Susceptibility to Mudflows in the Vicinity of Lassen Peak, California

By Donna C. Marron *and* Julie A. Laudon

Abstract

Mudflow deposits emplaced during eruptions of Lassen Peak in 1915 and those that predate the 1915 eruptions indicate that stream valleys in the vicinity of Lassen Peak, northeastern California, are susceptible to mudflows. Mudflows related to eruptions in 1915 traveled approximately 20 kilometers down Lost Creek, approximately 7 kilometers down Hat Creek, and less than 3 kilometers down Manzanita Creek. A different sequence of eruptive events in 1915 could have generated larger mudflows. Pre-1915 mudflow deposits possibly related to the extrusion of Lassen Peak are exposed in the headwaters of Manzanita Creek. The summit morphology and fracture patterns before and during the 1914-15 eruptions indicate that stream valleys that drain Lassen Peak to the northwest and southeast are most likely to be affected by eruption-related mudflows should future eruptions of Lassen Peak occur. Damage reports and existing 1915 mudflow deposits indicate that much of the apparent mudflow damage in 1915 was caused by hyperconcentrated streamflow downstream from a mudflow. An ancient landslide on a glacially undercut slope underlain by hydrothermally altered rocks in the valley of Mill Creek is temporally correlated with a 3,860 ± 50-year old mudflow deposit approximately 4 kilometers downstream; this finding indicates that landslides resulting from a combination of steep slopes and the low shear strength of hydrothermally altered rocks can generate mudflows in some stream valleys near Lassen Peak.

INTRODUCTION

Purpose and Scope

Recent study at Mount St. Helens (Janda and others, 1981; Waitt and others, 1983) in addition to research conducted at other Cascade volcanoes (Crandell, 1971; Miller, 1980) indicates that mudflows are the most laterally extensive and perhaps the most severe hydrologic hazard associated with volcanic activity in the Pacific Northwest. Lassen Peak, as a large volcanic dome, has a considerably more limited eruptive history than the stratovolcanoes that are more common in the Cascade Range. Volcanic domes are steep-sided features formed by the extrusion of viscous lava. Stratovolcanoes are built by the accumulation of alternating layers of lava, pyroclastic flow deposits, and mudflow deposits. Mudflows caused by eruptive activity at Lassen Peak in 1915 show that, despite these differences, the Lassen area is susceptible to mudflow hazards. The purpose of this study was to look for evidence of mudflows in the geologic record in the vicinity of Lassen Peak, and to examine the implications of recent work on volcanic-mudflow generation and movement with regard to future mudflow hazards in the Lassen area. An understanding of the geologic history of the Lassen area is stressed as being a critical part of evaluating both the susceptibility of stream valleys near Lassen Peak to mudflows and the degree to which mudflow hazards near Lassen Peak resemble mudflow hazards near other volcanoes.

Previous Work

Potential geologic hazards in Lassen Volcanic National Park were studied by D.R. Crandell and D.R. Mullineaux (U.S. Geological Survey, written commun., 1970). Their report discusses hazards associated with eruptive activity, landslides, mudflows, and floods. Statements regarding mudflow hazards are general, and indicate that stream valleys draining Lassen Peak are most susceptible to mudflow activity. Crandell and Mullineaux suggested that mudflows associated with future eruptive activity at Lassen Peak could be as large or larger than the mudflows that occurred in 1915.

The 1914-15 eruptions and associated mudflows at Lassen Peak were described and discussed by Day and Allen (1925), Finch (1930), and Williams (1932). Loomis (1926) provided excellent photography of the 1914-15 eruptions and mudflows. Eppler (1984) described the deposits left by the 1915 Lassen Peak mudflows and discussed the mechanics of the emplacement of the deposits.

Studies of mudflow deposits in the vicinity of several Cascade volcanoes provided the framework for the stratigraphic evaluation of mudflow deposits used in this study. To assess mudflow hazards near the Cascade volcanoes, Crandell and Mullineaux (1975) pointed out that stratigraphy and extent of mudflow deposits must be studied. Mullineaux and Crandell (1962) and Crandell and Mullineaux (1973, 1978) studied mudflow deposits from Mount St. Helens in Washington. Crandell (1971) studied mudflow deposits from Mount Rainier in Washington, and Miller (1980) studied mudflow deposits from Mount Shasta in California.

Observations of mudflow generation and movement caused by recent eruptions at Mount St. Helens also have been helpful in understanding modern mudflow hazards at Lassen Peak. Cummans (1981) and Janda and others (1981) discussed mudflows caused by the May 18, 1980, eruption of Mount St. Helens. Waitt and others (1983) discussed mudflows caused by a subsequent smaller eruption at Mount St. Helens. Pierson and Scott (1985) discussed the downstream dilution of a volcanic mudflow to a hyperconcentrated streamflow near Mount St. Helens. Hyperconcentrated streamflows have sediment loads of 40 to 80 percent by weight and have rheologic properties that are intermediate between those of mudflows and those of flowing water (Beverage and Culbertson, 1964).

ACKNOWLEDGMENTS

The authors are particularly grateful to Michael A. Clynne (U.S. Geological Survey) and Dean B. Eppler (Arizona State University) for field and office discussions and helpful manuscript reviews. Robert L. Christianson (U.S. Geological Survey) and Amy E. Cook (U.S. Geological Survey) pointed out key field relations. Radiocarbon dating was done by Deborah A. Trimble (U.S. Geological Survey). Richard L. Vance (U.S. National Park Service) provided helpful information and access to Lassen Volcanic National Park.

VOLCANIC MUDFLOW GENERATION

The generation of a volcanic mudflow requires a source of water and a large volume of easily mobilized sediment. Loose debris is commonly present on the flanks of volcanoes; hence, the sudden availability of water in volcanic areas commonly is the controlling condition in mudflow generation. The great relief common near volcanoes causes mudflows to increase or maintain their speed and to flow long distances downstream.

