accomplished.

## The State Factor of Climate: E=f(C,t,d,m,g,...)

Changing climatic conditions could mean increased stress on ecosystems, and changes in tephra transport and depositonal processes and material properties of the tephra. While long term and significant climate change was occurring during the Mazama eruptive period, the role of the Mazama tephra-falls in changing climate is thought to have been minimal.

The role of the Altithermal in causing change to the ecosystems of the Pacific Northwest has been discussed in great detail (Antevs 1948, 1953, 1955; Hansen 1947; Bryan and Gruhn 1964; Warren 1968; Bense 1972; Butler 1978; Chatters 1982; Lyman and Livingston 1983; Mehringer 1986; and many others). It has been postulated that the Altithermal was responsible for a reduction in suitable habitat for flora, fauna, and people on a regional scale. With the Mazama tephra-falls having occurred near the height of this warmer, drier climate period it is possible that locally the tephra would have had a greater effect on ecosystems than it would have otherwise had. Individuals which were already near their tolerance

limits in a particular habitat may have been pushed out of the habitat by the tephra-falls. Individual instances of such an occurrence may be indicated by withdrawal of organisms from drier habitats and continued existence in more mesic habitats under the same tephra-fall conditions.

The Altithermal may have also had an effect on the redeposition processes for the tephra after initial deposition. In the hotter, drier Altithermal, eolian retransportation of tephra may have been a relatively more important process than water driven processes in the more arid regions of the Great Basin and eastern Washington. That is not to say that eolian processes were the predominant erosional process, although in some localities they most likely were, but that the drier, hotter climatic conditions and removal of vegetation would allow a relatively greater amount of material to be removed by wind action. Conversely, during the Medithermal, water driven retransport processes would have increased in relative importance to its role during the Altithermal.

Climate is an important factor in plant growth. In some areas of eastern Oregon and Washington, climate is a limiting factor on the establishment and growth of various plant species (Daubenmire 1970; Franklin and Dyrness 1973). At the time that the Mazama tephra-falls occurred, the region was experiencing the height of the hot, dry Altithermal. The increasing aridity may have only caused the more mesophytic plant zones to move to higher elevations (Mehringer 1986) in the wetter mountain zones. In more xeric habitats, the Altithermal would have caused some of the more

mesophytic plants that were near the limits of their habitat requirements to become restricted in their occurrence to local sources of water or even to become locally extinct. Except for around perennial water sources only drought resistant plants may have thrived.

Since much of the region is part of an arid steppe biome most plants are already adapted to low moisture conditions. This xeric adaptation would have been even more important during the Altithermal. The moderately well to excessively well drained nature of the tephra derived soils would have had a minimal effect on xeric adaptive types, although some of the mesophytic plant adaptations may have been severely stressed and their habitats restricted to areas of permanent water sources. The occurrence of the Mazama tephra-falls during this period may have caused many species near their tolerance limits to become stressed even more so and some may have become locally extinct. The deeper rooted trees and shrubs within areas of coarser tephra (central Oregon) would be better adapted to survive since they would be rooted below the tephra zone in materials with better water availability characteristics. As the tephra became buried and the climate became wetter toward the Medithermal, mesophytic plants with shallow root systems could become reestablished above the coarser tephra layer. Toward northeastern and southeastern Oregon, where ash size particles begin to predominate, the greater water availability potential of the tephra may have actually acted to allow more mesophytic plants to become established.

Within the dry climate of eastern Oregon and Washington, the weathering of volcanic glasses and minerals would be fairly slow except in poorly drained locations and so release of essential elements for plant growth would be minimal. This might delay colonization of plants within the surface tephra and restrict plant root growth at various levels as the tephra was buried below the surface.

A depression of the temperature on average of less than one degree celsius and localized rainfall associated with the tephra-falls may have been caused by the eruptions. The drop in temperature and increased precipitation associated with the tephra-falls would have been of too short a duration, certainly much less than a decade, for any significant successional changes.

The climate will generally have little influence on the effects of the tephra on animal populations except as it relates to the food chain for all organisms, and turbidity and sedimentation for fish and mollusc populations. Changes in climate associated with Plinian eruptions are generally of small magnitude and of short duration (except possibly when associated with a period of regional or worldwide volcanism). Climate generally only effects plant distributions and by them the higher portions of the food chain which rely on the plants.

Fish may be harmed by increased sediment loading of streams and rivers associated with periods of increased precipitation and erosion. Conversely, if the stream or river does not have enough

competence, due to low rainfall amounts, to clear the bed of tephra from the initial fall-out then spawning areas may be ruined.

The greatest effects of climate on people would be the availability and scheduling of subsistence activities and possibly as a result, change of settlement locations. The loss of root crops that were exploited at various times of the year would have caused a shift to reliance on other plant or animal resources. As plant associations changed, so to would the distributions and densities of animal populations. This might mean the short term or long term use of plant species which had not been exploited to any great extent but which were relatively unaffected by the tephra-falls would increase.

More work is needed to understand the implications of climate change on the prehistoric populations of the region before the contributing effects of the Mazama tephra-falls can be assessed. With more precise modeling of past climates and climate change it may be possible to determine whether the Mazama eruptions actually caused certain climate sensitive ecosystems to be adversely affected.

