On the basis of frequency of past activity, recency of eruptions, and present state, Mount St. Helens is clearly the most likely Cascade volcano to erupt in the future, but several other volcanic centres are probably in a stage of relatively heightened potential for future eruptions. Glacier Peak, Mount Rainier, and Mount Shasta have been frequently active since 15 ka and have been active during the past few centuries. Medicine Lake volcano has not been active as recently as these three centres, but it ranks with them in terms of frequency of eruptive periods since 15 ka. Mount Hood and Lassen Peak, although less active than the above since 15 ka, have had very recent eruptions.

In light of the episodic pattern of eruptive stages thousands of years long with intervening apparently dormant intervals of similar duration, what is the outlook for centres that have been in repose for thousands, or in some cases tens of thousands, of years? Should eruptions at such centres as Mount Cayley, Mount Garibaldi-Garibaldi Lake, Mount Adams, Mount Jefferson, and Mount Mazama be considered overdue?

Considering the past frequency of eruption of basaltic volcanoes, as well as the large number of basaltic vents in some centres such as Newberry and Medicine Lake, the next eruption in the arc could well form a scoria cone and lava flow distant from any of the conspicuous, high, composite volcanoes of the arc.

Apparent synchroneity of eruptive activity along the arc on time scales of thousands of years raises the question of its cause. One or more of several possibilities might explain the observed pattern. (1) The apparent temporal clustering is essentially coincidental. As synchroneity of eruptive activity throughout the arc seems contradictory in light of major along-arc changes in convergence rate, state of stress, crustal structure, geometry of the subducting slab, and vent distribution, this option may have considerable merit. (2) About one-third of the recognized eruptive periods remain undated and others may not yet have been recognized, which leaves open the possibility that some might date from times that presently define hiatuses in activity. This option is attractive in that the apparent hiatuses cover only about 25% of the past 15,000 years. (3) Generation and rise of primary magma in the arc and eruption of primary and derivative magma are modulated by processes that result in arc-wide episodes of increased eruptive activity. Such processes include tectonic stresses within the mantle wedge and crust, and dynamics of fluid flow involved in generating, accumulating, and transporting magma. Whether or not such causes are plausible, confirmation of arc-wide episodicity in the Cascade eruptive record since 15 ka must await more accurate dating of many of the undated eruptive periods.

Acknowledgements
R.P. Hoblitt and C.D. Miller contributed greatly to compilation of eruptive-history data for the Cascade Range.

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Volcanic Hazards in the Pacific Northwest

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Summary
The Cascade Range stretches from southwestern British Columbia to northern California; the Range consists of major composite volcanic centres, most of which have been active during late Pleistocene and Holocene time. In addition, thousands of smaller basaltic or basaltic-andesite volcanoes have been active during the past few million years. Flowage and tephra hazards associated with future eruptions of composite volcanoes in the Range will endanger communities located within about 50 km of erupting volcanoes. Significant effects will extend to still greater distances downwind from the volcanoes and along stream valleys that head at the volcanoes. Volcanic-hazard assessments and hazard-zonation maps developed for volcanoes in the Range can be used by authorities for long-range land-use planning and provide information to help mitigate the effects of future eruptions.

Introduction

The Cascade Range is an active continental-margin volcanic arc consisting of more than 20 major volcanic centres that have been active for tens of thousands to hundreds of thousands of years. The Range stretches from the Garibaldi volcanic belt in southwestern British Columbia (Green *et al.*, 1988) to Lassen Peak in northern California. Volcanic hazards associated with the US part of the Cascade Range will be discussed in this report. For purposes of this discussion, two areas of bimodal volcanism, Newberry volcano and Medicine Lake volcano, are included with the major eruptive centres in the Range. Cascade Range volcanoes in the US have erupted more than 200 times during the past 12,000 years — an average rate of nearly two eruptions per century; at least five eruptions have occurred during historical time, the past 150 years in the Pacific Northwest (Crandell and Mullineaux, 1975). The most recent eruptions in the Range are the well-documented 1980-1986 eruptions of Mount St. Helens (Lipman and Mullineaux, 1981; Swanson, 1990), which claimed at least 57 lives and caused more than 970 million dollars in short-term losses to the State of Washington (MacCready, 1982).

