Characteristics of Debris Flows of Noneruptive Origin on Mount Shasta, Northern California

By James C. Blodgett, Karen R. Poeschel, and Waite R. Osterkamp

---

U.S. GEOLOGICAL SURVEY

Open-File Report 96–144

Sacramento, California
1996

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

Gordon P. Eaton, Director

For addtional information write to:

District Chief
U.S. Geological Survey
Federal Building, Room W-2233
2800 Cottage Way
Sacramento, CA 95825

Copies of this report can be purchased from:

U.S. Geological Survey
Information Services
Box 25286
Federal Center
Denver, CO 80225

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS

Multiply	By	To obtain
kilometer	0.6215	mile
meter	3.281	foot
meter per second	3.281	foot per second
millimeter	0.003281	foot

Air temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by the following equation:

$$\text{Temp °F} = 1.8 \text{ temp °C} + 32.$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Characteristics Of Debris Flows Of Noneruptive Origin on Mount Shasta, Northern California

By James C. Blodgett, Karen R. Poeschel, *and* Waite R. Osterkamp

Abstract

Studies of Mount Shasta indicate that eruptive activity has occurred, on the average, once every 800 years. Debris flows and deposits of noneruptive origin, in addition to those associated with eruptive activity (lava flows, pyroclastic flows, and ash fall), inundate the fans and channels and can endanger people or property on the flanks of the mountain. This study evaluates the source and characteristics of historical noneruptive debris flows in the vicinity of Mount Shasta.

At least 70 debris flows of noneruptive origin that occurred during the last 1,000 years have been identified in various stream channels on Mount Shasta. Of the four areas around the mountain, the most active are the McCloud River and The Whaleback-Ash Creek Butte depression; the Sacramento River area is the least active. Between 1900 and 1985, 37 debris flows occurred on different streams, with an average interval of 2.3 years between flows. Since 1900, Mud Creek (nine flows) and Whitney Creek (six flows) have been the most active channels.

The path followed by a debris flow is not always at the lowest point in the channel, and the extent of downstream movement depends on the size of the flow. Former channels are inundated by the new flows and deposits, and new channels are eroded. In time, most of the entire channel between valley walls is subject to reworking.

Most debris-flow deposits ranged in thickness from 0.4 to 2.5 meters. Thickness tends to decrease in a downstream direction. The deposits are generally of a convex shape, highest in the middle and lowest near the original valley wall. The ratio of water to solids in the slurry-sediment mixture of debris flows averages 68 percent by volume.

INTRODUCTION

The eruption of Mount St. Helens, Washington, on May 18, 1980, caused concern that this activity might signal the start of eruptive activity of other volcanoes in the Cascade Range. During the Holocene Epoch (last 10,000 years), eruptive activity at Mount Shasta in northern California has occurred on the average of about once every 800 years (Miller, 1980)—a frequency roughly equivalent to that of Mount St. Helens (Mullineaux and Crandell, 1981). Phenomena during eruptions that could endanger people or property in the Mount Shasta area include debris flows triggered by rapid runoff of melting snow and ice from pyroclastic flows, pyroclastic surges, lava flows, and tephra. Debris flows of noneruptive origin also may cause hazards to life and property along downstream reaches of channels if the capacity of streams is reduced by debris-flow deposits and overbank flooding occurs.

Mount Shasta is a large stratovolcano in northern California about 61 km south of the Oregon-California border (figs. 1 and 2). Of the volcanoes in the Cascade Range, Mount Shasta is the second highest (altitude, 4,316.6 m) and one of the largest. The average basal diameter of Mount Shasta is about 27 km. Williams (1934) indicated that the Mount Shasta cone is perhaps larger in volume and height than Mount Rainier, Washington, because the cone of Mount Rainier rises above an elevated platform of older formations at an altitude of 2,440 m.

The slopes of Mount Shasta consist of volcanic rocks, glacial rock debris, and debris-flow and fluvial deposits. The widespread and locally thick depositional terraces and alluvial fans bordering streams on the flanks of the mountain indicate that both debris flows and streamflow contributed to the development of the present landform. Historic debris flows on Mount Shasta could have been of both eruptive (volcanic) and noneruptive (nonvolcanic) origin.

Debris flows and floods related to eruptive activity as described by Crandell (1971) are caused by a number of mechanisms. Debris flows may occur after the water contained in a volcanic crater is ejected during an eruption and spilled on the slopes. Debris-flow material also may be extruded directly by volcanoes. Avalanches of rock debris may cause debris flows by temporarily damming streams. Eventually, water spilling over the dam causes erosion, and the deposits are swept downstream as debris flow. Avalanches of hot rock debris have caused debris flows by melting snow and ice. Eruptive explosions may cause landslides of rocks weakened by hydrothermal alteration. As these landslides descend the volcano, the snow and glaciers are melted and debris flows are created. Debris flows were apparently created by rapid snowmelt near the summit of Lassen Peak during a 1915 eruption (Marron and Laudon, 1987). On Mount Shasta, debris flows related to eruptions have not occurred since at least 1786 (Williams, 1934).

Debris flows are rapidly moving, gravity-induced slurries of granular solids, water, and air (Varnes, 1958). Debris flows refer to all types of flows that include rock debris, whereas mudflows include finer size debris. Varnes (1958) suggested that mudflows be defined as the mixture of water and sediment material that has at least 50-percent solids (sand size or smaller) by weight. In his discussion of potential hazards in the vicinity of Mount Shasta, Miller (1980) referred to the movement of water-saturated rock debris as mudflows or debris flows; some of these mudflows were actually debris flows.

Some flows described as debris flows on Mount Shasta may have been streamflows with extremely high concentrations of suspended sediment. These

Figure 1. View of Mount Shasta, California. Gravel Creek alluvial fan in The Whaleback-Ash Creek Butte depression in foreground. Photograph taken July 1984.

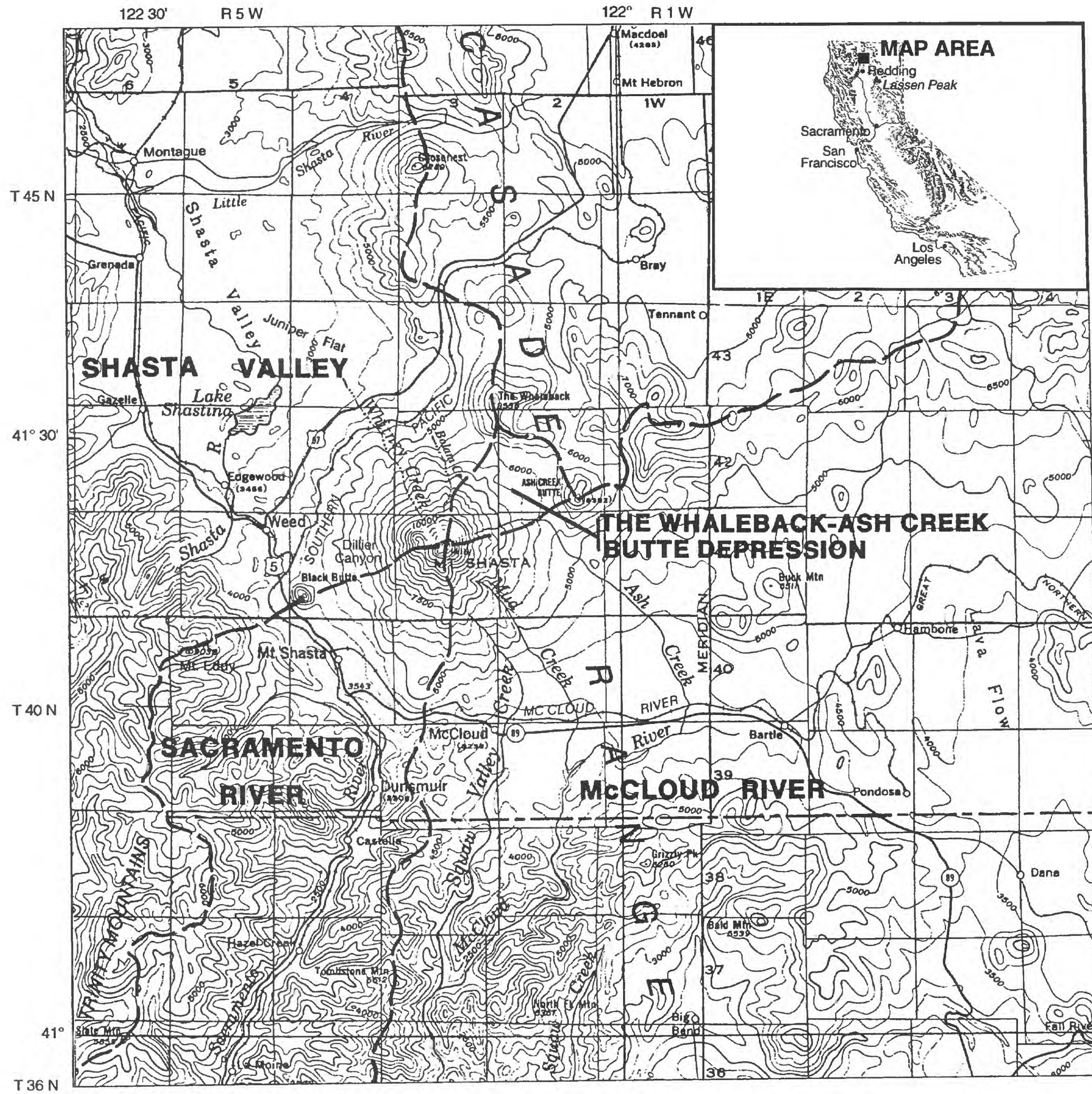

Figure 2. Location of Mount Shasta, California and hydrologic areas. (Dashed lines indicate approximate boundaries of hydrologic area.)

flows, defined as hyperconcentrated streamflow (Beverage and Culbertson, 1964), contain water with suspended-sediment concentrations between 40 and 80 percent by weight. When coarser particles are freely suspended in a mixture of water and fine particles, the flow is a hyperconcentrated fluid, in which the sediment-water mixture has no shear strength and acts as a typical (Newtonian) fluid. The conditions associated with the change from debris flow to hyperconcentrated flow vary, depending on the particle size and sediment concentration of the slurry (Pierson and Scott, 1987). Sedimentologic data for Mount Shasta were generally insufficient to distinguish hyperconcentrated flow from debris flows. In this report, the term "debris flow" is used to describe all types of flows (debris flows, mudflows, and hyperconcentrated streamflow) not related to eruptive activity.

