Reports

Recent Volcanic Activity at Glacier Peak

Abstract. *Previous reports suggested that Glacier Peak, a volcano in northern Washington State, has been dormant for the past 11,000 years. New radiocarbon dates for volcanic deposits indicate that major volcanic events, such as tephra eruptions, pyroclastic flows, and mudflows traveling tens of kilometers, occurred at least five times in the past 1800 years and nine times in the past 5500 years.*

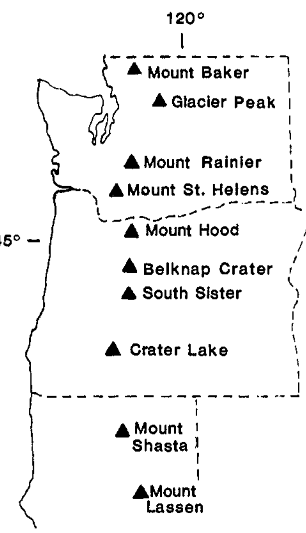
The most recent eruptions of Glacier Peak, a 3214-m volcano in northern Washington State (Fig. 1), are generally believed to have occurred 11,250 to 12,500 years ago, with at least 5 km^3 of pumice and ash being ejected. Deposits of this age have been recognized as far east as Montana and Alberta (*1*). Unlike many other Cascade volcanoes, Glacier Peak has no fumaroles at its summit, and there were no reliable reports of eruptions of Glacier Peak during the 19th century, when minor volcanic activity occurred intermittently at several other Cascade volcanoes (*2*). The apparent lack of historic activity, combined with geological studies in the 1960's which found no evidence of recent volcanic eruptions, led most earth scientists to conclude that Glacier Peak has been dormant for many thousands of years (*3*).

In this report I present a previously unrecognized history of activity at Glacier Peak. My conclusions are based on detailed studies of the origin and sequence of deposits produced during past volcanic events. More than 20 radiocarbon dates for mudflow, airborne tephra, and pyroclastic flow deposits, together with studies of the relative ages of some deposits, provide a chronological framework for the history (*4*). Radiocarbon dates for trees killed by volcanic deposits precisely date several events. Some deposits from Glacier Peak are intercalcated with ash deposits of known age produced by Mount St. Helens, Mount Mazama (Crater Lake), and Glacier Peak itself (*5*). Periods of dormancy, during which no new volcanic deposits were produced at Glacier Peak, are indicated by intervals of soil formation and by erosion of older deposits.

Only those volcanic events large enough to produce identifiable geological deposits are included in the chronology. It is likely that some small eruptions occurred which left no recognizable deposits, much as the many minor eruptions of several Cascade volcanoes during the 19th century produced only a few thin ash deposits of limited extent. Also, since volcanic deposits from successively older eruptions are increasingly likely to have been removed by erosion or buried by younger deposits, the history's coverage of older periods probably is not complete.

Initial estimates of the volume of products of past eruptions have been based on the mapped extent and measured thickness of preserved deposits. In most cases, only minimum estimates of volume can be made because valleys surrounding the volcano are so deeply buried by postglacial volcanic deposits that modern streams have not eroded to the base of the valley fills. Rough estimates of volume are reported to allow the magnitude of past eruptions at Glacier Peak to be compared with that of historic and prehistoric eruptions at other volcanoes.

The eruptions of Glacier Peak during the past 14,000 years (since the beginning of the retreat of ice-age glaciers from the Cascade Mountains) can be divided into eruptions that occurred from 12,750 to 11,250 years ago and a previously unrecognized series of events between 5500 and a few hundred years ago. The earlier eruptions were among the most violent and voluminous in postglacial time in North America. Volcanic ash was transported at least 1000 km east of the volcano, and pumice was deposit-



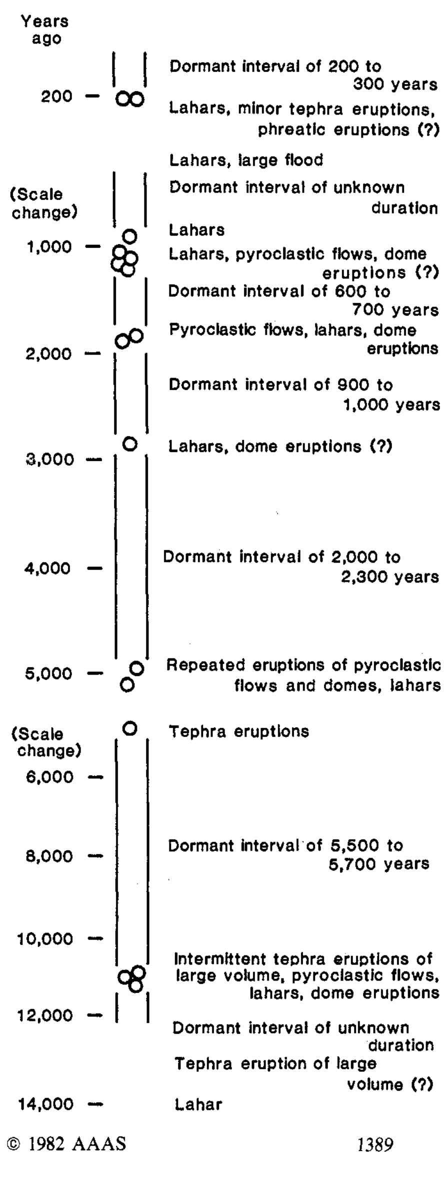


Fig. 1 (left). Map of the northwestern United States, showing the location of Glacier Peak and other Cascade volcanoes. Fig. 2 (right). Volcanic events and dormant intervals at Glacier Peak during the past 14,000 years. Circles represent events that have been radiocarbon-dated and vertical bars represent apparent dormant intervals (periods during which no significant deposits were produced by the volcano).

