Magnitude and Frequency of Debris Flows, and Areas of Hazard on Mount Shasta, Northern California

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CONVERSION FACTORS

For the convenience of readers who prefer to use inch-pound units rather than the metric International System units used in this report, the following conversion factors are provided:

Multiply metric unit	*By*	*To obtain inch-pound unit*
millimeter (mm)	0.03937	inch (in)
meter (m)	3.28	foot (ft)
kilometer (km)	0.62	mile (mi)
square kilometer (km^2)	0.386	square mile (mi^2)
cubic meter (m^3)	35.31	cubic foot (ft^3)
megagram (Mg)	1.1	ton, short (2,000 lb)
megagram/square kilometer/year ((Mg/km^2)/yr)	2.87	ton, (short)/square mile/year ((ton/mi^2)/yr)

MAGNITUDE AND FREQUENCY OF DEBRIS FLOWS, AND AREAS OF HAZARD ON MOUNT SHASTA, NORTHERN CALIFORNIA

By W.R. OSTERKAMP, C.R. HUPP, and J.C. BLODGETT

ABSTRACT

Debris flows on Mount Shasta, northern California, have occurred frequently during the late Holocene in response to rapid runoff from melting snow and ice. Glacial-meltwater streams that deeply incise unstable pyroclastic and related flow deposits typically form debris flows when high discharges cause slope failures within steep-walled gorges. The landslide material either absorbs streamflow quickly and becomes a slurry or briefly dams the stream and converts to a debris flow as breaching occurs.

All glacial-meltwater streams on Mount Shasta have had repeated debris-flow activity during the last 500 years. During this period, large-magnitude, potentially destructive flows on Mount Shasta have occurred at a rate of four per century, but smaller flows contained by stream channels may be 10 to 20 times more numerous. The smaller debris flows of Mount Shasta pose little hazard to human life or property, whereas larger, out-of-channel flows could cause minor damage. Only the City of McCloud and inhabited areas on the Whitney–Bolam fan appear to be threatened by possible debris-flow activity. None of the streams lacking glacial meltwater have had significant debris-flow activity during late Holocene time.

Sediment yields from upper fan areas of Mount Shasta are very high, but most of the sediment moved by debris flows from upper slopes is redeposited on lower fan areas, locally causing extensive and rapid aggradation of the fan surface. Little sediment enters a through-flowing stream network. Correspondingly high denudation rates in the areas that provide sediment for debris flows (the deep gorges) suggest that a high frequency of debris flows may be unique to recent centuries.

INTRODUCTION

Mount Shasta (fig. 1), in northern California, is a large stratovolcano whose slopes are formed dominantly by pyroclastic flows and other volcanic rocks, glacial rock debris, and debris-flow deposits. The widespread, locally thick occurrences of interbedded pyroclastic and debris-flow deposits on the slopes of Mount Shasta demonstrate that debris flows have been an important geomorphic process throughout the constructional and destructional history of the mountain. Recent observations and historically datable events show that sediment movement and fan development by noneruptive debris flows continue to be active processes around the mountain. Where communities, recreational areas, and transportation, water, and other land-use facilities have been developed around Mount Shasta, debris flows can be a potential hazard to both life and property.

The purpose of this chapter of Professional Paper 1396 is to evaluate the potential for future noneruptive debris-flow activity on Mount Shasta. Attention is restricted to "cold" flows, that is, to flows not directly related to volcanic activity. Areas where damage by cold debris flows could occur are identified on the basis of geologic, topographic, and historical evidence. From geologic and dendrochronologic observations indicating past frequencies and magnitudes of debris flows, areas interpreted to be prone to future activity are assigned relative degrees of hazard potential (pl. 1).

Mount Shasta, lying about 65 km south of the Oregon–California border (fig. 1), is the largest (4,317 m in elevation) volcano of the southern portion of the Cascade Range. The mountain is encircled by roads, highways, and railroads, principally on the western and southern sides. The towns of Weed, Mt. Shasta, and McCloud are on the lower slopes of Mount Shasta on the western, southwestern, and southern sides, respectively. Much of the mountain is included in the Shasta National Forest, although sizable areas are owned by companies with lumber interests.

Previously published papers concerning the geology, hydrology, and associated hazards of Mount Shasta are too numerous to be summarized here. Specific discussions of debris-flow activity at Mount Shasta are included in papers by Dickson and Crocker (1953), Hill and Egenhoff (1976), Miller (1980), and Hupp (1984).

