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Patterns of Volcanism in the Cascade Arc During the Past 15,000 Years

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Article abstract

About 110 well-dated and 70 poorly date deruptive periods less than 15,000 years old at individual volcanoes in the Cascade arc constitute a data set for identifying spatial and temporal patterns of eruptive activity. Key features of the record include: (1) the mean frequency of eruptive periods during the past 4,000 years is approximately two per century, however, the variance about the mean may belarge; (2) at most major centres, episodes of activity lasting several thousand years are defined by groups of eruptive periods separated by apparent dormant intervals of roughly similar duration, (3) arc-wide clustering of eruptive activity may exist at 0-4 ka, 6-8 ka, and 10-14 ka. Such clustering would be remarkable in light of significant along-arc changes in crustal structure, stress field, and subduct Ion-zone geometry.

was built by repeated extrusion of thick, steep-sided lava domes and flows, preceded by minor phreatic and pyroclastic activity. Debris-avalanches and block-and-ash flows have sometimes accompanied dome extrusion. More detailed summaries of the kinds of eruptive activities to be expected are presented by Miller *et al.* (1982).

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Patterns of Volcanism in the Cascade Arc During the Past 15,000 Years

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Summary

About 110 well-dated and 70 poorly dated eruptive periods less than 15,000 years old at individual volcanoes in the Cascade arc constitute a data set for identifying spatial and temporal patterns of eruptive activity. Key features of the record include: (1) the mean frequency of eruptive periods during the past 4,000 years is approximately two per century; however, the variance about the mean may be large; (2) at most major centres, episodes of activity lasting several thousand years are defined by groups of eruptive periods separated by apparent dormant intervals of roughly similar duration, (3) arc-wide clustering of eruptive activity may exist at 0-4 ka, 6-8 ka, and 10-14 ka. Such clustering would be remarkable in light of significant along-arc changes in crustal structure, stress field, and subduction-zone geometry.

Introduction

Studies of the eruptive history of individual volcanic centres provide important information about patterns of activity and repose, variations in magma-extrusion rate, petrologic evolution, and changes in eruptive behaviour. With sufficient details about the eruptive history of the centres in an arc, one can look for arc-wide patterns that might reflect arc segmentation, changing tectonic conditions, or differing processes of magma genesis. Of course, the length of time for which activity is reconstructed governs the degree of detail obtainable and the types of questions that can be addressed. Thus, eruptive patterns over time scales of millions of years are needed to discern the effects of major changes in plate convergence rates (*e.g.*, Verplanck and Duncan, 1987) or shifts in vent distribution (*e.g.*, Guffanti and Weaver, 1988).

The Cascade arc, which is of relatively modest size and vigour, includes the late Cenozoic Cascade Range of the United States and the Garibaldi volcanic belt of British Columbia (Figure 1). Owing to the past four decades of intense geologic study and radiometric dating, especially of the postglacial record, its eruptive history since 15,000 years ago (15 ka) is probably better known than that of any other volcanic arc. The following report summarizes the spatial distribution and age of Cascade eruptive periods since 15 ka, discusses some of the patterns that emerge from this record, and speculates briefly on processes that might contribute to the observed patterns.

Definition of Eruptive Periods

An eruptive period as used in this report represents a single eruption or a series of eruptions closely spaced in time at a volcanic centre or basaltic volcano (see definitions in "Vent distribution") that yield a preserved deposit and are differentiated from preceding and subsequent eruptive periods by one or more of the following criteria: (1) separated by an apparent dormant interval of decades to centuries, (2) distinguished by a change in vent location, and (3) marked by a distinct compositional change in eruptive products. Thus, the numerous eruptive events at Mount St. Helens between 1980 and 1986 are well recorded in a wide array of deposits, but are grouped here as a single eruptive period. In contrast, some other eruptive periods at volcanoes in the arc are thought to represent only brief single events such as a minor tephra eruption or extrusion of a single lava flow.