Crandell (1971) described a variety of conditions that have caused mudflows on and near various volcanoes. Conditions directly related to volcanic eruptions include the expulsion of a crater lake, the direct extrusion of mud from a vent or fissure, the temporary damming of a river by rock debris from an eruption, the melting of snow and ice by a volcanic blast or pyroclastic flow, the collapse of hydrothermally altered volcanic dome rocks as a result of volcanic or phreatic explosions, and the melting of snow and ice by contact with a lava flow. Conditions unrelated or indirectly related to volcanic eruptions include the breaching of large lakes on or near volcanoes, the release of water stored in or behind glacial ice, and the mobilization of loose pyroclastic deposits or other volcanic materials on steep slopes by intense rains or rapidly melting snow. Landslides that are common in hydrothermally altered areas near some volcanoes can generate mudflows by incorporating streamflow and mobilizing downstream into mudflows (Johnson and Rahn, 1970) or by damming a stream, creating a small lake that incorporates sediment and that flows downstream as a mudflow when the dam breaches.

GEOLOGIC HISTORY OF THE STUDY AREA

Lassen Peak is one of the southernmost Cascade volcanoes (fig. 1). Eruptions in the vicinity of Lassen Peak date back to the late Pliocene. Lavas, pyroclastic flow deposits, and mudflow deposits that form a large

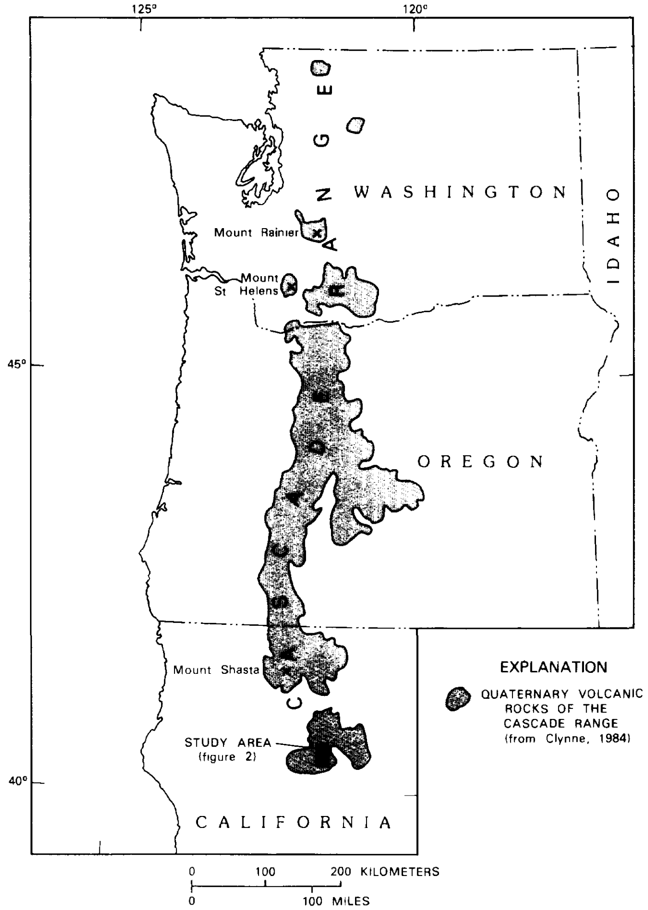

Figure 1. Location of the study area and Quaternary volcanic rocks in the Cascade Range.

plateau in the area have been attributed to three volcanic centers, each of which had a cone-building stage followed by a period of silicic dome building, lava flow extrusion, and pyroclastic flow emplacement (Clynne, 1984). The most recent of the three centers is called the Lassen volcanic center (Williams, 1932). Remnants of the stratovolcano created during the cone-building stage of this center (Brokeoff volcano) include Brokeoff Mountain, Mount Diller, and Mount Conard (fig. 2). Brokeoff volcano was constructed during the period between 0.35 and 0.70 million years ago (Clynne, 1984), after which the massive volcano was largely destroyed by glaciers that extensively eroded the hydrothermally altered cone (Williams, 1932). The long-lived volcanic centers are within an area of basaltic volcanism of a regional nature that has produced shield volcanoes, lava flows, and cinder cones (Clynne, 1984).

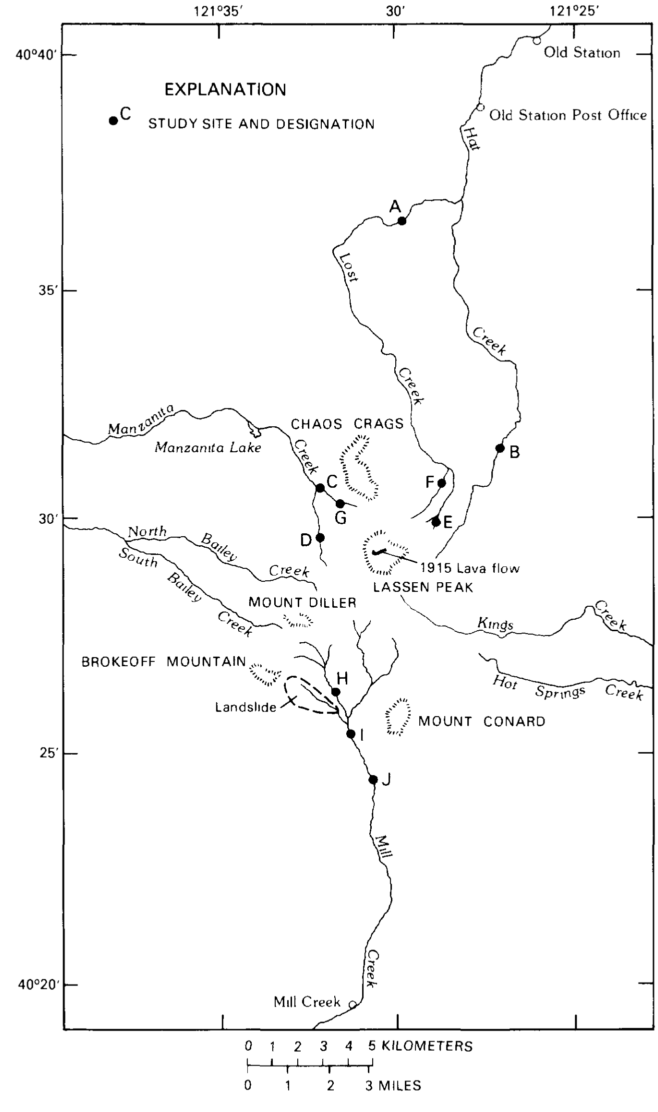

Figure 2. Location of study sites. Sites A-D mark the downstream extent of 1915 mudflow deposits. Locations of sites A and B from Eppler (1984).

