

DISTRIBUTION, THICKNESS, AND MASS OF LATE PLEISTOCENE AND HOLOCENE
TEPHRA FROM MAJOR VOLCANOES IN THE NORTHWESTERN UNITED STATES:
A PRELIMINARY ASSESSMENT OF HAZARDS FROM VOLCANIC EJECTA
TO NUCLEAR REACTORS IN THE PACIFIC NORTHWEST

by

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Introduction

The eruption of Mount St. Helens on May 18, 1980, and the widespread destruction and other effects of this eruption both in the immediate vicinity of the volcano as well as for several hundred kilometers downwind to the east are dramatic reminders of the potential explosiveness of volcanoes in the Cascade Range volcanic chain; they underscore the need to assess volcanic hazards for planned and existing nuclear reactor sites. The most widespread effect of explosive volcanic eruptions, and the one most likely to affect one or more reactor sites in the Pacific Northwest, is fallout of volcanic ash and coarser ejecta downwind from the volcano.

This report is part of a study to assess potential volcanic hazards to nuclear reactor sites in the Pacific Northwest from air-fall tephra (volcanic ash and coarser ejecta) erupted from Cascade Range volcanoes. The May 18 eruption of Mount St. Helens, Wash., is one of the best-documented historic eruptions in terms of volume and mass of material erupted, area covered, thickness of fallen ash, mass of material deposited, rate of progress of the airborne ash plume, and other parameters important to an assessment of volcanic hazards. This eruption can be used as a model to assess the kind and degree of impacts of possible future eruptions of this magnitude from Cascade Range volcanoes. In terms of volume of tephra erupted and area covered by tephra, the eruption of May 18 was moderate compared to several previous Holocene eruptions from this and other Cascade Range volcanoes (Crandell and Mullineaux, 1978; Sarna-Wojcicki and others, 1981a). Consequently, the damaging effects of the 1980 eruptions cannot be considered as the worst possible case in terms of potential volcanic hazards to reactor sites. Although for prehistoric Holocene eruptions of Cascade Range volcanoes much of the kind of information recorded for the May 18 eruption has been destroyed or obscured by erosion, redeposition and burial of tephra by younger deposits, it is the remaining geologic record of Holocene volcanism, combined with historic observations, from which prediction of the nature, frequency, and magnitude of future eruptions must be made.

Volcanic hazards other than air-fall tephra (avalanches, mudflows, floods, lava and ash flows, and gas emissions) can be important near all volcanoes and have been evaluated in other studies of volcanic hazards, (for example, Crandell and Mullineaux, 1978; Miller, 1980). This report is limited to the hazards of distal (farther than 50 km from source) air-fall tephra to reactors and reactor sites. Six nuclear-reactor sites, three of which have nuclear reactors (Humboldt Bay, Trojan, and Hanford) are located in the Pacific Northwest (fig. 1, map sheet) and, with the exception of the Humboldt Bay site, lie within areas of known ash fall of historic (approximately the past 200 yr) or Holocene (approximately the past 10,000-13,000 yr) eruptions.

The Cascade Range volcanic chain

The Cascade Range of the Northwestern United States (northern California, Oregon, and Washington) is a north-trending range of mountains composed largely of volcanic rocks (fig. 2). The eastern part of the chain is composed of geologically young volcanic rocks erupted within the last 2 million years (the Quaternary Period), while the western part consists of older volcanic rocks. The chain is dotted with volcanoes, most of which have been built up by volcanism in late Quaternary and Holocene time, and several of which have been active in historic time.

Plinian eruptions and their products
from Cascade Range volcanoes

Holocene eruptions from Cascade Range volcanoes have varied greatly in magnitude, as measured by the volume of material erupted, in explosiveness, as measured by the thermal and kinetic energy released per unit time, and in the type of material erupted. In this report we are concerned only with explosive volcanic eruptions that have introduced large amounts of volcanic ejecta into the atmosphere. Such eruptions--termed Plinian (for Pliny the Younger, who described this type of eruption from Mount Vesuvius in 79 A.D.)--are produced by the sudden release of confining pressure in magma (molten rock) reservoirs situated at shallow depths (about 5 to 10 kilometers) in the earth's crust. Typically, such eruptions are produced from viscous, silicic magmas (SiO₂ content from about 64 to 74 percent), containing high concentrations of dissolved gases. The silica polymerizes the magma, increasing its viscosity relative to low-silica magmas, such as basalt or andesite, which enables high concentrations of volcanic gases including H₂O, CO₂, H₂, Cl₂, H₂S, SO₂, and CO to accumulate and remain in solution. When pressure on the magma reservoir is suddenly released, either by the failure of the confining solid-rock crust through upward intrusion of magma, or through disruption of the confining crust by fault movement, earthquake, or landslide, gases are emitted rapidly from the magma, transforming it into a liquid-gas froth. The resultant rapid increase in volume of the magma froth is explosive, propelling it in the direction of low pressure--generally upward and into the atmosphere.

Large volumes of volcanic ejecta, collectively referred to as tephra (from the Greek word meaning ash), can be introduced into the atmosphere and lower stratosphere (altitude in excess of 11 km) within a relatively short period of time. During the May 18, 1980, eruption of Mount St. Helens, 1 to 2 km³ of tephra were erupted within about 10 hr, some material reaching altitudes of 23 km to possibly 27 km (Sarna-Wojcicki and others, 1981a). A layer of ash as thick as 5 cm accumulated on the ground within 300 km downwind from the volcano (vicinity of Ritzville, fig. 3), and lesser amounts extended 600 km from the volcano, covering an area of about 200,000 km².

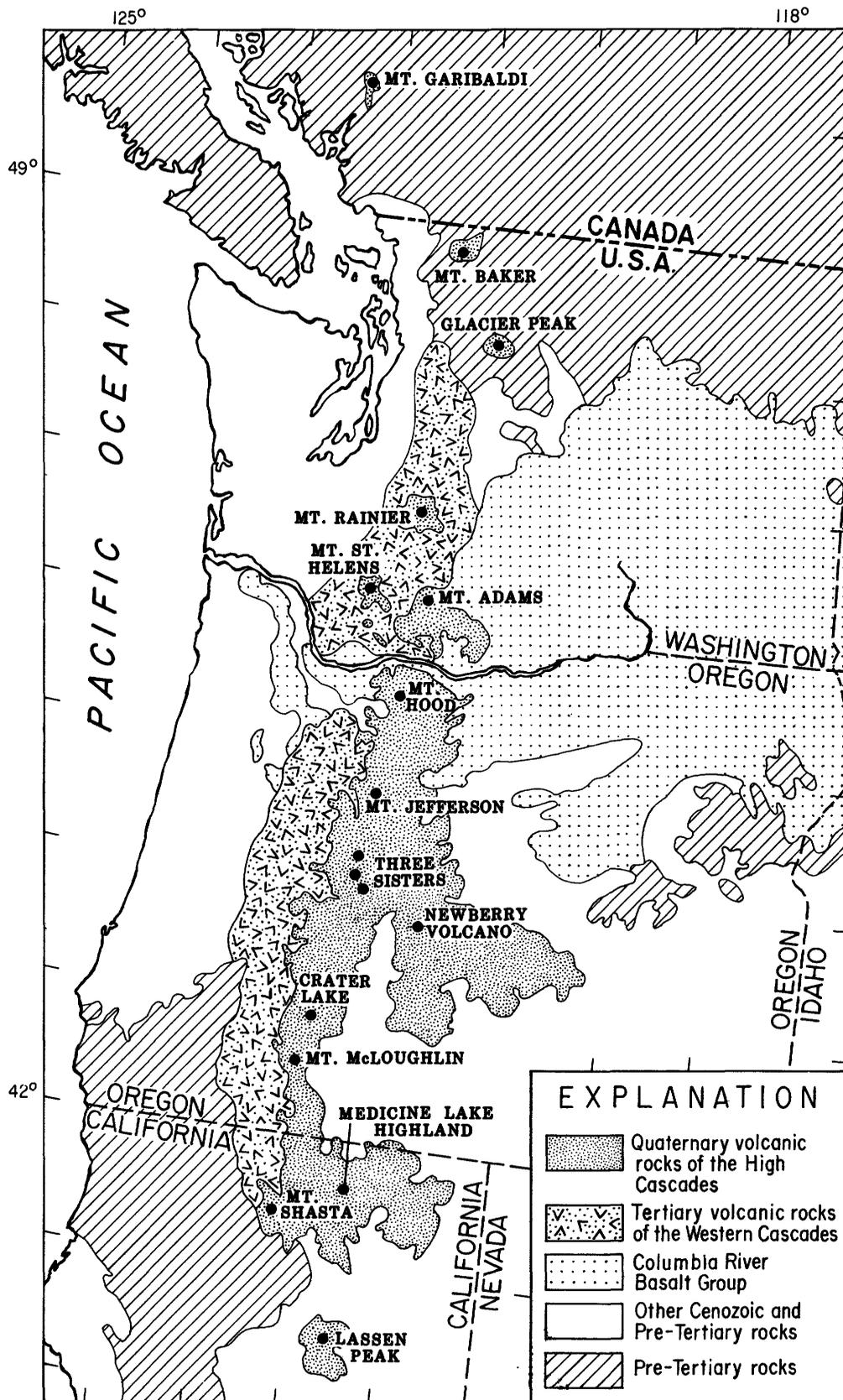


Figure 2--Generalized geologic map of the Cascade Range showing relation of Quaternary rocks to older basement rocks and lavas of the Columbia River Plateau and location of major Cascade volcanoes. Figure modified from McBirney (1968, p. 102).

Nature and composition of tephra

Tephra consists of several major components. All large Plinian eruptions contain material, termed juvenile, that is molten or had been molten at the time of the eruption. This material cools from rapid expansion and from contact with air, producing particles of ash and coarser ejecta that are solid by the time they fall to the ground. Pre-existing rocks can also be incorporated into the erupting material, particularly in the early phase of eruption.

The main components of tephra are:

Pumice: a solidified rock froth of volcanic glass, crystals of one or more kinds of minerals, and voids formed by gas bubbles. The glass is a supercooled, natural liquid. The crystalline mineral particles within the glass (crystals or crystal fragments) represent solid material that was crystallizing from the magma prior to eruption. The abundant voids in the pumice are formed by outgassing (removal of dissolved gases, usually caused by a decrease in pressure) of the molten rock material during eruption. By the time the pumice fragments fall to the ground, or shortly thereafter, the original gases from which these bubbles formed have escaped or are highly diluted by infiltrating air. Because of the large number of voids in pumice, the material has a low density, generally between about 0.7 and 1.2 g/cm³. If large amounts of material are erupted, floating mats of low-density pumice can accumulate on the surface of any body of water that lies in the downwind direction. If many of the voids in pumice are connected, as they often are in tubular pumice, the voids may fill with water and the pumice may sink. If the voids are not connected, the pumice may continue to float for an indefinite period. Pumice erupted from Cascade Range volcanoes is of both types. Pumice fragments are generally larger near the vent from which they were erupted and diminish in size in the downwind direction. Because most of the solid material of pumice is composed of glass, it has about the same hardness as glass (about 5 on Moh's hardness scale, somewhat softer than the blade of a steel knife). Crystalline minerals in the pumice, however, may be harder, (range of 5 to 7 on Moh's hardness scale; see below).

Glass shards: At distal locations, the finest particles generally consist of very small pumice shards and glass shards derived from the bubble walls and bubble-wall junctions of exploded rock froth. They are essentially pure glass, but may contain some gas bubbles, and small crystals or crystal fragments. Glass shards commonly have densities of 2.35 to 2.45 g/cm³, are irregular in shape with sharp, angular corners, and have a hardness of approximately 5 on Moh's hardness scale.

Lithic fragments: The force of an explosive volcanic eruption is commonly great enough to disrupt and disintegrate a significant part of the solid crustal rock that enclosed the magma reservoir. This material, commonly ejected simultaneously with the juvenile components as rock fragments, ranges from blocks that may be more than a meter in diameter near the volcanic vent to composite particles a fraction of a

millimeter in diameter deposited at greater distances. Lithic fragments consist of intergrowths of one or more kinds of minerals, commonly the same kinds as are found in pumice. Densities of these fragments generally range from 2.7 to 3.2 g/cm³. The hardness of such fragments depends on the kinds of minerals present, their relative abundance, and the texture of the rock (the way the mineral grains are packed together). In volcanic terranes such as the Cascade Range, the range of hardness will vary from somewhat softer to somewhat harder than that of a steel knife (from about 5 to 7 on Moh's hardness scale), although rare lithic grains containing both harder and softer minerals may also be found in tephra.

Crystalline minerals and crystal fragments:

This component of tephra can be derived both from the magma, as minerals crystallizing from the magma before eruption and subsequently incorporated into pumice fragments or erupted as discrete particles, and as accidental crystals and crystal fragments of minerals (fragmented from wall-rock of the vent and volcanic edifice during an explosive event). Commonly, magmatic crystals have a coating of volcanic glass, whereas accidental crystals of older rock do not, unless the older rock is also tephra. Physical properties of minerals found in tephra range widely. Densities vary from about 2.6 to 5.2 g/cm³, and the hardness commonly ranges from somewhat softer to somewhat harder than that of a steel knife (from about 5 to 7 on Moh's hardness scale).

Other components, such as organic matter, may be found in minor amounts in tephra. During the May 18, 1980, eruption of Mount St. Helens, organic matter was derived from the destruction of vegetation surrounding the volcano during the catastrophic initial lateral blast. Fragmented, charred bits of organic matter were subsequently entrained into the vertical eruption column and transported downwind. Of all the components of tephra, only pumice and organic material will float in water.

Chemical reactivity of tephra

Although the glass and crystalline minerals of which tephra is composed are relatively inert and decompose slowly under the normal climatic conditions of the Pacific Northwest, tephra fragments may be coated with soluble salts and liquid condensates from the eruption. Downwind tephra deposited from the May 18, 1980, eruption of Mount St. Helens was generally acidic, although initial pH measurements ranged from 5.6 to 8.2 when 20 mg of ash were mixed with 50 ml of water (Nehring and Johnston, 1981). A sample of downwind ash from the May 18, 1980, eruption for which an initial pH of 6.4 was measured, became more basic (pH of 7.5) after being stirred for several hours in distilled water. This change probably reflects leaching of alkalis (sodium and potassium) from the glass after the initial acidic components (HF, HCl, and H₂SO₄) had dissolved.