A debris-flow deposit is the sediment or rock mass layer that remains after cessation of flow. A debris fan develops when debris-flow deposits become repeatedly stacked and spread over an extensive area. These fans, such as those found on Mud Creek at Road 13 crossing (fig. 3), are typical of the alluvial fans on the flanks of Mount Shasta. Debris fans commonly are seen below 1,800-m altitude, which is about 10,000 m from the summit. These debris fans generally are incised between 1,200- and 1,800-m altitude; exceptions are Ash, Brewer, and Gravel Creeks, which have extensive debris-flow deposits with minor incision between 1,700- and 1,900-m altitude.

In response to the increased awareness of flood potential of streams on the flanks of volcanoes, this report was prepared with the purpose of describing the sources, potential, and characteristics of debris flows of noneruptive origin on Mount Shasta. This report presents an evaluation of data collected before and during the study and describes significant characteristics of debris flows. Attention was restricted to "cold" flows; that is, to flows not directly related to eruptive activity. Debris flows were evaluated on the basis of

Figure 3. Typical deposits from a series of debris flows (1924-31) on Mud Creek debris fan just upstream from Road 13 crossing, sec. 27, T. 40 N., R. 2 W. Many trees in the background, marked (A) (about 9 m tall), began growing after this series of debris flows. Photograph taken May 1981.

inferred origin, stream location, thickness, areal extent of inundation, and estimated velocity. Procedures used to estimate the probability of future debris flows and to identify potentially hazardous areas included geomorphic, climatic, and dendrochronologic techniques (Hupp and others, 1987). The definition of areas of debris-flow deposition and the present condition of channels on the flanks of the mountain were estimated using hydraulic analyses, topographic surveys, and aerial photographs. Flow depth and areas of inundation of various debris flows were estimated from studies and observations of historical debris flows and the resulting deposits.

The characteristics and hydrology of debris-flow activity and associated hazards of Mount Shasta are described by Osterkamp and others (1986), Hupp and others (1987), and Blodgett and others (1988). Debris-flow activity and glaciers on Mount Shasta are discussed by Hill and Egenhoff (1976), Hill (1977), Miller (1980), Hupp (1984), and Rhodes (1987).

GEOLOGIC SETTING

Mount Shasta (fig. 1) is a composite of at least four overlapping volcanic cones (Christiansen and others, 1977). Eruptive rocks are exposed on all sides of the mountain, but most areas are covered by varying thicknesses of till of Wisconsin or neoglacial age, pyroclastic flows, and debris-flow deposits. The widespread occurrences of interbedded pyroclastic and debris-flow deposits on Mount Shasta indicate that debris flows have been an important geomorphic process in the history of the mountain (Osterkamp and others, 1986).

Wisconsin-aged glacial deposits (older than about 10,000 years) generally are within 6 km of the Mount Shasta summit. Most neoglacial moraines, presumably less than 4,500 years in age, are restricted to upper slopes within a few kilometers of the present glacial termini. A few neoglacial-aged rock glaciers are within 6 km of the summit.

A summary of eruptive and noneruptive activities on Mount Shasta that includes pyroclastic flows, block-and-ash flows, ash and cinder fall, and debris flows (Miller, 1980) is given in table 1. On the basis of hydrologic factors, the area around Mount Shasta

Table 1. Erupive and noneruptive activities at Mount Shasta during the last 1,000 and 10,000 years

[Modified from Miller, 1980. See figure 2 for location of hydrologic areas]

Type of activity	Approximate number of occurrences in hydrologic areas: Sacramento River	McCloud River	The Whaleback-Ash Creek Butte depression	Shasta Valley
Last 1,000 years				
Debris flows (noneruptive related flows) based on dendrogeomorphic surveys[1] and carbon-14 dating	6	25	14	26
Last 10,000 years				
Hot and cold debris flows	0	37	22	4
Block-and-ash flows, pumice flows, pyroclastic flows	5	8	23	3
Lava flows	1	0	3	2
Ash, cinder, and pumice fall	([2])	5	1	([2])

[1]Hupp and others (1987).

[2]Unknown; may have been affected by eruptive activity in other areas near Mount Shasta.

of hydrologic factors, the area around Mount Shasta has been separated into four areas: Sacramento River, McCloud River, The Whaleback-Ash Creek Butte depression, and Shasta Valley (table 1, fig. 2) (Blodgett and others, 1988). The areas with the most eruptive activity around Mount Shasta are the McCloud River and The Whaleback-Ash Creek Butte depression (fig. 2). Significantly, and certainly advantageous to the populated areas around the city of Mount Shasta, the Sacramento River area is least active.

Many of the historic eruptive and noneruptive flows had sufficient volume and mobility to develop terraces and fans on the lower flanks of the mountain (fig. 3); these areas of deposition are now being developed and populated. New debris flows of noneruptive origin, comparable in size to historic flows, could be disastrous and could create a potential for loss of life and the disruption of communities and major transportation routes.

SOURCE AND OCCURRENCE OF DEBRIS FLOWS

The more recent debris flows [less than about 5,000 years ago (Miller, 1980)] that are not related to eruptions were caused by heavy precipitation, outburst floods from glacier-, moraine-, or debris-dammed lakes. The frequency and magnitude of these debris flows were affected by the high, steep slopes of erodible pyroclastic flow deposits and presence of earlier debris-flow deposits that resulted from eruptions on Mount Shasta.

Nonvolcanic-caused debris flows generally originate near the termini of glaciers above the 2,740-m altitude, an average 2.4 km from the summit, or downstream in the steep-walled canyons where banks of loose eruptive debris are continually sloughing into the channel (fig. 4). Bedded lava topping pyroclastic flows adjacent to active stream channels, which is subject to collapse because of lateral undercutting by stream erosion, is an additional source of material for debris flows.

At least 69 debris flows of noneruptive origin during the last 500 years (before 1985) were identified by Osterkamp and others (1986). The magnitude and frequency of these flows and the procedures used for dating are discussed by Hupp (1984), Osterkamp and others (1986), and Hupp and others (1987). An analysis of debris-flow activity between 1900 and 1985 (table 2) indicates that at least 37 flows occurred on the various streams, with an average interval of 2.3 years between flows. Some debris flows occurred on streams originating from snowfields that are regions of permanent snow cover, such as the upper areas of

Figure 4. Slopes of loose eruptive debris that supply material for debris flows. Site in Mud Creek Canyon, sec. 31, T. 41 N., R. 2 W., near McCloud. Flow from right to left. Photograph taken September 1984.

Table 2. Chronology of debris flows on Mount Shasta, California between 1900 and 1985

[Modified from Osterkamp and others, 1986. —, no data]

Stream	Year	Date (given where known)	Number of years between flows
Whitney Creek	1919		—
	1935	August 28	16
	1952		17
	1960		8
	1977		17
	1985	July 6	8
Bolam Creek	1935	August 28	—
	1955		20
	1973		18
Diller Canyon[1]	1921		—
	1947		26
	1961		14
Cascade Gulch[1]	1928		—
	1957		29
Panther Creek[1]	1924		—
	1967		43
Mud Creek	1910		—
	1920		10
	1924	August 4,[2] 6-19,[2] 23,[2] September 8[2]	4
	1925		1
	1926	July 15 to September 8[2]	1
	1931		5
	1955		24
	1964		9
	1977[3]	Prior to July 21	13
Ash Creek	1937		—
	1939		2
	1958		19
	1962		4
	1977		15
Gravel Creek	1902		—
	1937		35
	1939		2
	1958		19
	1971		13
Inconstance Creek	1918		—
	1939		21

[1]Streams originating from snowfields only.
[2]Dates from Hill and Egenhoff (1976).
[3]Possibly a hyperconcentrated flow of sediment that did not overtop the channel banks. Date from Mount Shasta Herald, July 21, 1977.

Diller Canyon (fig. 2). Because the snowfields varied extensively depending on precipitation during the previous winter, the analysis of debris-flow activity for streams downstream from snowfields was separated from those streams downstream from glaciers. The 1900-85 period was selected for detailed analysis because dates of debris flows were more reliable than for earlier flows, and climatic data for the vicinity of Mount Shasta were available.

For those streams originating from glaciers only (table 2), 30 debris flows were observed during 1900-85, giving an average interval of 2.8 years between flows. During any one year, several streams may experience a debris flow as shown below:

Year	*Streams affected by debris flow*
1935	Whitney, Bolam
1937	Ash, Gravel
1939	Ash, Gravel, Inconstance
1955	Bolam, Mud
1958	Ash, Gravel
1977	Whitney, Mud, Ash

Debris flows occurred most often since 1900 during 1918-39 and 1955-77 (fig. 5*A*). Debris flows in the 1930's and 1970's occurred during droughts, whereas the 1950's and early 1960's was a period of above-average precipitation. There appears to be no relation between antecedent conditions and the occurrence of debris flows as shown in figure 5*B*, in which the number of years since the previous debris flow on a stream is plotted. The data in table 2 indicate that for 1911-85, Mud Creek was the only stream affected by debris flows in successive years (1924-26). The cause of these successive annual flows on this stream is uncertain.