Crandell (1972) estimated the age of Lassen Peak to be about 11,000 years, based on glacial evidence and the geometry of the mountain. In particular, the lack of major well-defined cirques on Lassen Peak, the talus cone that could not have survived glaciation but that presently surrounds Lassen Peak, and glacial striations on rock surfaces close to Lassen Peak that are in orientations that do not parallel likely flow directions for glaciers that originated on Lassen Peak indicated to Crandell (1972) that the extrusion of Lassen Peak postdated the most recent major glaciation (11,000 to 15,000 years B.P.) in the area. Small glacial cirques and moraines on Lassen Peak were attributed by Crandell (1972) to minor glaciation (5,000 to 11,000 years B.P.) that corresponds to a late Tioga age glacial advance in the Sierra Nevada.

New evidence suggests that a part of Lassen Peak predates major glaciation in the Lassen area. Clasts, which have a lithology that is indistinguishable in hand specimen from the lithology of the Lassen Peak dome, are widespread in glacial deposits that extend more than 10 km downstream from Lassen Peak in the Lost Creek valley. Hand-specimen clasts in glacial material are considered to have the same lithology as Lassen Peak rocks if they have a silicic, glassy groundmass; abundant phenocrysts of feldspar, quartz, biotite, and hornblende; and distinctive emerald-green phenocrysts of augite. The groundmass, where fresh, is light gray to medium gray, the darker color indicating a higher glass content. Where oxidized, the groundmass appears pink to red. Phenocrysts consist of about 70 to 80 percent feldspar, 10 percent or more quartz, at least 5 percent biotite, 5 percent hornblende, and traces of augite (M.A. Clynne, U.S. Geological Survey, oral commun., 1984). Although none of these mineralogical characteristics alone is unique, together they produce a unique lithology that can be distinguished from other lithologies in the area.

The apparently unglaciated appearance of much of Lassen Peak contrasts with a bowl-shaped valley on the northeast side of Lassen Peak (the headwaters of Lost Creek), which resembles a glacial cirque more than the side of an unglaciated volcanic dome. Lassen Peak may have been extruded during more than one dome-building period—one preceding major glaciation, and another in postglacial times that obscured most of the glacial features of the older dome. Chemical data for Lassen Peak rocks show two distinct groups within the dome (M.A. Clynne, U.S. Geological Survey, written commun., 1985).

Known eruptive activity in the Lassen Peak area that postdates the extrusion of Lassen Peak includes the extrusion of Chaos Crags and associated pyroclastic flows, multiple eruptions of a small cinder cone about 18 km northeast of Lassen Peak (James, 1966), and the

1914-15 eruptions at Lassen Peak. The Chaos Crags dome-forming and pyroclastic events, dated at 1,050 years B.P. (Clynne, 1984), resemble other episodes of the silicic volcanism that characterizes the present stage of the Lassen volcanic center. The cinder-cone eruptions, which included the extrusion of lava flows and the formation of a small cinder cone, resemble other episodes of the hybrid andesite volcanism that also is characteristic of the present stage of the Lassen volcanic center (Clynne, 1984). The hybrid andesite volcanism is the result of mafic magma from deep in the Earth's crust mixing with a shallower body of silicic magma, from which nearby silicic domes and associated pyroclastic flows were derived (Clynne, 1984). Neither the Chaos Crags nor the cinder-cone eruptions apparently were associated with significant mudflows. Relief in the area was not sufficient to give potential mudflows much momentum. Also, the geometry and the cooling history of Chaos Crags and the cinder cone during the period of volcanism probably were not conducive to the collection of a large snowpack, which is an important source of water for mudflow generation.

1914-17 ERUPTIONS AND MUDFLOWS AT LASSEN PEAK

Until the May 1980 eruptions at Mount St. Helens, Lassen Peak was the site of the most recent volcanic eruption in the conterminous United States. The 1914-17 eruptions of Lassen Peak started with an eruption of clouds of ash and water in May 1914, and continued with similar mild eruptions until May 1915. A lava flow became visible at the summit of Lassen Peak on May 19, 1915. On that night, a sediment-rich flood carrying pieces of the new lava damaged property in the valleys of Lost and Hat Creek valleys. A volcanic blast on May 22, 1915, destroyed part of the forest on the northeast flank of Lassen Peak, and generated a large mudflow in the valley of Lost Creek and a smaller mudflow in the valley of Hat Creek (fig. 2). Smaller mudflows were emplaced in the valley of Manzanita Creek at an undetermined time on May 22, and on the northeast flank of Lassen Peak on May 22 after the large blast and its associated mudflows. Eruptions of ash and water vapor continued intermittently until June 1917.

The specific conditions that caused the first of the two large mudflows at Lassen Peak in 1915 are controversial. Diller (1916) and Day and Allen (1925) attributed the snowmelt, which provided the water for the mudflow, to a laterally directed volcanic blast. Finch (1930) reinterpreted the events and decided that contact with newly extruded lava melted the snow. The lava-flow hypothesis became widely accepted (Williams, 1932; Crandell, 1971) but has recently been contested by Eppler (1984) who supported the volcanic-blast hypothesis.