In addition to the prominent Quaternary stratocones in the Cascade Range, more than a thousand basaltic or basaltic-andesite volcanoes occur either individually or in fields of volcanoes between Mount Rainier and Lassen Peak (Hoblitt *et al.*, 1987). These volcanoes typically are active for only a single eruptive period and are far less explosive than composite volcanoes. Although future basaltic or basaltic-andesite eruptions could occur almost anywhere in the Cascade Range, they would strongly affect only limited areas near a vent and present a far less serious threat to life and property in the Cascade Range than do frequently active and highly explosive composite volcanoes. Discussions in this report concentrate on hazards associated with the 13 major eruptive centres in the US part of the Range.

All population centres with more than 100,000 inhabitants are located west of the Cascade Range or far to the east and are thus out of range of most products of volcanic eruptions (Figure 1). Furthermore, the sites of most large cities in the Pacific Northwest have not been covered by thick tephra, most of which is carried eastward from the Cascade Range by prevailing winds. Nevertheless, Crandell and Mullineaux (1975) pointed out that eruptions like those of the recent past could have both direct and indirect effects on significant numbers of people. They estimated that eruptions like those of the past several thousand years at Mount St. Helens and Mount Rainier volcanoes in Washington State could affect as many as 40,000 or 50,000 persons, respectively. They emphasized that the number of people at risk from future eruptions of Cascade Range volcanoes is certain to increase as population and recreational activities around these volcanoes increase.

The primary means of mitigating the effects of eruptions are prohibiting development in areas at risk around volcanoes (long-range land-use planning) and(or) evacuating people and moveable property from threatened areas during times of eruptive activity. For both of these purposes volcanic-hazard assessments and accompanying hazard-zonation maps have been developed for the Cascade Range (*e.g.*, Crandell *et al.*, 1979; Hoblitt *et al.*, 1987). Such assessments have been based upon the geologic record of past activity at each potentially active volcano, and the character of processes observed at active volcanoes in the Cascade Range or at similar volcanoes elsewhere. This paper discusses the nature of hazardous volcanic processes in the Cascade Range and discusses recently developed hazard-zonation maps for the Pacific Northwest (Hoblitt *et al.*, 1987) for tephra and flowage hazards.

Potentially Hazardous Volcanic Events

Cascade arc volcanoes range from simple cinder cones that have erupted only once to complex composite cones that have erupted many times over periods of thousands of years. The composition of eruptive products within the arc spans the range from basalt to rhyolite, with andesite and dacite being dominant at many of the major eruption centres. Eruptions during the past 12,000 years at these centres have varied in type, intensity, and volume of products, from non-explosive eruptions of much less than a cubic kilometre of lava, to cataclysmic events such as the climactic eruption of Oregon's Mount Mazama about 6,800 years ago, which produced about 50 km^3 of magma and formed the caldera now occupied by Crater Lake (Bacon, 1983).

Many kinds of Cascade Range volcanic events directly or indirectly endanger people and the works of man. These events can be classified as either flowage processes or fallout of tephra.

