tled. Gravitational energy released by the accretion process, a possible mechanism, requires that the BAP was at least of lunar size. Urey has commented on the existence of such bodies in the early solar system (*15*). The short-lived ^{26}Al radioisotope is another possible heat source. Its detection in primitive objects of the solar system is the subject of renewed interest (*16*).

C. J. ALLÈGRE
J. L. BIRCK
S. FOURCADE
M. P. SEMET
Laboratoire de Géochimie et Cosmochimie, Institut de Physique du Globe, Université de Paris VI, and Département des Sciences de la Terre, Université de Paris VII, 4 Place Jussieu, 75230 Paris Cedex 05, France

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Mount St. Helens Volcano: Recent and Future Behavior

Abstract. *Mount St. Helens volcano in southern Washington has erupted many times during the last 4000 years, usually after brief dormant periods. This behavior pattern suggests that the volcano, last active in 1857, will erupt again—perhaps within the next few decades. Potential volcanic hazards of several kinds should be considered in planning for land use near the volcano.*

Mount St. Helens, a prominent but relatively little known volcano in southern Washington (Fig. 1), has been more active and more violent during the last few thousand years than any other volcano in the conterminous United States. Although dormant since 1857, St. Helens will erupt again, perhaps before the end of this century. Future eruptions like those of the recent past would affect a broad area beyond the volcano, but the area most likely to be severely affected is not yet heavily populated.

The high probability, based on past behavior, that Mount St. Helens will erupt again indicates that potential volcanic hazards should be considered in planning for future uses of the land that could be affected by an eruption. The potential risk from future eruptions may be low in relation to the lifetime of a person or to the life expectancy of a specific building or other structure. But when dwelling places and other land uses are established, they tend to persist for centuries or even millennia. Major changes in long-established land-use patterns, which become necessary to protect lives or property, can themselves be economically disastrous and socially disruptive; therefore, potential volcanic hazards should be considered while choices can still be made with respect to future land use, even though eruptions may still be decades away.

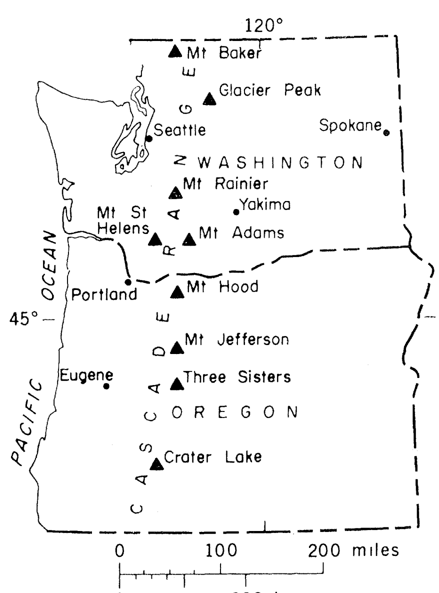


Fig. 1. Index map of Washington and Oregon showing location of Mount St. Helens and other volcanoes.

Because of its smooth, little-eroded slopes, Mount St. Helens has long been known to be younger than the neighboring volcanoes such as Mounts Rainier, Adams, and Hood (*1*). However, we have learned only recently how young St. Helens is and how often it has erupted in the recent past. Although its history extends back more than 37,000 years (*2, 3*), virtually the entire visible volcano has formed since about 500 B.C., and most of its upper part has been built within the last few hundred years (Fig. 2) (*4*). This knowledge of its formation resulted largely from detailed studies of the origin and sequence of the volcano's eruptive products, coupled with nearly 30 radiocarbon dates from which the volcanic chronology is inferred. The numerous dates were made possible by abundant charcoal in the deposits of many pyroclastic flows (avalanches of hot, dry rock debris) and by charcoal and other vegetative matter interbedded with tephra (explosively erupted, airborne debris).

Our purpose in this report is to summarize a remarkable and generally unrecognized record of recent activity at Mount St. Helens and to compare it with the history of some other well-known volcanoes. We also assess the significance of the present dormant interval, which has lasted nearly 120 years. The data now available suggest that since about 2500 B.C. the volcano has never been dormant for more than about five centuries at a time and that dormant periods of one or two centuries, or less, have been more typical.

Even apparently dormant intervals may have been broken by eruptions that did not leave a conspicuous deposit. The eruptions noted in our chronology include only those which produced deposits large enough to be preserved and recognized today. As many or more eruptions may have occurred for which stratigraphic evidence either does not exist or has not yet been recognized. We see clear stratigraphic evidence, for example, of only one of the dozen or so 19th-century eruptions that were reported by explorers and settlers after Lewis and Clark's pioneer expedition of 1806 (*5*).