Relative abundance of the major components of tephra

The relative abundance of the major components of tephra differs from place to place as a result of downwind sorting (selective removal of finer particles), prevailing meteorological conditions, and the nature of the eruption--primarily the amount of thermal and kinetic energy released, the rate at which

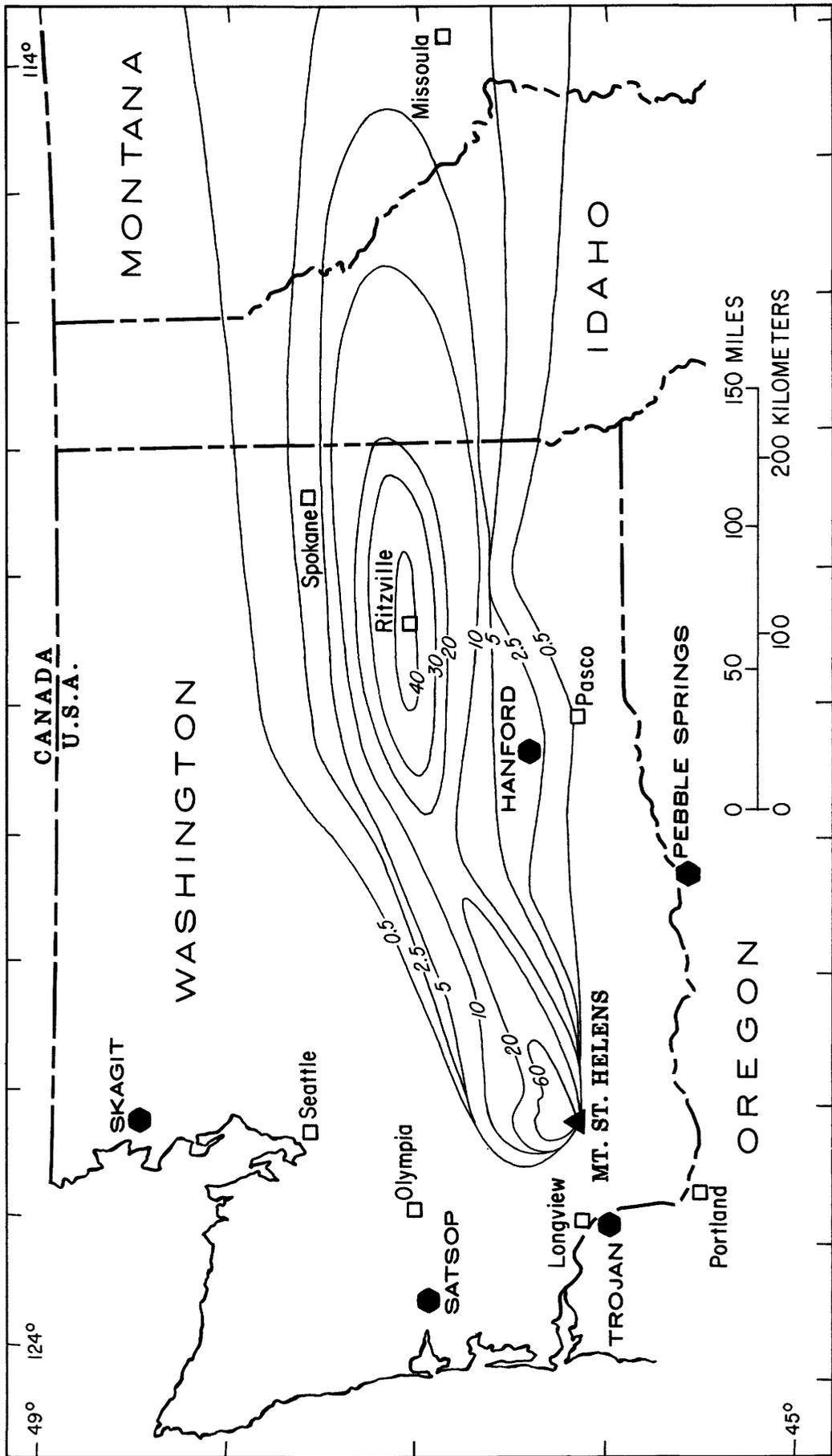


Figure 3--Thickness of air-fall ash erupted from Mount St. Helens on May 18, 1980. Isopachs represent uncompacted thickness of ash in millimeters. Hexagons indicate planned or existing nuclear-reactor sites. Modified from Sarna-Wojcicki and others (1981a).

the energy is released, and composition of material erupted. Interaction of magma with ground water can also affect the explosiveness of eruption and the degree of dispersal of ash. In general, coarsest and densest materials fall out first, closest to the volcanic vent. Because finer and less dense materials are carried farther downwind and take a longer time to settle, the finest and least dense components, fine glass and pumice shards, are relatively enriched at distal locations. For instance, volcanic ash from the May 18, 1980, eruption of Mount St. Helens, at distances of about 40 km downwind, contained 20 to 30 percent of material lighter than 2.5 g/cm^3 (dominantly volcanic glass and pumice shards), the remainder being crystals of minerals, fragments of crystals, and lithic fragments. In contrast, tephra deposited about 400 km downwind contained 80 percent by weight material lighter than 2.5 g/cm^3 (Sarna-Wojcicki and others, 1981b).

Specific hazards from airfall tephra to nuclear reactor facilities

Specific factors that should be considered in an assessment of hazards from airfall tephra to reactor facilities include:

Bearing strength of structures - Loading of structures by airfall tephra increases directly with thickness and density of the tephra (fig. 4). Dry, uncompacted tephra consisting mostly of glass and pumice shards from the May 18, 1980, eruption had an average density of about 0.5 g/cm^3 (fig. 4; Sarna-Wojcicki and others, 1981a). Tephra from Mount St. Helens that fell during rain or was wetted shortly after falling on May 25 and June 12, 1980, had average densities of 1.03 and 1.25 g/cm^3 , respectively. Tephra falling near its volcanic source may have higher densities if the proportion of lithic and crystal fragments is large relative to pumice and glass shards.

Filtering systems - Water- and air- filtering systems can be clogged by a heavy influx of tephra into water-supply and air-filtering systems. Tephra particles vary greatly in size, ranging from a mixture of large to small particles near eruptive vents, to very fine particles at long distances. Glass shards as small as about one-tenth of a micrometer are common in downwind ash collected from Moscow, Idaho, after the May 18, 1980, eruption (Sarna-Wojcicki and others, 1981 a, b). Most of the fragments smaller than about one-half micrometer, however, adhered to surfaces of larger fragments and were probably scavenged by the latter while falling.

Machinery - The hard, fine, angular ash particles can abrade the moving parts of machinery and cause excessive wear or breakdown. Channel switches and volume controls on radios in helicopters used in the vicinity of Mount St. Helens for periods of up to one year during the 1980-81 eruptive episode failed prematurely probably because ash infiltrated the mechanical parts (Mark Dufault, Western Skyways Avionics, oral commun., 1981).

Electrical equipment - The electrical conductivity of newly fallen tephra is greater than that of basalt or other rock used as aggregate for power-line foundations or surface dressing. When wet, volcanic ash is sufficiently conductive so that it becomes a hazard to life in the vicinity of powerlines, and can cause arcing and short-outs when it covers conductors on powerlines (Sarkinen and Wiitala, 1981). Although volcanic ash is generally unreactive, ash particles can be coated with soluble salts and liquids condensed from volcanic gases. Upon wetting, volcanic ash generally is acidic at first, then slowly turns neutral and eventually becomes slightly basic.

Leachates from freshly fallen tephra may corrode electrical equipment.

Water-cooling systems - Uncovered cooling ponds can be affected in two ways: low-density pumice and finer pumice shards floating on the surface will insulate the pond if a thick enough layer is deposited. Denser tephra components will sink, thereby reducing the capacity of the reservoir, clogging filters, and reducing or completely stopping circulation.

Indirect effects - As the eruption of May 18, 1980, has shown, people, structures, vehicles, other kinds of machinery, and roads can be adversely affected over a large area after a heavy tephra fall. These effects may persist because maintenance and emergency services are impaired or because fallout from successive closely spaced eruptions continues to be a problem. Service and maintenance personnel responsible for reactor operation and safety may not be able to perform their duties because of difficulties with breathing and vision. Staff and emergency personnel may not even be able to gain access to a reactor if vehicles fail or roads are impassable. For instance, during and after the eruption of May 18, 1980, many late model vehicles, including emergency vehicles, were immobilized because the paper air filters clogged with ash, eventually imploded, and clogged the air-fuel injection systems. Cars with the older, oil-bath filters or oil-wet foam filters ("dune-buggy" type) generally fared much better (J. O. Davis, oral commun., 1981). Helicopters, particularly jet-engine types, are particularly susceptible to damage from volcanic ash, which tends to be sucked into the air-intake systems. Lastly, reactor personnel may be unwilling to leave their families and homes in such an emergency.

Cascading effects - Cascading effects develop when tephra fallout impairs one function or group of functions, which then impairs other functions, and so on. An example would be failure of vehicular air-filtering systems, which delays or prevents travel by staff or emergency personnel, in turn hindering corrective or preventive maintenance on equipment designed to keep cooling-pond surfaces free from ash, ultimately causing filters to clog and hindering water circulation to the reactor.

Obviously, a thorough assessment of potential hazards to reactor plant, air and water supply, site, staff, emergency personnel, vehicles, and surrounding environment needs to be made, and possible cascading or compounding effects need to be analyzed. From such an assessment and analysis, contingency plans and back-up systems need to be designed to handle effects of tephra fallout from major volcanic eruptions in the Pacific Northwest.

Areal distribution and thickness of tephra erupted in Holocene time in the Pacific Northwest of the United States

In this report we summarize existing data on areal distribution and thickness of tephra erupted from major Cascade Range volcanoes in Holocene and latest Pleistocene time and compare these data with what we know about tephra deposits from the 1980 eruptions of Mount St. Helens. At the present time, we lack detailed knowledge of the areal distribution, thickness, and age of Holocene tephra from most volcanoes in the Pacific Northwest. Additional studies over the next several years will be required to document erosion, transportation, and redeposition of tephra from the 1980 eruption sequence of Mount St. Helens to provide an adequate basis for comparison of thickness and stratigraphy from these eruptions with products of prehistoric eruptions. Furthermore,

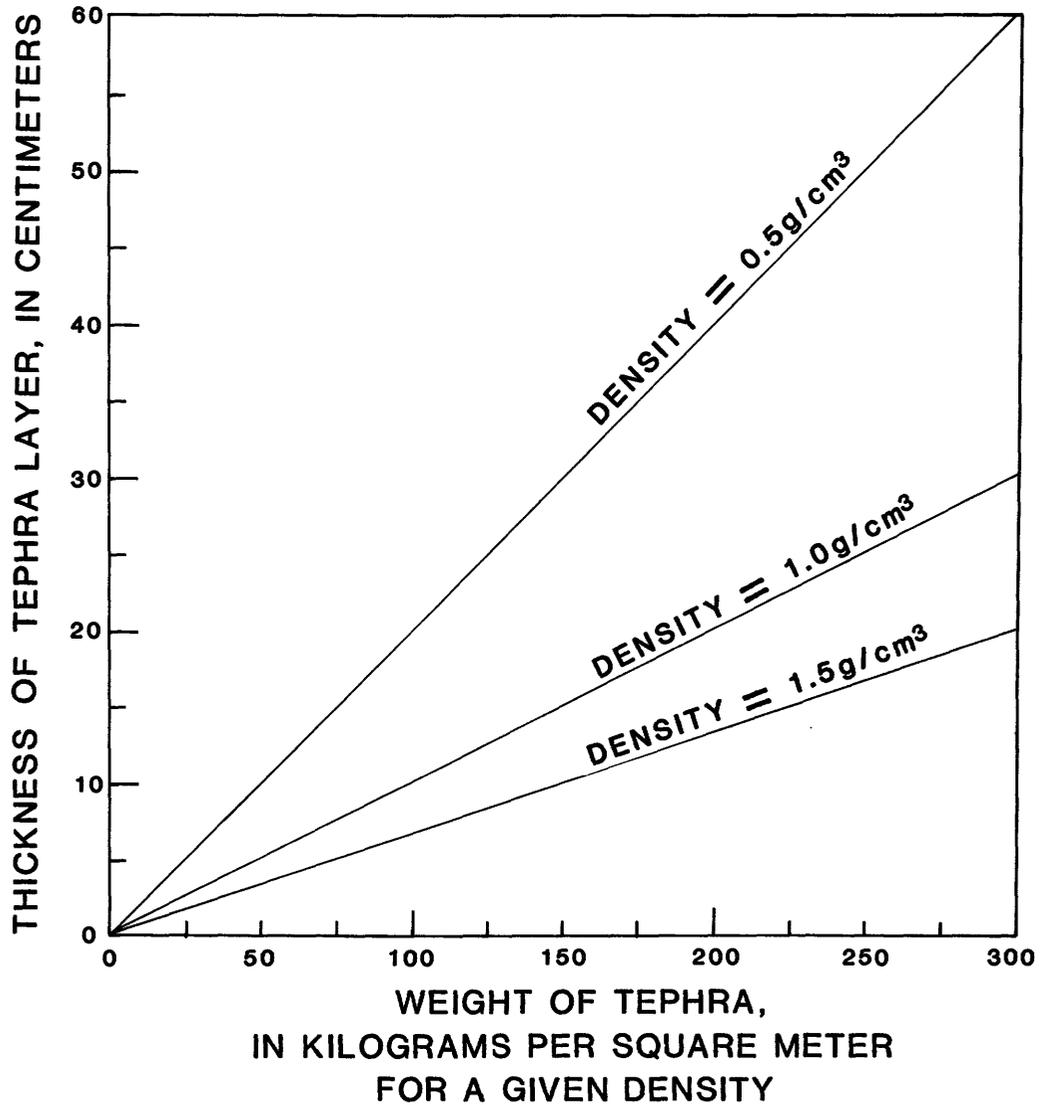


Figure 4--Relation between thickness of tephra layer and weight for three different bulk densities of tephra. A density of 0.5 g/cm^3 is similar to average bulk density of tephra erupted May 18, 1980 (tephra not compacted by rain). A density of 1.0 g/cm^3 is similar to average bulk density of tephra erupted on May 25 and June 12 (tephra compacted by rain). A density of 1.5 g/cm^3 is similar to average bulk density of lithic-crystal ash collected close (20-30 km) to the volcanic vent. The curves do not take into consideration effects of compaction. A tephra layer of low bulk density would probably begin to compact under its own weight as layer thickness increases.

detailed analyses need to be made of the meteorological conditions that existed during the 1980 eruptions of Mount St. Helens, together with studies of grain-size distributions of air-fall ash as a function of distance from the volcano, in order to predict the shapes and thicknesses of air-fall ash lobes under different meteorological conditions.