Flowage Phenomena. Flowage phenomena include all gravitationally directed mass movements of volcanic material down

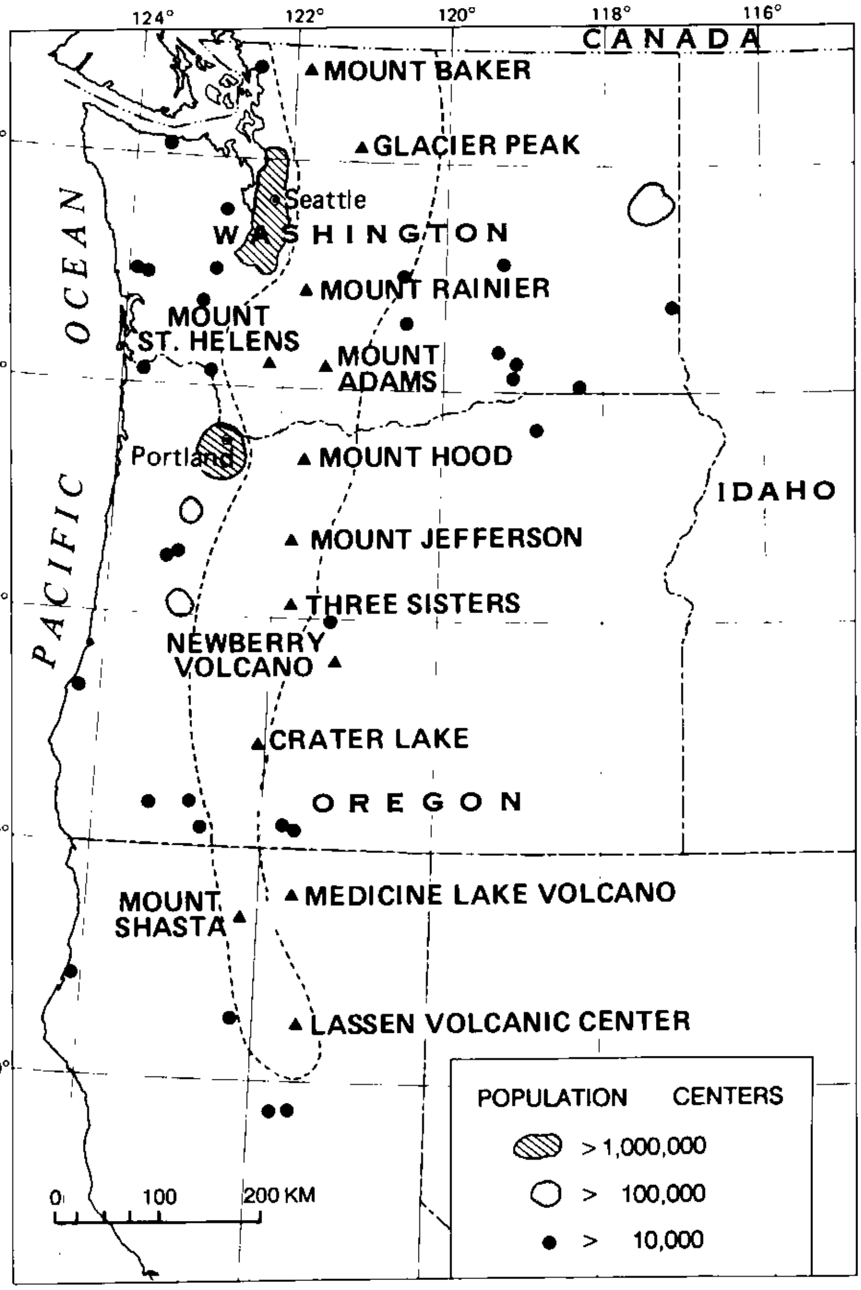

Figure 1 *Location of major composite volcanoes (triangles) in and near the Cascade Range (dashed line), and population centres in Washington, Oregon, and northern California. (From Crandell* et al., *1979).*

the flanks of volcanoes; some mass movements extend into lowlands and drainageways far beyond volcanoes. Hazardous flowage processes are briefly discussed below along with their effects on people and property.

1. *Debris avalanche.* Debris avalanches are sudden, rapid movements of incoherent masses of rock and soil mobilized by gravity. They form when part of a volcanic edifice fails catastrophically and moves downslope. Such events can occur with little or no warning, and debris avalanches can travel at high speeds and destroy everything in their paths by impact or burial. Debris avalanches occur relatively infrequently in the Cascades, but are extremely destructive: the May 18 debris avalanche at Mount St. Helens reached 28 km from the vent and covered about 70 km². A debris avalanche at Mount Shasta about 300,000 years ago reached a distance of more than 64 km and covered more than 675 km² (Crandell, 1989).