Eruptive periods are more difficult to define at volcanoes that have been active frequently over time intervals of many centuries. Detailed stratigraphic, radiocarbon, paleomagnetic, or petrologic evidence defines distinct eruptive periods within some long-lived active intervals, but, lacking such evidence, others are divided arbitrarily into several periods so that the entire active interval is represented.

At Newberry and Medicine Lake volcanoes and in some fields of basaltic volcanoes, several lava flows were erupted from separate vents, some aligned along rift zones, during relatively brief time intervals. In these cases, eruptive periods were defined for groups of lava flows on the basis of proximity of vents and similarity in age, rather than counting each lava flow and related scoria cone separately.

Deposits of debris avalanches and lahars are common at many Cascade volcanic centres, but their emplacement may not necessarily have been related to eruptive activity. Therefore, eruptive periods are inferred from such deposits only if they are accompanied by evidence of eruptive activity such as related pyroclastic debris or evidence that some clasts in the lahars were hot when emplaced.

Numerous eruptions of Cascade volcanoes observed during historical time have consisted of brief, probably phreatic, explosions. Many left little record other than areally restricted tephra-fall deposits, and these commonly accumulated either on steep exposed slopes or on ice and snow where there is little potential for long-term preservation. Only such explosions that left deposits likely to be preserved and recognized in the geologic record are counted as separate eruptive periods.

The above considerations demonstrate the subjectivity involved in defining eruptive periods and, therefore, the periods designated here may vary greatly from those of previous workers. For instance, the seven eruptive periods since 4 ka at Mount St. Helens defined by Crandell's criteria (1987) here number 20 by including many of Crandell's informal subdivisions under my definition of eruptive periods. However, such modification permits a more complete representation of the eruptive history in the accompanying figures.

Dating Eruptive Periods

The majority of eruptive periods have been dated by radiocarbon methods, and many of the younger eruptive periods by historical records or dendrochronology. A few periods have been dated by obsidian-hydration dating, age interpolation based on sedimentation rates in lakes, or, indirectly, by correlation with deposits dated elsewhere. All radiocarbon ages have been calibrated to sidereal (calendar)