The State Factor of Geomorphology: E=f(G,t,d,m,c,...)

The redeposition of tephra results in a mosaic of tephra and nontephra derived soil bodies. Tephra derived soil bodies generally have much different water availability and fertility characteristics than areas of other mineral soils. As well, the retransport of tephra by stream systems or redeposition in low lying areas could

have had grave consequences or possibly even benefits to various plant and animal species. A more thorough investigation of tephra dynamics and landforms of tephra storage will be needed to model the effects of the tephra on ecosystems.

As distance increases from the mountain and away from the main axis of an individual tephra lobe the amount of land surface covered by tephra decreases. This is true for both primary and secondary tephra bodies. On a northeasterly trend from Crater Lake, tephra is no longer a major portion of the landscape as is indicated by research in northeastern Oregon. Within this area, as well as to the north and east, the tephra is found mostly on northern exposures where dense stands of vegetation exist, and at toe slopes, alluvial fans, and canyon mouths as secondary deposits. At lower altitudes the tephra is under represented compared to the uplands, except in canyons and depressional areas.

This mosaic of tephra bodies would have meant that over time vegetation would have had to adjust to the material properties of the tephra. Those areas which did not have tephra on them would generally be much more conducive to plant growth until the tephra was buried on other areas.

## RESEARCH PROBLEMS

A model of the effects of the Mazama tephra-falls on flora, fauna, and people has been discussed which should help to answer some of the questions surrounding the history and possible influence of the events. The model still needs to be tested against specific archaeological data in the Pacific Northwest. Originally the model was going to be tested on the Lower Snake River region of southeastern Washington, but in doing so certain problems were encountered that prevented such testing. The major problem is that the model, and the archaeological and environmental data are not sufficiently robust to answer many of the questions which need to be addressed before the model can be applied.

Before the model can be applied in any concrete manner the hypotheses generated from it must have a semi-quantitative or quantitative expression. Such data can be derived from ecological, volcanic hazards, and archaeological research, as presented in Chapter II, although the present state of theory in each discipline may not allow unequivocal interpretation of that data. As well, some data that is essential to answering the some of the research questions just does not exist. These problems, along with a few examples and suggestions, will be addressed in the following sections.

Chronometric control

Without proper chronometric control, it is rather difficult to identify or correlate hypothesized effects with the archaeological or ecological data. For instance, Bense (1972) has suggested through her research that there was no fundamental change in the Cascade Phase on the Lower Snake River between 8000 and 4500 years b.p.. While essentially correct, this result was based on data which spanned 3500 years and did not take into account short term changes in the sociocultural system. In fact, most archaeological data can not be dated to within the time frame which would be appropriate for detailing the short term effects of the Mazama tephra-falls. Radiocarbon and other dating methods can not give results to within a decade or two and sometimes not to within a hundred years. The encapsulation of archaeological materials between or within Mazama tephra layers is one way of dating those materials, but in many cases the context is suspect due to cultural, biologic, and geologic mixing. At Lost Pass Bog in Montana, Blinman et al. (1979) were able to determine that grass pollen increased in relation to other herbaceous vegetation for a few years after the climatic tephra-fall because they had the proper data and a technique which was sensitive enough to see such an effect. Without such data and techniques we will not be able to determine whether there was any short term effect due to the tephra-falls.

To overcome these problems more research and specific data collection of chronological information needs to be undertaken. A

better understanding of the history and relationships of the eruptions can be gained through correlational studies of Mazama tephra within natural stratigraphic contexts (see correlation sections in Chapter IV). Such studies can tell us more about the extent of each tephra unit and therefore the cultural and ecological materials which are found in them, and the expected effects for each unit. Research into the duration, season of individual tephra-fall events, and residence time of the tephra in an ecosystem (see Chapter II) will suggest how long the tephra may have affected the ecosystems. Collection of large numbers of radiocarbon dates and their statistical analysis may give better resolution to determining the time period that cultural and natural materials refer to.

Ecological Data

One of the main arguments in the model is that to determine the effects of the Mazama tephra-falls on humans we must first consider the effects on flora, fauna, and ecosystems. To do so takes quantitative or semi-quantitative data on natural floral and faunal populations. The kinds of species and their population densities must be detailed for both the predisturbance and post-disturbance ecosystems to determine the effects of the events. This type of data can be obtained through pollen, macrofloral, microfaunal, and macrofaunal analyses of materials associated with the tephra or dated to this time period.

Unfortunately, detailed ecological data for the Mazama eruptive period is rare due to taphonomic factors or noncollection

by researchers. Even when collected, the data may not be as specific as needed. In the case of pollen analysis we can get presence/absence and relative quantities of the most abundant climax species, but little or no information about the minor although possibly important plant species or those species which reproduce without airborn pollen is available.