Debris flows are rapidly moving gravity-induced slurries of granular solids, water, and air (Varnes, 1978). They differ from flows of turbulent water containing suspended sediment in that they have higher

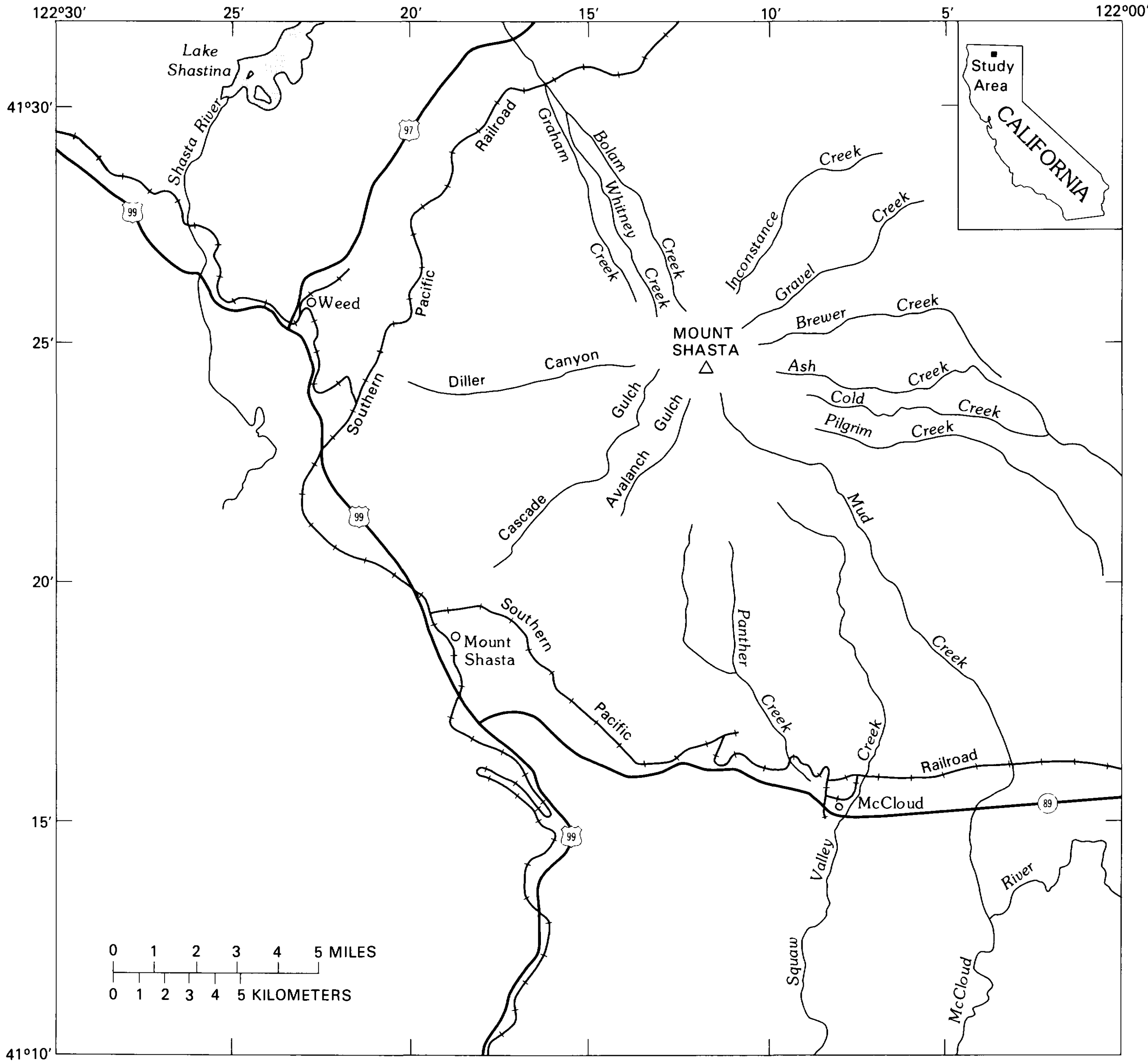


FIGURE 1.—Map of Mount Shasta area showing towns, roads, railroads, and major streams.

concentrations of sediment—typically 65 to 70 percent by weight—and also sediment-support mechanisms including cohesive strength, buoyancy, dispersive stress, and structural support. Debris flows, as used here, include mudflows, of which at least 50 percent of the sediment is sand size or finer (Varnes, 1978), and lahars, which are formed from sediment primarily of volcanic origin. A debris-flow deposit is the sediment or rock layer that results from cessation of flow. When debris-flow deposits repeatedly originate from a central source or sources and become stacked and spread over an extensive sloping area, a debris fan is formed. Such fans, including several around Mount Shasta, are commonly referred to as alluvial fans, although little of the deposition may have occurred by fluvial processes. The reader is referred to Costa (1984) for a comprehensive treatment of the physical characteristics, dynamics, and sedimentology of debris flows.