Air-fall tephra from several voluminous late Pleistocene and Holocene eruptions is widely distributed throughout the Pacific Northwest and adjacent areas (fig. 1, map sheet). Tephra layers preserved in the geologic record, together with documented historic activity, indicate that the Cascade Range volcanoes that produced the most widespread tephra layers in latest Pleistocene and Holocene time are Mount St. Helens, Wash. (Crandell and Mullineaux, 1978; Mullineaux and Crandell, 1981), Crater Lake, Ore. (Mount Mazama) (Williams, 1942; Mullineaux and Wilcox, 1980), and Glacier Peak, Wash. (Porter, 1978). Other volcanoes in the Cascade Range that produced tephra layers of small to moderate areal extent are Mount Baker, Mount Rainier, Mount Hood, Newberry volcano, Mount Shasta, Medicine Lake caldera, and Lassen Peak. Lassen Peak, Mount Shasta, Mount Rainier, and Mount St. Helens have been active in historic time. Mount Lassen was active during 1915-17, and Mount St. Helens in about 1800, and in 1831-56, as well as in 1980-82. Measurable volumes of tephra were not produced or are not preserved beyond the flanks of Mount Adams and Mount Hood. Mount Thielsen, Mount McLoughlin, and Mount Jefferson are composed largely of volcanic cinder; ejecta does not extend far beyond their flanks. Numerous Holocene basaltic cinder cones are present throughout the Pacific Northwest; air-fall tephra from these cones, however, is generally limited to their vent areas, and is not shown on the map (fig. 1, map sheet).

The distribution of tephra in the Pacific Northwest is determined largely by the location of the more explosive volcanoes and by the prevailing wind directions. Tephra lobes of most eruptions are elongate and somewhat narrow, reflecting relatively stable wind directions during eruption. For other eruptions, however, such as those of Mount St. Helens on May 25, June 12, and October 16-18, 1980, as well as the eruption about 7000 yr B.P. (before present) from Crater Lake, Oregon (Mount Mazama of Williams, 1942), the lobes are broad or multiple and reflect changing wind directions during or between eruptions. Lobe boundaries shown in figure 1 (map sheet) can be considered to represent the minimum areal extent of each eruption because fine ash from all eruptions has been carried far beyond the mapped boundaries. The boundaries delineate areas of observed fallen tephra only. For example, the airborne tephra plume from the May 18 eruption of Mount St. Helens was tracked across the United States and completely around the globe (Sarna-Wojcicki and others, 1981a). The finest ash may remain suspended for several years, as was documented for the eruption of Krakatau in 1883 (Symons, 1888).

Tephra from older eruptions has been extensively reworked by erosion, redeposition, and downward translocation into soil profiles and is now covered by younger deposits in most areas. Consequently, evidence for prehistoric eruptions is patchy, particularly for thin, fine-ash layers deposited far from their vents. It is difficult therefore to estimate the original maximum thickness of individual prehistoric tephra layers. Redeposition of tephra along former stream channels and in bogs, depressions, and other closed basins commonly thickens the tephra layer beyond the original air-fall thickness. Conversely, most exposures of ancient tephra layers showing initial air-fall thickness are likely to be less than the maximum thickness at that distance

because the probability of finding an exposure at the lobe axis is low or because tephra has been significantly eroded. Reports of identifications and thicknesses of tephra units from the literature must be carefully screened to verify that (1) tephra units are correctly identified with respect to source area and age, and (2) thicknesses reported represent initial air-fall deposits.

With the exception of the 1980 Mount St. Helens isopach data, very few thickness data have been included in figure 1 (map sheet) because the tephra layers have been extensively reworked after initial deposition. In distal areas of certain tephra deposits, individual data points have been plotted as minimum air-fall thicknesses (fig. 1, map sheet). These points were chosen because site descriptions suggest that the tephra layer represents initial air-fall thickness. Thickness data at proximal sites (generally less than about 50 km from source) for prehistoric tephra units of late Pleistocene and Holocene age (Crater Lake, Mount St. Helens, Mount Rainier, and Glacier Peak) probably represent more closely the original air-fall thicknesses reduced somewhat by post-depositional compaction. Holocene tephra layers close to the source are relatively coarse and thick and are less likely to have been reworked by wind and water. Features suggestive of primary stratigraphy and absence of secondary depositional features in such layers can also suggest that original thicknesses are represented.

For several reasons, ash thicknesses shown in figure 1 (map sheet) for both historic and prehistoric eruptions are probably minimum values. First, compaction of air-fall tephra begins immediately after deposition. For instance, thickness of distal ash measured in Idaho immediately after the May 18, 1980 eruption was two to three times greater than that measured in the same location two days later (Sarna-Wojcicki and others, 1981a). Freshly fallen ash is very loosely packed; initial packing may be controlled to some extent either by weak static electrical charges acquired by falling particles or by moisture surface tension. Rainfall can reduce the thickness of a newly deposited tephra layer by as much as one-half (Sarna-Wojcicki and others, 1981a). Lastly, many tephra units from prehistoric eruptions in the Cascade Ranges have been further compacted by burial. Mass of air-fall tephra measured over a specific unit area is generally a much more constant and useful parameter than thickness in determining the amount of tephra deposited at a site.

Recurrence intervals between volcanic eruptions in the Cascade Range

The record of Holocene and latest Pleistocene volcanism in the Cascade Range is too short relative to the frequency of major tephra eruptions to allow us to make accurate predictions of the site and frequency of future eruptions. In general, however, there appears to be an inverse relation between eruption magnitude and frequency: large eruptions tend to occur less frequently than smaller ones.

In the Cascade Range volcanic chain, there have been between about 12 and 22 volcanic eruptions that are equal to or greater in magnitude than that of the May 18, 1980, eruption of Mount St. Helens (bulk volume equal to or greater than about 1-2 km³ of tephra) within about the last 13,000 years (table 3). The number of such eruptions is based on the available geologic record of tephra layers preserved in the vicinity and downwind of the major active volcanoes within the Cascade Range, and the magnitudes of such eruptions are estimated from the thickness of the tephra layers relative to the thickness of the May 18, 1980, layer at comparable distances. The chron-

Table 1.--Summary of eruptive history of Mount St. Helens
(from Mullineaux and Crandell, 1981)

d. dacite; a, andesite; b. basalt; , greater than

Eruptive periods or dormant intervals	Approximate age, years before 1950 ¹	Tephra unit		Other eruptive products ²
		Set	Layer	
Goat Rocks-----	150-100			Dome (d). Lava Flow (a).
Dormant interval of about 200 yr ³			T (d)	
Kalama-----	450-350			Pyroclastic flows (d). Dome (d). Pyroclastic flows (a). Lava flows (a).
		X (a)		
		W (d)		Pyroclastic flows (d).
Dormant interval of about 700 yr				
Sugar Bowl-----	1,150			Dome (d), pyroclastic flows (d). deposits of lateral blast (d).
Dormant interval of about 600 yr				
Castle Creek-----	2,200-1,700		Bu (b) Bi (d)	Lava flows (b). Pyroclastic flow (a), lava flow (a).
		B	Bo (a)	Lava flow (b). Pyroclastic flow (d)
			Bh (a)	Lava flow (a)
Dormant interval of about 300 yr				
Pine Creek-----	3,000-2,500	P (d)		Pyroclastic flow and domes (d).
Dormant interval of about 300 yr				
Smith Creek-----	4,000-3,300	Y (d)		Pyroclastic flows (d).
Dormant interval of 4,000 yr				
Swift Creek-----	13,000- 8,000	J (d)		Pyroclastic flows (d), and domes (d),
			S (d)	Pyroclastic flows (d).
Dormant interval of about 5,000 yr				
Cougar-----	20,000-18,000	K (d)		Pyroclastic flows (d), domes (d), and a few lava flows (d).
		M (d)		
				Pyroclastic flows (d).
Dormant interval of about 15,000 yr				
Ape Canyon-----	40,000(?) - 35,000	C (d)		Pyroclastic flows (d).

¹Ages of Goat Rocks and Kalama periods are in calendar years; ages of older periods are in radiocarbon years.

²Lahars were formed during many eruptive periods but are not included here.

³Dormant intervals are intervals during which no unequivocal eruptive products from Mount St. Helens have been recognized.

ology of these eruptions is derived from the stratigraphic relations (superposition) of the tephra layers, combined with other independent age evidence such as radiocarbon age determinations and dendrochronology (age estimates determined from tree-ring counts), as well as the historic record. Because the stratigraphic record of moderate-magnitude eruptions such as that of May 18, 1980, may have been obscured or destroyed by post-depositional erosion, and because geologic mapping within the Cascade Range is probably not so complete that all eruptions of this magnitude have been identified, we may underestimate the number of such eruptions during this period. Based on the geologic and historic record, the recurrence interval for eruptions greater or equal to about 1-2 km³ for the Cascade Range as a whole is between about 600 and 1100 yr (12-22 eruptions in 13,000 yr). Such calculations of recurrence interval are subject to considerable error not only because the stratigraphic record and field mapping in the Cascade Range may be incomplete, but also because we have difficulty in interpreting the stratigraphic record. For instance, the climactic eruption of Mount Mazama about 6800-7000 yr ago has been interpreted as one eruption by Williams (1942), but as at least six eruptions or pulses that produced several distinct downwind lobes, by Mullineaux and Wilcox (1980). Each of these latter inferred events was probably greater than that of the May 18, 1980, eruption of Mount St. Helens because the volume of tephra erupted from Mount Mazama was about 30 to 40 km³ (Williams and Goles, 1967) compared to only about 1 to 2 km³ from the May 18, 1980 eruption of Mount St. Helens. Another example that illustrates the difficulties in interpreting the stratigraphic record comes from studies of the pre-magmatic eruptions at Mount St. Helens during the spring of 1980 (Sarna-Wojcicki and others, 1981c). Multiple eruptions of volcanic ash were interspersed with snowfalls, resulting in a complex ash-snow layer stratigraphy. Thaw in early May telescoped the ash layers into an irregular, single layer. Such a layer would quite likely be interpreted as the result of a single eruption if found in the stratigraphic record.

Calculations of recurrence interval of eruptions of a given magnitude will also vary depending on the time interval that we are considering. The Cascade Range as a whole, and individual volcanoes such as Mount St. Helens in particular (Mullineaux and Crandell, 1981), appear to undergo periods of volcanic activity separated by periods of effective dormancy. By varying the length of time over which we attempt to estimate a recurrence interval, we vary the proportion between active and dormant periods and, consequently, the frequency of volcanic eruptions for a given period. Mount St. Helens alone has produced 15 to 17 eruptions equal to or greater than that of May 18, 1980 (greater than or equal to about 1-2 km³; tables 1-3) over about the last 35,000 to 40,000 yr. On this basis, we estimate that a moderate tephra eruption from Mount St. Helens occurred on an average of once every 2100 to 2700 yr. Based on this estimate, the probability that an equivalent or greater eruption would occur within any given year is between about 4×10^{-4} and 5×10^{-4} . This 35,000 to 40,000-yr period, however, includes long periods of dormancy, some as long as 15,000 yr--greater than the length of the entire Holocene epoch (table 1). If we consider the activity of Mount St. Helens over about the last 13,000 yr only, we estimate that between 9 and 11 Plinian eruptions greater or equal to about 1-2 km³ in volume have occurred within this period (tables 1-3), from which we calculate a recurrence interval of between about 1200 and 1400 yr, and an annual probability of between about 7×10^{-4} and 8×10^{-4} . If we consider, however, the activity of Mount St. Helens over about the last 500 yr only (four eruptions, represented by layers Wn, We, T, and that of May 18, 1980), the recurrence interval for eruptions of this

magnitude is only about 125 yr, and the probability of such an eruption occurring within one year is about 8×10^{-3} .

If it is difficult to estimate recurrence intervals of Plinian volcanic eruptions in the Cascade Range from the limited data base presently available, it is even more difficult to determine whether the Cascade Range as a whole is presently active, dormant, or in an intermediate state of activity. Furthermore, as Mullineaux (1976) has pointed out, in order to assess the future frequency of eruptions from the Cascade Range, as well as from individual volcanoes within the chain, it is also important to determine whether the Cascade Range and individual volcanoes within it are undergoing systematic evolutionary changes that can result in an increase or decrease of eruption frequency. It is not possible to make such an assessment for the Cascade Range as a whole on the basis of presently available data.

Mount St. Helens should be considered active in view of its frequent activity within the last several hundred years, and particularly in view of its continuing activity during 1980-82. Furthermore, from the recurrence intervals calculated from table 3 (see above), it would appear that Mount St. Helens is becoming more active with time. This apparent increase in activity in recent and historic time, however, may be an artifact of the stratigraphic record; ash layers from the younger eruptions of this volcano may be better preserved than those of the older eruptions. If this is the case, then the activity of Mount St. Helens during much of its history may have been greater than what we can infer from the stratigraphic record.

The recurrence interval for eruptions equal to or greater than that of layer Yn from Mount St. Helens (equal to or greater than about 3-6 km³) in the Cascade Range is difficult to estimate because such eruptions were few, and some ash layers can be interpreted as constituting one or more eruptions, as in the case of the Mount Mazama ash layer. For the Cascade Range as a whole, there have been between four and nine such eruptions within about the last 12,000 yr, depending on whether the Mazama ash layer is considered to have formed from one or six eruptions, and the magnitude of the eruption from Newberry volcano (table 3). This gives an average recurrence interval of between about 1200 and 3000 yr for an eruption of this magnitude, with probabilities of occurrence between about 3×10^{-4} and 8×10^{-4} per year. There has been only one eruption of this magnitude within about the last 3,500 yr from Mount St. Helens (the eruption producing layer Yn), and two within about the last 35,000 to 40,000 yr (the eruptions producing layers Yn and Cy; tables 1-3). On this basis, the recurrence interval for eruptions of this magnitude from Mount St. Helens is between about 3,500 and 20,000. Recurrence intervals and annual probabilities calculated from so few data are probably not very meaningful. Crandell and Mullineaux (1978) have estimated that an eruption equivalent to that which produced layer Yn occurs once every 2,000 to 3,000 yr, or an annual probability of between 3×10^{-4} and 5×10^{-4} .