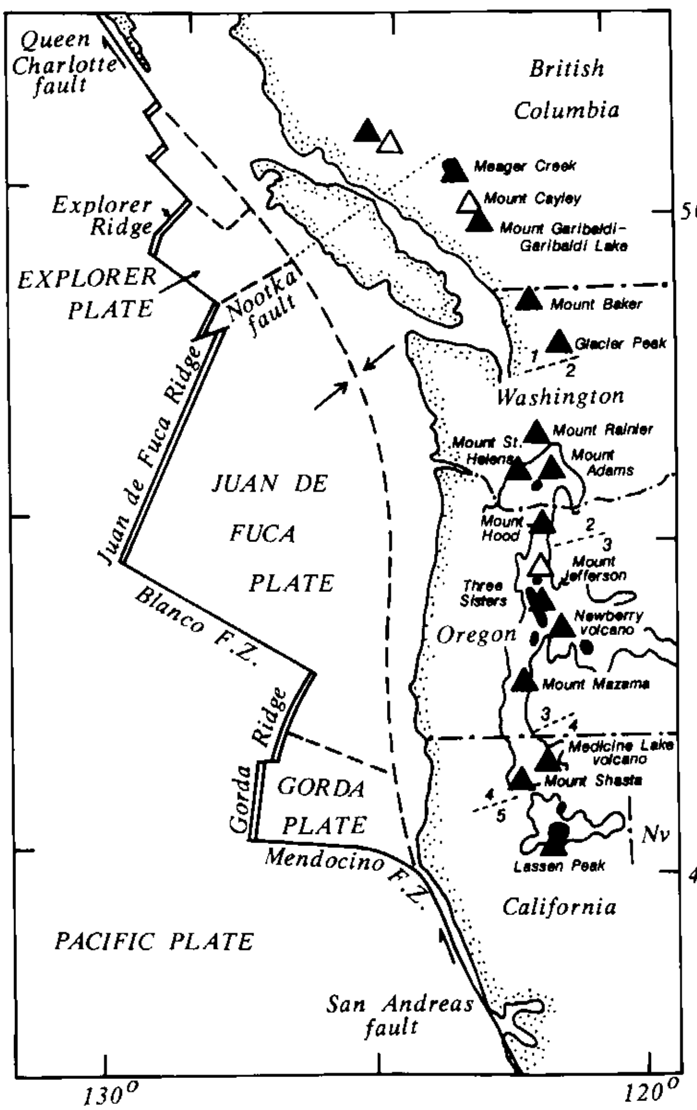

Figure 1 *Cascade arc in relation to major plate-tectonic features (modified from Duncan and Kulm, 1989). Dashed line parallel to coast is boundary between Juan de Fuca and North America Plates; arrows show convergence direction. Dotted line is extrapolation of Nootka fault. Triangles are major Quaternary volcanic centres of Cascade Range (United States) and Garibaldi volcanic belt (British Columbia); filled ones were active since 15 ka. Areas outlined in southern Washington, Oregon, and northern California are zones of vents younger than 5 Ma in the Cascade Range and heavy lines demarcate numbered arc segments 1-5 (both from Guffanti and Weaver, 1988). Small filled areas are zones of post-15 ka basaltic volcanoes.*

years using methods described in Stuiver and Kra (1986) to account for variations in radiocarbon content of the atmosphere. Radiocarbon ages less than 3 ka are typically within 1-2 centuries of their sidereal equivalents, those between 3 and 4 ka are as much as 500 years too young, and those older than 4 ka are as much as 1,100 years too young.

Three types of uncertainty limit the accuracy of radiocarbon dating of eruptive periods. (1) Analytical errors of radiocarbon ages are typically less than ±200 years at one standard deviation (1σ), and ages of many deposits have much smaller uncertainties owing to averaging of several ages. (2) Except for instances in which short-lived organisms were killed by eruptions and their remains incorporated in eruptive products, many of the dated materials can provide only limiting ages. Thus, the ages of some eruptive periods are determined by averaging maximum and minimum limiting ages. A significant source of uncertainty in determining the accuracy of limiting ages arises from the great age (up to 500 years or more) of wood in living and dead, but non-decayed, trees that can be incorporated into volcanic deposits. Although careful selection of samples and dating of multiple samples have minimized the problem locally, this uncertainty remains, especially for deposits dated by a single wood or charcoal fragment. (3) Radiocarbon ages are also subject to uncertainties owing to post-depositional contamination of samples with younger or older organic matter, although for most samples in the age range considered here, such problems are comparatively minor.

The combined uncertainty (1σ level) from analytical and other errors for most of the ages plotted in the following figures is estimated to be 500 years or less. In most cases, the major contributor to this uncertainty is the closeness of limiting ages, which, unfortunately, is not readily measurable. The best check on ages is afforded by multiple determinations and dating of superposed units. In addition, regional tephra layers provide widespread reliable datums. Some ages have been adjusted to agree with age controls provided by stratigraphic relations.

Poorly dated or undated deposits furnish evidence of additional eruptive periods at most Cascade volcanoes. Stratigraphic relations to dated deposits provide age limits for many undated deposits that typically span a few thousand years. Numerous undated eruptive periods occurred during the waning phases of the last ice age. Environmental conditions at that time were apparently unfavourable for the existence and(or) preservation of datable organic materials in many areas of the arc.

Eruptive Periods in Space and Time since 15 ka

Eruptive history data from the Cascade arc are shown in Figures 2 to 4. Space limitations prohibit including tables and references to the voluminous basic data on volcanic deposits and their dating. Such information for most of the US part of the arc is presented in Hoblitt *et al.* (1987), although I have made some corrections and additions. Data for the Garibaldi volcanic belt are from Clague (1981), Green *et al.* (1988), and C.J. Hickson (written communication, 1989).