Debris flows not directly related to volcanic eruptions are common on Mount Shasta for several reasons: (1) volcanism has produced high, steep slopes that in many places are underlain by large thicknesses of erodible pyroclastic flow deposits and related interbeds of debris flows; (2) alpine glaciers have deposited local accumulations of easily mobilized rock debris; (3) rapid releases or surges of glacial meltwater, as well as intense precipitation events, periodically discharge large slugs of sediment-deficient streamflow; (4) pronounced erosion of the pyroclastic and associated beds by large, perhaps steady, runoff events results in deep, steep-walled, generally unvegetated incisements that are highly susceptible to slope failure caused by such processes as fluvial undercutting, sapping, and seepage erosion; (5) unconsolidated material deposited in stream channels by slope failures and avalanches causes a probable combination of damming and short-term storage of water and rock debris as well as rapid absorption of streamflow to a point of saturation and formation of a slurry; (6) breaching of a debris dam by continuing streamflow from above or by mobilization of a water–debris slurry may cause a rapid conversion from fluvial-transport to debris-flow processes; and (7) all combinations of slumping and other slope failures, damming, and bulking or incorporation of sediment in a flow by erosion of the flow boundary (K.M. Scott, U.S. Geological Survey, written commun., 1983) may result in debris flows ranging in size and hazard from insignificant to highly destructive.

METHODS

The techniques used in this study to evaluate potential debris-flow hazards on Mount Shasta rely almost exclusively on (1) past activity as indicated by geologic, botanical, and historical information, and (2) identification of areas where current conditions indicate a debris-flow hazard. (Some areas are underlain by extensive pyroclastic and debris-flow deposits, but currently the potential supply of water or sediment does not appear sufficient to result in the formation of destructive debris flows.)

Where a series of layered debris-flow deposits is exposed by stream incision, stratigraphic evidence on magnitudes of events and minimum frequency is provided. If datable wood, charcoal, pyroclastic deposits, or soil horizons are interbedded with the debris-flow deposits, relatively accurate estimates of magnitude and frequency for some time intervals may be possible. Unfortunately, deeply incised stream channels are generally limited to the upper slopes of Mount Shasta (above about 1,600 m). Thus, the exposed deposits may be more numerous, thicker, and coarser grained than correlative and younger sections lower on the mountain, where debris flows pose a greater threat to human activities. In areas where historical records and sediment and dendrochronological evidence suggest relatively recent debris-flow activity, pits were dug at selected sites by backhoe to allow near-surface stratigraphic observations, sediment sampling, and collection of wood and charcoal fragments for carbon-isotope dating. A small number of wood and root samples was also collected from cutbanks at higher levels of the mountain for carbon-isotope dating.

Relative ages of debris-flow sequences were determined by a variety of techniques, including (1) stratigraphic correlation of traceable sedimentary and volcanic rocks, (2) identification of soils and erosion surfaces that can be related to datable periods of glacial, volcanic, or recent debris-flow activity, (3) geologic mapping of datable pyroclastic deposits, both at the surface and interbedded with debris-flow material, and (4) identification and dating of debris-flow surfaces and deposits by botanical methods (see Hupp, 1984, for a detailed description of the botanical methods used).

Aerial photographs, supplemented by field observations, were used extensively to determine areal extents of debris flows, stream incisement, areas of damaged vegetation, occurrences of pyroclastic and glacial-till deposits, and areas not subject to burial by debris flows owing to topographic relief. Deposits as old as 250 years were mapped using color aerial photos if appropriate botanical and other field data were available. Many pyroclastic flows of Mount Shasta have a distinctive yellow hue owing to iron-oxide rinds on the clasts. This characteristic facilitated mapping of surficial pyroclastic deposits from aerial photographs. Except for several events during the last millennium on the east flank of Mount Shasta, most pyroclastic flows occurred at least 1,800 years ago, and many occurred during an eruptive period more than 9,000 years ago (Miller, 1980, pl. 1). In most areas, therefore, a surficial pyroclastic layer is indicative of debris-flow inactivity. Even where pyroclastic layers are relatively fresh (200 to 1,000 years old), a lack of overlying debris flows suggests that future activity is unlikely without renewed volcanic activity.

Samples from selected debris-flow, pyroclastic, and fluvial deposits were collected for particle-size analysis. Results were used to distinguish downslope changes in size, sorting, angularity, and mode of transport and deposition. Mineral composition and clay content of some samples were determined by x-ray analysis.

For the purposes of this report, the areas of Mount Shasta that may be susceptible to burial by debris flows are assigned to one of three hazard categories—high, medium, and low (pl. 1). In general, the "high-risk" areas have had debris-flow activity within the last 200 years, and conditions continue to be suitable for periodic activity. The "medium-risk" areas include places where debris-flow activity during the last 2,000 years is evident, but where conditions now and during recent centuries suggest that renewed activity during the next century is improbable. Areas designated "low risk" have had Holocene debris-flow activity, but either activity has not occurred in recent millennia or conditions appear unlikely for renewed activity.