During 1900-85, more debris flows occurred on Mud and Whitney Creeks (fig. 6) than on any other streams on Mount Shasta. The number of debris flows recorded on a given stream, however, is related to the location of the reach studied because large-magnitude flows travel farther downstream than smaller flows. For example, a small debris-flow deposit on Whitney Creek at an altitude of 2,440 m (fig. 7) did not reach the debris fan. For this study, most debris flows large enough to extend below timberline (about 2,590 m) were documented. Large debris flows that traveled below an altitude of 2,130 m were observed on Mud, Ash, Gravel, Inconstance, Bolam, and Whitney Creeks. The debris flow on Whitney Creek in July 1985 extended downstream to an altitude of 914 m.

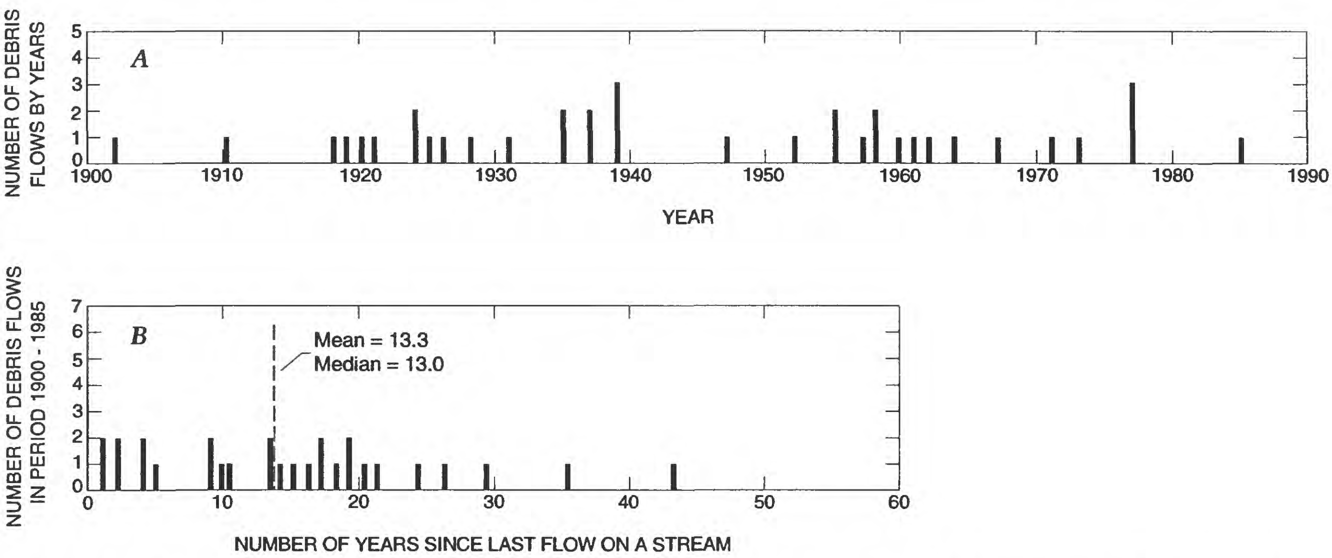

Figure 5. Frequency distribution of debris flows on Mount Shasta, California. *A*, By years. *B*, By number of years since last event on a stream.

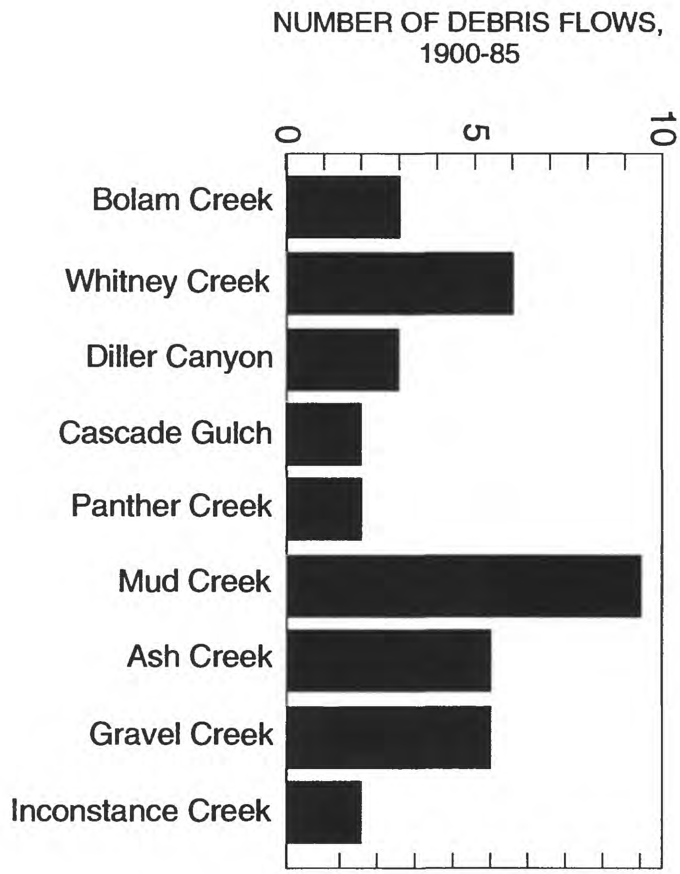

Figure 6. Occurrence of debris flows on Mount Shasta streams, 1900-85. (Modified from Osterkamp and others, 1986.)

Figure 7. View upstream of small debris-flow deposit (1.5 m thick) on Whitney Creek. Altitude is 2,440 m. Channel slope is 0.18. Accumulation of large boulders and cobbles at the downstream front (terminal lobe) is shown. Photograph taken August 1981.

FACTORS ASSOCIATED WITH OCCURRENCE OF DEBRIS FLOWS

The occurrence of debris flows have been recorded during the summer season only. This indicates that warm air temperatures, and ablation in association with antecedent glacial movement and precipitation, are primary factors associated with the formation and passage of debris flows on the flanks of Mount Shasta. Specific conditions causing debris flows are generally a combination of water released from impoundments, snow and glacial melt, and direct precipitation on the various stream basins during the summer snow/glacial melt season.

Release of Water from Channels Blocked by Debris Deposits

Lava flows that lie unconformably on the land surface or debris deposits that are highly fractured periodically break off, falling into a channel and causing the potential for temporary blockage of the channel (fig. 8). This debris then becomes a source of material for transport by future debris flows. The potential for channel blockage is also illustrated at sites on Mud and Whitney Creeks (fig. 9), where local scour and bank failure formed caverns in the loose, uncompacted material that subsequently collapsed and created temporary dams. These dams cause lateral channel migration and create the potential for flow impoundment. The sudden release of water from the impoundment, sediment transported from upstream

Figure 8. Bank erosion of Whitney Creek (fig. 2) channel beneath the Lava Park lava flow in sec. 19, T. 42 N., R. 3 W. Flow is from left to right. Scale is indicated by fallen trees on left bank of channel near left foreground. Photograph taken in 1983.

reaches, plus entrained material in the debris dam could cause the formation of debris flows that travel to lower reaches of the channel.

The influence of ground water is another factor in the formation of debris deposits. Ground water recharged by precipitation or snowmelt, and perched on less permeable eruptive deposits and seeping from the pyroclastic deposits, may cause slump failure and mass movement downslope into a stream channel. These deposits may block the channel and create a

A

B

Figure 9. Bank erosion as a source of material for debris-flow formation. Photographs taken August 1984. *A*, Undercut bank on Mud Creek (sec. 8, T. 40 N., R. 2 W.). Note man in center of picture. Flow is from left to right. *B*. Undercut bank on Whitney Creek (sec. 19, T. 42 N., R. 3 W.). Flow is from left to right.

small lake that incorporates sediment and flows downstream when the dam is breached (Marron and Laudon, 1987).

Release of Water from Channels Blocked by Snow and Ice

The only detailed account of debris-flow formation due to channel blockage by snow and ice was provided by Williams (1934). A number of observers, however, have reported that ice flows and flood flows on Mud Creek have lodged in the canyon as a result of ice or debris blockage. Flood flows also may undermine the canyon walls, resulting in landslips (slides) that form temporary dams that may be breached, causing debris (mud) flows (Denand, 1924; Williams, 1934). The eyewitness accounts in the following paragraph provide the best evidence of the relation between channel blockage by the breakup of glacial snow and ice, formation of temporary impoundments during flood flows, and the subsequent occurrence of debris flows.

In his description of the debris flows during 1924-31, Williams (1934) indicated that a large torrent of water emerged from under the glacier, which he described as "tumbling down the cliff below, and carrying with it large blocks of ice from the glacier front, the swollen stream rushes down the deep and narrow canyon, undermining its loose banks of tuff and breccia. From time to time parts of the steeper eastern wall of the Mud Creek canyon collapse into the gorge, forming temporary dams behind which the water is impounded until able to overflow and carry away the obstacle." The onrushing flood (debris flow) then continued down the canyon for about 10 km, spilled over its banks, and left behind in the flat country (debris fan) thick sheets of bouldery detritus (fig. 3) in a matrix of sand and mud that crossed the McCloud River Railroad and inundated the road bed (fig. 10).

Following the series of debris flows on Mud Creek in 1924, an investigation of the Konwakiton Glacier was completed by R.L. Egenhoff in 1925 (Hill and Egenhoff, 1976). Egenhoff wrote, "On July 28, we ascended Mt. Shasta to a point above timber line from which a clear view could be had of the end of Konwakiton glacier and the canyon immediately below it. At this time there was very little snow on the mountain. The main part of the glacier at its lower extremity was about 800 feet (244 m) wide and 100 feet (30.5 m) thick, and was practically solid ice. The material underneath the end of the glacier, consisting of unconsolidated volcanic debris of all kinds, seemed to be standing in a wall several feet high at a very steep slope which was practically vertical in places. At intervals of a few minutes, great masses of this material broke off and slid down into the canyon. Two large caverns, each about 300 feet (91.4 m) wide, had thus been formed by caving material extending probably two or three hundred feet back under the glacier and leaving the ice over-hanging. A waterfall from underneath the ice was pouring out of each cavern

Figure 10. McCloud River Railroad train stalled at crossing of debris flow on Mud Creek, 1924 (sec. 35, T. 40 N., R. 2 W.). Photograph courtesy of Kite Photo-News, McCloud, California.

over the caving material. As the glacier throughout its length was badly fissured transversely, the waterfalls were no doubt produced by water from the top of the melting glacier flowing into the fissures and thus reaching its under side. At the time of inspection the west branch of Konwakiton glacier terminated at the same point as the main part described above, but with the face of its lower end at right angles to that of the main glacier. A waterfall was also pouring from the end of this branch, and caving was going on below it."

