# Catastrophic flooding and eruption of ash-flow tuff at Medicine Lake volcano, California

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## ABSTRACT

**Catastrophic flooding has eroded a discontinuous network of oversized anastomosing channels on the northwest flank of the Medicine Lake volcano. Most of these previously unrecognized channels were cut into an andesitic ash-flow tuff; boulders as large as 2 m in intermediate diameter were moved in terrain where little rain falls today and stream erosion is nonexistent or minimal. The flooding was probably triggered by eruption of andesite tuff through a late Pleistocene ice cap on the volcano, about 60,000 to 70,000 or about 130,000 B.P.**

## INTRODUCTION

Medicine Lake volcano (MLV) is a large Pleistocene and Holocene shield volcano in northeastern California, about 50 km northeast of Mount Shasta. It rises about 1200 m above the Modoc Plateau to an elevation of 2376 m, and its lava flows cover about 2500 km$^2$. At the center of the volcano is a 7 × 12 km caldera containing Medicine Lake. The lake is 1 × 2 km in size and is the largest, and one of the few, standing bodies of water on MLV. Surface water on the volcano is rare because of the high permeability of the volcanic rocks.

## CHANNELS AND EVIDENCE FOR FLOODING

The lower northwest flank of the volcano displays a discontinuous network of previously undescribed relict channels that in some places disappear altogether onto gravel-covered plains. Measured channels are as large as 1700 m$^2$ in cross-sectional area and contain boulder deposits with clasts as large as 2 m in intermediate axis. Channel bottoms are flat and filled with alluvium in most places. Lack of postdepositional incision severely limits exposure of channel deposits. No mudflow deposits are seen, and all deposits found are thought to have been deposited by nonviscous flows. Deposits such as levees or flow fronts, indicative of debris-flow activity, were not found. In addition to channel deposits, many broad areas adjacent to the channels are covered by a thin layer of gravel. The distribution of channels, gravel veneer, andesite tuff, and younger lavas is shown in Figure 1. If gravels and channels existed on the south side of MLV, they have been buried by younger lavas.

The size of the largest bed-material clasts has been measured at six channel sites around MLV. The largest and most abundant clasts found at Site 1. This site is at the head of expanding reach immediately below a steep narrow reach. The intermediate axes of the five largest boulders found at Site 1 averaged 910 mm. Boulder sizes decrease rapidly below Site 1.

The morphology of the relict channels at MLV is similar in many respects to channels formed during catastrophic flooding in the Channeled Scabland of eastern Washington. Bretz (1969) and Baker (1973, 1978) described scabland channels as oversized anastomosing channels having low sinuosity. Channels at MLV fit this description; they show an anastomosing pattern and many long straight reaches (Fig. 1). All the channels discussed in this paper are extremely oversized. Although some channels contain small ephemeral streams in downstream reaches, most channel segments contain no evidence of active channel erosion. Thus, the channels are far larger than can be accounted for by present-day processes.

## ANDESITE TUFF

Many of the channels are incised into a partially welded andesitic ash-flow tuff (AT). Most AT is found low on the northwest flank of MLV. Outcrops have been discovered high on the northwest side of the volcano, on the east side, and at one locality within the caldera. Distribution of the tuff, together with an increase in size of pumices and lithic fragments toward the caldera, indicates that AT erupted from within the caldera, although the exact location of the vent is unknown and may be covered by younger flows or by Medicine Lake. The outcrop at Schonchin Spring, 1 km northwest of Medicine Lake, contains by far the largest pumices and lithic fragments in AT. Some of the tuff and underlying rocks at Schonchin Spring are hydrothermally altered.

No outcrops of AT have been mapped on the caldera rim, although AT postdates formation of the caldera and postdates some of the lavas that are found on the rim. The previously recognized distribution of AT low on the northwest flank of the volcano suggested to workers that it was the volcano's oldest unit (Anderson, 1941; Mertzman, 1977). Attempts to date AT and overlying lavas by the potassium-argon method have been unsuccessful. The lack of AT on the caldera rim suggests that the presence of ice and/or snow may have prevented AT from depositing directly on the ground surface.