Because the May 19 mudflow and its presumed initiating event occurred at night, and because the May 22 blast and mudflows covered much of the area affected by the May 19 mudflow and possible volcanic blast, indirect evidence must be used to test the different hypotheses. Calculations by Eppler (1984) indicate that the heat transfer resulting from contact of the May 19 lava flow with underlying snow was not sufficient to melt the water required for the rather large May 19 mudflow. Eppler (1984) also made calculations indicating that the steam released by juvenile magma was not an adequate source of water for the May 19 mudflow. Photographs of the crater taken before the May 19 mudflow show a small lake; however, its apparent volume is orders of magnitude smaller than the estimated water requirement for the May 19 mudflow. Tentative evidence of a small May 19 volcanic blast is seen in photographs taken before May 19 and between May 19 and May 22. According to Eppler (1984), these photographs show the denudation, probably by a small volcanic blast, of a small, previously forested area that lies outside the path of the May 19 mudflow. A volcanic explosion may have broken up the lava flow, facilitating more efficient heat transfer between lava and snow. A major eruption, during which a laterally directed volcanic blast denuded considerable parts of the northeastern flank of Lassen Peak, was associated in time with the first May 22 mudflow in Lost Creek. Although the May 22 blast covered a larger area in the headwaters of Lost and Hat Creeks than did the May 19 mudflow and possible blast, the volumes of the May 22 mudflow deposits were smaller than the volume of the May 19 deposit. Possibly, the May 19 mudflow had greatly depleted sources of water and sediment before the May 22 mudflows. The second May 22 mudflow in the Lost Creek valley and the mudflows in the Manzanita Creek valley were not obviously associated with explosive volcanic activity.

During the 1915 eruptions of Lassen Peak, a hybrid andesite magma, which was more mafic than the parent magma of Lassen Peak, reached the Earth's surface through a conduit in the Lassen Peak dome. It is unlikely that the 1915 magma was extruded from the magma chamber that produced the Lassen Peak dome (MacDonald and Katsura, 1965). Lava flows that have lithologies different from those of surrounding rocks are not found on other silicic domes in the Lassen Peak area.

METHODS OF STUDY

Initial field investigations were conducted in stream valleys that contain 1915 mudflow deposits, including the valleys of Lost Creek, Hat Creek, and Manzanita Creek (fig. 2). These valleys were of particular concern because the geologic, climatic, and topographic factors that controlled mudflow occurrence in 1915 might also control mudflow occurrence during possible future eruptions. Subsequent investigations were conducted in the valleys of North and South Bailey Creeks because of their proximity to Lassen Peak. Finally, the valley of Mill Creek was examined because of its proximity to Lassen Peak and its potential for landsliding in the extensively hydrothermally altered rocks in the northern part of the basin. Time did not permit an examination of the valleys of Kings Creek and Warner Creek, which were given low priorities because of the complex topography between the main parts of those valleys and Lassen Peak.

Field investigations entailed walking stream valleys and looking for mudflow deposits. The distinction between mudflow deposits and glacial and volcaniclastic deposits commonly was ambiguous. Distinctive but not universal features of volcanic mudflows include abundant void spaces within the matrix, crude inverse grading, and an outcrop pattern consisting of a thin veneer on terraces or benches within stream valleys (Crandell, 1971). Where exposed and preserved, a bedded sandy layer at the base of some mudflow deposits (Schmincke, 1967) is helpful in distinguishing mudflow from glacial deposits. Although striated and faceted clasts are distinctive of glacial till, the possibility that mudflows could have incorporated glacial material enroute down-valley prevents the use of such clasts as indicators of glacial origin (Crandell, 1971). Distinctive characteristics of pyroclastic flows include the presence of a pumiceous matrix, welding (which may or may not be present in the pyroclastic materials), abundant charcoal at the bases of deposits, and uniform rather than random directions of thermoremnant magnetism (Crandell, 1971). Mudflow deposits of 1915 or later were distinguished from all other deposits by their inclusion of pieces of the distinctive black, glassy dacite that was extruded in 1915.

MUDFLOW STRATIGRAPHY IN STREAM VALLEYS

1915 Deposits

Mudflow deposits were emplaced in the valleys of Lost Creek, Hat Creek, and Manzanita Creek during the eruptions of Lassen Peak in May of 1915. The deposits were mapped by Williams (1932) and MacDonald (1963), and were examined in more detail in the valleys of Lost and Hat Creeks by Eppler (1984). The following discussion summarizes and augments previous work on the 1915 deposits.

Lost Creek

The Lost Creek valley received the largest mudflows generated during the 1915 eruptions of Lassen Peak. Deposits left by the 1915 mudflows extend approximately 20 km downstream from the peak (site A in fig. 2). Eppler (1984) distinguished three mudflow deposits in the Lost Creek valley—one emplaced on May 19, and two on May 22. According to Eppler, the May 19 deposit ranges from 0.15 to 1.5 m in thickness and contains about 6×10^6 m^3 of material; the first May 22 deposit ranges from 0.1 to 1.0 m in thickness and contains about 2×10^6 m^3 of material; and the second May 22 deposit is thicker than the first May 22 deposit, contains about 1×10^6 m^3 of material, and is found only in the southern parts of the Hat Creek and Lost Creek valleys.

The three mudflow deposits differ considerably in their average thickness, their morphology as deposits, and their grain-size distribution (Eppler, 1984). The May 19 and the second May 22 mudflow deposits are thick, very poorly sorted, coarse grained, and have steep-sided margins, leveed channels, and an uneven surface morphology. The first May 22 deposit, in contrast, is finer grained, better sorted, and has thin margins and a flat surface morphology. Differences between the deposits may reflect differences in the velocity and water content of the mudflows during emplacement and grain-size distribution of the sediment entrained in the flows.

Hat Creek

Williams (1932) and MacDonald (1963) mapped 1915 mudflow deposits along the entire reach of Hat Creek upstream from its junction with Lost Creek. Eppler's (1984) map and our investigation show 1915 mudflows extending only about 7 km downstream from Lassen Peak along Hat Creek to a point well upstream from the junction of Hat and Lost Creeks (site B in fig. 2). The greater extent of 1915 mudflow deposits in the Lost Creek as opposed to the upper Hat Creek valley probably reflected the orientation of the volcanic blasts and the deflection of mudflows by the low ridge that separates the headwaters of Lost and Hat Creeks (D.B. Eppler, Arizona State University, oral commun., 1984).

Manzanita Creek

Williams' (1932) map of the Lassen Peak area shows 1915 mudflow deposits extending down both headwater forks of Manzanita Creek to just downstream from their junction. Our field investigation, however, revealed a more limited extent of 1915 mudflow deposits in the Manzanita Creek drainage (sites C and

D in fig. 2). Photographs taken before and after the May 22 eruptions indicate that the bulk of the 1915 mudflow deposits in the Manzanita Creek drainage were emplaced on May 22 (Day and Allen, 1925). The deposits in both the unnamed north and south forks of Manzanita Creek resemble the May 19 and particularly the second May 22 mudflow deposits in Lost Creek in their coarse texture, poor sorting, and well-defined levees and flow margins.