Since about 400 B.C., Mount St. Helens has shown considerable diversity both in its behavior and in the chemical composition of its eruptive products. Eruptions of basaltic and andesitic lava flows and tephra have been interspersed with eruptions of dacitic domes, tephra, and pyroclastic flows (*6*). Mount St. Helens has had a complex recent history, and the lithologic diversity of the resulting deposits makes it possible to recognize more volcanic events than if the eruptive products had all been of a single rock type.

Eruptive chronology. The known eruptions of about the last 4000 years can be roughly grouped into four periods: 2500 to 1600 B.C., 1200 to 800 B.C., 400 B.C. to A.D. 400, and A.D. 1300 through the first half of the 19th century (Fig. 3).

From 2500 to 1600 B.C., following a dormant period that may have lasted as long as 4000 years, Mount St. Helens repeatedly erupted large volumes of tephra, and successive domes were formed at the eruptive center. Shattering of the domes, perhaps by volcanic explosions, produced pyroclastic flows that moved beyond the volcano. Pumiceous tephras that were erupted at various times were carried downwind and some covered large lobate areas; at least one of these reached into northeast Oregon and another into western Alberta (*2*). A quiet interval of perhaps as much as 400 years may have occurred during this eruptive period.

In about 1200 B.C., after an interlude of no more than a few centuries, the volcano began to erupt domes and pyroclastic flows, but with smaller volumes of tephra. During this period, which lasted four or five centuries, many large hot pyroclastic flows of nonvesicular rock debris, pumice, or both, moved away from the volcano in nearly every direction. Some of the rock debris became mixed with water and formed lahars (volcanic mudflows) that streamed many tens of kilometers down river valleys. Radiocarbon dates from charcoal in volcanic deposits suggest that eruptions occurred sporadically throughout this period.

The eruptions of 400 B.C. to A.D. 400 produced both basaltic and andesitic lava flows, which were lacking in the earlier products of the volcano. However, the intermittent explosive eruptions of more silicic tephra, which had characterized the volcano's earlier history, continued and alternated with the eruptions of the more basic lava flows. Thus, the new behavior pattern was characterized by eruptions of several different types and of different kinds of rock in quick succession, perhaps even simultaneously from different vents. Eruptions of the volcano formed andesitic or dacitic tephra at least twice, basaltic tephra six times, dacitic or andesitic pyroclastic flows no less than three times, and lava flows at least twice. During this period the volcano initially produced lava flows, as well as tephra; then a series of pyroclastic flows was formed starting about 300 B.C.

Although a brief episode of explosive volcanism occurred about A.D. 840, the next major period of frequent and diverse activity evidently began between A.D. 1200 and 1300. From that time on, Mount St. Helens erupted basaltic or andesitic lava flows, dacitic domes, pyroclastic flows, and tephra. The largest tephra eruption of this period occurred about A.D. 1500 and spread pumice at least as far as northeastern Washington. The dacitic dome that forms the present summit of the volcano also was extruded during this period, probably between A.D. 1600 and 1700. The period of activity that roughly coincided with the first half of the 19th century produced tephra, a dacitic dome, and perhaps a few lava flows.

Frequency, duration, and volume. The frequency of eruptive activity can be inferred from the record and dates of known volcanism, but little is known about the duration of individual eruptions. Many eruptions, even relatively violent and voluminous ones, could have occurred within periods of a few days or months; other eruptions probably consisted of a series of small events spread over many decades. Volcanism at Mount St. Helens probably has included many brief but violent eruptive episodes like the catastrophic "Plinian" eruption of Vesuvius in A.D. 79, the eruption of Mount Lamington in Papua (New Guinea) in 1951 and 1952, or the violent outbursts at Santa Maria Volcano, Guatemala, that started in 1922 and still intermittently continue.