On the edifice of MLV, AT is typically found in swales and low areas. As AT traveled down the flanks of the volcano, it was apparently channelized, and it rarely overtopped topographic obstacles. On the far northwest flank of the volcano, beyond the change in slope from the edifice to the surrounding plateau, AT spread out over broad flat areas. Typical thicknesses are less than 1 to about 5 m.

The present distribution of AT indicates that the eruption may have been a directed one. The thickest, coarsest exposures of AT are located to the west and northwest of the caldera. Outcrops to the north and east are thin and scattered. The original distribution of AT is unknown; large areas of the volcano are covered by younger flows, and it is unknown whether AT traveled to the south. Although the age of AT is unknown, the tuff is stratigraphically younger than rhyolite obsidian dated at 0.30 Ma (unpub. K-Ar dating; J. Donnelly-Nolan). On the basis of outcrop and weathering characteristics, AT is probably significantly younger than the obsidian.

## GLACIATION

Evidence of glacial activity such as glacial striations, polish, and erratics are common at higher elevations on MLV. Anderson (1941) estimated that ice reached thicknesses up to 150 m. The ice overrode cinder cones more than 100 m high on the northwest and west rim of the caldera, most of which is at an elevation of about 2100 m. Evidence for ice extends down to about 1920 m; the floor of the caldera is about 2010 m in elevation and almost certainly was covered with ice. Outside the caldera, outcrops of AT are found only below 1920 m.

AT must have erupted prior to the most recent glaciation because lava flows younger than AT were glaciated during the most recent glaciation and show no evidence of interaction with ice during their eruption. Deposition of AT on glaciated surfaces of late Pleistocene

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flows west of the main edifice indicates that the eruption took place later than the greatest extent of late Pleistocene glaciations. By correlation with the deep-sea oxygen-isotope record, Colman and Pierce (1981) indicated times of cooling at about 130,000 to 150,000 B.P. during oxygen-isotope stage 6, and at about 60,000 to 70,000 B.P. during stage 4. Eruption of AT probably took place during stage 4 or late in stage 6.