The hazard designations, as applied, are interpretations of the probability that a given site will be affected by debris-flow activity within the next 100 years. It is emphasized that these estimates of hazard potential do not signify that a site in a high-hazard area will be affected during the next century, or that a site in a low-hazard area will not be affected; the categories refer only to inferences of relative probabilities of debris-flow activity. In addition, the estimates do not consider the possibility of renewed volcanic activity, which would invalidate the interpretations of hazard given here.

EVIDENCE AND MAGNITUDE OF PAST DEBRIS-FLOW ACTIVITY

Twelve principal drainages, six of which receive meltwater from glaciers on the upper slopes, radiate from the summit of Mount Shasta (fig. 1). In figure 2, available dates of past debris-flow activity in the basins of these streams and major tributaries are plotted. For convenience, the various streams are divided into six groups corresponding to drainage-basin divides and sources of material for the principal debris fans that form much of the slope area of Mount Shasta (fig. 2). In the following discussion, however, each of the 12 drainages and several tributaries are considered individually because conditions, available data, and inferred potential for debris-flow activity of each differs from those of other drainages.

WHITNEY–BOLAM DEBRIS FAN

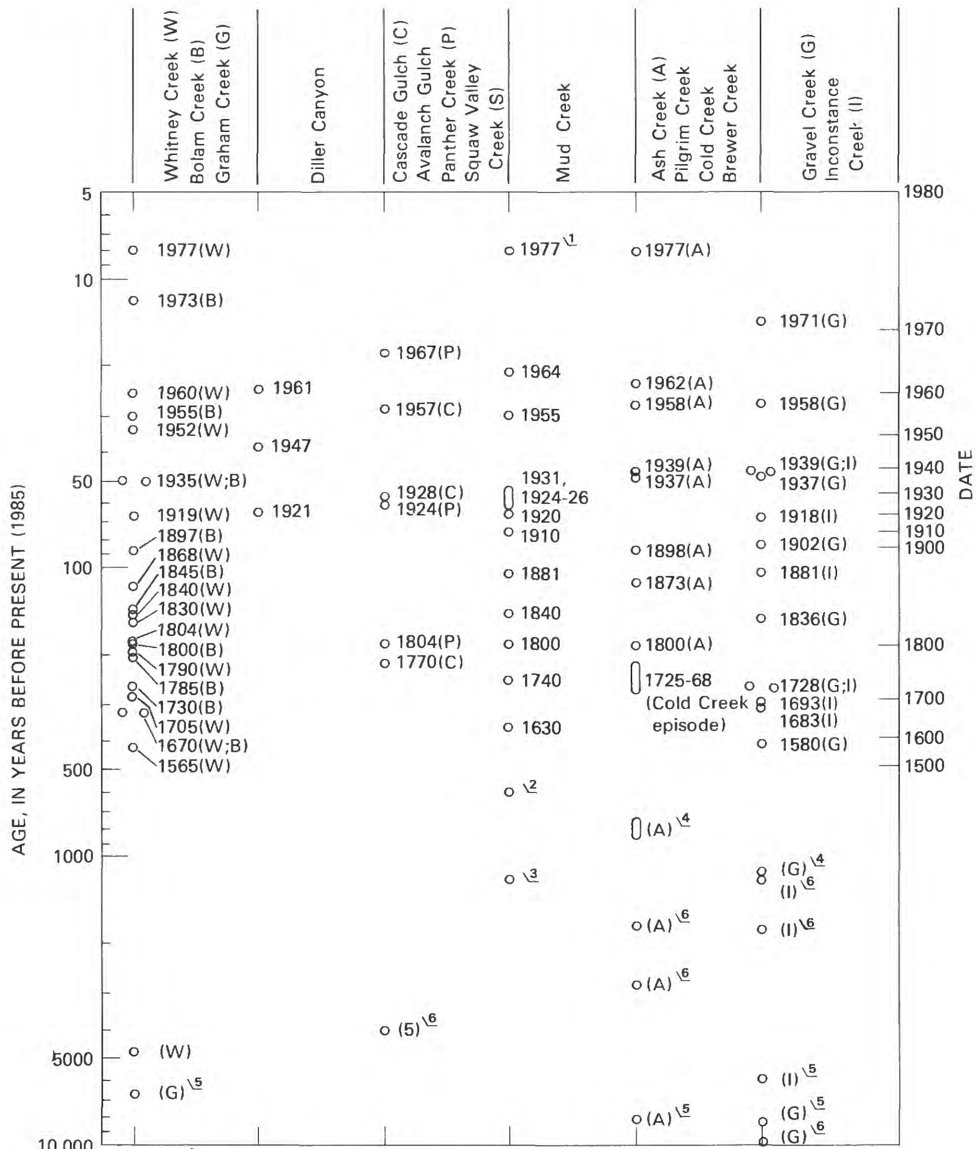
Whitney Creek, including its principal tributaries, Bolam and Graham Creeks, drains the northwest flank of Mount Shasta (fig. 1) and is fed by meltwater from Whitney and Bolam Glaciers. Deeply incised fan deposits, mostly pyroclastics, along both Whitney and Bolam Creeks occur within 8 km of the summit. The fan deposits spread out and apparently thicken downslope from the Whitney Creek–Bolam Creek confluence, forming a surface at least 20 km^2 in size. The Whitney–Bolam fan extends to the Shasta River, more than 20 km from the summit of Mount Shasta (fig. 1; pl. 1). Except during unusually large runoff events, flow in Whitney Creek infiltrates the fan deposits before reaching the Shasta River.