Figure 4 is a comparison of the volcanic activity at Mount St. Helens, Vesuvius, Fuji, and Hekla. The historic record at Vesuvius includes at least 10 and possibly 14 eruptions in the 1060 years following the one in A.D. 79 which buried Pompeii (*7, 8*); seven of these also can be identified in

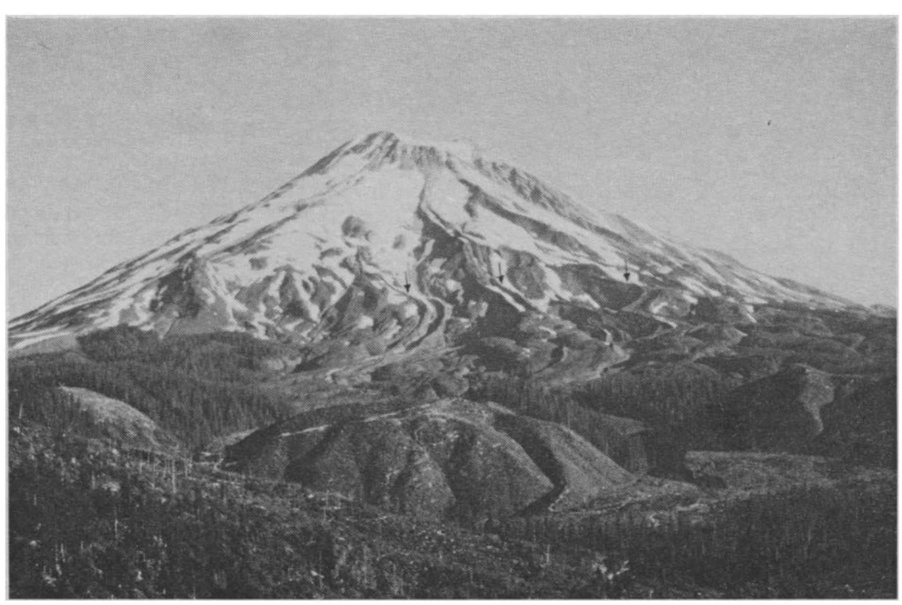


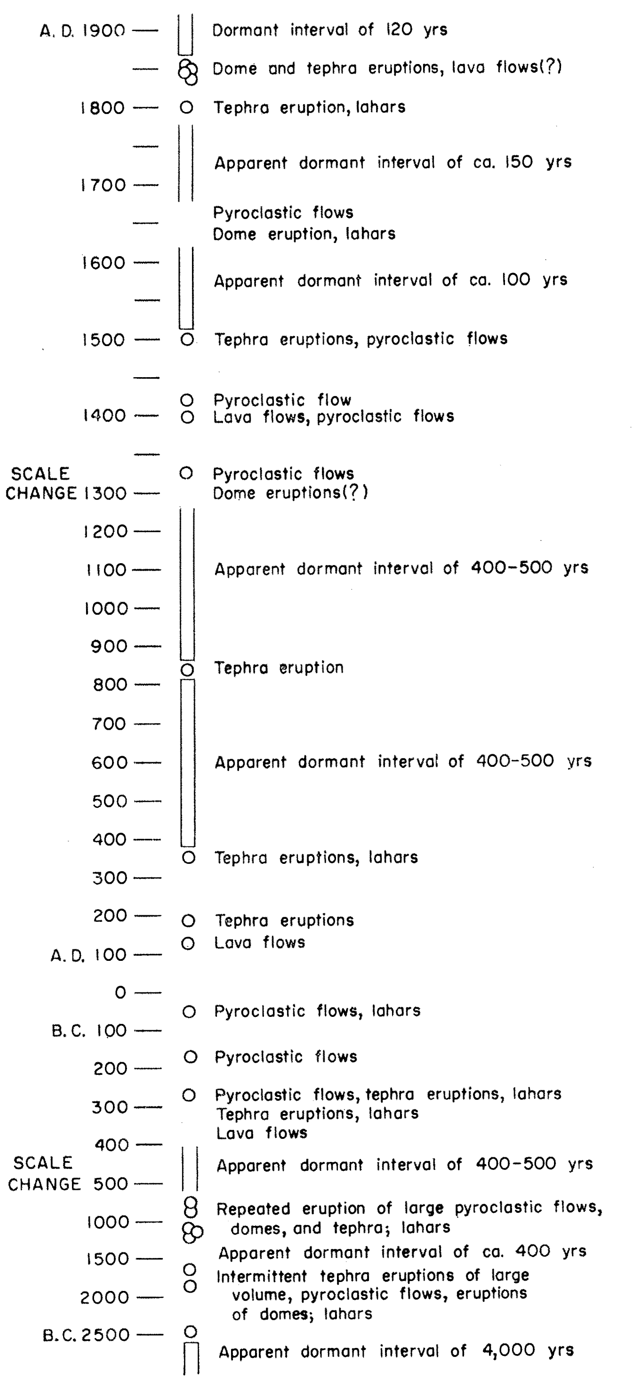
Fig. 2. South side of Mount St. Helens volcano (altitude, 2950 m). The summit consists of a volcanic plug probably emplaced between A.D. 1600 and 1700. Lava flows on the lower flank of the volcano in the center of the photograph are marked by sharp, curved ridges (arrows) formed along margins of flowing lava.

the stratigraphic record. Then a period of almost 500 years elapsed during which no unequivocal eruptions occurred; this period ended with the large 1631 eruption. Since 1631, however, the volcano has erupted at intervals of no more than a few decades.