The recurrence interval of tephra eruptions equivalent to that produced by Mount Mazama (about 30-40 km³ of bulk tephra) about 6800-7000 yr ago is not known because there was only one such eruption (or sequence of six eruptions) within the last 10,000-12,000 yr. If this eruption is considered as a single event, its recurrence interval may be between about 7000 and perhaps as much as 100,000 yr for both Crater Lake, Oregon, and the Cascade Range chain as a whole. The annual probability of such an event would then be between about 10^{-4} and 10^{-5} . Although the

Table 2.--Partial sequence of air-fall tephra deposits at Mount St. Helens
(from Mullineaux and Crandell, 1981)

Eruptive periods of dormant intervals	Tephra unit		Fe-Mg phenocrysts ¹	Other air-laid deposits (d) ² and soils (s)
	Set	Layer		
Goat Rocks		T	hy, hb, ag	
Dormant interval				
Kalama	X	We	hy, hb	
	W	Wn	hy, hb	
Dormant interval				s
Sugar Bowl ³				
Dormant interval				
Castle Creek	B	Bu	ol	
		Bi	hy, ag	
		Bo	ol, ag	
		Bh	hy, ag	
Dormant interval				d
Pine Creek		P	hy, hb	
Dormant interval				s d
Smith Creek	Y	Ye	cm, hb	
		Yn	cm, hb	
		Yb	cm, hb, bt	
Dormant interval				s
Swift Creek	J		hy, hb	
	S	So Sg	cm, hb, hy cm, hb, hy	d
Dormant interval				s d
Cougar		K	cm, hb	s d
	M	Mm Mp Mo	cm, hb, hy cm, hb, hy cm, hb, ol	
	Dormant interval			
Ape Canyon		C	cm, hb, bt	s d s d
		Cw	cm, hb, bt	s

¹Minerals used for identification of tephra units: ag, augite; bt, biotite; cm, cummingtonite; hb, hornblende; hy, hypersthene; ol, olivine.

²These fine-grained deposits are interbedded with tephra, but their origin has not been determined.

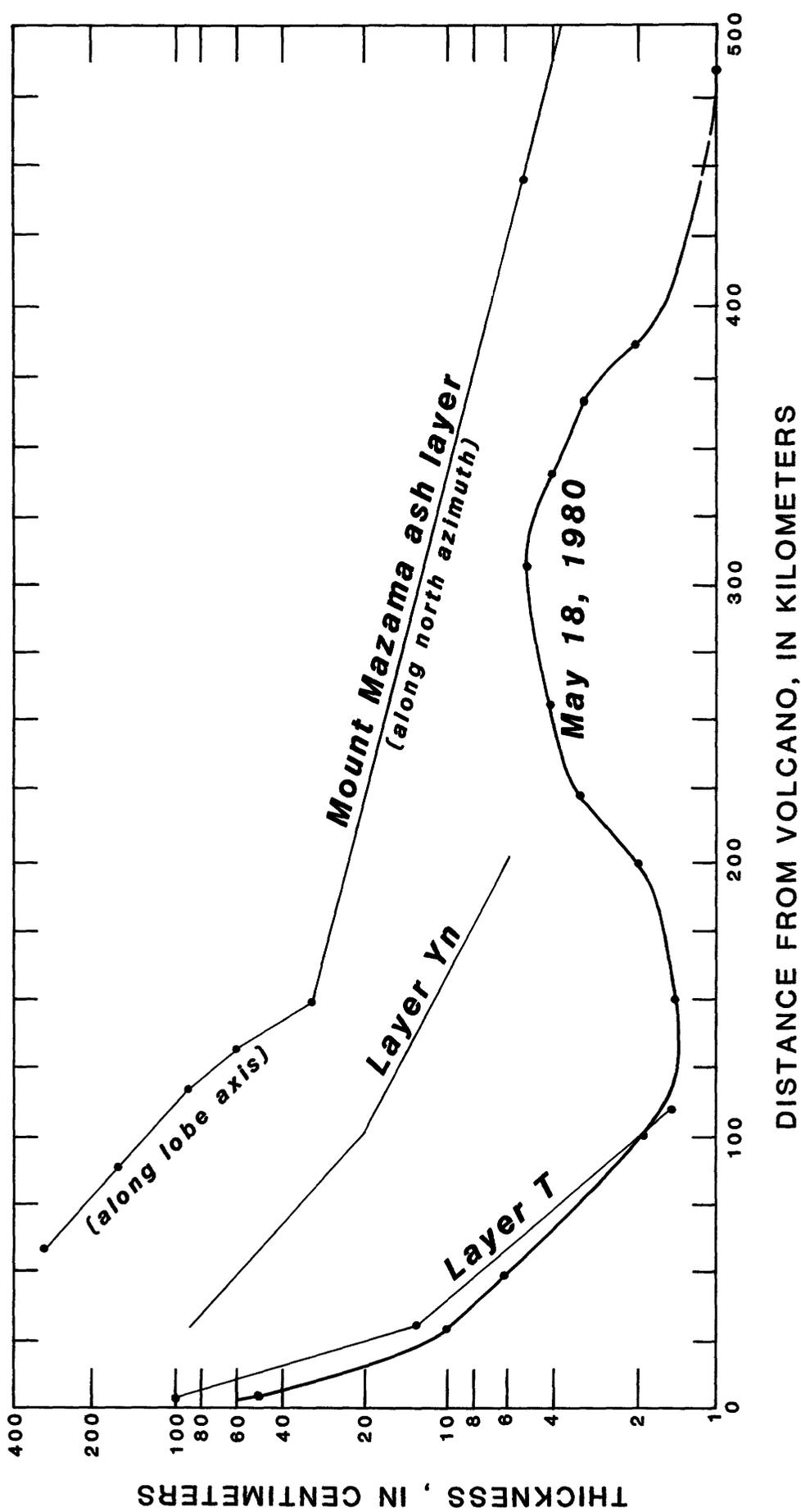
³Air-fall tephra deposits associated with the Sugar Bowl eruptive period have not been recognized.

Table 3. Estimate of the number of moderate and large Plinian volcanic eruptions of latest Pleistocene and Holocene age erupted from volcanoes in the Cascade Range, for calculations of average recurrence intervals. Moderate eruptions are defined as those equal to or greater in magnitude than that of May 18, 1980, from Mount St. Helens (equal to or greater than about 1 to 2 km³ of bulk tephra); large eruptions are defined as equal to or greater in magnitude than that which produced layer Yn of Mount St. Helens (equal to or greater than about 3 to 6 km³ of bulk tephra). High and low estimates are given for each category of eruption. Numbers on the right side of the table indicate the periods, in years, during which eruptions occurred from each of the four major volcanoes. Data for Mount St. Helens from Mullineaux and Crandell (1982); data for Glacier Peak from Porter (1978), and Beget (1982); data for Mount Mazama from Williams (1942), and Mullineaux and Wilcox (1980); data for Newberry Volcano from Sherrod and MacLeod (1979).

Tephra Layer	Moderate		Large		
	Low	High	Low	High	
Mount St. Helens					
May 18, 1980	1	1	0	0	
T	1	1	0	0	
We	1	1	0	0	
Wn	1	1	0	0	
					500 yr
p ¹	0	1	0	0	
P ¹	0	1	0	0	
Ye	1	1	0	0	
Yn	1	1	1	1	
J	1	1	0	0	
So	1	1	0	0	
Sg	1	1	0	0	
					13,000 yr
K	1	1	0	0	
Mm	1	1	0	0	
Mp	1	1	0	0	
Mo	1	1	0	0	
Cy	1	1	1	1	
Cw	1	1	0	0	
					35,000-40,000 yr
Glacier Peak					
x ²	0	1	0	0	
B	1	1	1	1	
M	0	1	0	0	
G	1	1	1	1	
					12,000 yr
Mount Mazama					
O	1	6	1	6	
					7,000 yr
Newberry Volcano					
Unnamed	1	1	0	1	
					1,500 yr

1 Two ash beds of set P exposed in Mount Rainier National Park (Mullineaux, 1974).

2 Tephra layer or layers of unknown extent erupted about 5,500 yr B.P. (Beget, 1982).



DISTANCE FROM VOLCANO, IN KILOMETERS

Figure 5--Thickness of ash with distance from the volcano for four tephra layers: the layer produced by the May 18, 1980, eruption of Mount St. Helens and layer T, erupted from Mount St. Helens about A. D. 1800 (both of moderate magnitude, with volumes of about 1-2 km³ of tephra); layer Yn of Mount St. Helens, erupted about 3,500 yr B. P. (about 3 to 6 km³ of tephra), and the Mount Mazama ash layer erupted from the Crater Lake, Ore., area about 6,800 to 7,000 yr B. P. (about 30-38 km³ of tephra). Data for layers T and Yn, from Crandell and Mullineaux, 1978; data for the layer produced by the May 18, 1980, eruption of Mount St. Helens, from Sarna-Wojcicki and others, 1981a; data for the Mount Mazama ash layer, from Williams and Goles, 1967.

probability of such an event is low, its effects would be quite severe and widespread (figs. 1, map sheet; Fig. 5).

The probability of tephra fallout at specific sites

The probability that a tephra layer of a specific thickness and mass per area is deposited at a specific site within a specific period depends on a large number of mutually-dependent and independent variables. In the most simple terms, this probability varies directly with eruption magnitude and frequency (or inversely with recurrence interval) for active and dormant vents within the region, directly with the proximity of these vents to the site, and directly with the probability that winds blow from the vents toward the site. Other factors such as eruptive column height, eruptive pulse pattern, explosivity of eruption, the actual wind velocity- and wind direction-distribution with altitude that exist at the time of the eruption, as well as the way these factors change with time, are all important. These latter factors, however, are much more difficult to assess because they interact in a complex way, and the number of possible conditions resulting from such interactions is large. Studies of historic eruptions are few and not sufficiently complete to evaluate relationships among the numerous factors.

We give several examples of rough estimates of the probability of tephra fallout at specific downwind sites in the following description of the activity of Mount St. Helens. For a thorough assessment of the probability of tephra fallout at a specific site, however, the probability of fallout from each geologically young volcano to the site should be calculated separately; from such calculations, a summary probability for the site can be derived. Under favorable circumstances, it may be possible to check such a calculation if a complete record of the depositional history at or near a site exists. Such sites are rare, and in most instances the best that can be hoped for is a minimal composite record of Plinian activity compiled from a number of localities near a site.

Brief descriptions of late Pleistocene and Holocene Plinian activity at specific volcanoes in the Cascade Range

Major tephra layers erupted from the major Cascade Range volcanoes are discussed below, under a heading for each volcano. The most explosive volcanoes are discussed first, after which we describe those that have produced moderate, small, or no tephra deposits as preserved in the geologic record.

Mount St. Helens

Mount St. Helens is a stratovolcano (a volcano composed of lava flows, tephra layers, and intruded domes) situated in southwestern Washington (fig. 1, map sheet). Explosive eruptions of tephra from this volcanic center, interspersed with quieter eruptions of andesitic and basaltic lava flows and emplacement of viscous, dacitic lava domes, have occurred sporadically for about the past 35,000 to 40,000 yr (Mullineaux and others, 1975; Mullineaux and Crandell, 1981). At least 19 tephra eruptions of different magnitudes have taken place at this volcano in about the past 4,500 yr (Crandell and Mullineaux, 1978). We estimate that between 9 and 11 tephra eruptions from Mount St. Helens in the past 13,000 yr have been equal to or greater than the May 18, 1980 eruption, and that 15 to 17 eruptions have been of this magnitude within the past 35,000 to 40,000 yr (tables 1-3). Mount St. Helens thus accounts for most of the Plinian eruptions within the Cascade Range during Holocene and latest Pleistocene time.

Of the tephra layers erupted from Mount St. Helens, those of 1980 are the best documented because tephra distribution, thickness, and mass per unit area were mapped within a few days after each eruption, before wind or rain significantly modified the deposits.

The most extensive tephra lobe of the 1980 eruptive sequence, that of May 18, extends east-northeastward in the direction of the prevailing wind (map sheet, figs. 1 and 6, see insert, fig. 1). Lobes from subsequent eruptions lie in virtually all directions from the volcano. Contrary to the general assumption that ash-fall thickness decreases systematically with increasing distance from the vent, distal thickness maxima have been documented for five of the six eruptions of 1980, a discovery which suggests that the distribution of prehistoric tephra units might follow the same pattern. Data for the July 22 eruption are sparse; a distal thickness maximum may have existed for this eruption but cannot be documented.

As a first step in an attempt to assess the thickness of tephra that might be deposited at specific sites in the Pacific Northwest from future eruptions of Mount St. Helens, we have drawn isolines of potential tephra thickness (fig. 7) as concentric circles around Mount St. Helens to indicate the thickness of tephra that might be deposited by an eruption equivalent in magnitude to that of May 18 under various wind directions, assuming wind velocities and probabilities of transport are the same regardless of direction. Thickness values assigned to the circles correspond to maximum measured thicknesses along the axis of the May 18 lobe at progressively greater distances from the volcano. Using this approach, the distal thickness maximum from the May 18 eruption near Ritzville (fig. 3) becomes a distal thickness ring with a maximum of about 40-50 mm at a radial distance of about 270-300 km (fig. 7). Under these conditions, Skagit, Satsop, Pebble Springs, and Hanford could receive between 20 and 40 mm (1-1.5 in.) of tephra and Humboldt Bay could receive between 2.5 and 5 mm (less than 0.25 in.) of air-fall ash. The Trojan site, closest to Mount St. Helens, could receive somewhat more than 50 mm (about 2 in.) of tephra from an eruption equivalent to that of May 18. In the unlikely event that the prevailing wind had been directed toward Trojan during all six eruptions of 1980, the site would have received between 50 and 80 mm (2.0-3.2 in.) of air-fall ash (fig. 8).

This analysis fails to take into consideration the prevailing wind distribution with altitude in the Pacific Northwest and variable wind velocities associated with wind directions. Crandell and Mullineaux (1978) have calculated the percentage of time that wind blows toward a given direction in western Washington (fig. 6, see insert, fig. 1, map sheet), and Mullineaux (1976) has calculated average wind velocities associated with these directions (fig. 9, see inset, fig. 1, map sheet). On the basis of these data, winds blow eastward of Mount St. Helens on an average 87 percent of the time. Winds blowing eastward also have greater velocities, on the average 66 km/hr, whereas westward winds average only 42 km/hr. These data indicate that tephra from any eruption of Mount St. Helens is more likely to be carried toward the east than toward the west, and that it is more likely to travel farther to the east than to the west. Tephra carried to the west of Mount St. Helens, however, will tend to be thicker closer to the volcano than tephra carried to the east, for eruptions of equivalent magnitude.