Vent distribution. Cascade vents active since 15 ka include most major Quaternary volcanic centres and numerous basaltic volcanoes that lie between centres (Figure 1). The major centres are long-lived foci of eruptions of mafic to silicic lavas, are generally coincident with the major composite volcanoes, and typically contain numerous flank and satellitic vents. The category, basaltic volcano, comprises volcanoes that have erupted only basalt and(or) basaltic andesite (53-57% SiO_2). In many cases, these are monogenetic volcanoes that occur typically in fields of vents. Excluded from the category of basaltic volcanoes are vents on composite volcanoes that erupted basalt or basaltic andesite. Eruptive activity since 15 ka has occurred in all of the arc segments defined by Guffanti and Weaver (1988). Most basaltic volcanoes active since 15 ka are concentrated in and around the major volcanic centres.

Mount St. Helens leads the volcanic centres in number of eruptive periods with 27; Glacier Peak, Mount Rainier, Medicine Lake volcano, and Mount Shasta have 14-18 each; among the remainder, each has less than 10 (Figure 2). Mount Cayley and Mount Jefferson are the only major Quaternary centres south of the Nootka fault that have been apparently dormant since 15 ka, although basaltic volcanoes have erupted close to Mount Jefferson and preliminary evidence suggests that Mount Cayley may have erupted during middle Holocene time (Evans, 1990).

The greatest concentration of basaltic volcanoes active since 15 ka is in the central Oregon Cascades (Figures 1 and 2) between Crater Lake and Mount Jefferson, especially near Three Sisters. Other areas of significant numbers of basaltic vents include the Bridge River cones (Salal) of the Garibaldi volcanic belt, the southern Cascades of Washington, and the Cascades of California north of Lassen Peak.

Eruption frequency. The frequency of dated eruptive periods in the Cascade arc since 15 ka shows a pattern found typically in compilations of volcanic activity, namely that many more younger events are recognized than older ones (Figure 3). Rather than a real increase in eruption frequency, such relations more likely reflect (1) better preservation of the younger part of the record and thus an improved chance that investigators can decipher the younger record in detail, and (2) poorer dating control for older parts of the record.

The frequency of eruptive periods arc-wide since 15 ka, including the undated periods that are not tabulated in Figure 3, is 1.2 per century (about 180 eruptive periods/15,000 years). The better-dated, younger part of the record yields frequencies of 1.7 per century (past 4,000 years) to 2.5 per century (past 1,000 years); these frequencies compare favourably with the two eruptive periods of the past century (Lassen Peak, 1914-1917, and Mount St. Helens, 1980 to present). However, 8-11 eruptive periods date from the late 18th and early 19th centuries (representing as many as 6 centres and 1 basaltic volcano) and suggest that the frequency of activity on the scale of centuries has varied significantly