Although no debris flows threatened the town of McCloud during 1925 (Hill and Egenhoff, 1976), it is considered probable that small debris flows caused by the meltwater described by Egenhoff in 1925 occurred on Mud Creek. Wood (1931) indicated some debris-flow deposits occurred on the fan of Mud Creek and in the McCloud River in 1925.

Snow bridges (fig. 11) are formed by the scouring action of streamflow as meltwater from more exposed parts of the mountain flows downstream. Most snow bridges are formed in deep-shaded parts of incised channels on the mountain. When these bridges catch earth and silt (debris) as described by the Mount Shasta Herald (July 21, 1977), or the snow tunnels collapse, a temporary reservoir may be formed. These dams then may be dislocated or breached, thereby creating surges of water and debris that may cause debris flows downstream.

Debris flows caused by glacier outbursts and snowmelt (Williams, 1934; Hill and Egenhoff, 1976) generally have occurred during the warm summer months (Meier, 1969; Miller, 1980; Blodgett and others, 1988). Debris flows attributed to the effects of warm air temperatures have occurred on Mount Shasta a number of times. The relation between air temperature and glacial melt is not one of cause and effect; rather, air temperature is an index of solar radiation that actually causes melting of snow and glacial ice (Tangborn, 1980), which in turn combines with material/sediments beneath and down gradient from

Figure 11. Entrance of snow tunnel in incised channel formed by melting or scouring action of streamflow. Location is about 3 km upstream from Mud Creek Dam. Slope is 0.073. Flow is from right to left. Photograph taken July 1984.

glaciers, to initiate debris flows. Hill and Egenhoff (1976) and Wood (1931) reported that debris flows were seen on Mud Creek in 1881 and 1920 and repeatedly during the summer months of 1924, 1925, 1926, and 1931. The most common occurrences were in July (1926) and August (1924, 1925, and 1926). The Redding Searchlite and the Mount Shasta Herald reported that tons of muddy water flowed down Mud Creek during July 1977. On July 6, 1985, a debris flow reportedly caused by glacial meltwater occurred on Whitney Creek.

Direct Runoff from Precipitation

Heavy or intense rainfalls on the snowfields and glaciers of Mount Shasta have been noted over the years (Nutting, 1935; Carter, 1987). Convective precipitation in the vicinity of the mountain is especially common during June, July, and August. On August 28, 1935, a deluge of water, mud, sand, and boulders that flowed down Whitney and Bolam Creeks (fig. 2) first covered and then washed out the Southern Pacific tracks. Studies of the Whitney, Bolam, and Graham Creek basins by Southern Pacific indicated that the resulting debris flows were due solely to rainfall (Southern Pacific Transportation Co., 1935). However, as shown in table 2, no debris flows that were documented in this report from the 1935 storm actually occurred on Graham Creek.

The August 1935 debris flow on Whitney Creek continued downstream 6 km, blocking U.S. Highway 97 (fig. 2) and partly burying several automobiles (fig. 12). In a report of this flood by the California Department of Highways and Public Works, Nutting (1935) reported that the debris flow was attributed to a "warm thunderstorm on the [Whitney and Bolam] glaciers that started the snow and ice to melt and the resulting flow soon assumed the proportions of an avalanche." The assumption that the August 1935 debris flow on Whitney Creek was caused by precipitation is confirmed by a review of climatological data reports for 1935 (Bowie, 1935). Although climatic data for the storm on August 28, 1935, are not available for the Whitney Creek area, data from the U.S. Department of Agriculture Weather Bureau climatic stations at

Figure 12. Debris flow from Whitney Creek covering U.S. Highway 97 following rainstorm on August 28, 1935. The highway was buried to a depth of 1.2 m by mud and boulders for a distance of 370 m. Flow from right to left. Photograph courtesy of California Department of Transportation.

nearby Yreka and Montague indicate that a storm front passed through the area August 26-29, 1935, and that precipitation was greatest on August 28 (Bowie, 1935). The dates of miscellaneous phenomena summary, as given in the climatological data report for the month of August, gives the 28th as the date of a thunderstorm at Montague, 45 km northwest of Whitney Creek (Bowie, 1935). The debris flows on Whitney and Bolam Creeks on August 28, 1935, therefore, are attributed to intense convective precipitation and melting snow centered on parts of the Whitney and Bolam Creek basins.

CHARACTERISTICS AND PROPERTIES OF DEBRIS FLOWS

The characteristics of debris flows on Mount Shasta, which change dramatically in a downstream direction, are indicated by the various travel distances, sizes, location, thickness, cross-sectional shapes, and physical properties of the deposits (tables 3 and 4 figs. 13 and 14). A comparison of stream profiles for different channels on Mount Shasta (fig. 13) indicates that the slope of most channels near the summit is about 35°. On Whitney Creek, the upper slope is about 25°.

Table 3. Characteristics of channels and debris flows on Mount Shasta, California, 1983 and 1984.

[km, kilometers; m, meters]

Site (fig. 17)	Stream	Distance from summit (km)	Average thickness of deposits (m)	Number of flow deposits in sample
	Whitney-Bolam Creeks debris fan			
1	Pits 1 and 2	20	0.73	6
2	Pit 3	19	.55	5
3	Pits 5 and 6	16	.64	7
	Mud-Ash Creeks debris fan			
4	Pit A	15	.55	4
5	Pit B	14	.55	4
6	Pit E	12	.82	3
7	Pit C	10	.76	2
8	Whitney Creek canyon	8.0	2.5	1
9	Upper Ash Creek	11	.91	1
10	Upper Ash Creek	12	.76	1
11	Upper Gravel Creek	11.9	.43	1
12	Upper Gravel Creek	8.5	1.92	1
[1]13	Mud Creek	17	1.65	1

[1]Not used in graphical analysis (fig. 18).

Table 4. Physical properties of debris-flow deposits on Mount Shasta, California

[km, kilometer; mm, millimeter; Φ units, phi units; —, no data]

Site	Date of sampling	Channel slope	Downstream distance from summit (km)	Grain diameter		Estimated solids concentration	
				Median D50 (mm)	Mean (Φ units)	Weight	Volume
Whitney Creek near terminus of north debris flow Shasta Valley, sec. 28, T. 43 N., R. 4 W.	10-85	—	17.8	0.72	+0.46	0.85	0.68
Whitney Creek near terminus of south debris flow Shasta Valley, sec. 19, T. 43 N., R. 4 W.	7-85	—	18.4	.45	+115	.85	.68
Whitney Creek at U.S. Highway 97 crossing, sec. 34, T. 43 N., R. 4 W.	10-85	0.0665	13.3	5.40	-2.45	.90	.77
Whitney Creek on left bank, at Southern Pacific crossing, sec. 2, T. 42 N., R. 4 W.	9-84	—	11.1	—	—	.87	.72
Whitney Creek on right bank, at Southern Pacific crossing, sec. 2, T. 42 N., R. 4 W.	10-85 9-84	— —	11.1 —	3.20 —	-1.70 —	.86 .84	.70 .66
Whitney Creek at 1670 terrace, sec. 13, T. 42 N., R. 4 W.	9-84 7-85	— —	8.4 8.4	— .45	— +1.15	.83 .86	.64 .70
Whitney Creek upstream from Whitney Falls, sec. 30, T. 42 N., R. 3 W.	8-85	.104	6.90	2.10	-1.10	.88	.73
Bolam Creek on left bank, at ford, sec. 19, T. 42 N., R. 3 W.	7-84	—	5.85	—	—	.86	.70
Mud Creek at Road 13 crossing, sec. 27, T. 40 N., R. 2 W.	7-84	.0381	11.8	.83	+.24	.83	.65
Mud Creek, sec. 5, T. 40 N., R. 2 W	7-84	.0747	7.6	3.40	-1.8	.87	.72

Table 4. Physical properties of debris-flow deposits on Mount Shasta, California —*Continued*

Site	Date of sampling	Channel slope	Downstream distance from summit (km)	Grain diameter		Estimated solids concentration	
				Median D50 (mm)	Mean (Φ units)	Weight	Volume
Mud Creek at terrace, 1.6 km upstream from Mud Creek Dam, sec. 31, T. 41 N., R. 2 W.	7-84	0.0889	6.4	—	—	0.83	0.65
Ash Creek downstream from Cold Creek, near Sugar Pine Butte Road, sec. 24, T. 41 N., R. 2 W.	7-84	.0889	10.4	—	—	.83	.65
Ash Creek at Bedrock, near Military Pass Road, sec. 14, T. 41 N., R. 2 W.	7-84	.0627	7.3	0.34	+1.55	.84	.66
Gravel Creek at Military Pass Road crossing, sec. 21,[1] T. 42 N., R. 2 W.	7-84	.0457	6.7	.19	+2.38	.82	.63
Gravel Creek at crossing No. 2, sec. 29, T. 42 N., R. 2 W.	—	—	5.1	.43	—	—	—
Gravel Creek on left bank, at crossing No. 4, sec. 31, T. 42 N., R. 2 W.	7-84	.0784	4.3	.54	+.84	.82	.63
Gravel Creek on right bank, at crossing No. 4, sec. 31, T. 42 N., R. 2 W.	7-84	.0784	4.3	—	—	.81	.62
Inconstance Creek at switchback on left bank, 2.7 m below deposit surface, sec. 26, T. 42 N., R. 3 W.	7-84	.0952	4.7	.64	—	.86	.70
Inconstance Creek at switchback on right bank, 3.0 m below deposit surface, sec. 26, T. 42 N., R. 3 W.	7-84	.0952	4.7	—	—	.86	.70
Average of values for 18 sites						0.85	0.68

[1]In incised channel 0.4 km upstream from road crossing.