Deposits Not Related to 1915 Eruptions

We attempted to identify and map pre-1915 mudflow deposits in the Lassen Peak area in order to assess the present-day susceptibility of the stream valleys there to mudflows. Ancient mudflows that apparently originated from the now-extinct Brokeoff volcano therefore were not considered in this investigation. Mudflows related to glacial activity on Lassen Peak are mentioned but not emphasized. Postglacial mudflow deposits that occur in hydrothermally altered areas and that appear unrelated to eruptions of Lassen Peak are discussed. References to pre-1915 mudflows originating from Lassen Peak in the valleys of Lost and Hat Creeks have been made by Finch (1929), Williams (1932), and Crandell (1972). No evidence of mudflow activity was found in the valley of Bailey Creek.

Lost Creek

Two mudflow sequences are exposed in steep walls of gullies near the headwaters of Lost Creek. The exposure at site E (fig. 2) is at least 2.5 m thick and consists of 0.5- to 1.2-m thick, poorly sorted layers interbedded with 7- to 10-cm thick, moderately to well-sorted sandy layers. Charcoal from one of the sandy layers yielded a radiocarbon age of 7,980 ± 50 years (M.A. Clynne, U.S. Geological Survey, oral commun., 1985). A 13- to 17-m thick sequence of mudflows interbedded with alluvium is exposed at site F (see fig. 2) (Crandell, 1972). These deposits differ from other mudflow deposits in the Lassen Peak area in their extensive association with alluvium. Although the deposits described by Crandell (1972) could not be dated directly, a tentative correlation with a sand-and-gravel deposit downstream that underlies a 5,400-year-old peat deposit, and the similarity of the weathering profile on the mudflows to the weathering profile on moraines of late Tioga age, indicated to Crandell (1972) that the deposits resulted from the mobilization of debris by meltwater during the late Tioga glacial retreat. There is no evidence that either of the mudflow sequences extended beyond the flanks of Lassen Peak. The apparent limited extent of the mudflows, and their likely temporal association with late Tioga glacial activity, diminishes their importance from a modern hazards perspective.

Williams (1932) described pre-1915 mudflow deposits in the form of "moraine-like mounds" adjacent to and outside the 1915 mudflow deposits in Lost Creek. Williams (1932) believed that the older mudflows were associated with the formation of Lassen Peak and were more extensive than the 1915 mudflows. Finch (1929) also described pre-1915 deposits along Lost Creek, some of which he believed were emplaced within the last 500 years.

Our field investigation along Lost Creek was conducted between 1 and 30 km from the summit of Lassen Peak (fig. 2). Beyond the flanks of Lassen Peak, most exposures in the banks of the creek consist of 1915 mudflow deposits, underlain in places by Chaos Crags pyroclastic flow deposits, and glacial deposits beneath and on streambanks adjacent to and outside the younger deposits. Exposures, mentioned as pre-1915 mudflow deposits by Williams (1932) and Finch (1929), appear to be glacial deposits and 1915 mudflow deposits.

Hat Creek

Williams' (1932) geologic map of the Lassen Peak area shows about 1 km^2 of pre-1915 mudflow deposits along the headwaters of Hat Creek. More recent field studies indicate that, rather than older mudflow deposits, a thin, unsorted deposit containing solidified pieces of 1915 lava is widespread in that area (R.L. Christianson, U.S. Geological Survey, oral commun., 1984). Our investigation along the upstream reaches of Hat Creek for the present study was conducted between 1 and 10 km from the summit of Lassen Peak (fig. 2). The pre-1915 exposures in the banks of the creek consists of pyroclastic flow deposits, fluvial deposits, glacial deposits, and lava flows.

Manzanita Creek

Mudflow deposits that pre-date the Chaos Crags pyroclastic flows are exposed in gully walls at the head of the unnamed north fork of Manzanita Creek (site G in fig. 2). At least two mudflow deposits, each of which is approximately 0.3 and 0.5 m thick, overlie a deposit that consists of considerably weathered, angular clasts with a lithology that appears identical in hand specimen to that of Lassen Peak. Clasts in the mudflow deposits also are exclusively of the Lassen Peak lithology. In contrast to mudflow deposits identified by Crandell (1972) in the headwaters of Lost Creek, the Manzanita Creek deposits contain very angular clasts and are not associated with fluvial deposits. Bedded basal layers distinguish the mudflow deposits from glacial till; a lack of pumiceous matrix distinguishes the mudflow deposits from pyroclastic deposits. These pre-1915 mudflows may have been related to the initial extrusion of the Lassen Peak dome. No evidence of these mudflows was found farther downstream. Between site G (fig. 2) and Manzanita Lake, stream cuts expose Chaos Crags pyroclastic flows, glacial deposits, and the considerably weathered deposit consisting exclusively of angular fragments of Lassen Peak lithology. Downstream from Manzanita Lake, the course of Manzanita Creek was disrupted by the collapse of a part of the Chaos Crags dacite dome field about 300 years ago (Crandell and others, 1974). Glacial deposits and various volcanic units are exposed along the abandoned course of Manzanita Creek, but there is no evidence of mudflow activity.

Mill Creek

Mudflow hazards in the Mill Creek valley differ from those in the valleys discussed previously because (1) the Mill Creek valley is separated from Lassen Peak by complex topography that could deflect or dissipate mudflows, and (2) landslides on the streamside hillslopes that have been glacially steepened and extensively altered hydrothermally can mobilize into mudflows. Mudflows generated directly from volcanic activity are less likely here than in other stream valleys draining Lassen Peak, as indicated by the lack of 1915 mudflow activity in the Mill Creek valley. Mudflows generated by mass-movements on steep slopes underlain by hydrothermally altered bedrock, however, are a significant hazard, as indicated by the mudflow deposits discussed below.