BOLAM CREEK

Bolam Creek heads at the terminus of Bolam Glacier on the northwest side of Mount Shasta. Like most other streams of the area, Bolam Creek is ephemeral, generally flowing in direct response to precipitation or to seasonal and diurnal melting of snow and ice. Partly because of the capacity of Bolam Glacier to store and rapidly release water, debris-flow activity along Bolam Creek has sometimes been intense. Within 7 km of its headwaters, Bolam Creek locally incises as much as 120 m of fan deposits. The ages of the incised fan deposits are inferred to range between about 9,300 and 12,000 years; nearby andesite flows resting on the fan surface have been dated by Miller (1980) at about 9,300 years. Thus, the majority of the fan deposits adjacent to Bolam Creek in the upper Whitney–Bolam debris fan are presumed to be of Pleistocene age. Fluvial incisement of the fan has occurred during Holocene time, although many debris flows have helped erode the gorge as well as partially refill it periodically during that period. Botanical dating shows that formation of numerous paired dikes and lobate termini of debris flows occurred in the Bolam Creek area as recently as 1973 (fig. 3). Other flow surfaces yielding tree-ring dates as old as 1670 are preserved as terraces along Bolam Creek in the same area (fig. 2).

From the gorge area, the incisement depth of Bolam Creek decreases to about 2 m near its confluence with Whitney Creek. Southwest (left) of the lowermost 2-km reach of Bolam Creek, moderate fluvial erosion of weathered pyroclastic and debris-flow deposits shows that no recent activity has occurred. To the right of the lower reach, however, a debris flow yielding tree-ring data suggesting a date of 1897 diverged from the Bolam Creek channel and flowed nearly straight north toward and 1 km past the railroad siding of Bolam (pl. 1). The flow covered an area about 3 km^2 with a thin layer of predominantly sand and silt; the yield of the flow is estimated to have been about 3×10^6 Mg (megagrams), or about 3 million metric tons of rock debris. Evidence in and adjacent to the area, including tree-ring data, weathered and fluvially incised pyroclastic and debris-flow deposits, and dissected volcanic rocks, indicates that the 1897 flow may have been the only event in that area during the last 2,000 years.

Debris flows confined to the channel incisement of lower Bolam Creek have been common during recent centuries. Several, ranging in age from 50 to 315 years, are indicated by dendrochronological evidence from debris-flow terraces above the Whitney Creek–Bolam Creek confluence. No debris flows along Bolam Creek



\1 From Miller (1980); not confirmed during this study.
\2 Determined by dendrochronology; from Dickson and Crocker (1953).
\3 Estimated from soil characteristics by Dickson and Crocker (1953).
\4 From carbon-isotope analyses; may represent a single debris flow.
\5 From Miller (1980); age of deposit not well known.
\6 From Miller (1980); based on carbon-isotope analysis.

FIGURE 2.—Ages of Holocene debris-flow occurrences, Mount Shasta, Calif.

are known to have passed the confluence since 1935. Preservation of several poorly dated debris-flow surfaces within the Bolam Creek incisement and elsewhere that probably range in age between 200 and 1,200 years suggests that activity may have been relatively high during the latter Neoglacial interval.

WHITNEY CREEK

Upper Whitney Creek is principally a meltwater stream receiving runoff from Whitney Glacier. The ephemeral stream roughly parallels Bolam Creek about a kilometer or less to the southwest before the two merge 11 km northwest of the summit of Mount Shasta (pl. 1). Below the confluence, a 5-km reach of Whitney Creek flows on fan deposits that are restricted to a width of less than 2 km by adjacent lava flows. Downslope from the bedrock constriction, the Whitney–Bolam debris fan widens to nearly 4 km and extends to the Shasta River valley, near Lake Shastina (pl. 1), where fan deposits become interbedded with

FIGURE 3.—Terminal lobes of debris flows deposited in 1973 along upper Bolam Creek, northwest side of Mount Shasta. View is across the channel, to the northeast.

fluvial sediments of the river. Much of the lower Whitney–Bolam debris fan, which includes fluvial deposits and possibly glacial till, rests on thick flows of Plutos Cave basalt (Williams, 1949) that are exposed in a large area north of the fan, including Juniper Flat. Water in Whitney Creek readily infiltrates the fan deposits and underlying basalt, and it reappears as seepage and springflow in or near the Shasta River (Mack, 1960). Streamflow in Whitney Creek rarely reaches the Shasta River.