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ed to a thickness of 2 to 3 m as far as 30 km downwind. Pyroclastic flows extended more than 20 km, and some mudflows traveled as far as 120 km downstream. Approximately 5 km^3 of airborne tephra and 3 to 5 km^3 of pyroclastic and debris flows were produced (*6*).

After an apparent hiatus of approximately 5700 years, Glacier Peak again became active (Fig. 2). The resumption of eruptive behavior after thousands of years of dormancy underscores the difficulty of determining whether quiescent volcanoes are dormant or truly extinct. From 5500 to 5100 years ago, domes were emplaced near the summit of Glacier Peak and block and ash flows repeatedly swept down the flanks of the volcano. Valleys adjacent to the volcano were buried by at least 9 km^3 of debris. At the same time, mudflows and floods carried volcanic detritus at least 100 km down the Skagit River valley (*7*).

Apparently there followed a 2300-year interval of dormancy, during which streams and glaciers from the volcano cut valleys 100 to 300 m deep in the older volcanic valley fills. Around 2800 years ago, several mudflows traveled more than 20 km down the valley west of Glacier Peak. These may have been generated as a consequence of dome emplacement near the glaciated summit of the volcano, although no pyroclastic deposits of this age have been recognized.

Eruptions 1700 to 1800 years ago produced pyroclastic flows and mudflows which buried valleys on the east and west flanks of the volcano beneath as much as 100 m of debris. Mudflows and floods carried volcanic debris at least 100 km to the Skagit River delta. Several small towns in the lower Skagit River valley are built on volcanogenic sedimentary deposits of this age. Approximately 0.5 to 1.0 km^3 of new lithic material was ejected.

Sometime after 1800 years ago, a large mudflow containing hydrothermally altered volcanic rock traveled at least 30 km down the valley west of Glacier Peak. It is not known whether this flow was associated with a volcanic eruption, as other debris flows at Mount St. Helens (May 1980) and Mount Rainier (*8*) have been.

Many mudflows and some pyroclastic flows were produced in a complex series of events 1100 to 1000 years ago. Deposits of this age can be traced as much as 30 km downstream, and they locally buried valleys to depths of 80 to 100 m. About 0.10 to 0.25 km^3 of debris was ejected.

Between 1000 and 300 years ago, large floods and mudflows deposited debris 30 to 50 km down the valleys heading on the volcano. It is possible that small eruptions triggered the floods and mudflows, although no correlative pyroclastic deposits have been identified on the flanks of the volcano.

Early settlers and explorers did not record any eruptions of Glacier Peak. Nonetheless, Indian accounts suggest that Glacier Peak erupted sometime in the 18th century (*9*). These oral accounts are corroborated by the discovery of pumice and ash on moraines that are about 350 years old, indicating that the most recent eruption of Glacier Peak occurred in the 17th or 18th century.

The geological record shows that, during the past several thousand years, Glacier Peak has been one of the most active Cascade volcanoes. It erupted at least once in the past few centuries and many times since the end of the most recent ice age. If future eruptions at Glacier Peak resemble those of the past several thousand years, the chief hazards would be pyroclastic flows and superheated ash clouds near the volcano and mudflows and floods extending tens of kilometers. However, a sequence of events similar to that which occurred at Mount St. Helens in 1980, including the emplacement of a dome high in the glaciated cone and the concomitant eruption of a directed blast and large volumes of pumice and ash, is also possible. The recency and frequency of past volcanic events at Glacier Peak indicates that future monitoring is warranted.

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Kinetics of Delignification: A Molecular Approach

Abstract. *A treelike model has been proposed for the structure of lignin. Kinetics of delignification are formulated to account for the cleavage of linkages along the linear primary chains and at the cross-links. Experimental data obtained from isothermal delignification are used to verify this theory. Good agreement has been obtained in calculating the delignification curves. Activation energies are found to be 172 kilojoules per mole of cross-links and 132 kilojoules per mole of aryl ether bonds.*

Delignification is a major chemical process in the pulping of wood. The process has a long history, with a highly empirical kinetic description developed 40 years ago. Recently, I proposed a molecular model for lignin structure and a kinetic scheme associated with the delignification process (*1*). The model is broad enough to account for the linear and branched-chain structure of lignin; the kinetics are simple and flexible enough to allow for detailed curve fitting of experimental data. Experimental verification of this kinetic scheme is reported here.

The structural model used to describe lignin is the treelike model for branched polymers (*2–4*). Natural and insoluble lignins are regarded as a polymeric gel which coexists with the sol (soluble) fraction at any stage of delignification. The structure of lignin is described by units, linkages, and functionality defined as follows. (i) The basic unit is a phenylpropane (C_9) unit. Each unit contains one phenolic hydroxyl group, which may be free or bound (as aryl ether). (ii) Two C_9 units can be connected by only one linkage, regardless of the number of bonds between them. Thus in Fig. 1a, a linkage contains one bond. The linkages in Fig. 1, b and c, have two and three bonds, respectively. (iii) The units are linked monofunctionally and bifunction-

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