Mudflow deposits that postdate glacial activity were observed at several locations in the Mill Creek valley (fig. 2). At site H, about 4 m of fluvial deposits interbedded with more poorly sorted layers, which may be mudflow deposits, are overlain by a mudflow deposit about 1 m thick. This uppermost mudflow deposit is unsorted; contains rounded, subangular, and angular clasts; does not contain clasts of Lassen Peak lithology; and is underlain by a sandy, bedded layer. At site I, about 1 km downstream from site H, a poorly sorted, roughly bedded deposit containing charred logs is exposed in steep streambanks about 10 m above the present level of Mill Creek. One of these logs has been dated at 3,310 ± 55 years B.P. (Clynne, 1984). The land surface along the left bank of the creek at that location is hummocky and contains elongated boulder ridges that may have resulted from mudflows.

About 3 km farther downstream, a continuous deposit extends 240 m along both sides of Mill Creek (site J in fig. 2). Streambed exposures of the deposit are unbedded, and 5 to 8 m thick (fig. 3). Clasts are angular to subangular, and both clasts and matrix appear hydrothermally altered. The matrix is considerably more clayey than mudflow deposits observed in the valleys of

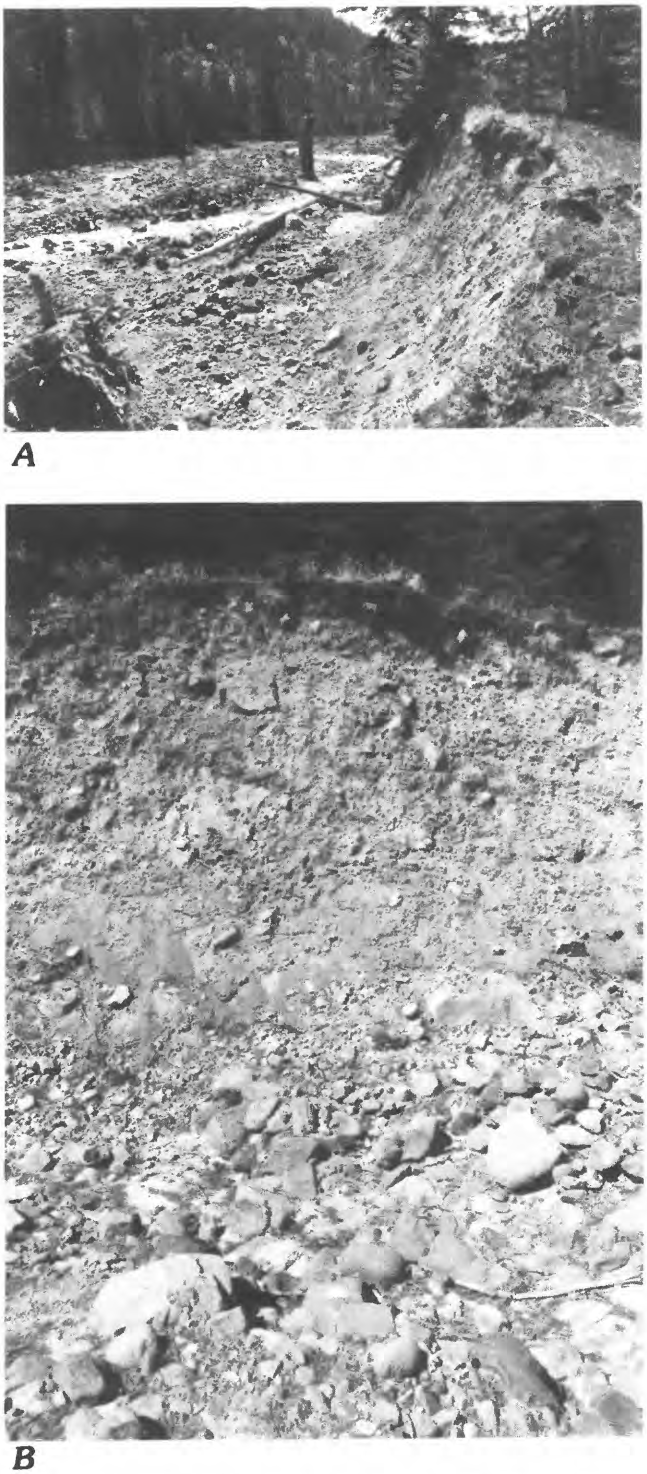

Figure 3. Mudflow deposit at site J (fig. 2) in the Mill Creek valley. Deposit is 5 m thick at this location. *A*, Downstream view of deposit on right bank. *B*, In-channel view of deposit on right bank.

Lost, Hat, and Manzanita Creeks. The deposit slopes away from Mill Creek toward both valley walls, thins downstream, and ends abruptly on both sides of the valley. Charcoal collected from a continuous organic-enriched layer at the base of the deposit on the left bank was dated at 3,860 ± 50 years B.P.

Similar radiocarbon ages of the deposits at sites I and J (fig. 2) indicate that the deposits resulted from a single mudflow. Active streamside landsliding along Mill Creek may have removed intermediate parts of the deposit. Clynne (1984) correlated the deposit that he dated with a large landslide identified by D.R. Crandell and D.R. Mullineaux (U.S. Geological Survey, written commun., 1970) adjacent to one of the headwater tributaries of Mill Creek (fig. 2). The correlation was based on clasts of similar lithologies in the deposits and, in the lower deposit, the inclusion of a log from a tree species that grows only at the higher altitudes where the landslide occurred. The landslide identified by Crandell and Mullineaux may have incorporated streamflow and mobilized into a mudflow. This mudflow apparently traveled about 4 km downstream, leaving the deposits dated by Clynne (1984) and by the present study.