Mullineaux (1976) has estimated limits of ashfall-hazard zones from volcanic eruptions of a

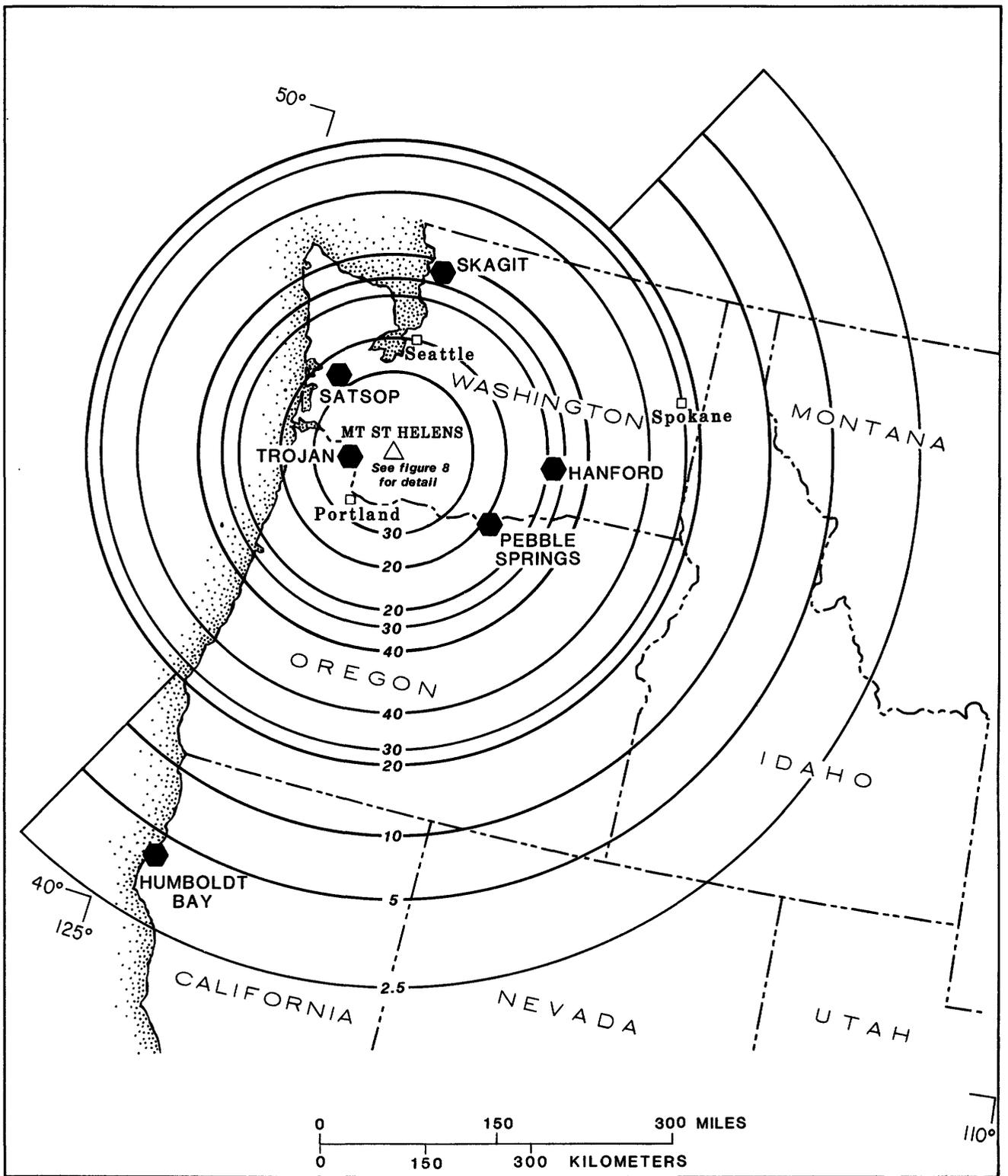


Figure 7--Potential thickness of air-fall tephra deposits in the northwestern United States from an eruption of Mount St. Helens equivalent to that of May 18, 1980, for all wind directions, assuming the same wind velocities as those of May 18. Thickness values for the zones (given in millimeters) are taken from maximum thicknesses along the axis of the May 18, 1980, lobe (fig. 3). Thicknesses shown by isolines do not take into consideration the probabilities of wind blowing in any given direction, nor the velocities of wind blowing in any given direction. Hexagons indicate nuclear-reactor sites. See text for further explanation. See figure 8 for detailed isopach map in the vicinity of Mount St. Helens.

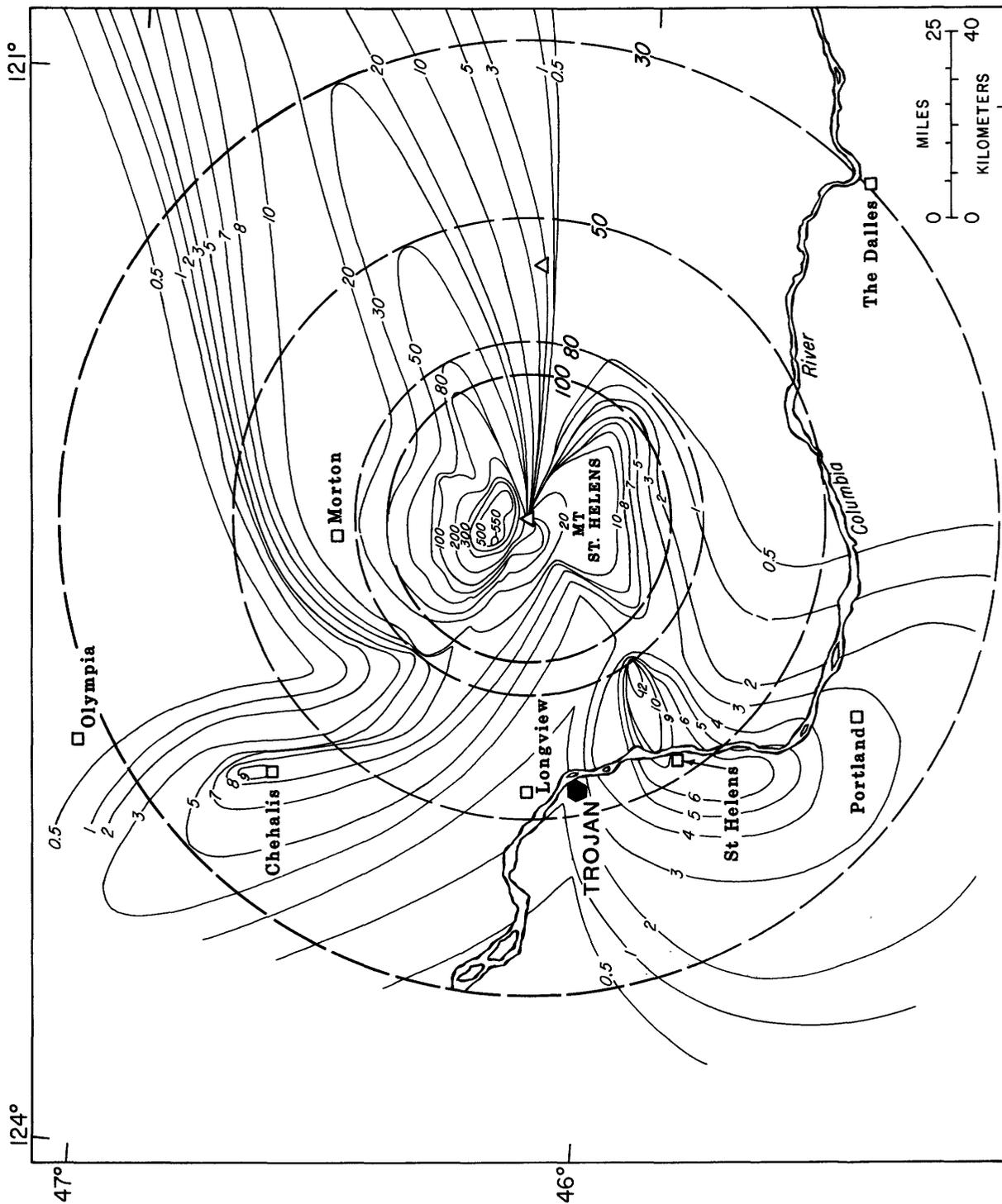


Figure 8--Total thickness of air-fall tephra deposited by the six major eruptions of Mount St. Helens in 1980 within about 100 km of the volcano. Solid contours represent ash thickness, in millimeters. Dashed circles enclose zones showing the estimated thickness (in millimeters) of air-fall tephra that might be deposited from an eruption equivalent to that of May 18, 1980, regardless of wind direction or associated wind velocities (see fig. 7). Hexagon indicates Trojan nuclear reactor site.

▲ **LARGE VOLCANO**--Built mostly by repeated eruptions at a central vent and probably active within the last 100,000 years. Eruptions range from quiet to explosive. Volcano flanks are subject to lava flows and to all other kinds of volcanic hazards.

● **VENT AREA**--Source of one or more extremely explosive and voluminous eruptions within the last 2 million years.

○ **AREAS SUBJECT TO SPECIFIC VOLCANIC HAZARDS**
 Lava flows--Areas of groups of volcanic vents termed "volcanic fields," in which geologically recent volcanic activity indicates that future eruptions, chiefly of lava flows and small volumes of ash, are more likely than in other nearby areas.

▬ **Volcanic ash and gases**--Limits of ashfall-hazard zones; these zones are subject to deposition of 5 cm or more of volcanic ash from eruptions of "moderate" to "very large" volume.

▬ **Zone A**--Area subject to 5 cm or more of ash from a "moderate" eruption, similar to the Mount St. Helens eruption about A.D. 1800. Also subject to deposition of about 1 cm from smaller eruptions similar to the Mount St. Helens eruption of A.D. 1842.

▬ **Zone B**--Area subject to 5 cm or more of ash from a "large" eruption, similar to the Mount St. Helens eruption about 3,400 years ago.

▬ **Zone C**--Area subject to 5 cm or more of ash from a "very large" eruption, similar to the Mount Mazama (Crater Lake) eruption about 6,600 years ago.

▨ **Sectors in zone A** downwind from relatively active and explosive volcanoes--Most ash (75-80 percent) from these volcanoes expected to fall within these areas.

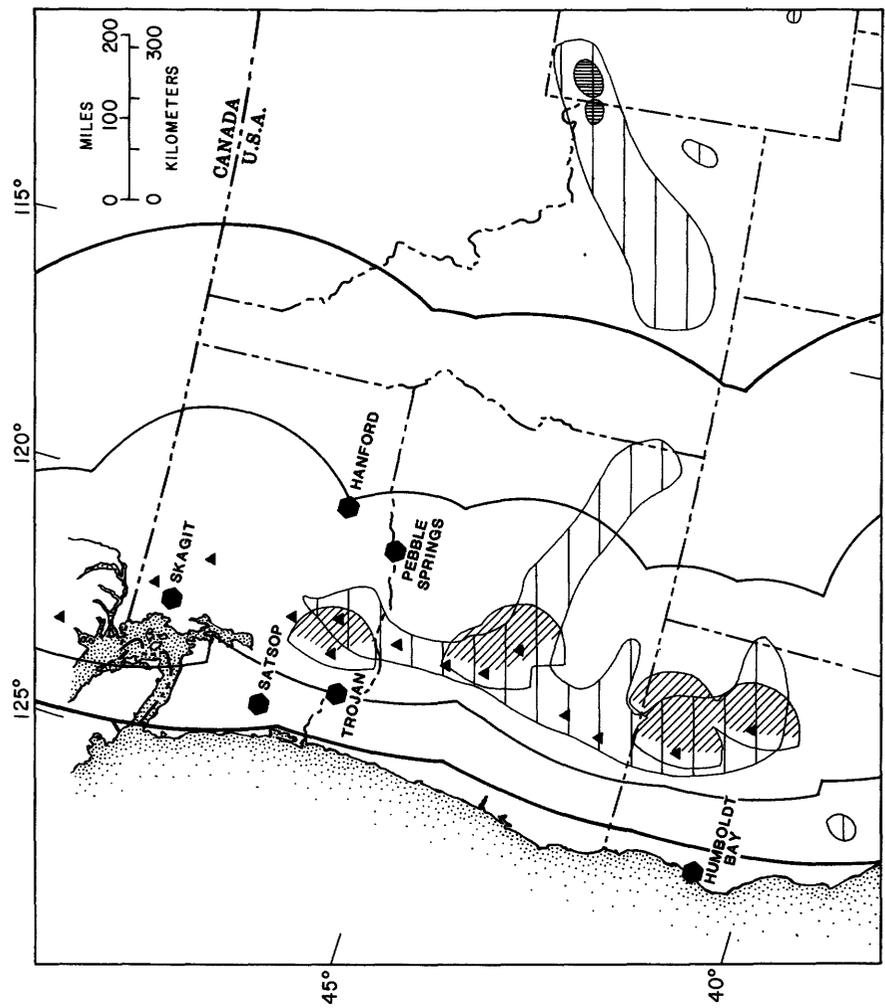


Figure 10--Sources of volcanic eruptions, and areas subject to volcanic hazards in the Pacific Northwest. Modified from northwest portion of Volcanic Hazards Map of Conterminous U.S. (Mullineaux, 1976).

range of magnitudes: those similar to the A.D. 1800 eruption of Mount St. Helens and, by our estimates, approximately equal to the May 18, 1980 eruption of Mount St. Helens, those similar to the eruption that produced layer Yn of Mount St. Helens about 3500 yr ago, and those similar to the Mount Mazama eruption from Crater Lake, Ore., about 6,800-7,000 yr ago (fig. 10). Because of the average prevailing wind distribution and associated velocities in the Pacific Northwest, as well as absence of thick tephra layers to the west of Mount St. Helens, Mullineaux (1976) has drawn boundaries of ashfall zones west of the Cascade Range vents at distances that are only 25 percent of the distances of the eastern boundaries (fig. 10). This is a valid approach in light of the prevailing wind conditions in this region.

Because average wind directions and associated velocities vary somewhat over the Pacific Northwest, we cannot predict, other than perhaps on a daily basis, what the actual path of an airborne ash plume may be. Furthermore, because only average wind conditions were considered by Mullineaux (1976) the boundaries shown in figure 10 do not necessarily define probable maximum expected thicknesses for the Pacific Northwest. In considering the safety of critical facilities such as nuclear reactors, we must attempt to define the maximum credible conditions as well as the average. Lastly, the 1980 sequence of eruptions of Mount St. Helens have shown us that (1) tephra distributions from volcanic eruptions can be quite complicated, and, because five of the six eruptions from this sequence formed one or more distal thickness maxima (Sarna-Wojcicki and others, 1981a), the formation of such maxima may be a relatively common phenomenon. Although distal thickness maxima have not been described for other Holocene tephra layers in the Pacific Northwest, such features may have been obscured by post-depositional erosion and deposition. Consequently, estimates of maximum thickness of ash layers as a function of distance from their volcanic vents may be underestimated for many pre-1980 ash layers. (2) Three of the six documented 1980 eruptions of Mount St. Helens had significant easterly components (May 25, June 12, and Oct. 16-18). This suggests that westward transport of tephra plumes in the Cascade Range is not as rare as previously supposed. If any of these three eruptions had been equal in magnitude to that of May 18, a significantly thicker layer of tephra than those deposited on May 25, June 12, and Oct. 16-18, would have been deposited west of Mount St. Helens. These observations suggest that relatively thick tephra layers can be deposited to the west of Mount St. Helens, although the probability of deposition is much smaller than that for sites east of the volcano.