Pattern of Travel and Deposition

The paths of debris flows are dependent on the size of the flow, capacity, sinuosity and slope of the channel, presence of overflow areas, and patterns of deposition of previous flows. Overbank flow caused by debris flows generally occurs in reaches below altitudes of 2,130 m (slopes flatter than 15°). An example of the effects of previous flows on existing channels can be seen from data obtained for Ash Creek. On the upper road crossing of Ash Creek (fig. 14), previous flows had partly filled the channel, and the debris flow of 1962 was so large that it could not be contained in the channel. Where the existing channel curved, a part of the debris flow continued straight downslope, with the leading edge coming to rest more than 700 m from the original channel.

Debris-flow deposition is affected also by the capacity of the existing channel and the height of channel banks. If banks are low, large debris flows may overtop them, and the new flow path may diverge from the main channel. During the series of debris flows on Mud Creek between 1924 and 1931, one or more flows overtopped the right bank near the Mud Creek Dam and traveled 6,000 m outside the main channel before coming to rest (fig. 15). Near the terminus of the overbank flow, this deposit (fig. 15) lies more than 3.2 km from the Mud Creek (main) channel.

An additional example of a debris flow occupying both existing and new channels occurred on Whitney Creek July 6, 1985. The path of this debris flow and the areas subject to inundation were not confined to the existing channel in the lower reaches even though parts of the channel were diked. Inundation of

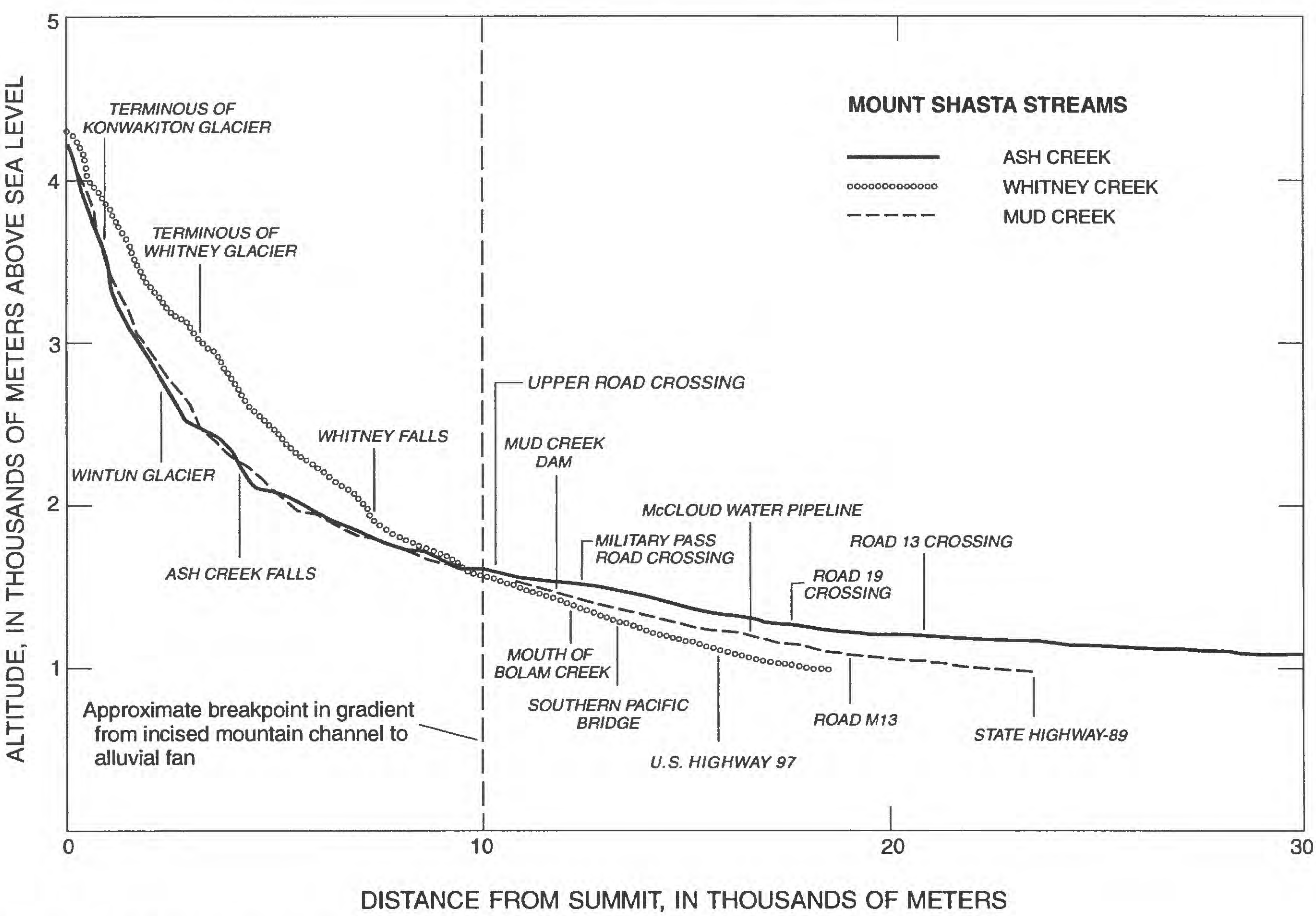

Figure 13. Longitudinal profiles for major streams on Mount Shasta, California.

the flood plain began below an altitude of about 1,070 m and extended about 27 km from the summit. Areas of overflow were documented by aerial photographs taken during July 1985. The inundated areas of the fan, known as Juniper Flat in Shasta Valley (fig. 16), included the existing main (east) channel, an old left bank overflow (west) channel, and the adjacent fan. Deposits from this debris flow tended to feather out and were less than 0.3 m thick near the terminus, rather than ending with an abrupt snout as noted for earlier debris-flow deposits at higher altitudes on Whitney Creek.

Thickness of Debris-Flow Deposits

Stratigraphic surveys of historical debris-flow deposits were made by inspecting cut banks and excavating pits at selected locations (fig. 17) in the

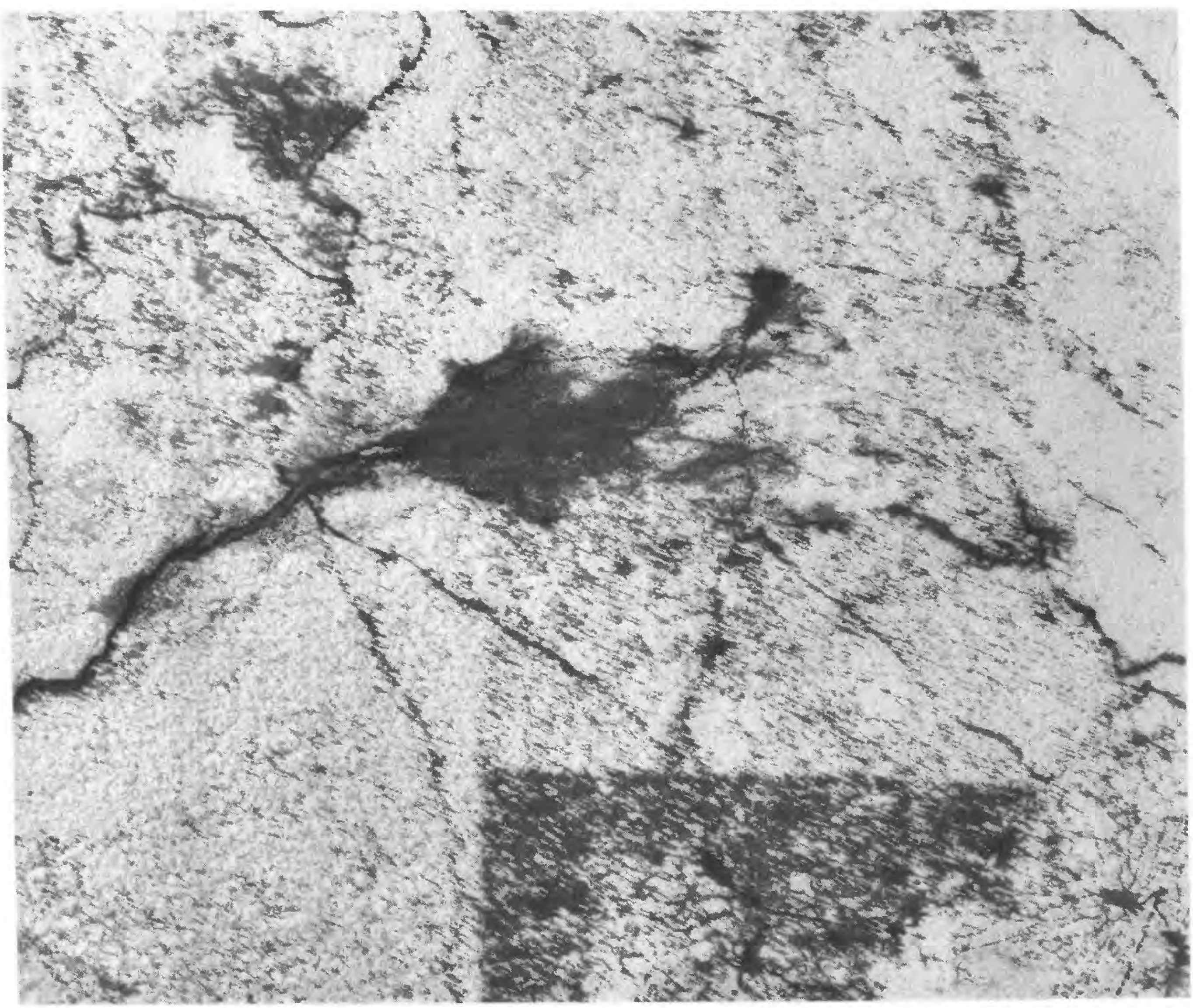

Figure 14. Aerial view of debris-flow deposits of 1962 and 1977 on Ash Creek fan near upper road crossing (parts of secs. 10, 15, and 16, T. 41 N., R. 2 W.). U.S. Geological Survey aerial photograph taken July 24, 1981.