At Fuji, another famous volcano with a long historic record (*9*), clusters of activity have been separated by dormant periods of varying length, up to 428 years; the volcano has now been inactive for more than 265 years. In contrast, Hekla Volcano in Iceland has erupted at least every hundred years or so since the island was settled (*10*).

With respect to the volume of material erupted into the air (in contrast to lava flows), Mount St. Helens has produced much less than did prehistoric Mount Mazama at the site of Crater Lake, Oregon, about 6600 years ago, or Tamboro in the East Indies in 1815; the latter was one of the most voluminous (if not the most voluminous) explosive eruptions of historic time. The volume of ejecta produced by some of Mount St. Helens' largest eruptions of the last four millennia, however, has been similar to that produced at certain times by Vesuvius, Fuji, and Hekla. Tephra erupted from Mount St. Helens in 1900 B.C., for example, is estimated to have a volume of at least 3 km^3, and an eruption in about A.D. 1500 laid down roughly 1 km^3 of similar ejecta. For comparison, the tephra from the 1707 eruption of Fuji is about 0.8 km^3 in volume (*9*). The largest deposit from a historic Hekla tephra eruption in A.D. 1104 is about 1.5 km^3 in volume (*10*), and the volume of the tephra deposit resulting from the Vesuvius eruption of A.D. 79 has been calculated to be about 2.6 km^3 (*11*).

Dormant intervals of thousands of years during the older history of Mount St. Helens can be recognized from buried weathering profiles in volcanic deposits. The profiles indicate that the



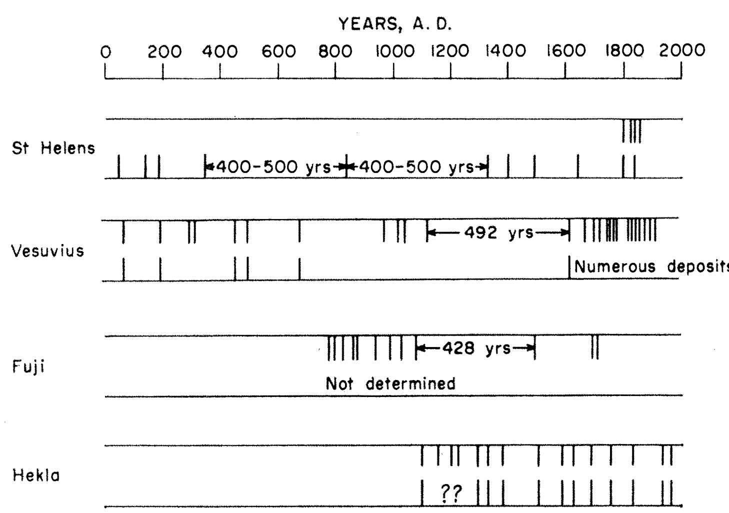


Fig. 3 (left). Eruptions and dormant intervals at Mount St. Helens since 2500 B.C. The circles represent specific eruptions that have been dated or closely bracketed (*13*); the vertical boxes represent dormant intervals. The known eruptions at Mount St. Helens can be roughly grouped into four periods: 2500 to 1600 B.C., 1200 to 800 B.C., 400 B.C. to A.D. 400, and A.D. 1300 through about the middle of the 19th century. Dormant intervals have typically lasted no more than a few centuries, and the recent behavior of the volcano has been variable. Fig. 4 (right). Volcanic activity at Mount St. Helens compared with the activity at Vesuvius (*7, 13*), Fuji (*8*), and Hekla (*9*), as shown by the historical records (upper scales) and the stratigraphic record (lower scales). The recent stratigraphic record at Mount St. Helens, together with the early 19th century historic record, suggests that if the area had been occupied by record-keeping people, the eruptive history would resemble that of some volcanoes for which long written records are available. Some eruptive episodes probably were virtually single large events; others probably were smaller events repeated at intervals of a few years over a long time.

weathered deposits were exposed at the surface for a long time before being covered by products of the next eruption. Radiocarbon dating of the youngest weathered deposit in such a profile, as well as of the oldest deposit above it, discloses the approximate length of a dormant interval. The imprecision of the radiocarbon dating method, which amounts to only a few hundred years, is minor relative to the total length of the dormant interval.