Because of uncertainties in evaluating meteorological variables, we have not modified isolines in figures 7 and 8 to reflect predominant wind directions and wind velocities. It is important to note, however, that even the thickness estimates shown in figures 7 and 8 may not represent credible maxima for an ash layer produced by an eruption equivalent in magnitude to that of May 18, 1980. For example, for any given eruption, the slower westward winds will form thicker tephra layers closer to the volcano than the faster eastward winds, and westward winds may also form distal thickness maxima closer to the volcano than eastward winds, as was the case for the May 25, 1980 eruption of Mount St. Helens. Such considerations are particularly pertinent in assessing hazards of air-fall ash to the Trojan reactor. In general, for any eruption of a given magnitude (volume), the faster the wind velocity, the greater the area covered, and the thinner the ash blanket. Conversely, the slower the wind, the smaller the area covered, and the thicker the ash with proximity to the vent. The wind patterns in the Pacific Northwest can

also be complex because of wind shear--winds blowing in different directions at different altitudes. In general, the greater the wind shear, the broader the area covered and the thinner the ash blanket, and, conversely, the smaller the wind shear, the narrower and straighter the ash lobe, and the thicker the ash blanket. Like the wind patterns, patterns of tephra distribution and thickness can be quite complicated. For future eruptions of Mount St. Helens (or those of any other volcano in the Pacific Northwest), prediction of the actual thickness that may be deposited at any location from an eruption of any given magnitude must await further detailed analysis of the 1980 eruption sequence and correlation of distribution patterns with analysis of eruption pulse pattern, tephra grain-size distribution, particle fall velocities, and meteorological conditions existing during the eruption. In view of the large number of variables affecting tephra distribution and the large uncertainties involved in evaluating such variables, we feel that there is a correspondingly large margin of error in predicting the thickness of ash that may be deposited at any particular reactor site from a volcanic eruption.

Mass of tephra per unit area deposited from the May 18, 1980, eruption of Mount St. Helens

Mass of tephra per unit area has been mapped for the May 18 eruption (fig. 11) and subsequent eruptions of Mount St. Helens (Sarna-Wojcicki and others, 1981a). As with isopach data, we have drawn circles around Mount St. Helens to indicate zones in which specified amounts of tephra might be deposited at any reactor site if an eruption equivalent to that of May 18, 1980 were to occur, again ignoring the prevailing wind directions and associated velocities for reasons mentioned above. In this estimate, Skagit would receive between 2 and 2.5 g/cm² (20-25 kg/m²), Hanford and Satsop, between 1.4 and 2 g/cm² (14-20 kg/m²), Pebble Springs, about 1.4 g/cm² (14 kg/m²), and Trojan, about 5 g/cm² (50 kg/m²). Using isomass data for all 1980 eruptions (Sarna-Wojcicki and others, 1981a), we estimate that a total of about 7.2 g/cm² (72 kg/m²) would have fallen at the Trojan site if winds were blowing uniformly to the west. The same cautions apply to this estimate as to that of thickness because of the difficulty in assessing the complex meteorological and volcanological variables.

Post-May 18, 1980, air-fall ash layers from Mount St. Helens

Only in the vicinity of the volcano are post-May 18 air-fall deposits thick enough to be recognized as discrete layers. The July 22, August 7, and October 16-18 tephra near the volcano area consists predominantly of scattered coarse pumice. These deposits cannot be easily distinguished from each other, but they can be mapped as a unit where they locally lie on finer grained ash and lapilli of May 25 and June 12. Because small volumes of tephra were ejected during post-May 18 eruptions, the deposits in proximal areas probably will be preserved in the geologic record as a single coarse layer atop the uppermost fine grained deposit of May 18. At distal sites, ash layers of the post-May 18 eruptions will probably not be preserved. It is likely that many of the major prehistoric eruptions of Cascade Range volcanoes occurred during eruptive episodes which included multiple smaller eruptions similar to those of 1980 from Mount St. Helens.

Rate of accumulation of tephra from the 1980 eruptions of Mount St. Helens

Little is known of rates of accumulation from the 1980 eruptions of Mount St. Helens. Hooper (1980) noted that between 1.00 and 1.25 cm were deposited at

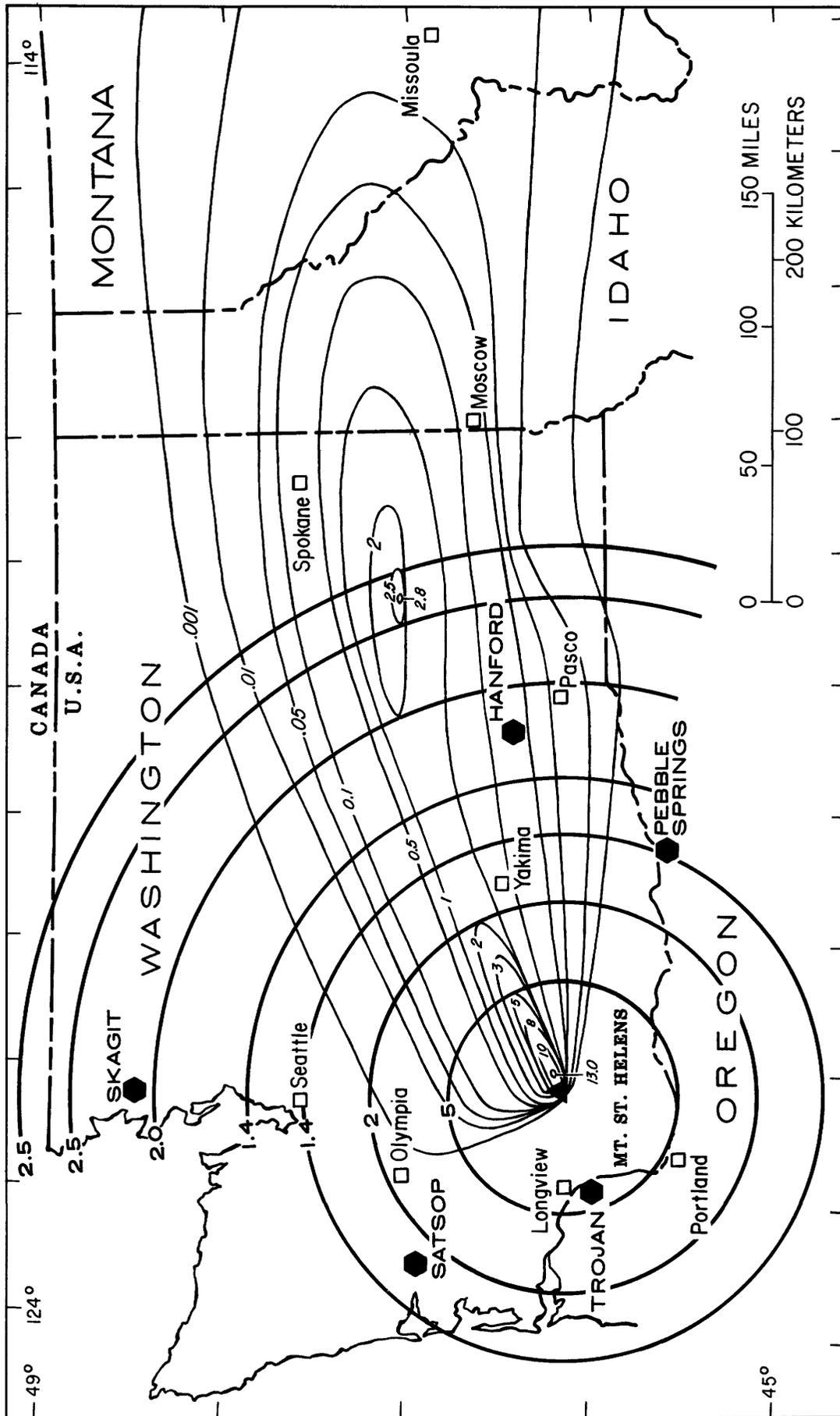


Figure 11--Isomass (mass per unit area) map of air-fall tephra erupted from Mount St. Helens on May 18, 1980. Isolines represent mass of tephra in grams per square centimeter. Dashed circles and arcs represent mass of tephra that could be deposited from a May 18-equivalent eruption, regardless of wind direction. Average annual wind directions and average velocities associated with wind directions are not taken into consideration. Hexagons indicate planned or existing nuclear-reactor sites. Modified from Sarna-Wojcicki and others (1981a).

Pullman, in eastern Washington, and at Moscow, Idaho over a period of about 12 hr, from the May 18, 1980, eruption. Unpublished data from Coeur d'Alene, Idaho (Steven L. Levine, written commun., 1980) suggests that much of the mass of ash was deposited during the first hour of fall, although ash fell for a period of about 8 hours. Beaulieu and Peterson (1981) report that on May 18, 1980, 4.5 cm of ash were deposited at a rate of 1.3 cm per hour at Packwood, Washington, at a distance of about 50 km from the volcano.

Prehistoric tephra eruptions of Mount St. Helens

Mullineaux and others (1975), and Mullineaux and Crandell (1981) have identified eight major tephra sets erupted from Mount St. Helens over the past 37,500 - 40,000 yr, before the eruptions of 1980. The minimum extents of sets Y (about 4000-3300 yr. B.P.) and W (about 1150-450 yr. B. P.) have been mapped (fig. 1, map sheet; Mullineaux and others, 1975). Tephra layers distinguished within the older sets (for example, layers Yn and Ye of set Y of Mullineaux and others) may be multiple eruptions from an eruptive episode of short duration such as that of 1980. Within a number of sets, however, incipient soil development between some of the layers indicate periods of minimal or no volcanic activity between eruptions within an episode (D. R. Mullineaux, oral commun., 1981).

The long, narrow lobes of each layer of sets W and Y suggest that wind directions were generally constant during the eruptions. Although only sparse thickness data are available, it is likely that the lobes had diffuse margins and were asymmetrical relative to their axes of maximum thickness, similar to the lobes of the 1980 eruptions. Smith, Okazaki, and Knowles (fig. 1, map sheet; 1977) reported layer We to be 1 cm (about 0.4 in.) thick in a bog in Idaho. This thickness may be somewhat greater than the original air-fall thickness if tephra was eroded from adjacent terrain and redeposited in the bog. It does indicate that layer We is probably of greater extent than is shown in figure 1 (map sheet). Spot thickness data for several tephra sets for which the areal extent is not well determined are shown in figure 1 (map sheet) to indicate minimum distributions and thicknesses. Set J (erupted between 8,000 and 12,000 yr B.P., Mullineaux and others, 1975) is 1 m (3.3 ft) thick 10 km to the southeast and 20 cm (8 in.) thick 40 km southeast of Mount St. Helens (Mullineaux and others, 1975). Set T, erupted about 1800 A.D. (Crandell and Mullineaux, 1978), has been identified to the northeast of the volcano where it is 1 cm (about 0.4 in.) thick southeast of Wenatchee, Wash. (fig 1, map sheet; Okazaki and others, 1972);. Set S, erupted about 13,000 yr B.P. (Mullineaux and others, 1978), has been identified in all directions from the volcano, although it lies predominately to the east-northeast (Mullineaux and others, 1975).

Estimates of air-fall ash thicknesses at specific sites from an eruption of Mount St Helens equivalent to the eruption that produced layer Yn

Tephra layer Yn is the thickest Holocene layer erupted from Mount St. Helens, and probably represents the largest eruption from the volcano in Holocene time. Layer Cy, erupted from Mount St. Helens between about 35,000 to 40,000 yr ago, was as thick or thicker, and consequently may have been produced by a greater eruption than that which produced layer Yn. Figure 5 shows the thickness of layer Yn with distance from the volcano. The average annual velocity of winds blowing from Mount St. Helens toward Hanford (69-70 km/hr) and the Pebble Springs site (67 km/hr) (fig. 9, see inset, fig. 1, map sheet) is about the same as that (66 km/hr) which blows in the direction towards which layer Yn was carried (north-northeast). If we assume that the average wind

velocity that transported tephra of layer Yn was about the same as the current average annual velocity (66 km/hr) towards the north-northeast, then, using the thickness data in figure 5, we estimate that the Pebble Springs and Hanford sites would receive 10 and 5 cm, respectively, from an eruption of equivalent magnitude, if the wind were directed directly from the volcano to these sites. At the present time we cannot estimate potential thicknesses from a Yn-equivalent eruption for the Trojan, Satsop, and Skagit sites because of the much slower average wind velocities from Mount St. Helens toward the western sector. It is conceivable that the Trojan site could receive less, as much, or more, than the 45 cm (17.7 in.)-thickness that is observed for layer Yn at 60 km distance from Mount St. Helens (equivalent to the distance between Mount St. Helens and the Trojan site; figs. 7, 8). Estimates of air-fall ash thickness for these sites must await further studies that consider grain size, grain settling velocities, as well as meteorological variables such as variable average wind velocities with azimuth.

Calculation of probability of tephra fallout at specific sites from future eruptions of Mount St. Helens

A rough estimate of the annual probability that a specific thickness of ash will fall from a moderate eruption (equivalent to that of May 18, 1980), a large eruption (equivalent to that which produced layer Yn), and a very large eruption (equivalent to the Mount Mazama eruption) from Mount St. Helens can be made for the Pebble Springs and Hanford sites using estimated recurrence intervals for each category of eruption, the downwind ash thickness for each category of eruption (fig. 5), and the percentage of time annually that winds blow from Mount St. Helens toward the sites (fig. 6, see inset, fig. 1, map sheet). Such estimates can be made for these sites because they lie within the sectors of prevailing wind directions from Mount St. Helens towards the sites, and because in the three examples of eruptions of varying magnitude which we use in these estimates, tephra was also transported towards these sectors. Wind velocities that existed at the time of these three eruptions were probably similar to modern average annual wind velocities toward the same directions. Such estimates cannot be made at this time for sites west of Mount St. Helens because we do not know what the thickness profile of tephra lobes would be as a consequence of the much slower westward winds.