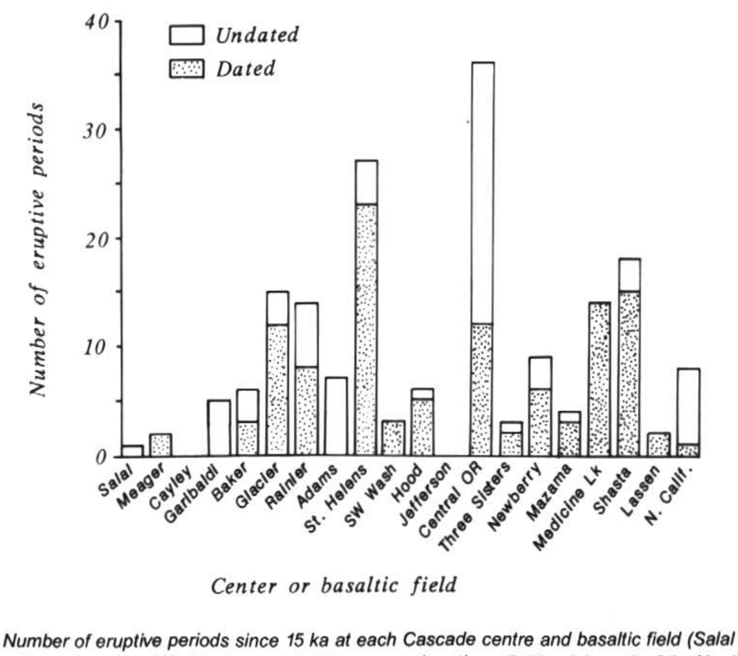

Figure 2 *Number of eruptive periods since 15 ka at each Cascade centre and basaltic field (Salal [Bridge River Cones], southwestern Washington, central Oregon, and northern California) south of the Nootka fault.*

from the long-term frequency of about 2 per century for dated eruptive periods of the past several millennia.

By examining the frequency of dated eruptive periods with respect to individual segments of the arc (Figure 3), several relations emerge. (1) The only segment having no dated eruptive period during the past millenium is segment 3 (central and southern Oregon), which had numerous eruptive periods during at least the preceding 7 millennia. Further, none of the undated periods in segment 3 appear likely to be less than 1,000 years old. (2) Segment 5 (the area around Lassen volcanic centre) has dated eruptive periods only during the past millennium. Even though several undated basaltic volcanoes in the segment are probably less than 15,000 years old (Figure 2), segment 5 appears to have been the least active of Cascade segments. (3) For each of the past 7 millennia, 3-4 segments were active, but for each of the preceding 8 millennia only 1-2 segments have dated eruptive periods; this trend probably reflects the incompleteness and poorer dating of the older part of the record. The dated eruptive activity since 15 ka of most of the major volcanic centres has been distinctly episodic on a scale of thousands of years (Figure 4). As demonstrated by Crandell (1987), the eruptive record of Mount St. Helens is divisible into stages that lasted several thousand years and contained intermittent eruptive periods; the stages were separated by apparent dormant intervals of several thousand years. This general pattern applies to other centres that have had abundant eruptive activity since 15 ka such as Baker, Glacier Peak, Rainier, Hood, Newberry, and Medicine Lake. Mount Shasta is a possible exception in that its eruptive periods are distributed more evenly through time than those of other centres and do not define distinct stages. Some other centres, such as Meager Creek, Mount Garibaldi-Garibaldi Lake (poorly dated late-glacial eruptions), Three Sisters, Mount Mazama, and Lassen Peak, have had only a single stage of activity since 15 ka.

In addition to each volcanic centre displaying episodic behaviour as evidenced by their eruptive stages, these stages may be broadly synchronous among many centres (Figure 4). For example, the records at Glacier Peak and Mount Rainier are strikingly similar, with clusters of eruptive periods from 0 to 3 ka, from about 6 to 8 ka, and, although poorly dated at Mount Rainier, from 10 to 14 ka. Newberry volcano has a similar pattern if the youngest cluster is extended to 4 ka. Mounts Baker, St. Helens, and Hood and Medicine Lake volcano have groups of eruptive periods dating from the early and late clusters, but were apparently dormant during the middle one. Some centres are characterized by dated (and poorly dated late-glacial) eruptive periods within only one cluster. Mount Garibaldi-Garibaldi Lake has periods only in the early cluster, Mount Mazama has periods only in the middle cluster, and Meager Creek and Lassen Peak have periods only in the late cluster. As mentioned previously, Mount Shasta provides a distinctly less episodic pattern of activity, although much of its activity may date from the early and late clusters. The eruptions of basaltic volcanoes also fall largely within these clusters of eruptive periods, with a few exceptions near latitudes 43-44° and 46°.

Arc segmentation appears to exert little influence on this pattern of apparent clustering of eruptive periods. In fact, the similar timing of activity at Glacier Peak and Mount Rainier carries across one of the arc's most marked segment boundaries (Guffanti and Weaver, 1988).