Dormant intervals of a few centuries are hard to recognize because weathering profiles developed in such short intervals are weak. The lengths of short intervals are also determined by radiocarbon dates, but the imprecision of the method is then large relative to the length of an interval. However, the radiocarbon method seems adequate to approximate intervals of several hundred years (Fig. 3) where there are many dates and good stratigraphic control.

During the last four millennia there has not been a dormant interval of as much as a thousand years at Mount St. Helens. Within this time, however, there were five or six intervals of more than two to about five centuries before A.D. 1800 during which the volcano seems to have been dormant. In addition, 12 dormant periods of one or two centuries in length have tentatively been identified, and many intervals of a few years or a few decades surely occurred during extended periods of eruptive activity.

A forecast. The repetitive nature of the eruptive activity at Mount St. Helens during the last 4000 years, with dormant intervals typically of a few centuries or less, suggests that the current quiet period will not last a thousand years. Instead, an eruption is likely within the next hundred years, possibly before the end of this century. Because of the variable recent behavior of the volcano, we cannot predict whether the next eruption will be of basalt, andesite, or dacite, and whether it will produce lava flows, pyroclastic flows, tephra, or volcanic domes. But if the eruptive period lasts years or decades, a variety of eruptive events and lithologic types can be anticipated (*12*).

DWIGHT R. CRANDELL
DONAL R. MULLINEAUX
U.S. Geological Survey, Denver Federal Center, Denver, Colorado 80225
MEYER RUBIN
U.S. Geological Survey, National Center, Reston, Virginia 22092

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Callisto: Disk Temperature at 3.71-Centimeter Wavelength

Abstract. *We observed the radio emission of Callisto with a three-element interferometer at the time of the 1973 opposition of Jupiter. Special care was taken to remove the residual, unresolved contribution from Jupiter itself in the antenna side lobes. The resulting disk temperature at a wavelength of 3.71 centimeters, assuming a radius of 2500 ± 75 kilometers for Callisto, was 101° ± 25°K. This temperature is much more consistent with emission from a simple dielectric sphere than the considerably higher temperatures that have been reported for wavelengths of 3.5 and 8.2 millimeters.*

To determine the feasibility of making radio measurements of the Galilean satellites, one can calculate approximately what flux density to expect for thermal emission from a given satellite at a given wavelength. The radii are known from optical measurements, the disk-average temperatures can be estimated from infrared measurements or from equilibrium considerations, and a guess can be made for the radio emissivity. The Galilean satellites turn out to be very weak radio sources but, nevertheless, are well above the detection limit for some existing instruments in the wavelength range from a few millimeters to a few centimeters.

In this case, however, the detection limit is not the only constraint. Another problem is the close proximity of Jupiter, a radio source about three orders of magnitude stronger than the Galilean satellites. This problem has delayed attempts to measure the disk temperatures (T_D) of the Galilean satellites, and it makes Callisto the easiest satellite to measure and Ganymede the next easiest, partly because of their larger sizes but mainly because of their larger distances from Jupiter.

The first published measurement was that of Gorgolewski (*1*). The resulting T_D for Callisto at a wavelength (λ) of 3.5 mm was 276° ± 87°K, assuming a radius of 2500 km. This is about twice the value that was expected, and an attempt to explain the high value was made by Kuz'min and Losovsky (*2*). They assumed that Callisto has a thick ice crust (*3*) that is very transparent to radio waves and has a temperature gradient that increases toward the interior. For their model they argue that in the microwave range one will "see" a brightness temperature of 200° to 220°K independent of the frequency.

Evidence has been reported (*4*) for water ice or frost on Callisto, but for only a small fraction of the surface area. Kuz'min and Losovsky argue that there may be a very thin layer of silicate debris overlying and obscuring the ice. A serious difficulty, however, is the very large penetration depth determined by Kuz'min and Losovsky and required to get a significant brightness temperature enhancement from their model. The ice will be very transparent, to be sure, but a penetration depth of many tens of kilometers, as required, appears to be some orders of magnitude too large according to recent determinations of the opacity of ice. The next published measurement was by Kuz'min and Losovsky (*5*). Their result at $\lambda = 8.2$ mm was $T_D = 234° \pm 100°K$, assuming a radius of 2500 km. They believed that this measurement gave added support to their model.

To shed some light on these matters and to gain experience in difficult detection observations, we measured the T_D of Callisto at $\lambda = 3.71$ cm near