2. *Pyroclastic flow.* Pyroclastic flows are relatively dense mixtures of hot, dry rock fragments and hot gases that move at high speeds. They typically result from explosive eruption of molten or solid rock fragments or from collapse of eruption columns. Pyroclastic flows destroy everything in their paths by impact, burial, or fire. More than 325 pyroclastic flows are known to have occurred in the US part of Cascade Range during about the last 15,000 years, and others are certainly unrecognized. Pyroclastic flows can travel several tens of kilometres down valleys heading at volcanoes, and pyroclastic flows from the climactic eruption of Mount Mazama reached a downvalley distance of 60 km from the vent (Williams, 1942).

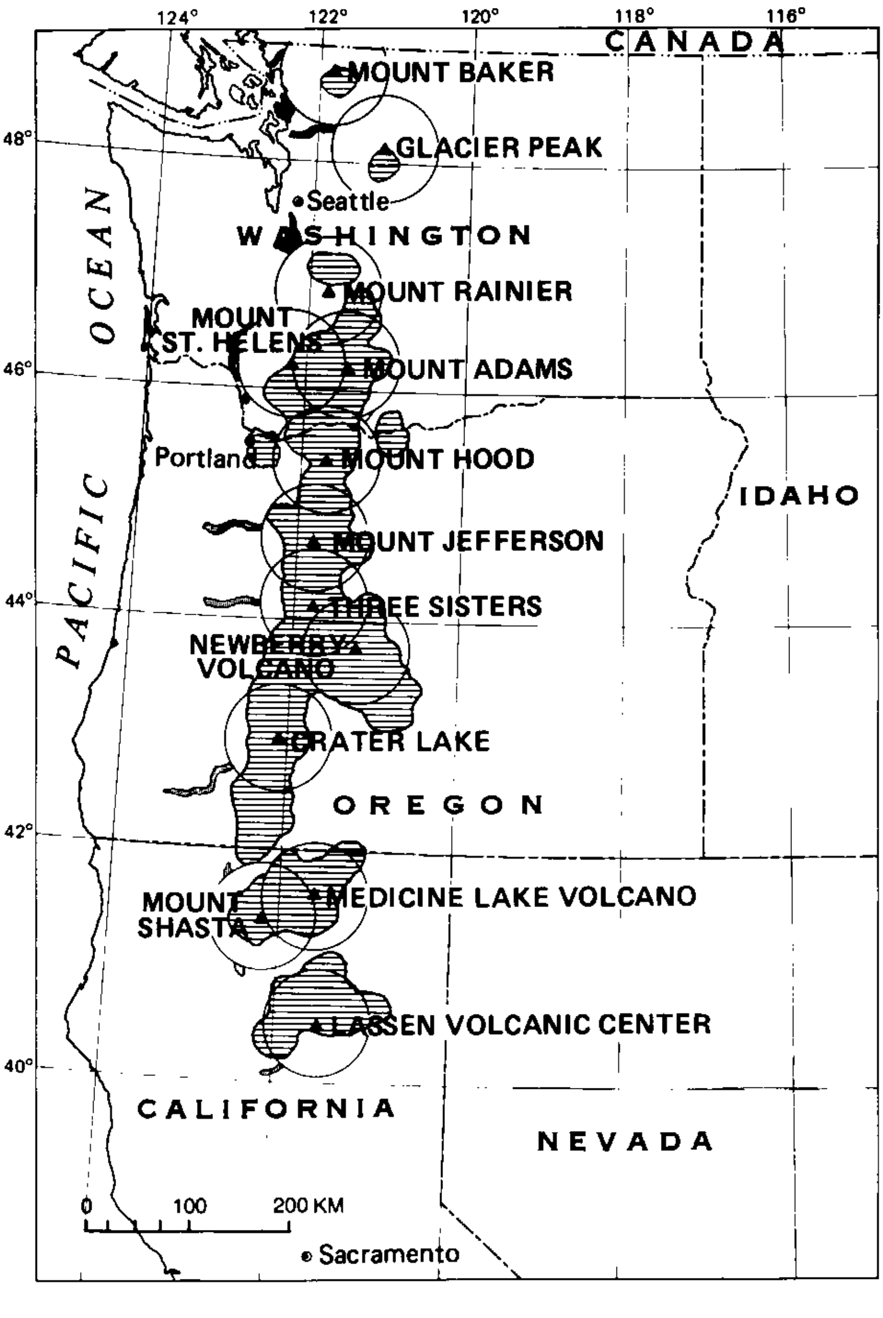

Figure 2 *Volcanic-hazard zones in the Cascade Range.* **Circles**, *proximal hazard zones with radius of 50 km;* **lined pattern**, *hazard zones from eruptions of basaltic volcanoes and volcanic fields;* **gray-shaded "fingers"**, *distal lahar- and flood-hazard zones. (After Hoblitt* et al., *1987).*

3. *Pyroclastic surge (includes blasts).* Pyroclastic surges are turbulent, relatively dilute clouds of rock debris and gases that move at high speeds. Surges result from explosions or collapse of eruptive columns and can be either significantly above 100°C and dry, or below 100°C and wet. They may extend for tens of kilometres from their vents and destroy hundreds of square kilometres. Surges may surmount significant topographic barriers, and they typically devastate all life and property in their paths by impact, burial, incineration or asphyxiation. The devastating high-energy surges that we refer to as blasts occur infrequently in the Cascades and only a few are known. Two have occurred at Mount St. Helens: a small one that occurred about 1100 years ago; and the May 18, 1980 pyroclastic surge, which reached a distance of 28 km from the vent and destroyed about 600 km² (Crandell and Hoblitt, 1986).