As an example of such a probability calculation let us consider the Hanford reactor site, and a moderate eruption under conditions identical to those that existed on May 18, 1980, except that the axis of the ash lobe is directed toward Hanford rather than north of this site. We calculate a recurrence interval of about 125 yr for an eruption of this or greater magnitude (see above). The reactor site is situated in a sector toward which wind blows on an average 16 percent of the time (fig. 6, see inset, fig. 1, map sheet). The probability that the thickest part of the tephra lobe falls directly atop the site is about $1/8 \times 16/100$, because the width of the thickest part of the lobe at that distance is only about one-eighth the width of the sector. The thickness of the ash layer in the axial region of the lobe from an eruption of this magnitude at the distance of Hanford from Mount St. Helens (about 210 km) would be between about 2 and 3 cm (figs. 3, 5). Thus, the annual probability that 2 to 3 cm of ash or more are deposited at Hanford from an eruption of this magnitude or greater is $1/125 \times 16/100 \times 1/8$, or about 1.6×10^{-4} . The annual probability that about 0.5 cm or more is deposited at the same site is higher, $1/125 \times 16/100$, or about 1.2×10^{-3} , because the tephra lobe between these isopachs is wider and encompasses most

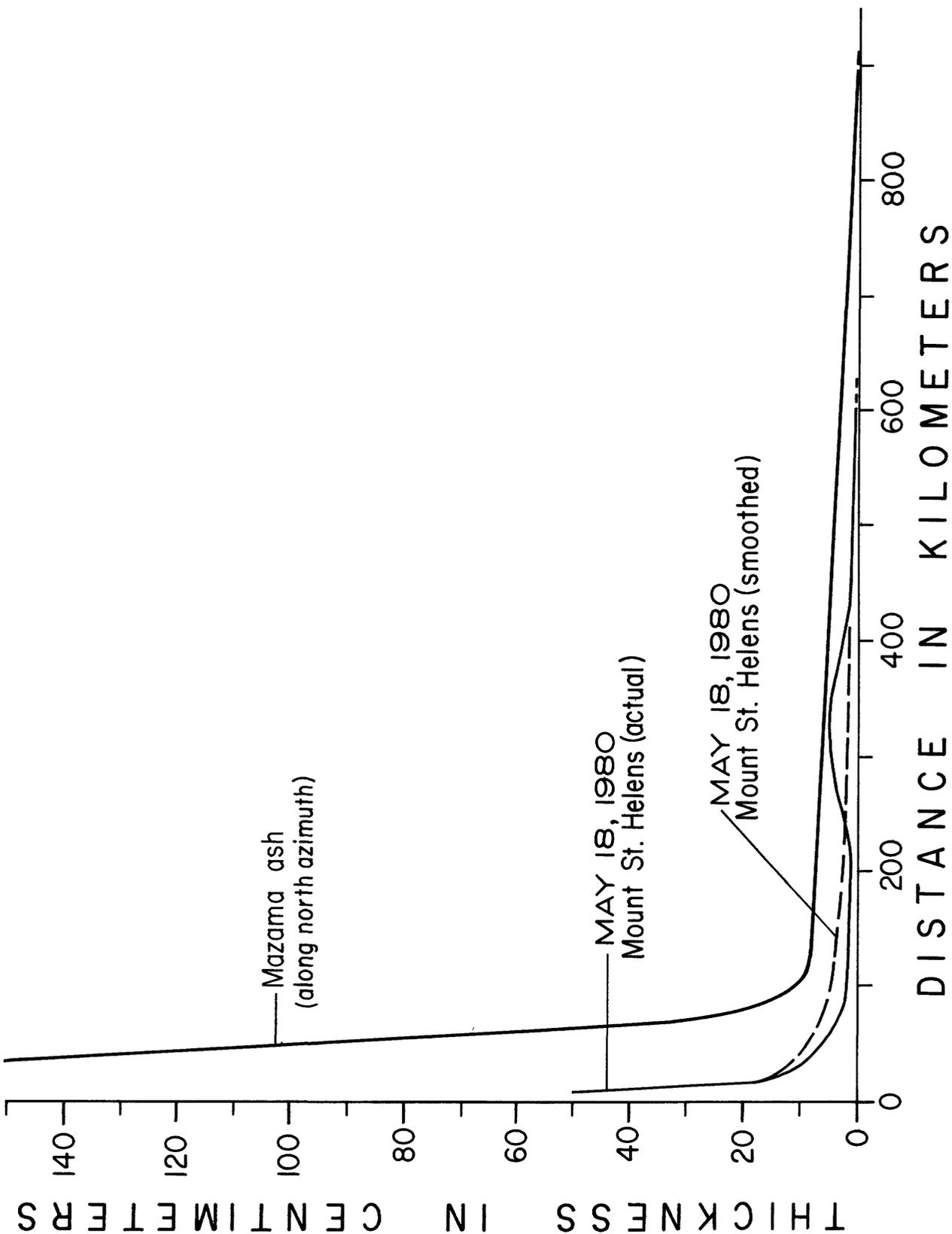


Figure 12--Comparison of the downwind profiles of the Mount Mazama ash, erupted at Crater Lake, Ore., and the ash erupted on May 18, 1980, from Mount St. Helens. The dashed line represents the smoothed profile of the May 18, 1980 layer, drawn so that approximately the same cross-sectional area of the downwind lobe axis is maintained. The profile for the Mount Mazama ash is drawn along a north azimuth (data from Williams and Goles, 1967. Data for the ash erupted on May 18, 1980, is from Sarna-Wojcicki and others, 1981a).

of the sector at that distance. If we "smoothed" the profile of the downwind ash lobe of the May 18, 1980, ash layer, eliminating the distal thickness maximum near Ritzville, Wash. (fig. 12), sites closer to the volcano than Ritzville, such as Hanford, would receive a thicker deposit of ash. Similarly, if winds blowing toward Hanford during such an eruption were slower, then the distal thickness maximum might fall at or closer to Hanford, again with a resultant thicker ash layer than that calculated here.

Crandell and Mullineaux (1978) suggest that a large eruption of Mount St. Helens, equivalent to that which produced layer Yn, may occur about once every 2000 to 3000 yr. Using this recurrence interval and the same annual wind probabilities as above, we calculate an annual probability of 10^{-5} ($1/2000 \times 16/100 \times 1/8$) to deposit a tephra layer 5 to 6 cm thick (thickness from figure 5) at Hanford. Should a very large eruption, equivalent in magnitude to that produced by Mount Mazama, take place at Mount St. Helens, the annual probability that about 20 to 25 cm (thickness from fig. 5) are deposited at Hanford is between about 2×10^{-5} and 2×10^{-6} ($1/7000$ to $1/100,000 \times 16/100$). We dropped the last term, $1/8$, in this calculation because the lobe for such a large eruption would probably cover a much wider sector than that of smaller eruptions. For instance, the ash lobe from the Mount Mazama eruption is 65 km wide and 15-30 cm thick at a distance of about 140 km downwind from Crater Lake, the site of the eruptive vent.

The above calculations are offered as examples only. They do not necessarily represent minimum, maximum, or average thicknesses and probabilities for each category of eruption, not only because of the uncertainties in assessing meteorological variables, but also because it is difficult to relate thicknesses measured or inferred from the stratigraphic record to actual thicknesses of ash layers that may fall from eruptions of different magnitudes. For example, Crandell and Mullineaux (1978) caution that original thicknesses of ash layers T and Yn of Mount St. Helens may have been as much as twice the thicknesses measured in the field.

Crater Lake

Crater Lake, in southern Oregon (fig. 1, map sheet), is a truncated stratovolcano, the former Mount Mazama of Williams (1942), whose eruptive history began at least 7000 yr B.P. and continued until 800 yr B.P. (Williams, 1942). Mazama ash, the most extensive and voluminous Holocene tephra deposit erupted from Cascade Range volcanoes known to date, has been identified from Saskatchewan, Canada to central California (fig. 1, map sheet; R. E. Wilcox, written commun., 1981; Adam, 1967; Williams and Goles, 1967). Estimates of total volume of air-fall tephra are 30 to 38 km³, (Williams and Goles, 1967). Six tephra layers of the Mazama ash have been identified by Wilcox and Mullineaux (1980), and as many as four discrete lobes (R. E. Wilcox, written commun., 1981).

Isopach data are available for the proximal area (fig. 13) where coarse deposits have been preserved (Williams, 1942). Beyond the 15-cm (6-in.) contour, thickness data are sparse and highly variable (Williams, 1942; R. E. Wilcox, oral commun, 1981). From pollen studies, Mehringer and others (1977) suggest that 7.3 cm (about 3 in.) of Mazama ash fell intermittently over a period of 3 yr in western Montana. Their study was based on measurements of an ash layer in a bog, however, and this layer may include locally reworked tephra. The six tephra lobes identified by Wilcox and Mullineaux (1980) may correspond to at least 6 major eruptions. Mazama air-fall ash mapped within Mount Rainier National Park by Mullineaux (1974) occurs as a layer of irregular

thickness ranging from 1-5 cm (0.4-2 in.). Profiles showing attenuation of thickness of Mazama ash with distance from Crater Lake along a north azimuth are shown in figures 5 and 12. Predominant wind directions in the southern Cascade Range that would affect tephra distribution from eruptions of Crater Lake, Ore., as well as from Mount Shasta, Medicine Lake Highland, and Mount Lassen, Calif., are generally similar to those in the northern Cascade Range, although somewhat more northeastward (fig. 14, see inset, fig. 1, map sheet).

Glacier Peak

Glacier Peak, situated in northwestern Washington (fig. 1, map sheet), is a stratovolcano that has produced extensive tephra deposits in latest Pleistocene time, during a period between 12,750 and 11,250 yr B.P. (Porter, 1978). Nine Glacier Peak tephra layers have been identified by Porter (1978) to the east and southeast of the volcano; he has mapped the inferred extent of three principal layers (G, M, and B). Layer G extends east, layer B, east-southeast, and layer M to the south-southeast. Porter also has mapped other minor tephra layers that extend as far as 50 km from the volcano. According to Beget (1982), Glacier Peak has been active at least five times in the past 1800 yr, and nine times in the past 5500 yr; eruptions producing tephra layers of unknown extent occurred about 5500 yr. B.P. Although most of the major tephra-producing volcanism occurred before Holocene time, we include the available areal distribution and thickness data for this volcano because it may be dormant, with long intervals between eruptions.

Mount Rainier

Mount Rainier, the largest stratovolcano in the Cascade Range, is located in west-central Washington (fig. 1, map sheet). It has been active intermittently during the past 10,000 yr (Mullineaux, 1974); the last known eruption occurred in the early 19th century. Mullineaux has identified eleven tephra layers erupted from Mount Rainier, eight of which were erupted between 6,500 and 4,000 yr B.P. The most voluminous ash-fall was erupted between 2,500 and 2,000 yr B.P.

The minimum extent of the eleven tephra layers mapped by Mullineaux (1974) lies primarily within a quadrant northeast to southeast of the volcano (fig. 1, map sheet). The inferred distal margin of the mapped lobe has been shown beyond the actual mapped boundaries to indicate minimum known extent. Tephra deposits from Mount Rainier have been poorly preserved beyond the Mount Rainier National Park boundaries. Several layers, however, occur as narrow lobes that extend several kilometers beyond the park. Mullineaux (1974) has estimated uncompacted volumes of each layer. The estimated total volume within the area of known distribution (fig. 1, map sheet) is about 5.1×10^8 m³. Individual isopach maps of four of the major tephra layers within the area of known distribution have been combined into a minimum total isopach map (fig. 15). Based on volume estimates by Mullineaux (1974), the estimated uncompacted volume of these four layers is 4.5×10^8 m³.

Newberry volcano

Newberry volcano, located in central Oregon, is a shield volcano (a volcano composed of lava flows) with a 6-km-wide summit caldera (volcanic basin formed by subsidence of the volcano). Its most recent eruption occurred 1,350 to 1,550 yr B.P. and produced a narrow tephra lobe that extends east of the volcano (fig. 1, map sheet, Sherrod and MacLeod, 1979). The distribution of the tephra beyond the 25-cm contour

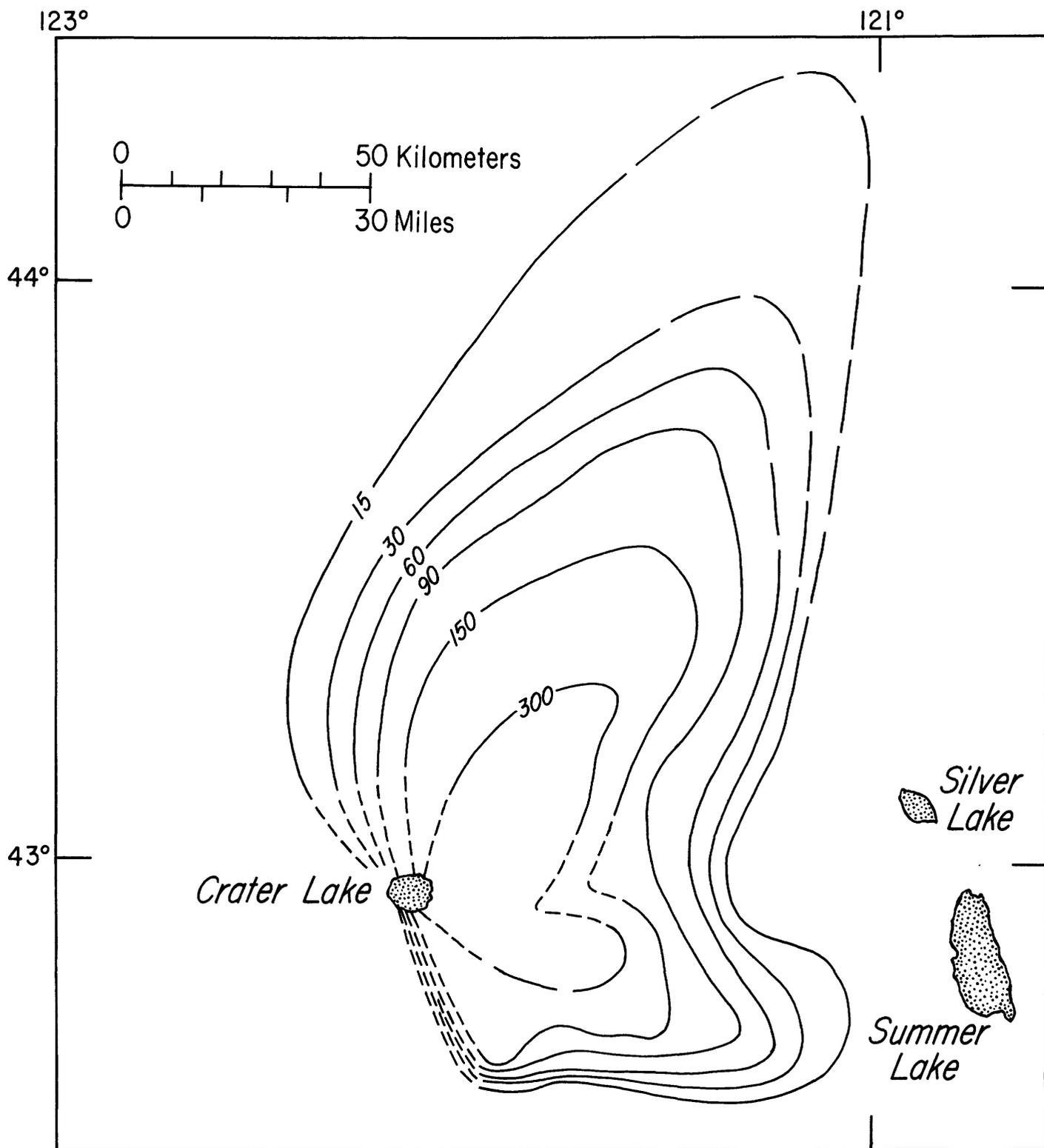


Figure 13--Thickness of air-fall tephra erupted from Mount Mazama (Crater Lake, Ore.) about 7000 yr B.P. Isopachs represent compacted thickness, in centimeters; dashed where inferred. Modified from Williams (1942, p. 70). See figure 1 (map sheet) or location.