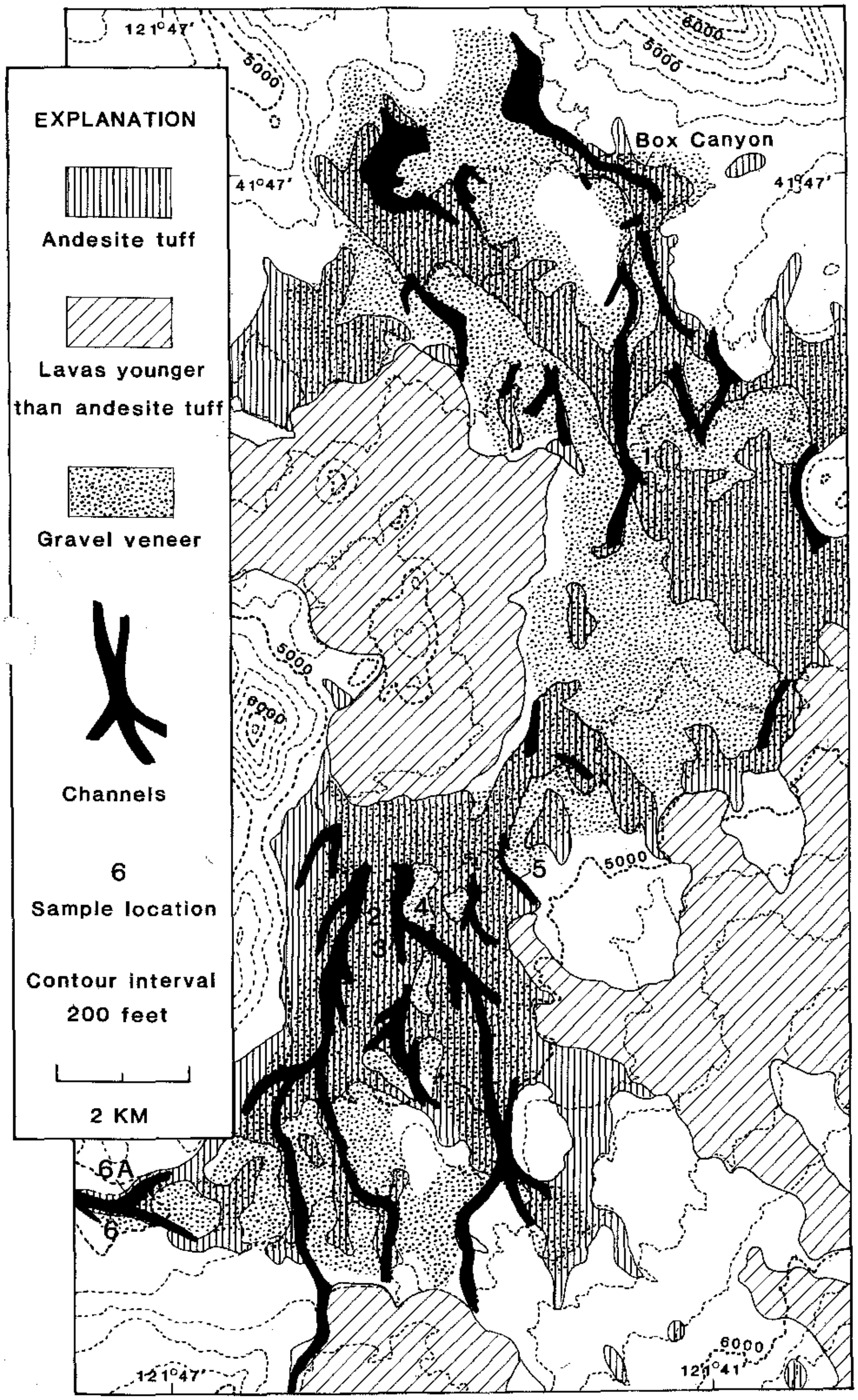


Figure 1. Distribution of andesitic ash-flow tuff (AT), younger lavas, channels, and gravel veneer on northwest flank of Medicine Lake volcano. Numbers refer to measured sites (see text and Table 1). Medicine Lake is located 5 km southeast of area shown at southeast corner of figure.

## LITHOLOGY OF FLOOD DEPOSITS

Boulders of AT are common in the channel deposits. Other boulder types are derived from flows older than AT. These flows crop out within a few kilometres upstream of the flood deposits. No boulders of lavas younger than AT were recognized. Thus, the flood deposits postdate AT but predate upstream lavas younger than AT.

## POSSIBLE CAUSES OF FLOODING

### Eruption Under or Through Ice

Melting of ice by an eruption under or through an ice cap on MLV would provide a source of heat capable of producing a large volume of water. It is unclear whether hot lava flowing over or hot pyroclastic material falling on ice or snow could produce a sudden melting that would yield the kind of catastrophic flooding indicated by the channel evidence. Such eruptions might melt ice and snow; the water would then perhaps be stored temporarily in a lake on top of the ice. The heat from the impending eruption of AT may have helped to create or enlarge an existing lake, or a lake may have been present before AT erupted. Volcanic activity in Iceland has generated lakes several cubic kilometres in volume and produced volcano-glacial jökulhlaups having peak discharges as high as 100 000 m$^3$/s (see Thorarinsson, 1957; Björnsson, 1974). Hot AT falling on the flanks of MLV may also have dislodged and mixed with snow and ice, causing melting (see Fairchild and Dunne, 1985). A hot explosive eruption of Mount St. Helens in 1982 (Waitt et al., 1983) interacted with the snowpack and produced an avalanche, a transient lake, and a lahar. The lake had an estimated volume of 4 × 10$^6$ m$^3$.

There are no lava flows at MLV that show signs of having erupted through ice. AT, however, because of its fragmental nature, could have erupted through ice without showing direct interaction effects. The lack of AT anywhere on the caldera rim suggests that a covering of ice or snow may have prevented direct deposition of the tuff on the ground surface. It is difficult to imagine any other reason for nondeposition of an ash-flow tuff near its source. If AT was deposited on the rim, then some mechanism is required to remove it entirely. Ice is the only likely mechanism, but 100% efficiency in removing all traces of AT on the caldera rim seems improbable.