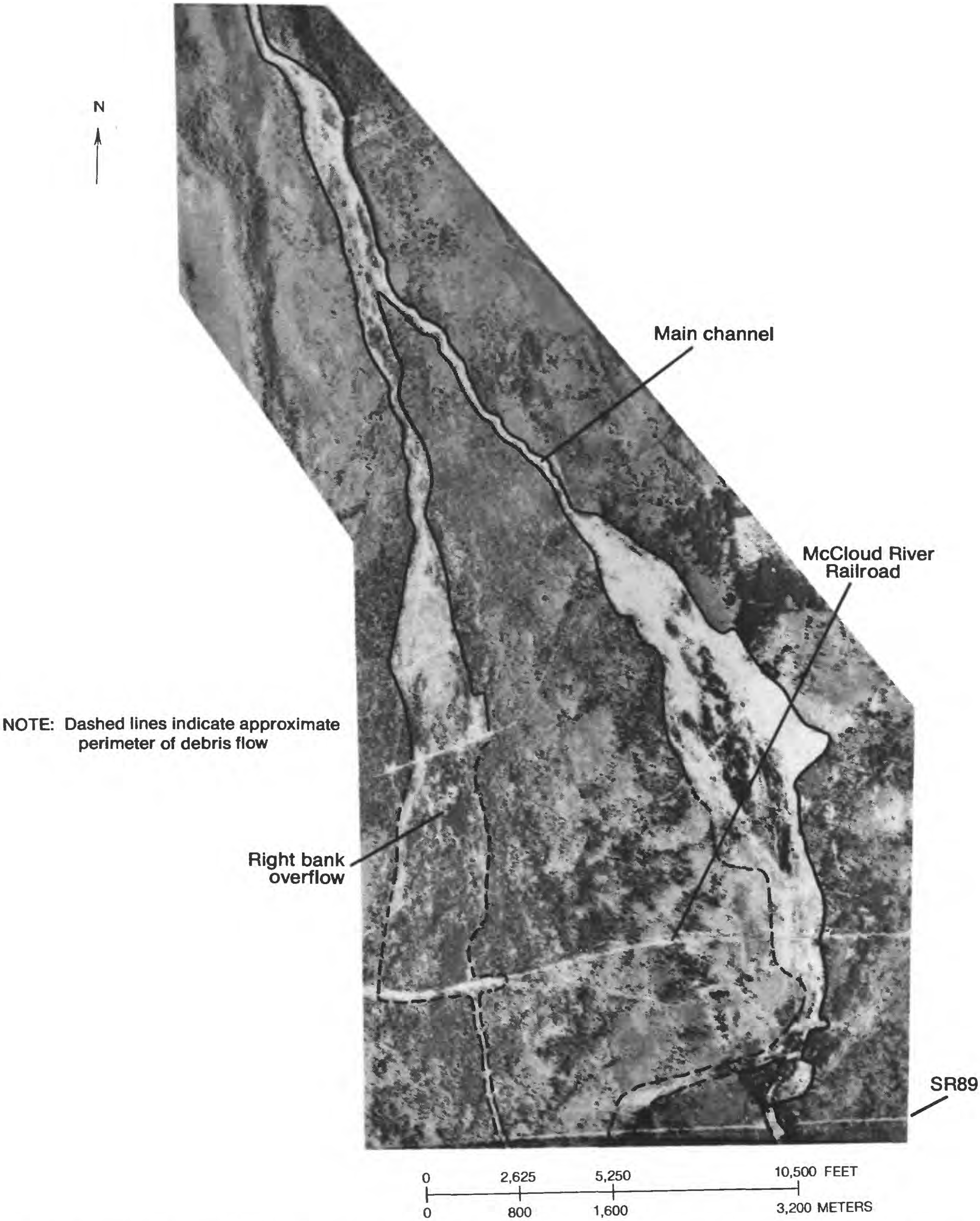

Figure 15. Aerial view of debris-flow deposits on Mud Creek fan near McCloud, California. Deposits from the 1924-31 series of debris flows on right (west) bank. Overflow deposits are separated 3.2 km from main channel flow at McCloud River Railroad. U.S. Geological Survey aerial photograph taken July 30, 1951.

channels and on fans of several streams on the flanks of Mount Shasta. These data (table 3), collected during 1983 and 1984, indicate that the average thickness of debris-flow deposits on fans is about 0.98 m, with an approximate range between 0.4 and 2.5 m. The thickness varies laterally across the channel or fan. The data in figure 18 indicate that the thickness of deposits tends to decrease in a downstream direction. Most debris-flow deposits occur on fans between 10 and 20 km from the summit.

The greatest thickness of historical deposits are found in stream channels that confined the flow. Deposits with depths of more than 1 m commonly represent a terminal lobe or inundation in a former

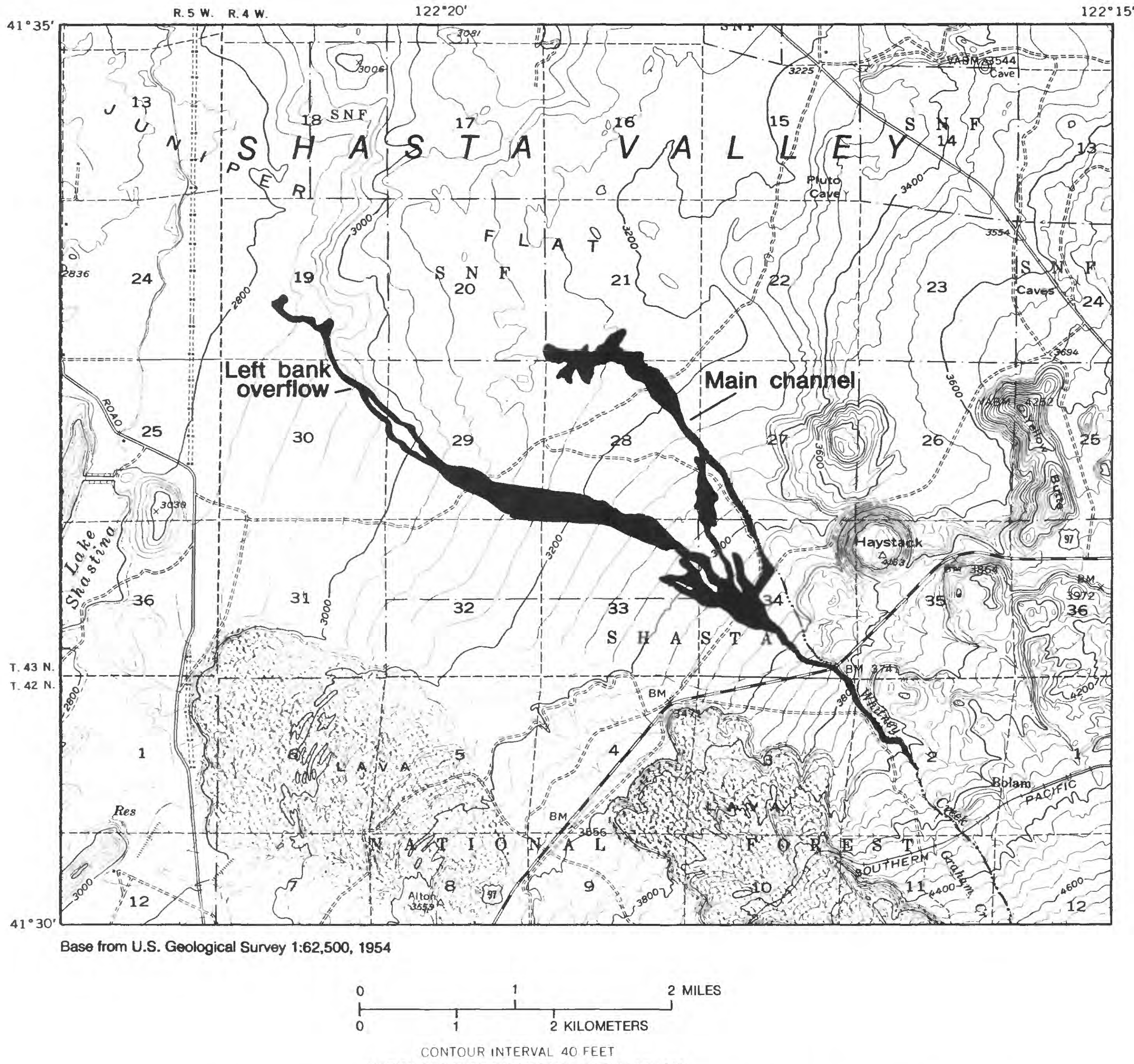

Figure 16. Deposition on Whitney Creek fan (Shasta Valley) by the debris flow of July 6, 1985. Area of deposition (shown in black) mapped from U.S. Geological Survey aerial photograph taken July 24, 1985.