In the bedrock-confined upper portion of the Whitney–Bolam fan, Whitney Creek incises the thick sequence of pyroclastic and debris-flow deposits that are also cut by Bolam Creek a short distance northeast. At a site 2.5 km upstream from the Bolam Creek confluence, Whitney Creek cuts nearly 40 m of fan deposits (pl. 1; T. 42 N., R. 3 W., sec. 13, SE1/4, SE1/4). Within the gorge area, evidence of at least four episodes of incisement and refilling by fluvial and debris-flow processes is preserved (fig. 4). Stratigraphic units, including a nearby andesite flow and a remnant rock glacier overlying the oldest sequence of fan deposits, carbon-isotope dates, traceable pyroclastic beds, and disconformities, suggest that debris-flow activity at Whitney Creek gorge has been most pronounced during late Holocene time. Evidence of relatively recent deposition of debris flows and subsequent cutting by discharge of Whitney Creek is provided by dendrochronological evidence from terraces within the gorge. Prominent among these are surfaces yielding dates of approximately A.D. 1670 and 1840. The most recent debris flow for which strong evidence is preserved in Whitney Creek gorge occurred in 1935 (fig. 2); several smaller, poorly preserved flows along the channel have probably occurred since then.

Available data for the upper Whitney–Bolam debris fan suggest that most of the fan surface has remained relatively unchanged by debris-flow activity during Holocene time. Local deposition of eolian sand and silt, fluvial erosion, and soil formation have caused minor modifications of the surface, and at least one pyroclastic layer about 1,800 radiocarbon years in age overlies the other fan deposits in some parts of the area. Because no surficial pyroclastics are known within Whit-

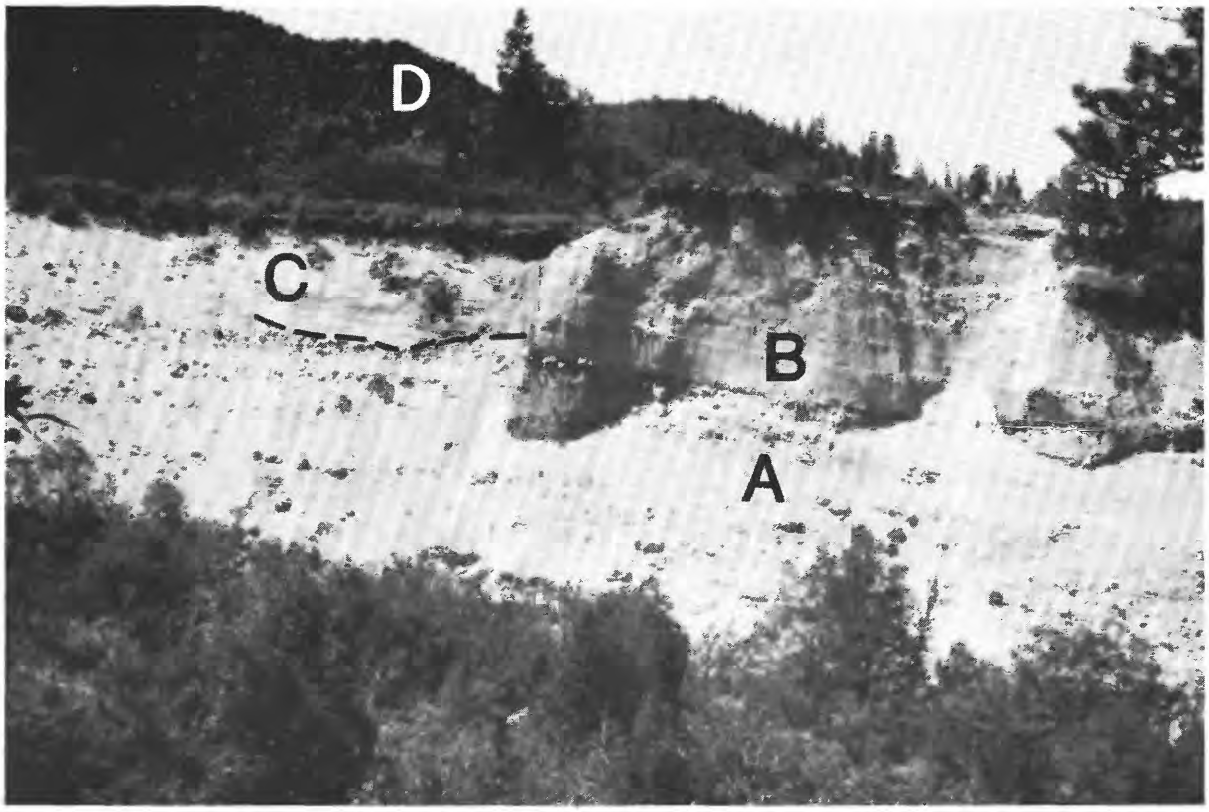


FIGURE 4.—Southwestern escarpment above upper Whitney Creek. View is to the southwest, from a lower surface formed by debris-flow deposition about 1670. Shown are a thick section of lithic pyroclastic flows and debris flows (*A*) overlain by various fan deposits (*B*). The sequence was incised about 12 m by a former stream channel that was partially refilled with fluvial and glaciofluvial deposits (*C*) before channel shifting and renewed incisement. Both sections predate a basaltic andesite flow of about 9,300 years B.P. (*D*).

ney Creek gorge, much of the cutting of the present gorge is inferred to have occurred within the last 1,800 years. Preserved debris-flow deposits of that period are either in the gorge or on lower parts of the fan.