Discussion

The compilation of Cascade eruptive activity presented above provides a 15,000-year perspective for addressing such topics as identifying the most active parts of the arc, estimating eruption frequencies, and considering the causes of some of the observed patterns.

The current millennium has been as vigorous in terms of eruptive activity as any of the past 15. In fact, if the temporal clustering of activity along the arc suggested in Figure 4 is real, then we reside in a time period of relatively increased activity that has persisted for about 4,000 years. The activity of the past century is about average for this 4,000-year period, but owing to evidence of great variations in rate on the scale of centuries, the next century could see a marked increase or decrease.

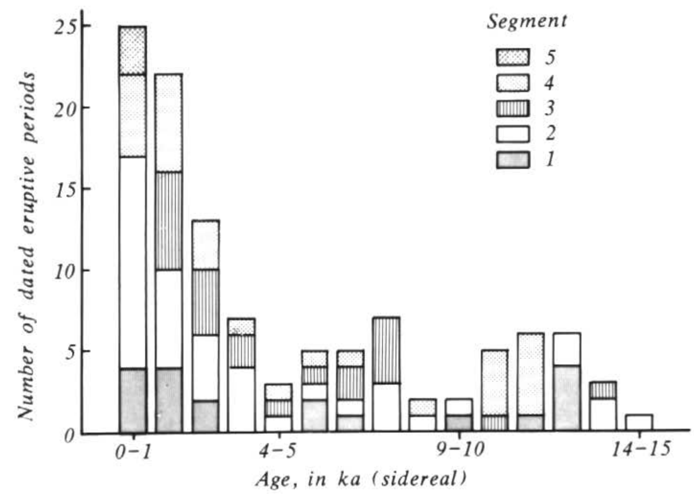

Figure 3 *Number of dated eruptive periods per millennium since 15 ka identified by arc segment. Segment 3 includes Newberry volcano, which Guffanti and Weaver (1988) suggest may be part of segment 6 of eastern and central Oregon.*

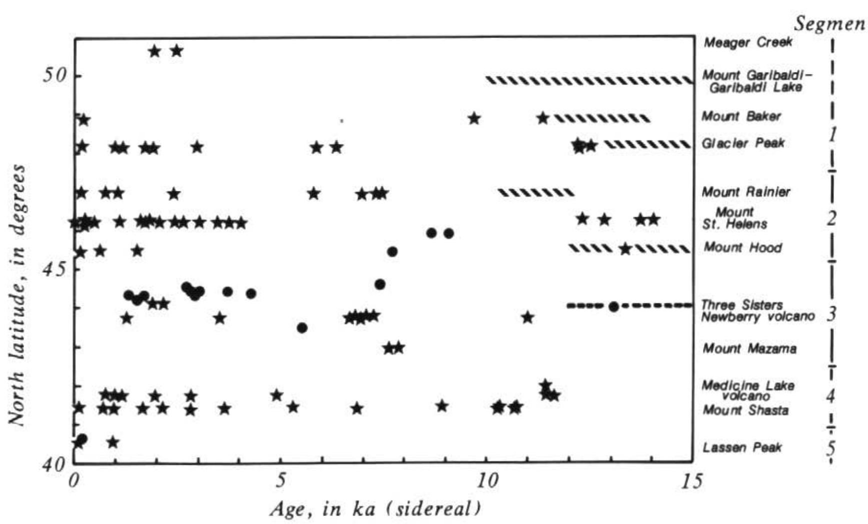

Figure 4 *Plot of dated eruptive periods of major centres (stars) and basaltic volcanoes (dots) since 15 ka by latitude and age. Closely spaced periods are locally shown diagrammatically; latitude of Medicine Lake displaced northward to differentiate from Mount Shasta. Diagonal-slash and short-dash lines represent time intervals that encompass poorly dated late-glacial eruptions of major centres and basaltic volcanoes, respectively.*

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.

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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