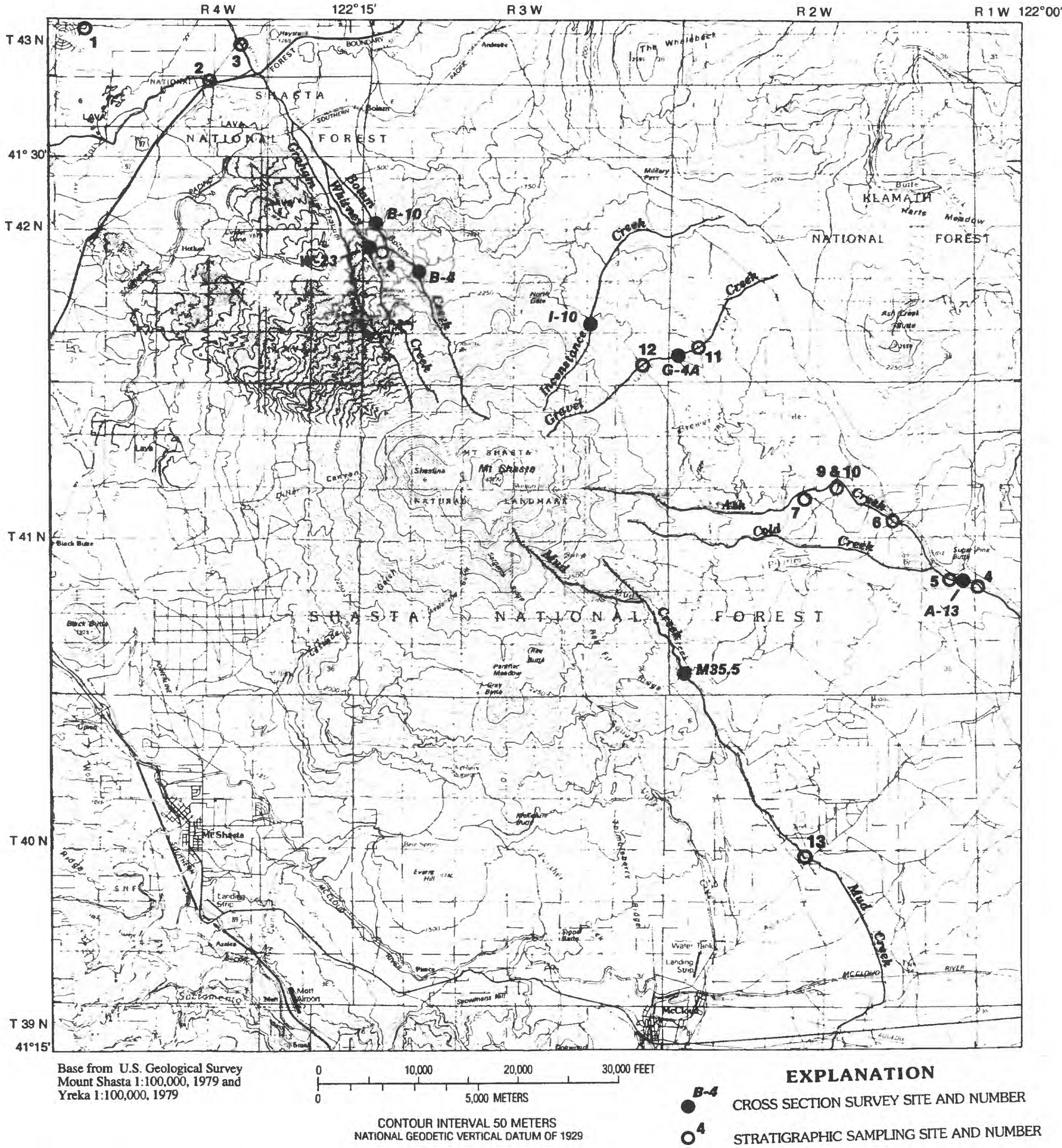

Figure 17. Location of debris-flow deposit cross-section surveys and sampling sites used to determine stratigraphy of historical debris-flow deposits on Mount Shasta, California.

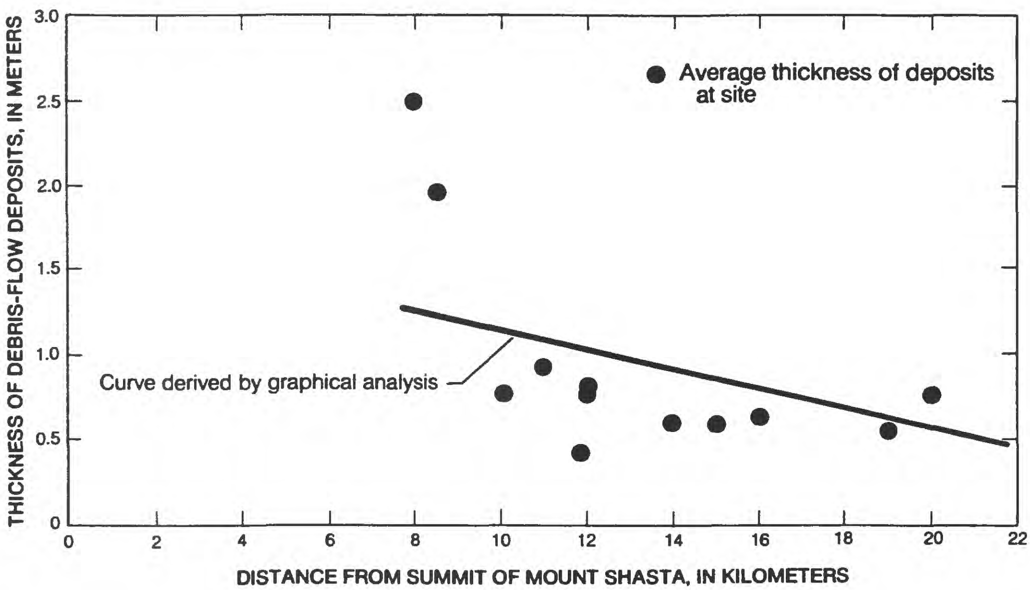

Figure 18. Downstream change in thickness of debris-flow deposits for selected channels on Mount Shasta, California.

channel. Debris-flow deposits from different flows were difficult to separate because of the similarity of the transported material and lack of distinct bedding planes. Thus, one deposit might, in some cases, represent several flows that occurred within a few days or a few years of each other. Figure 18 represents average thickness of debris flow deposits at several sites on five streams.

Cross-Sectional Shape of Deposits

Debris-flow deposits on Mount Shasta have a convex-shaped transverse profile. Cross sections of flows at seven selected locations on Mud, Inconstance, Gravel, Whitney, Bolam, and Ash Creeks (fig. 17) illustrate the convex surface shape typical of the larger debris deposits (fig. 19) on Mount Shasta. The cause of the convex shape of the deposits is unknown, but is possibly related to the physical composition of the debris-flow slurries. A cross section of Mud Creek (M35.5, fig. 19) shows remnants of various multiple debris-flow deposits that are incised within terraces formed by more current flows. Generally, the centers of the deposits are as much as 5 m higher than margins near the canyon walls.

Existing debris flow deposits on Mount Shasta indicate that as new flows occur, older incised channels are filled and obliterated. Subsequent streamflow then cuts a new channel, which may not occupy the lowest part of the valley cross section. For some debris flows, large boulders and rubble (debris-flow levees) line the outer perimeter of the deposit (fig. 20).

Sediment and Water Ratio of Debris-Flow Slurries

Using analytical procedures described by Pierson (1985), the approximate original water-sediment ratios of debris-flow slurry deposits at 19 sites on Mount Shasta (table 4) were determined by reconstituting dry samples in the laboratory. The results indicated that, on the average, original debris-flow mixtures consisted of a ratio of solids to the total mass by volume of 0.68 (table 4). Slurry consistency was sensitive to very small changes in water content. For example, a decrease of only 1 to 2 volume percent from optimum rendered the slurry too viscous to flow;

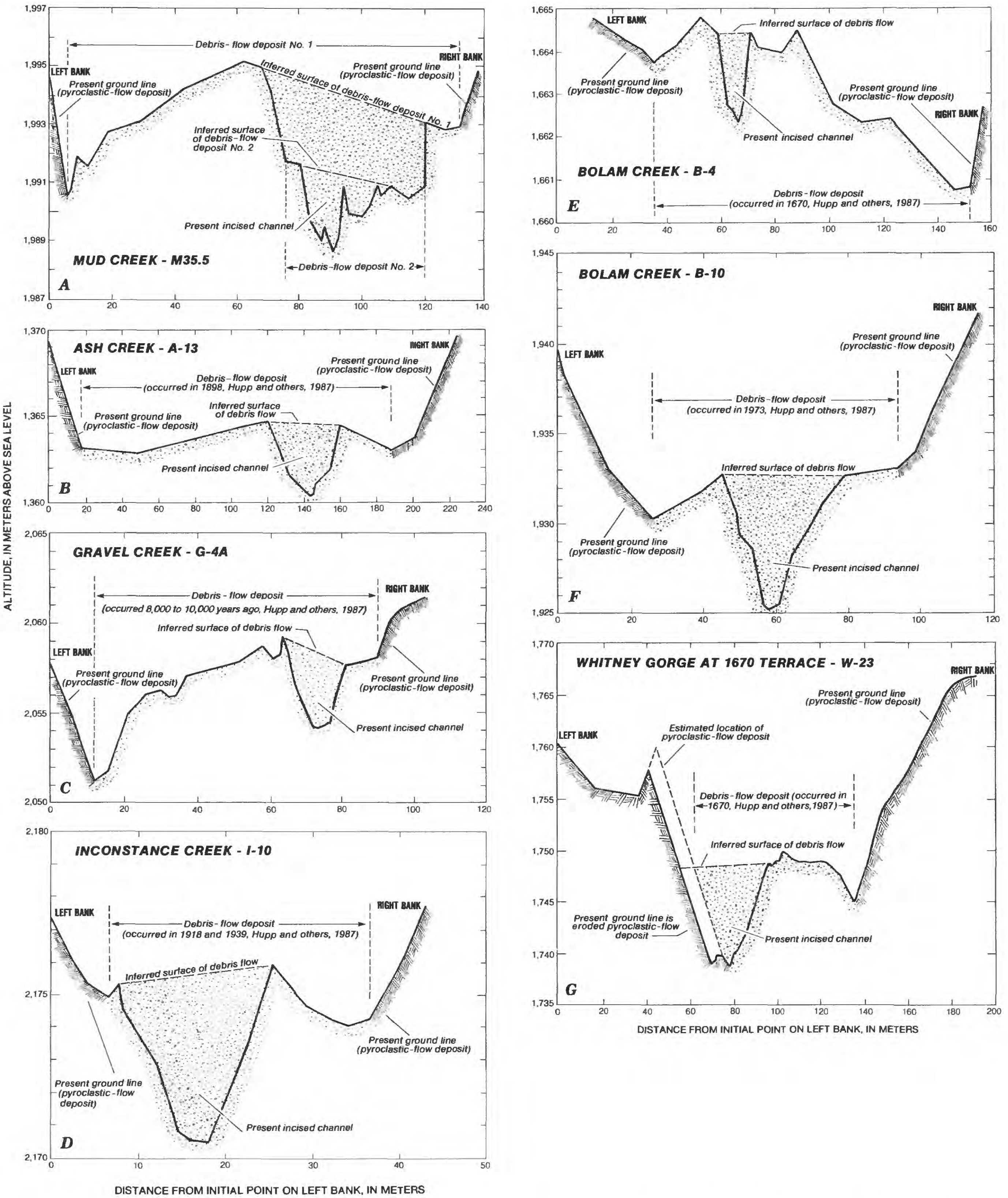

Figure 19. Typical convex shape of cross sections at debris-flow deposits for selected streams on Mount Shasta, California.