4. *Lahar (volcanic mudflow).* Lahars are mixtures of water-saturated rock debris that move downslope under the force of gravity. Water for mobilization may be supplied by groundwater or a hydrothermal system, rainfall, eruption into a crater lake, or, as occurs frequently, by melting when hot debris is erupted onto snow or ice. Lahars destroy everything in their paths by impact, burial, or dislodgement. Lahars are restricted to stream valleys and depressions, but may reach hundreds of kilometres at average speeds of tens of kilometres per hour. Lahars occur frequently in the Cascades; more than 445 are known to have occurred in the US part of the Range in postglacial time. Many more are undoubtedly unrecognized.

5. *Lava flow.* Lava flows are masses of molten to partly solidified volcanic rock that flow under the force of gravity. Lava flow geometry, size, and speed are controlled by lava effusion rate, lava fluidity, volume erupted, slope, and topographic obstructions. Lava flows may reach tens of kilometres from their sources and cause extensive damage by burning, crushing, or burying objects in their paths. Lava flows seldom threaten life because they move slowly enough to be avoided by people and animals. Lava flows have occurred frequently in the Cascades. During postglacial time, more than 425 lava flows are known to have occurred in the US part of the Range, counting lava flows erupted at or near major centres and those erupted at vents in basaltic fields. Most reach no more than about 15 km from their vents, but ex-

tremely fluid flows may reach 50 km from their vents (Hoblitt *et al.*, 1987).

Tephra fall. Tephra (Greek for "ash") consists of fragments of lava or rock blasted into the air by explosions or carried upward by convection. Tephra particles fall to the ground to form a thin blanketing deposit that decreases in thickness and particle size downwind from the vent. Thin tephra deposits commonly reach hundreds of kilometres from their vents and cover thousands of square kilometres. The main hazards posed by these deposits result from burial, impact of large fragments, and, close to a volcano, high temperatures. Damage may occur to machinery, electrical equipment, and the respiratory systems of people and animals. The distribution of tephra is chiefly a function of eruption intensity, volume erupted, and wind speeds and directions. Prevailing westerly winds in the Cascade Range carry most tephra to the east or northeast.