### Limnoglacial Jökulhlaup

A jökulhlaup (glacial outburst flood) unrelated to an eruption could have cut the channels. The caldera is the only logical site on MLV where water could be stored. At MLV, the lowest point on the caldera rim is on the southeast side of the caldera, not the northwest side where water would run downhill to the channels. The southeast side of the caldera is about 90 m lower than the northwest rim. This southeast area shows considerable evidence of glacial action and may have been filled with ice moving out of the caldera. For such a jökulhlaup to produce the flood, an accumulation of ice to the southeast would have had to act as a dam allowing water to overtop to the northwest. Sources of water would be rainfall and snowmelt such as feed Medicine Lake today, and possibly melting of ice during warmer periods. Such a jökulhlaup would have had to occur following emplacement of AT but prior to emplacement of younger lavas upstream from the channels.

### Glacial Melting

It is difficult to envisage a process of glacial melting that would act rapidly enough to produce the channel features that are seen. A climatic change might produce meltwater that could accumulate on the ice cap and contribute to a jökulhlaup.

## FLOOD DISCHARGE ESTIMATES

Peak water discharges in the channels were estimated by use of techniques outlined by Costa (1983). No estimate was made of discharge over the broad upland areas covered by gravel veneer. Costa's methods use the size of maximum particle transport together with channel slope to estimate both average water velocity and depth. Velocity at a site is estimated by using the average intermediate axis of the five largest boulders transported and an equation that relates velocity to boulder size. This equation represents the arithmetic average of two theoretical and two empirical relationships determined by other investigators. Average depth is estimated by using boulder size and the arithmetic average of depths computed by the Manning equation, unit stream power, Shields' Function, and a relative smoothness equation. Costa (1983) found these methods to be much more accurate than many "order of magnitude" estimates of peak discharge made for paleofloods by other authors. Costa's reconstruction of peak discharges in small streams in the Rocky Mountains averages 28% below estimates obtained by using slope-area techniques, and were 76% higher than slope-area estimates for the 1976 peak on the much larger Big Thompson River. Reconstruction of peak flow in MLV channels assumes that the channels were cut and boulders deposited during a single paleoflood, that the channels have not been significantly modified since, and that boulders were not transported by viscous or hyperconcentrated flows.