Faunal data in most cases is entirely missing and only rarely does one find instances where life tables can be constructed for natural populations. The chances of finding such sites and the researchers actually looking for such sites are probably close to nil. There are instances where faunal data for the time period exist, but they are generally from archaeological sites such as Marmes Rock Shelter (Gustafson 1972) in southeastern Washington in which the data have been skewed by prehistoric hunters selecting out certain species, sexes, and ages of animals which may or may not represent the structure of the natural population and most likely does not represent the entire range of variability for the existing species.

Since the abiotic system is a major control on the biotic system the predisturbance and post-disturbance systems must be detailed also. One of the most important abiotic factors is climate. During the Mazama eruptive period the region was experiencing the hotter, dryer Altithermal. Since the Altithermal certainly had some influence on floral and faunal distributions (Mehringer 1986) across the Pacific Northwest these effects must be separated from the effects of the Mazama tephra-falls.

Unfortunately, the data derived from pollen analyses are not of a quantitative or very specific nature. This leads to equivocal results when the effects are detailed.

Suggestions for future research are many and varied. Detailed pollen columns for a wider range of locations may help establish the presence or absence of certain plant species of past ecosystems for specific locations. The location and study of paleontological sites may give information for construction of life tables for pre- and post-disturbance faunal populations to determine changes in populations. Use of well controlled experimental analogs from modern ecosystems that are similar to past ecosystems could help to determine past ecosystem compositions. Volcanic hazards research and experiments to determine species tolerance to tephra would help to determine how specific plants and animals would have been affected by the tephra-falls. Climatic reconstruction through pollen data and other methods can help detail the effects of climate on past ecosystems. Each of these points is considered in more detail in Chapters II through VI.

Subsistence Resource Data

Since the prehistoric hunter-gatherers of the Mazama eruptive period relied on local floral and faunal resources for sustenance, this type of quantitative or semi-quantitative data must also be gathered. Without such data it is extremely difficult to know whether a change in the technoeconomic system was likely or if such a change is seen whether the Mazama tephra-falls were the cause.

The same problems which plague the collection of ecologic data apply to subsistence data as well.

An example which illustrates such problems can be found in the exploitation of anadromous fish resources on the Lower Snake River. Both Brauner (1975, 1976) and Galm (1975) have suggested that the Cascade adaptation in the Lower Snake River canyon was centered on the salmon runs. If true, the destruction of the salmon runs by the Mazama tephra-falls could have had grave consequences for the people of the region. Since fish bones preserve poorly and there is little evidence of salmon fishing technology in the archaeological sites which have thus far been excavated, it is difficult to say with any real certainty just what the effects on humans may have been. There is no way, except through analogy with other peoples who rely on fishing, to create a model of the fishing subsistence system to test for effects due to the tephra-falls.

Great attention must be payed to collection of pollen, macrofloral, and faunal data from archaeological sites to determine subsistence resources. Stratigraphic contexts must be well controlled to determine short term changes in subsistence resource use. If sufficiently detailed models of past subsistence systems can be created, various changes in floral and faunal resources due to tephra-falls and their subsequent effects on resource use may be explored and tested.

Subsistence Technologies

It has been argued in the model that subsistence technologies and settlement locations or locations of resource use should be sensitive to changes in ecological resources. While this is probably true, the state of the art at this time may not be of sufficient sensitivity to be able to determine short term changes in subsistence resource use.

The location of the artifact can give important information about how resources may have been used across space, but this information may be confused by cultural and natural processes that cause an artifact to finally come to rest some place other than where it was originally used (Schiffer 1976; Wood and Johnson 1982). Without such contextual information it is impossible to determine if the location of resource use may have changed from the predisturbance to a new post-disturbance pattern.

Due to a lack of signature criteria for the determination of specific tool functions the significance of specific types of wear may be unclear. Without being able to tell what type of plant or animal a tool was used on or how it may have been used the conclusions of such an analysis are disappointing at best.

The model asserts that any long term change or introduction of new tools within a subsistence technology is a fundamental change and significant. It is difficult to prove what the change in use or introduction of a tool type actually means. For instance, does the introduction of the Cold Springs projectile point style in the Lower

Snake River canyon after the Mazama tephra-falls (Bense 1972) mean that the people needed a new technological trait to overcome ecologic stress? And if it does, was the source of the stress due to the Mazama tephra-falls, the Altithermal, or something else.

All of these problems are difficult to overcome. Attention paid to disturbance processes and their effects on tool location is important. A larger sample of sites may help to make settlement and resource use locational patterns clearer. Further experimentation to determine signature criteria for functional interpretation of wear patterns may lead to insights about how tools are used. Careful analysis of tools within Mazama contexts to include wear patterns for functional interpretation may give indications of changes in subsistence technologies.

## FINAL REMARKS

Within this thesis a model of the effects of the Mazama tephra-falls has been presented which will hopefully add some new insight into how flora, fauna, and people may have been influenced by the events. The Mazama tephra-falls were of a regional scope and may have had a significant influence on many of the ecosystems of the Pacific Northwest. As such, the questions raised by such research can help us to understand how people adapt to ecological stress.

As more data becomes available and as other researchers with a more indepth background in some of the many facets of this research become interested in the subject we will come to understand what

these events may have meant to prehistoric peoples. Even with the limitations of the data there are many fascinating avenues of research that can be completed.

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