Volcanic-Hazard Assessments

Volcanic-hazard assessments for the Cascade Range (Crandell and Mullineaux, 1975; Crandell *et al.*, 1979; Hoblitt *et al.*, 1987; Miller, 1988) provide forecasts of the kinds of eruptions expectable in the future, the specific types of volcanic events that will endanger people and property, and the areas most likely to be affected by eruptive events. Volcanic-hazard assessments were developed initially to be used by authorities and public officials in the Pacific Northwest for long-range planning; they have been based on the assumption that future volcanism will be similar in type, scale, and frequency to past activity at each volcanic centre.

Hazard assessments for the Cascade Range have been based on studies of both historical eruptions and the prehistoric geologic record for each volcano. Studies of the stratigraphy of rocks and unconsolidated deposits of the past 10,000 years and evaluation of the eruptive processes that formed the deposits reveal the character and sequence of past events.

A critical component of most volcanic-hazard assessments is a volcanic-hazard-zonation map. Such a map designates areas of relative risk around a volcano and has two primary purposes: one is to help authorities plan land use around volcanoes, and the other is to help authorities determine which areas near volcanoes should be evacuated or avoided during future eruptions (Crandell *et al.*, 1984).

In a recent report on potential volcanic hazards to be considered for siting nuclear powerplants in the Pacific Northwest, Hoblitt *et al.* (1987) noted that the most damaging volcanic events are largely restricted to within about 50 km of their sources. Therefore, they recommended creation of proximal-hazard zones with radii of 50 km centred at each of the major volcanic centres in the Cascade Range (Figure 2).

Two groups of volcanic processes commonly affect areas at distances greater than 50 km from a vent: lahars and floods, and tephra falls. Hoblitt *et al.* (1987) documented that lahars from at least five Cascade volcanoes have inundated valley bottoms at distances more than 50 km from their sources. They established distal hazard zones for lahars and floods that extend beyond 50 km down major drainages from volcanoes with significant mantles of snow and ice (Figure 2). Distal flowage-hazard zones depicted in Figure 2 include active river channels, adjacent flood plains, and most low river terraces.

Hoblitt *et al.* (1987) also developed a method of computing annual probabilities of tephra fall; the method considers the conditional probabilities of the frequency of explosive eruptions, tephra thickness at various distances downwind from a vent, and wind directions. For example, the annual probability of 10 cm or more of tephra accumulating in the northwestern United States ranges from 10^{-2} near and immediately downwind from Mount St. Helens, to 10^{-6} at distances of about 400-500 km east of the Range (Figure 3).