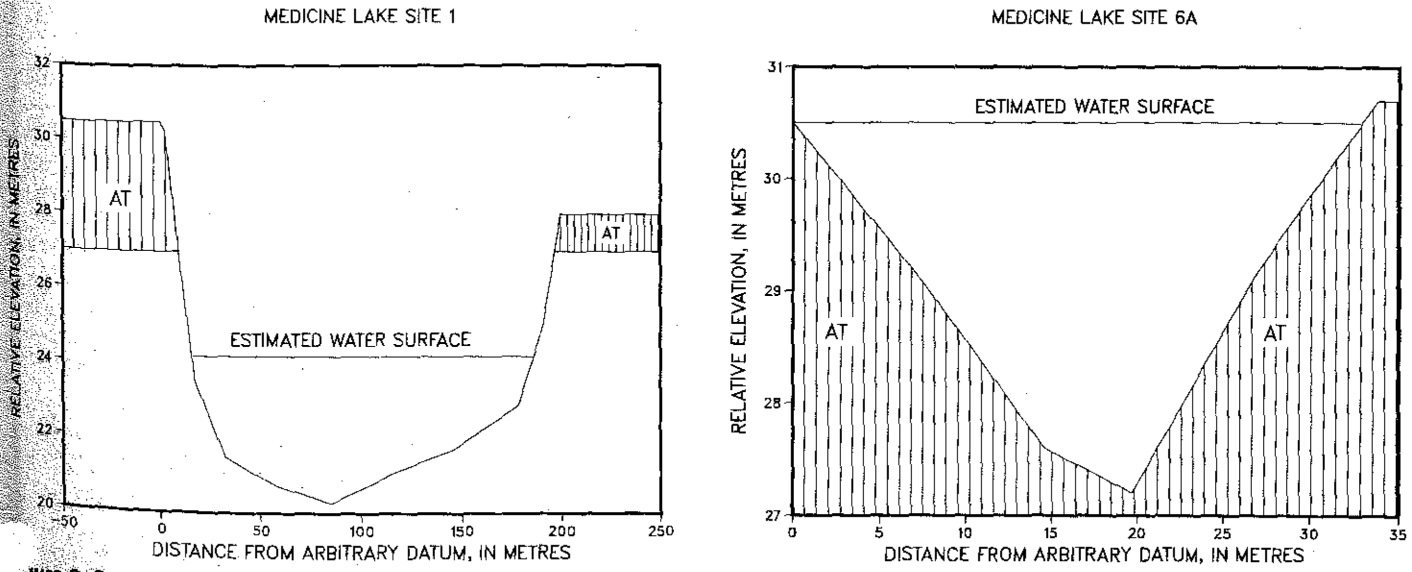
Peak discharges were estimated by using the maximum boulder transport technique rather than slope-area techniques (Dalrymple and Benson, 1967) because high-water marks were difficult to find and because flood flows appear to have significantly scoured some channels. Such scour would leave high-water marks, if present, anomalously high and thereby produce erroneously high estimates of water discharge if slope-area techniques were used (see Costa, 1983, p. 999). Estimates of water surface elevations by using maximum particle techniques appeared reasonable when channel scour was considered. In channels that had scoured through AT, estimated water surfaces were well below the tops of channel banks. Where AT still crops out in channel bottoms, and scour was less, estimated water surfaces were at, or near, the tops of channel banks (Fig. 2).

Although the maximum boulder transport technique appeared more appropriate than slope-area methods for estimating peak water discharge, two problems were encountered with the maximum particle technique which may cause discharge estimates to be conservative. (1) The fracture pattern of AT, the rock type that was probably most available to flood waters, limits the potential size of boulders available for transport. This means that boulders deposited at some sites may not fully represent the transport capacity of flood waters. (2) Boulders larger than those measured may be buried beneath alluvium in some places.

### Field Methods

Surveyed channel cross profiles were used for discharge estimates. Where possible, they were surveyed in relatively straight, depositional reaches that had bedrock banks. Intermediate axes of the five largest boulders at cross-profile sites were measured. To eliminate the possibility of using colluvial blocks rather than fluvially transported boulders, only boulders having lithologies different from those of adjacent hillslopes or channel banks were measured. In some cases this means that the boulders measured were not the largest found, so some discharge estimates may be conservative. This was particularly true at Sites 3 and 4.

Slopes at Sites 3 to 6 were measured by using tape and level for approximately 10 channel widths above and below cross-profile sites. At these sites, AT was exposed in most channel bottoms. Much more channel fill is present at Sites 1 and 2. Discharge calculations from surveyed slopes at Sites 1 and 2 were unrealistically low. Therefore, slopes at these two sites were measured from topographic maps, thus allowing slopes to be averaged over longer distances, thereby giving more realistic estimates of water discharge. Channel fill after pas-



ure 2. Cross profiles surveyed at Sites 1 and 6A showing estimated water surface and position of AT. Channel and flood parameters for Site 6A are included in downstream Site 6 (see Table 1).

sage of the flood peak apparently reduced channel slope at these sites.

One very large channel is not described here because no boulders could be found in it for calculating discharge. The boulders probably exist and are buried by finer grained sediment deposited by later stages of the flood. This channel, Box Canyon (Fig. 1), is about 30 m deep and begins abruptly in a flat area of 2- to 3-m-thick AT. We think that the omission of Box Canyon from flood calculations does not significantly change our estimate of the size of the flood because the canyon would have collected water from measured upstream channels.