RELATION BETWEEN MUDFLOW DEPOSITS AND DAMAGE

Reports of damage caused by the May 19, 1915, mudflows and related floods near Lassen Peak, although inconsistent and difficult to interpret, indicate that damage extended downstream from the present (1985) extent of May 19, 1915, mudflow deposits. Accounts from Loomis (1926) indicate that cabins on Hat Creek owned by Wilcox, Sorenson, and Hall were severely damaged or destroyed on the night of May 19, 1915. Accounts of cabins filled with mud indicate that the damage was done by mudflows or extremely sediment-rich streamflows. A sketch map of homestead and ranch locations in a 1915 account of mudflow damage (Richard L. Vance, U.S. National Park Service, written commun., 1985) and descriptions of the location of cabins and ranches by Willendrup (1976) indicate that (1) the Wilcox and Sorenson cabins were part of homesteads located between the junction of Lost and Hat Creeks and the present (1985) Old Station Post Office; (2) the Hall ranch was between the Old Station Post Office and Old Station (fig. 2); and (3) the Wilcox Ranch was downstream from the Hall ranch. A report in Loomis (1926) of damage to a Wilcox cabin downstream from the Hall ranch possibly is a confused account of damage to a cabin on the Wilcox homestead upstream from the junction of Lost and Hat Creeks. Eppler (1984) mapped the downstream extent of the May 19, 1915, mudflow deposit at about 2.5 km upstream from the junction of Lost and Hat Creeks (fig. 2). Much of the damage attributed to the May 19, 1915, mudflow in the Hat Creek valley, therefore, probably was caused by hyperconcentrated streamflow downstream from the mudflow.

Accounts of the May 19, 1915, mudflow also indicate that the height of the flow was well above the height of the resulting deposit. Mud lines on trees in the valley of Lost Creek about 7 km downstream from Lassen Peak were an estimated 4 to 6 m above the top of the mudflow deposit (Loomis, 1926). The thickness of the deposit in that area is commonly less than 1 m.

POSSIBLE FUTURE MUDFLOWS

Mudflows Related to Eruption

Mudflows directly related to eruptions of Lassen Peak are the most significant mudflow hazard in most stream valleys draining the peak. Therefore, the probability of future large mudflows in these valleys is a function of the probability of future eruptive activity on Lassen Peak. Although no volcanic domes in the Lassen area except for Lassen Peak show evidence of eruptions long after their period of formation, the 1915 and possible prior eruptions indicate that future eruptions of Lassen Peak are possible.

Conditions controlling the magnitude and direction of mudflows that could be caused by future eruptions are variable, and some are difficult to predict. Such conditions include the depth of the snowpack and the direction and area affected by blast or pyroclastic flows. There is general consensus that the snowpack was unusually thick before the May 1915 eruptions of Lassen Peak. Day and Allen (1925) reported that snow depths ranged from 5 to 13 m in the bowl at the head of Lost Creek in May 1914, and also that the cumulative snowfall during the winter of 1914-15 at nearby weather stations was similar or greater than that during the winter of 1913-14.

Although a thicker snowpack could provide a greater source of water and thus increase the size of potential mudflows, the effects of recent volcanic activity on glaciers at Mount St. Helens indicate that a single pyroclastic flow or volcanic blast does not always melt all the snow and ice in its path. Brugman and Meier (1981) reported the melting and erosion of about 6 m of snow and ice on glaciers in the paths of pyroclastic flows at Mount St. Helens. They also reported a change from 45 to 20 m—in the estimated average thickness of a glacier in the area affected by the May 18, 1980, volcanic blast. This change may overestimate the thickness of snow and ice actually removed by the blast because the original thickness is an average of the thickness of the entire glacier, whereas the posteruption thickness is an average of the lower part of the glacier (the upper part having been removed by a massive landslide), which most likely was thinner than the upper part even before the eruption. The capacity of a pyroclastic flow to erode a snowpack may exceed the potential of such a flow to erode more densely packed glacial snow and ice.

The size of the snow-covered area affected by a pyroclastic flow or volcanic blast can affect the volume of snow melted and hence the size of a resulting mudflow. Day and Allen (1925) concluded from an examination of photographs taken in May 1915, that the May 22, 1915, blast at Lassen Peak covered a larger area on the flanks of Lassen Peak than did the mudflow and possible blast of May 19, 1915. If the May 22 blast had occurred before the May 19 mudflow and possible blast had removed much of the snow in the headwaters of Lost Creek, the resulting mudflow in that valley may have been larger than the one that occurred on May 19, 1915.

Although controls on the eastern orientation of the May 22 blast and the possible May 19 blast are not understood, several lines of evidence indicate that the east and west sides of Lassen Peak have a greater probability of being affected by eruptions than other sides; therefore, the valleys of Lost, Hat, and Manzanita Creeks have a relatively greater probability of being affected by mudflows related to eruptive activity. Before the 1914-15 eruptions of Lassen Peak, notches on the east and west sides of the summit indicated a zone of weakness and possible earlier eruptions oriented along an east-west-trending line (Day and Allen, 1925). During the early stages of the 1914-15 eruptions, fractures extending from the crater and the elongation of the crater itself also were oriented in an east-west direction (Day and Allen, 1925). During the May 19-22, 1915, eruptions, lava was extruded down the northeast and west flanks of Lassen Peak (fig. 2).

Mudflows Not Related to Eruption

Mudflow deposits in Mill Creek indicate that hydrothermally altered areas near Lassen Peak are susceptible to large mudflows that are not directly related to eruptions. The most likely mechanism for generating these mudflows involves the occurrence of landslides on glacially oversteepened valley walls underlain by the weak, hydrothermally altered rocks. These landslides can mobilize downstream into mudflows or can dam streams; when the dam breaches, the collected water and incorporated sediment can flow downstream as a mudflow. The significance of rapid mass-movement and clayey mudflows in hydrothermally altered areas near volcanoes was recognized by Crandell (1971). Substantial clay contents of such mudflows add to their mobility (Rodine and Johnson, 1976) and consequent destructive potential.

SUMMARY

Mudflow deposits in stream valleys draining Lassen Peak demonstrate a potential for mudflows in this area. Mudflow deposits that resulted from eruptions in May 1915 extend about 20 km down the valley of Lost Creek, about 7 km down the valley of Hat Creek, and less than 3 km down the valleys of two unnamed headwater tributaries of Manzanita Creek. Deposits left by mudflows unrelated to the 1915 eruptions of Lassen Peak were found in the valleys of Lost, Manzanita, and Mill Creeks.