Figure 20. View downstream of boulder levees along margins of 1918 and 1939 debris flows, Inconstance Creek, California, in sec. 26, T. 42 N., R. 3 W. Photograph taken July 1984.

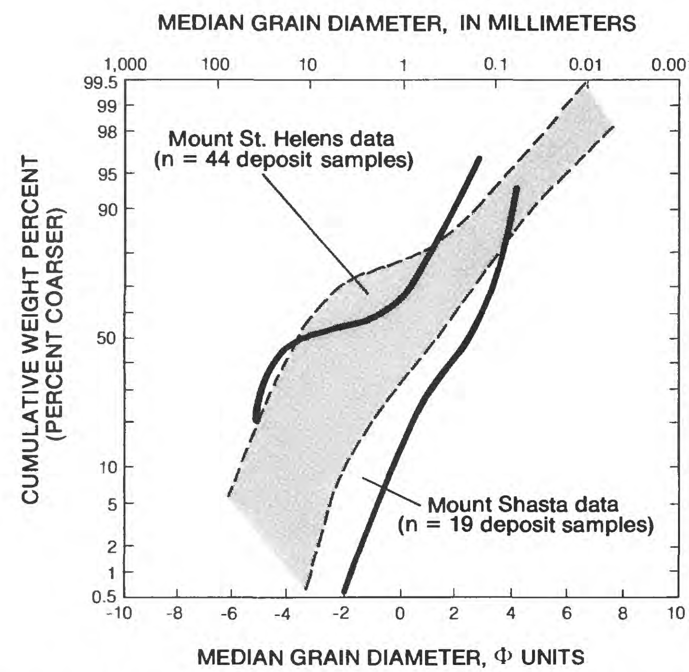

Figure 21. Envelope of cumulative grain-size curves for debris flows on Mount Shasta, California. Sampling is limited to peak-flow deposits and sites where clasts are finer than about 100 mm.

an increase of 1 to 2 volume percent diluted the slurry to the point at which it could not hold coarse particles in suspension. All debris flows were characterized by a fairly small range of sediment concentrations (table 4), with the ratio of solids to water by volume ranging from 0.62 to 0.77, which is equivalent to a minimum water concentration of 32 percent by volume. A cumulative size distribution curve of debris-flow deposits for the Mount Shasta volcano (fig. 21) shows that the median grain diameter of the smaller material in the deposits was larger than 0.01 mm, which is very fine sand.

SUMMARY

In the last 500 years, at least 69 debris flows of noneruptive origin have occurred on Mount Shasta. Between 1900 and 1985, 37 debris flows occurred on the various stream channels draining the volcano, giving an average interval of 2.3 years between debris flows on Mount Shasta. During any one year, however, several streams may experience a debris flow such as in 1977 when flows occurred on Whitney, Mud, and Ash Creeks. Debris flows occurred in successive years on Mud Creek (1924, 1925, and 1926). For a given stream, the mean interval between flows on a stream is 13.3 years. Between 1900 and 1985, the greatest number of debris flows occurred on Mud and Whitney Creeks. Most debris flows occurred in July, but they also were observed in August and September.

Debris flows may be formed when banks of eruptive debris or lava flows are undermined by streamflow and collapse into the channel, causing temporary blockage. An additional potential cause of debris flow is the formation of snow and ice dams as the result of melting glaciers and snowpack, creating temporary dams that are subsequently breached. Debris flow also occurs when heavy amounts of localized precipitation fall on the slopes of Mount Shasta during the summer season (June, July, and August).

The pattern of debris-flow deposits is dependent on the capacity and sinuosity of the channel, presence of overflow areas, and patterns of deposition of previous flows. In 1985, a debris flow on Whitney Creek traveled 27 km from the summit. The depth of the deposits, ranging from 0.4 to 2.5 m and averaging 1 m, tends to decrease in a downstream direction. Cross-section shapes of debris-flow deposits are convex. Surveys of seven sites on streams on Mount Shasta indicate that the maximum height of the deposits relative to the low point (usually near the margins of the debris flow) is about 5 m. The sediment-water ratios of reconstituted debris-flow slurries at 19 sites averaged 0.68, which is equivalent to a minimum water concentration of 32 percent by volume.

References Cited

Beverage, J.P., and Culbertson, J.K., 1964, Hyperconcentrations of suspended sediment: American Society of Civil Engineers, Journal of the Hydraulics Division, v. 90, no. HY-6, p. 117-128.

Blodgett, J.C., Poeschel, K.R., and Thornton, J.L., 1988, A water-resources appraisal of the Mount Shasta area in northern California, 1985: U.S. Geological Survey Water-Resources Investigations Report 87-4239, 46 p.

Bowie, E.H., 1935, Climatological data, California section, August 1935: U.S. Department of Agriculture, Weather Bureau, v. 39, no. 8, p. 57-64.

Carter, E.S., 1987, Mount Shasta Challenge of the mountain: California Geology, v. 40, no. 9, p. 210-211.

Christiansen, R.L., Kleinhampl, F.J., Blakely, R.J., Tuchek, E.T., Johnson, F.L., and Conyac, M.D., 1977, Resource appraisal of the Mt. Shasta Wilderness Study Area, Siskiyou County, California: U.S. Geological Survey Open-File Report 77-250, 53 p.

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

Denand, P.J., 1924, Mount Shasta's melting glacier: The Record, Associated Oil Co., p. 6-11.

Hill, Mary, 1977, Glaciers of Mount Shasta: California Geology, v. 30, no. 4, p. 75-80.

Hill, Mary, and Egenhoff, E.L., 1976, A California jökulhlaup: California Geology, v. 29, no. 7, p. 154-158.

Hupp, C.R., 1984, Dendrogeomorphic evidence of debris flow frequency and magnitude at Mount Shasta, California: Environmental Geology and Water Sciences, v. 6, no. 2, p. 121-128.

Hupp, C.R., Osterkamp, W.R., and Thornton, J.R., 1987, Dendrogeomorphic evidence and dating of recent debris flows on Mount Shasta, Northern California: U.S. Geological Survey Professional Paper 1396-B, p. B1-B39.

Marron, D.C., and Laudon, J.A., 1987, Susceptibility to mudflows in the vicinity of Lassen Peak, California, *in* Subitzky, Seymore, ed., Selected papers in the hydrologic sciences, 1986: U.S. Geological Survey Water-Supply Paper 2310, p. 97-106.

Meier, M.F., 1969, Glaciers and water supply: Journal of American Water Works Association, v. 61, no. 1, p. 8-12.

Miller, C.D., 1980, Potential hazards from future eruptions in the vicinity of Mount Shasta Volcano, Northern California: U.S. Geological Survey Bulletin 1503, 43 p.

Mullineaux, D.R., and Crandell, D.R., 1981, The eruptive history of Mount 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. 3-15.

Nutting, G.H., 1935, August storms damage State highways: California, Department of Highways and Public Works, September, p. 26-29.

Osterkamp, W.R., Hupp, C.R., and Blodgett, J.C., 1986, Magnitude and frequency of debris flows, and areas of hazard on Mount Shasta, Northern California: U.S. Geological Survey Professional Paper 1396-C, 21 p.

Pierson, T.C., 1985, Initiation and flow behavior of the 1980 Pine Creek and Muddy River lahars, Mount St. Helens, Washington: Geological Society of America, v. 96, no. 8, p. 1056-1069.

Pierson, T.C., and Scott, K.M., 1987, Downstream dilution of lahars from Mount St. Helens, Washington: Defining the boundary between debris flow and hyperconcentrated streamflow, *in* Glysson, G.D., ed., Proceedings of the Advanced Seminar on Sedimentation, August 15-19, 1983, Denver, Colorado: U.S. Geological Survey Circular 953, p. 16-17.

Rhodes, P.T., 1987, Historic glacier fluctuations at Mount Shasta: California Geology, v. 40, no. 9, p. 205-211.

Southern Pacific Transportation Co., 1935, Mudflow and washout at Graham, California: San Francisco, California, unpublished report, 4 p., 6 exhibits.

Tangborn, W.V., 1980, Two models for estimating climate-glacier relationships in the North Cascades, Washington, U.S.A: Journal of Glaciology, v. 25, no. 91, p. 3-20.

Varnes, D.J., 1958, Landslide types and processes, *in* Eckel, E.B., ed., Landslides and engineering practice: National Research Council, Highway Research Board Special Report 29, chap. 3, p. 20-47.

Williams, Howel, 1934, Mount Shasta, California: Zeitschrift Vulkanologie, v. 15, p. 225-253.

Wood, W.A., 1931, Mudflow in McCloud River, California: California Debris Commission report to Chief of Engineers, Washington, D.C., 10 p.