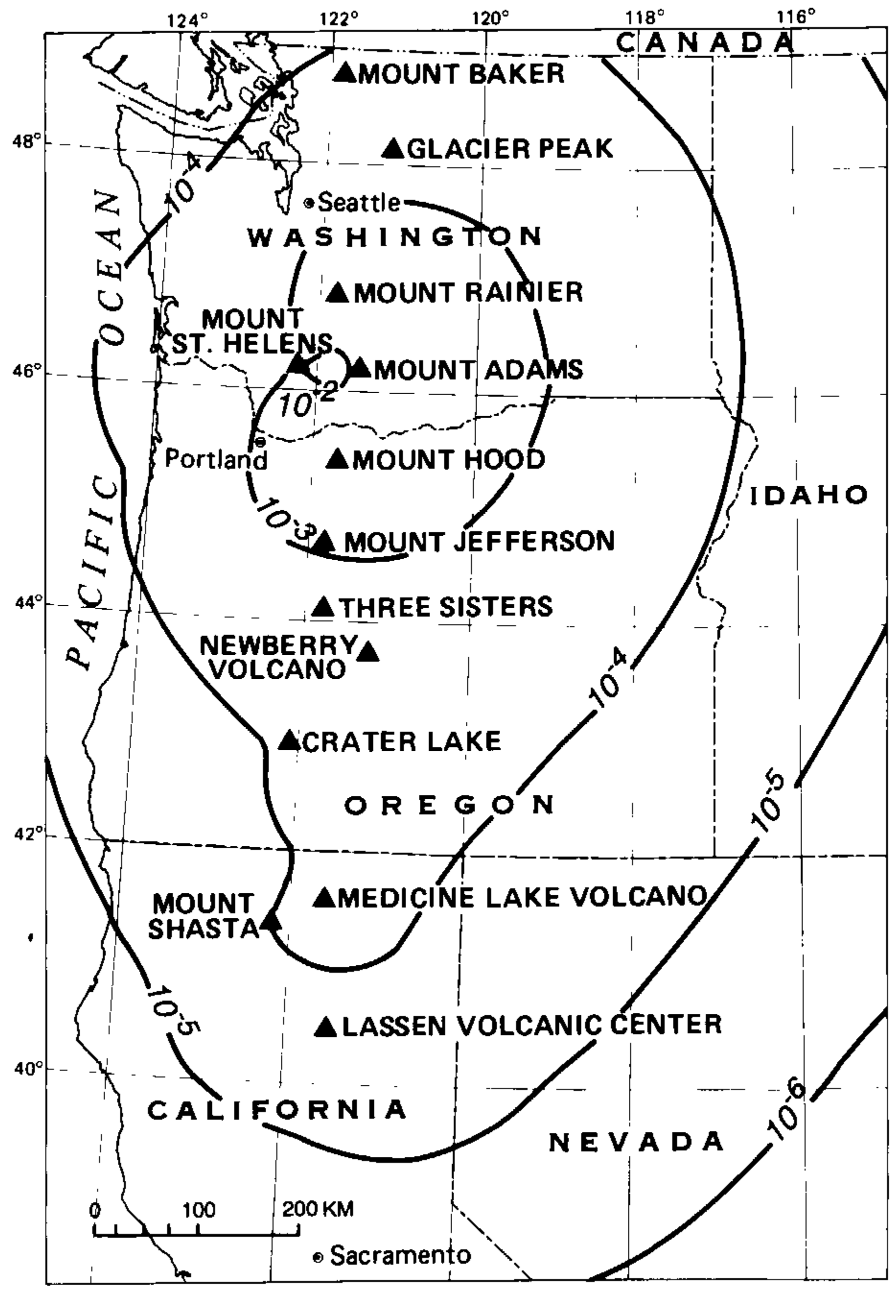

Figure 3 *Contour map of the estimated annual probability of accumulation of 10 cm or more of tephra in the northwestern United States from eruptions at 13 major volcanic centres in the Cascade Range. (After Hoblitt* et al., *1987).*

Discussion

The long geologic record of explosive eruptions at volcanoes in the Cascade Range combined with the consequences of the 1980 eruptions of Mount St. Helens documents the serious nature of potential volcanic hazards in the Pacific Northwest. Future eruptive events will most seriously affect many areas within about 50 km of the main eruptive centres in the Range; valleys leading away from many volcanoes will be affected to even greater distances by flowage events. Tephra hazards threaten large areas mostly near and to the east of explosive volcanoes. The importance and usefulness of volcanic-hazard assessments for mitigating the effects of eruptions were demonstrated during the 1980 eruptions of Mount St. Helens, when loss of life was minimized by the use of a long-range assessment in conjunction with volcano-monitoring techniques.

Acknowledgements

Data presented in this paper and many of the conclusions are the results of joint work by R.P. Hoblitt, W.E. Scott, and the author. Reviews and comments on this manuscript by Ed Wolfe and D.R. Mullineaux are gratefully acknowledged.

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