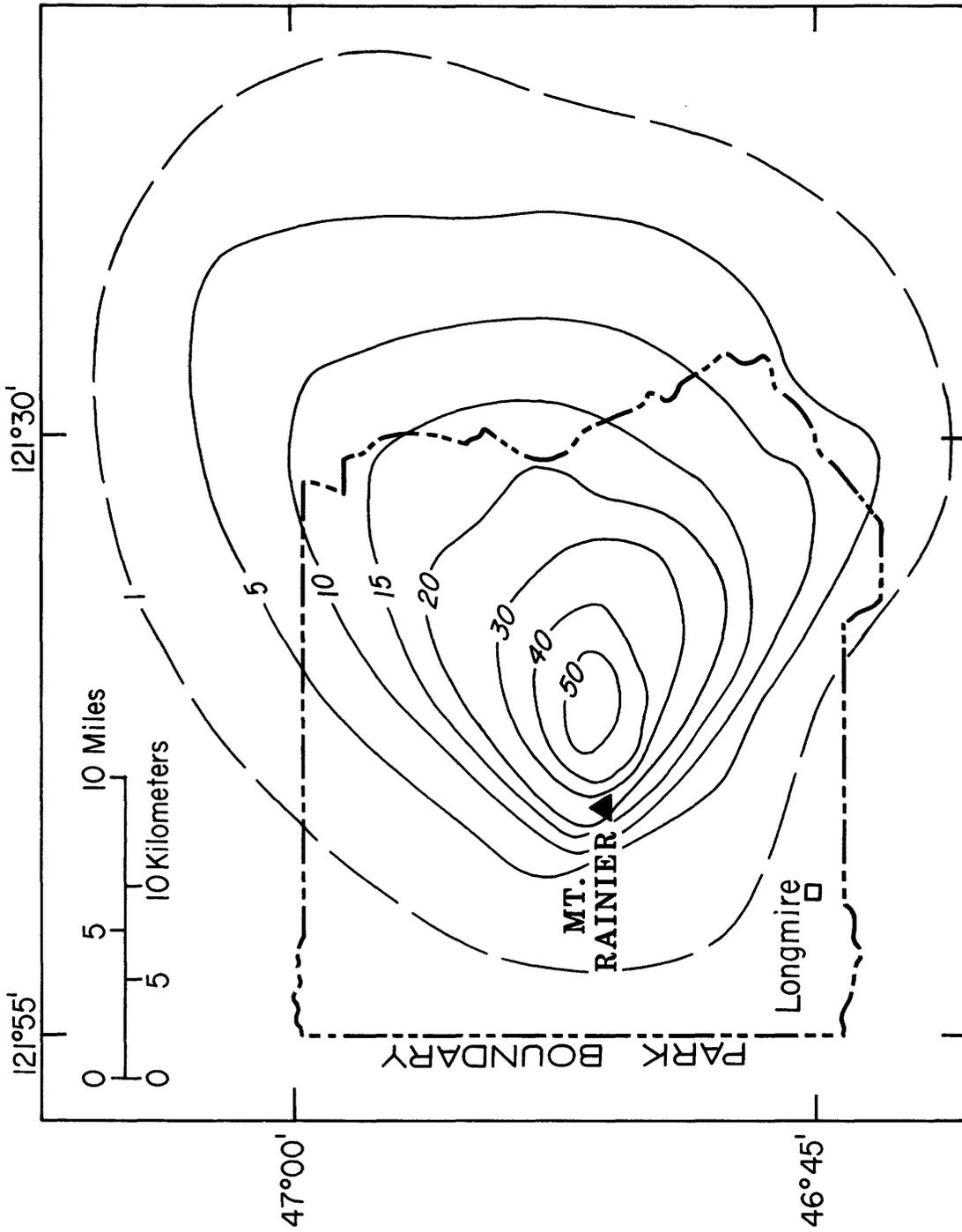


Figure 15--Total thickness of four air-fall tephra layers from Mount Rainier (about 8750-2200 yr B.P.). Isopachs show compacted thickness, in centimeters; lines dashed where inferred. Isopach data for individual layers from Mullineux (1974). See figure 1 (map sheet) for location.

has not been studied but the ash probably extends many tens of kilometers farther, and probably represents an eruption of large magnitude. Older tephra deposits from Newberry volcano, particularly those of about 6,000 yr B.P., are thick on the northeastern, eastern, and southeastern flanks of the volcano, but their regional distribution has not been investigated. The volcano has been active for at least 700,000 yr (N. S. MacLeod, written commun., 1981).

Mount Shasta

Mount Shasta is a stratovolcano situated in northern California (fig. 1, map sheet) that has erupted on the average at least once every 800 yr over the last 10,000 yr, and about once every 600 yr over the last 4,500 yr (Miller, 1980). Its last known eruption occurred about 200 yr B.P. The eruption of tephra that extends beyond the volcano, however, has been minor. The known tephra deposits extend east of the volcano in the direction of modern prevailing winds (figs. 1, 14, see inset, fig. 1, map sheet). The lobe represents the Red Banks tephra, the most extensive known air-fall deposit from Mount Shasta, erupted between about 9,600 and 9,700 yr B.P. (Miller, 1980). Thicknesses within this area range from 65 cm (about 26 in.) 7 km east-southeast of the volcano to 8 cm (3.2 in.) 15 km to the northeast. A 2-cm (0.8 in.)-thick layer of tephra tentatively identified as Red Banks is located 77 km northeast of Mount Shasta (fig. 1, map sheet). Miller (1980) estimates the minimum volume of this deposit within the mapped area to be about 0.1 km³. Geologic evidence suggests that moderate or major eruptions of tephra from Mount Shasta have occurred very infrequently, if at all.

Mount Baker

Mount Baker, a stratovolcano in northern Washington, has erupted small volumes of tephra at least 4 times over the past 10,000 yr (Hyde and Crandell, 1978). The dashed circle around the volcano in figure 1 (map sheet) indicates a zone of potential 5-cm (2-in.) thickness of airfall tephra deposit. The zone has been defined using sparse thickness measurements made east of the mountain; no tephra has been recognized to the west.

Fourteen kilometers northeast of the volcano, a tephra layer 1-2 cm (0.4-0.8 in.) thick has been tentatively identified as the oldest tephra layer, erupted about 10,350 yr B.P. (Hyde and Crandell, 1978). The next younger layer is more than 3 cm (1.2 in.) thick 6 km to the northeast. The second youngest layer, erupted between 6,600 and 500 yr B.P., is the thickest and most extensive deposit. It also extends to the northeast, where it is 0.5 m (23 in.) thick 10.5 km from the summit. Hyde and Crandell (1978) estimate the volume of this layer to be 0.1-0.2 km³. The youngest layer, probably only a few centuries old, is 1-3 cm (0.4-1.2 in.) thick east of Mount Baker.

Medicine Lake Highland

Medicine Lake Highland is a shield volcano in northern California characterized by a summit caldera flanked by two major volcanic vents. Two small layers of tephra (fig. 1, map sheet) were erupted from the vicinity of Medicine Lake caldera in Holocene time (Heiken, 1978). One eruption or series of eruptions was from Glass Mountain (fig. 1, map sheet), situated on the east rim of the caldera. Measurable thicknesses of tephra were deposited east-northeast of the volcano over an area of about 320 km². Total estimated volume of this deposit is 0.09 km³. The other eruption or series of eruptions was from Little Glass Mountain (fig. 1), situated about 4 km to the west-southwest of the caldera rim. Tephra from this eruption was deposited to the west-southwest over an

area of about 200 km² (an estimated volume of about 0.04 km³), and pumice lapilli from this eruption were found as far as 50 km from the vent, on the flanks of Mount Shasta (Heiken, 1978).

The age of these eruptions is about 1100 yr B.P., as determined by radiocarbon analyses on tree trunks buried by the tephra (Heiken, 1978).

Lassen Peak

Lassen Peak is one of several eruptive centers located within Lassen Volcanic National Park (fig. 1, map sheet). Two of these centers, Lassen Peak and the Chaos Crags, have produced obvious tephra deposits. The centers are single and multiple volcanic domes, respectively, formed by intrusion and accompanied by the extrusion of lava.

Emplacement of the Lassen Peak dome about 11,000 yr B.P. (Crandell, 1972) evidently was not accompanied by the production of tephra (Williams, 1932). The principal tephra deposit derived from Lassen Peak was erupted during the 1914-17 eruptive episode. Mapping is incomplete, but there is evidence of at least 2 explosive eruptions in 1915. The bulk of the tephra was deposited east of the volcano; minor deposits are found to the south.

The eruptive episode during the extrusion of the Chaos Crags domes occurred between 1000-1200 yr B.P. (Crandell and others, 1974). Tephra eruptions during this period may have been as frequent as one every several decades. The deposit is more than 2 m (about 6.5 ft) thick at the north base of Lassen Peak, but generally trends to the northeast where it is 0.3-0.6 m (1-2 ft) thick 3.5 km east of the Chaos Crags and as much as 1 cm (0.4 in.) 19 km to the northeast. Only traces of the deposit have been recognized 4 km west of the Chaos Crags.

The Three Sisters

The eruptive history of the Three Sisters in central Oregon is not well known. Three ash layers erupted from South Sister about 2000-3000 yrs. B.P. are thin but widespread; they extend at least 30 km east and south of the volcano. Over most of this area the tephra is only about 1-2 cm thick except within a few kilometers of the vent, where it is up to several meters thick (N. S. MacLeod, written commun., 1981).

Other Cascade Range volcanoes

Of the remaining major Cascade Range volcanoes, Mount Adams and Mount Hood have erupted tephra deposits which are not known to extend beyond their flanks. Mounts Jefferson, Thielsen, and McLoughlin have produced thick deposits of ejecta, but these, too, were deposited on the flanks of the volcanoes. The geologic history of these volcanoes suggests that their potential for explosive eruptions may be low.

Discussion

In the Pacific Northwest, the effects of tephra on nuclear reactors and reactor sites are likely to be most severe in the vicinity of and several hundred kilometers downwind from Mount St. Helens, Wash. (Trojan, Pebble Springs, and Hanford). Of all volcanoes in the Cascade Range chain, Mount St. Helens has had the most frequent, large, explosive Holocene eruptions (Crandell and Mullineaux, 1978; Mullineaux and Crandell, 1981). Crater Lake, Ore., and Glacier Peak, Wash., have been active in latest Pleistocene and Holocene time, and produced large volumes of tephra that covered large areas of the Pacific Northwest with thick layers of ash. These two volcanoes may be dormant, with long intervals between

eruptions. In view of their Holocene record of activity, the intervals between very large Plinian eruptions may be 10,000 yr or more.

Other volcanoes in the Cascade Range have produced small eruptions of tephra, and areas covered by ash have been small, even though tephra blankets in the vicinity of some of these volcanoes are thick. There is no assurance, however, that a large, explosive eruption of tephra equivalent to that of May 18, 1980, or to the event that produced layer Yn from Mount St. Helens, or even to the one that produced the Mazama ash from Crater Lake, could not take place from any of the Holocene Cascade Range volcanoes. The record of historic and Holocene volcanism in this region is too short for us to make accurate predictions of the site and frequency of future eruptions. In general, there appears to be an inverse relation between eruption magnitude and frequency: large eruptions tend to occur less frequently than smaller ones. Within the Cascade Range, eruptions equivalent in magnitude to that of May 18, 1980 from Mount St. Helens may be expected to occur once in about one hundred to several hundred years; eruptions equivalent in magnitude to the St. Helens Yn eruption may occur once in about every 2000 to 4000 yr, while eruptions equivalent to that of Crater Lake (Mount Mazama, 7000 yr B.P.), may have recurrence intervals on the order of 10,000 to 100,000 yr.

Several catastrophic eruptions of large magnitude have occurred from sources east of the Cascade Range in Quaternary time. Calderas at which these eruptions occurred are located in the Yellowstone National Park area of northwestern Wyoming and eastern Idaho, the Long Valley caldera of east-central California, and the Valles caldera of New Mexico. Each of these eruptions produced about 300 km³ or more of volcanic material, including pumice-ash flows, tephra plumes, and lava flows, and they affected large areas of the Western and Central United States. For instance, primary airfall ash about 5 cm thick from one of these eruptions (Huckleberry Ridge ash) has been found in the Ventura area of California, more than 1,400 km downwind from its presumed source in the Yellowstone area. A layer of reworked Lava Creek ash nearly 2 m thick has been identified in southeastern California, over 1100 km from the same eruptive source area. Known eruptions of this magnitude are the following:

Name	Vent locality	Age (m.y.)	Volume (km ³)
Lava Creek Tuff	Yellowstone area, Wyoming	0.6	1000 ^{1/}
Bishop Tuff	Long Valley caldera, California	0.7	500 ^{2/}
Upper Bandelier Tuff	Valles caldera, New Mexico	1.15	300 ^{3/}
Mesa Falls Tuff	Yellowstone area, Wyoming	1.27	280 ^{1/}
Lower Bandelier Tuff	Valles caldera, New Mexico	1.47	300 ^{3/}
Huckleberry Ridge Tuff	Yellowstone area, Wyoming	2.01	2000 ^{1/}

1. Christiansen (1979).
2. Bailey and others (1976).
3. Smith (1979).

From the few eruptions of this type, we can estimate only roughly that such an eruption occurs once every several hundred thousand years, and, on an average, about once every 350,000 yr within the

western coterminous United States. No such eruptions have been documented for the Cascade Range in Quaternary time, although an eruption approaching this magnitude did occur in the southern Cascade Range in late Pliocene time (the Nomlaki Tuff Member of the Tehama Formation, about 3.4 million yr ago; Evernden and others, 1964). An eruption of this magnitude could affect sites in the Pacific Northwest regardless of whether the vent was in the Cascade Range or other volcanic areas in the Western United States.

Catastrophic eruptions of such large magnitude have a very low probability of occurrence within short time spans (for instance, 1/3,500 within a period of 100 yr, calculated by taking the reciprocal of the estimated average recurrence interval of this type of eruption, 350,000 yr, and multiplying it by 100 yr). Nevertheless, the probability is finite and needs to be considered for long-lived structures, facilities, and repositories (Mark and Stuart-Alexander, 1977).

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