Below U.S. Highway 97 (fig. 1), the Whitney–Bolam debris fan widens because of reduced constraints by adjacent lava flows. As is the case for other meltwater streams of Mount Shasta, the depth of incision of Whitney Creek into the fan deposits decreases markedly in the downstream direction. Thus, large flows that are well contained in the incisements of the upper channel reaches are free to spread out as they approach and pass the area of the highway. The result is that the high-risk area of the Whitney–Bolam fan, the area that has had recent debris-flow activity, is much wider in the lower part than in the upper part of the fan (pl. 1). Consequently, the deposits of most debris flows of the Whitney–Bolam drainage, which recently have occurred at a rate of at least once every 15 years (fig. 2), remain temporarily in the gorge reaches of the upper fan. Fluvial transport and bulking later redistribute these relatively small-volume deposits onto the lower part of the fan.

Aerial photography, supplemented by field reconnaissance and data from soil pits dug by backhoe at six sites, provides evidence of the areas affected by recent activity on the lower Whitney–Bolam debris fan. Most of the lower fan has received debris-flow deposition in recent decades, much of the area having been covered in 1935 by a flow well documented dendrochronologically (Hupp, 1984).

Wood and charcoal fragments collected from the soil pits in the Whitney–Bolam fan and dated by carbon-isotope analysis indicate rates of deposition. Calculations based on thicknesses of debris flows exposed in the pits and areal extents mapped from aerial photographs suggest volumes or magnitudes of individual events. In a pit near the south edge of the "high-hazard" area of the lower Whitney–Bolam fan (T. 43 N., R. 4 W., sec. 32, NW1/4, SE1/4; pl. 1), wood and charcoal were collected from depths of 0.5 and 0.7 m, respectively. The charcoal was embedded in a debris flow overlying the previously mentioned widespread pyroclastic layer that has been dated at about 1,800 years B.P. (before present). The wood, with a carbon-isotope age of 210 ± 50 years, was recovered from a soil zone formed on a botanically dated debris flow that probably occurred in 1790 (fig. 2). Two other buried soil-root zones overlie the sampled soil, the upper one probably having been covered by the debris flow of 1935. Lower on the fan but in a more central position of the high-risk area (T. 43 N., R. 4 W., sec. 30, SE1/4, SE1/4; pl. 1), wood from a depth of 1.8 m yielded a carbon-isotope age of 420 ± 60 years. At least two debris flows that are interbedded with fluvial deposits overlie the sampled layer, the uppermost flow having been deposited in 1935.

The carbon-isotope dates, soil horizons, and stratigraphic relations apparent in the soil pits suggest that in recent centuries debris flows have reached lower portions of the Whitney–Bolam fan at least once every 150 years. These deposits are up to 2 m thick but typically are less than 0.5 m thick. The deposits are mostly fine grained ($d_{50} \simeq 0.12$ mm), although some contain rounded gravel at least as coarse as 40 mm. Determinations of mineralogy by x-ray analysis show that most of the material is reworked pyroclastic, debris-flow, and fluvial sediment that has been bulked from channels and sideslopes higher on the fan. By contrast, the surface of much of the southwest part of the fan that is designated as a medium-hazard area (pl. 1) is formed by a pyroclastic layer yielding an 1,800-year carbon-isotope date. Although this area has not been subject to debris-flow deposition since then, the occurrence of underlying flow deposits and its topographic position suggest that renewed activity is possible.

Debris flows that terminate upslope from U.S. Highway 97 along the channels of Whitney and Bolam Creeks occur much more commonly than those that continue onto lower parts of the fan. The smaller, more frequent flows deposit sediment in the channel that ultimately becomes a major source of material deposited on lower parts of the fan. Data from Whitney Creek gorge, for example, indicate that a typical debris-flow deposit may be 2 m thick. If the flow were deposited along a 4-km length of the Whitney Creek channel and had an average width of 50 m, the volume of debris would be 0.4×10^6 m^3 (cubic meters). Based on observations at soil pits and other sites on lower Whitney–Bolam fan, the 1935 debris flow covered an estimated 8-km^2 area to a depth averaging 0.5 m. Conversely, botanical data indicate up to 7 m of channel degradation by bulking during the 1935 debris flow in Whitney Creek gorge. The indicated volume of deposited sediment, therefore, is 4.0×10^6 m^3, or about 10 times as much as the hypothetical smaller flow. Because fluvial processes result in the winnowing and redeposition on the lower fan of part of the finer fraction of debris-flow material, there appears to be little doubt that debris flows represented by a 0.4×10^6 m^3 event occur more than 10 times as often as those represented by the 1935 debris flow. This ratio suggests, therefore, that debris flows in the Whitney–Bolam drainage system presently occur more frequently than once every 15 years. Documented flows summarized by figure 2 appear to support this generalization.