Mudflows resulting from eruptions of Lassen Peak are the most significant mudflow hazard in most valleys in that area. Although repetitive eruptive activity does not appear typical of volcanic domes in the Lassen Peak area, the 1914-15 eruptions of Lassen Peak demonstrate that future eruptions of that dome are possible. The summit morphology before the 1914-15 eruptions, summit fractures created during the 1914-15 eruptions, and the orientation of lava flows extruded in 1915 indicate that the valleys of Hat, Lost, and Manzanita Creeks are particularly susceptible to the effects of volcanic activity on Lassen Peak. A different sequence of eruptive activity in May 1915 could have generated a larger mudflow than the one that travelled about 20 km down the valley of Lost Creek. Much of the damage attributed to May 1915 mudflows in the valleys of Hat and Lost Creek was probably caused by hyperconcentrated streamflows.

Mudflow deposits in the Mill Creek valley indicate that glaciated stream valleys draining hydrothermally altered rocks are susceptible to large mudflows that are not directly related to volcanic activity. A likely correlation of two dated deposits along Mill Creek with a large streamside landslide upstream indicate that the landslide incorporated water and flowed about 4 km down the valley of Mill Creek as a mudflow.

REFERENCES CITED

Beverage, J.P., and Culbertson, J.K., 1964, Hyperconcentrations of suspended sediment: Proceedings, American Society of Civil Engineers, Journal of Hydraulics Division, 4136, HY6, p. 117-1.

Brugman, M.M., and Meier, M.F., 1981, Response of glaciers to the eruptions of Mt. St. Helens, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 743-756.

Clynne, M.A., 1984, Stratigraphy and major element geochemistry of the Lassen volcanic center, California: U.S. Geological Survey Open-File Report 84-224, 168 p.

Crandell, D.R., 1971, Postglacial lahars from Mount Rainier volcano, Washington: U.S. Geological Survey Professional Paper 677, 75 p.

———1972, Glaciation near Lassen Peak, northern California, *in* Geological Survey Research 1972: U.S. Geological Survey Professional Paper 800-C, p. C179-C188.

Crandell, D.R., and Mullineaux, D.R., 1973, Pine Creek volcanic assemblage at Mount St. Helens, Washington: U.S. Geological Survey Bulletin 1383-A, 23 p.

———1975, Technique and rationale of volcanic-hazards appraisals in the Cascade Range, northwestern United States: Environmental Geology, v. 1, no. 1, p. 23-32.

———1978, Potential hazards from future eruptions of Mount St. Helens volcano, Washington: U.S. Geological Survey Bulletin 1383-C, 26 p.

Crandell, D.R., Mullineaux, D.R., Sigafoos, R.S., and Rubin, Meyer, 1974, Chaos Crags eruptions and rock-fall avalanches, Lassen Volcanic National Park, California: U.S. Geological Survey Journal of Research, v. 2, no. 1, p. 49-61.

Cummans, John, 1981, Mudflows resulting from the May 18, 1980, eruption of Mt. St. Helens, Washington: U.S. Geological Survey Circular 850-B, 16 p.

Day, A.L., and Allen, E.T., 1925, The volcanic activity and hot springs of Lassen Peak: Washington, D.C., Carnegie Institution of Washington Publication 360, 190 p.

Diller, J.S., 1916, Volcanic history of Lassen Peak: Science (new series), v. 43, p. 727-733.

Eppler, D.B., 1984, Characteristics of volcanic blasts, mudflows, and rock-fall avalanches in Lassen Volcanic National Park, California: Tempe, Arizona State University, unpublished Ph.D. dissertation, 261 p.

Finch, R.H., 1929, Lassen Report No. 19: The Volcano Letter, no. 237, p. 1.

———.1930, Mudflow eruption of Lassen Volcano: The Volcano Letter, no. 266, p. 1-4.

James, D.E., 1966, Geology and rock magnetism of Cinder Cone lava flows, Lassen Volcanic National Park, California: Geological Society of America Bulletin, v. 77, no. 3, p. 303-312.

Janda, R.J., Scott, K.M., Nolan, K.M., and Martinson, H.A., 1981, Lahar movement, effects, and deposits, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mt. St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 461-478.

Johnson, A.M., and Rahn, P.H., 1970, Mobilization of debris flows: Zeitschrift fur Geomorphologie, v. 9, p. 168-186.

Loomis, B.F., 1926, Pictoral history of the Lassen volcano: Mineral, Calif., Loomis Museum Association, Lassen Volcanic National Park, 110 p.

MacDonald, G.A., 1963, Geology of the Prospect Peak Quadrangle, California: U.S. Geological Survey Geologic Quadrangle Map GQ-345, scale 1:62,500.

MacDonald, G.A., and Katsura, Takashi, 1965, Eruption of Lassen Peak, Cascade Range, California, in 1915—Example of mixed magmas: Geological Society of America Bulletin, v. 76, p. 475-482.

Miller, C.D., 1980, Potential hazards from eruptions of Mt. Shasta, California: U.S. Geological Survey Bulletin 1503, 43 p.

Mullineaux, D.R., and Crandell, D.R., 1962, Recent lahars from Mount St. Helens, Washington: Geological Society of America Bulletin, v. 73, no. 7, p. 855-870.

Pierson, T.C., and Scott, K.M., 1985, Downstream dilution of a lahar—Transition from debris flow to hyperconcentrated streamflow: Water Resources Research, v. 21, no. 10, p. 1511-1524.

Rodine, J.D., and Johnson, A.M., 1976, The ability of debris, heavily freighted with coarse clastic materials, to flow on gentle slopes: Sedimentology, v. 23, no. 2, p. 213-234.

Schmincke, H.V., 1967, Graded lahars in the type sections of the Ellensburg Formation, south-central Washington: Journal of Sedimentary Petrology, v. 37, no. 2, p. 438-448.

Waitt, R.B., Jr., Pierson, T.C., MacLeod, N.S., Janda, R.J., Voight, Barry, and Holcomb, R.T., 1983, Eruption-triggered avalanche, flood, and lahar at Mt. St. Helens—Effects of a winter snowpack: Science, v. 221, no. 4618, p. 1394-1397.

Willendrup, A.W., 1976, The Lassen Peak eruptions and their lingering legacy: Chico, Calif., Chico State University, unpublished M.A. thesis, 229 p.

Williams, Howell, 1932, Geology of the Lassen Volcanic National Park, California: University of California, Department of Geological Sciences Bulletin, v. 21, no. 8, p. 195-385.