### Discharge Estimates

Estimates of peak discharge at the six sites studied on the northwest flank of MLV are summarized in Table 1. If the peak discharge occurred simultaneously in all channels, it would have been at least 3300 $m^3/s$. This value represents a minimum peak discharge, for several reasons: Conservative methods were used to identify channels and transported boulders; the flood estimate does not include flow over broad areas covered by gravel veneer outside of channels; and younger lavas have probably covered evidence of flooding in some areas. For comparison, the widely publicized 1976 flood in the Big Thompson Canyon, Colorado, produced a peak discharge at the mouth of between 884 $m^3/s$ (U.S. Geological Survey, 1977) and 1552 $m^3/s$ (Costa, 1983). A peak discharge of 960 $m^3/s$ was recorded at a stream-gaging station 58 km from Mount St. Helens after the 1982 eruption-triggered flood documented by Waitt et al. (1983).

We have no method of estimating the duration of peak flow and therefore have no estimate of total flood volume. However, the ice cap is estimated to have covered 90 $km^2$. If AT covered only half of this area and sufficient heat were transferred to melt 2.0 m of ice, $8.10 \times 10^7$ $m^3$ of water would have melted from the ice cap (assuming an ice density of 0.9 $g/cm^3$). This would be sufficient water to sustain a peak flow of 3300 $m^3/s$ for about 7 h.

TABLE 1. SUMMARY OF RELICT CHANNEL CHARACTERISTICS, MAXIMUM SIZE OF TRANSPORTED BOULDERS, AND ESTIMATES OF PEAK WATER DISCHARGES

| Site no. | Channel slope (m/m) | Avg. diam. of B-axis; largest boulders (mm) | Est. depth (m) | Cross-section area below est. water surface ($m^2$) | Est. velocity (m/s) | Est. discharge ($m^3/s$) |
|---|---|---|---|---|---|---|
| 1 | 0.010 | 910 | 3.0 | 495* | 5.0 | 2500 |
| 2 | 0.010 | 660 | 2.2 | 60 | 4.2 | 250 |
| 3 | 0.025 | 220 | 0.8 | 22 | 2.8 | 62 |
| 4 | 0.031 | 238 | 0.6 | 7.3 | 2.6 | 19 |
| 5 | 0.036 | 350 | 0.8 | 37 | 3.1 | 115 |
| 6 | 0.026 | 680 | 1.4 | 84 | 4.3 | 360 |
|  |  |  |  |  |  | 3300† |

*Represents average of two cross profiles surveyed at this site.
†Total rounded to maintain consistency of significant figures.

## DISCUSSION

We favor the hypothesis that AT erupted when ice covered much of the top of MLV. We think the channels were cut by catastrophic flooding soon after the eruption of AT. The flooding required the availability of a large amount of water at a single time such as might be stored in a lake in the ice cap after the eruption. Venting of AT in the western half of the caldera, particularly if the eruption were directed toward the northwest, would facilitate formation or enlargement of a local lake and would leave the remaining ice to the east to block the southeast outlet. Thus, the lake could rise and overtop the ice on the northwest rim of MLV. A lake covering about the same area as the present Medicine Lake and 35 m deep would contain $7 \times 10^7$ $m^3$, and if emptied completely would sustain the estimated peak flow for about 6 h.

The flooding could have occurred during a subsequent glaciation, but this requires a hiatus in volcanism so that lavas younger than AT would be unavailable to form part of the flood deposits. Moreover, the close spatial association of AT with the channels and gravels suggests a cause-and-effect relationship. We think that the eruption and flood occurred in close succession late in oxygen-isotope stage 6 (about 130,000 B.P.), or during stage 4 (60,000–70,000 B.P.).

## CONCLUSIONS

The passage of time has obscured evidence pertaining to both the flood and the andesite tuff. It is difficult to reconstruct in detail the events associated with eruption of AT and with the subsequent flooding. The available field evidence is limited, and there are uncertainties about the shape and size of the probable ice cap and about whether a lake existed and how large it might have been. However, the relict channels provide evidence that catastrophic flooding did occur. Similar undocumented flood evidence may exist around other potentially active volcanoes and provide a means of assessing the magnitude of possible flood hazards.

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