GRAHAM CREEK

Graham Creek flows northwest, roughly paralleling Whitney Creek before joining it about 13 km northwest of the summit of Mount Shasta. Whitney Glacier does not contribute meltwater or rock debris to Graham Creek, so debris-flow activity is much less intense than it is in the Whitney and Bolam Creek drainages immediately to the northeast. Graham Creek flows onto the upper Whitney–Bolam debris fan about 3 km southeast of the confluence of Whitney and Bolam Creeks (pl. 1), where it may define the southwest extent of Holocene debris-flow deposition by Whitney Creek. The lowest 2-km reach of Graham Creek (pl. 1; T. 42 N., R. 4 W., secs. 11 and 12) traverses a large terminal lobe of old pyroclastic fan deposits in an area of low debris-flow hazard. Well-developed weathering of the surficial deposits and fluvial dissection by a stream network partially buried by early Holocene volcanic rocks (Miller, 1980, pl. 1) provide compelling evidence that the deposits of the lower Graham Creek area are of late Pleistocene or early Holocene age.

DILLER CANYON FAN

Diller Canyon incises fan deposits formed principally of pyroclastics and related volcanic flows that have accumulated on the western side of the Shastina cone and crater (pl. 1). The Shastina crater currently does not contain a glacier. Carbon-isotope data (Miller and Crandell, 1975; Christiansen and others, 1977) indicate that the eruptive flows were deposited during a 2,000-year period ending 9,400 years ago. Particularly in the upper half to two-thirds of the Diller Canyon fan, topographic expression of the most recent eruptive flows shows that most of the fan has not been modified by debris-flow activity through most of Holocene time.

The Diller Canyon fan consists of at least two distinct parts (pl. 1), but only the largest segment drained by Diller Canyon shows surficial evidence of debris-flow activity. A segment north of Diller Canyon, designated as a low-hazard area, may contain mostly volcanic debris but few debris-flow deposits, and a portion of the fan east of Black Butte (pl. 1) does not appear to be subject to debris flows under current conditions. Within Diller Canyon, dendrochronological dating indicates that at least three debris flows have occurred during the last century (fig. 2), but all have been easily contained by the incisement. Potential exists for a fanning out of debris-flow material downslope from the entrenchment, should a relatively large event occur in the upper part of the Diller Canyon basin. This possibility seems relatively small, however, owing to the steepness and small drainage area of the basin, a limited potential for large slugs of water, and a lack of abundant sediment available for bulking.

CASCADE GULCH, AVALANCHE GULCH, PANTHER CREEK, AND SQUAW VALLEY CREEK

Much of the southwestern and southern slopes of Mount Shasta are drained by Cascade Gulch, Avalanche Gulch, Panther Creek, and Squaw Valley Creek. These drainages are cut into a variety of volcanic rocks and flow deposits, and the upper basins of all four have limited potential for the storage of sufficient water (or ice and snow) and sediment necessary for destructive debris-flow activity. Of the four streams, only Panther Creek has developed definable fan deposits, those being in the lower part of the basin northwest of McCloud (pl. 1). The fan shows fluvial dissection and does not appear to be highly susceptible to blanketing by debris flows. Scars on trees and deposition of coarse sediment along Panther Creek near McKenzie Butte (pl. 1) suggest significant movement of debris during the last 200 years, but much of the activity may have been fluvial rather than as debris flows.

Upslope from the Everitt Memorial Highway (pl. 1), Cascade Gulch cuts a sequence of interbedded pyroclastic, debris-flow, and fluvial deposits that are restricted to the low areas along the channel. Although dendrochronological evidence shows that debris flows or destructive floods occurred along Cascade Gulch in 1957, 1928, and about 1770, the flows were confined to the lowest parts of the channel incisement.

Panther Creek and Squaw Valley Creek both flow generally to the south, meeting at the town of McCloud (fig. 1). Evidence of previous flow events along Panther Creek several kilometers northwest of McCloud demonstrates that the town could sustain damage by unusually large discharges. There has been no known recent activity along Panther Creek near McCloud, however. Squaw Valley Creek exhibits a very stable alpine channel and appears to present little potential for future debris-flow activity. The lower part of Squaw Valley, south of McCloud, could be susceptible to debris-flow damage by spillage from the Mud Creek basin if a very large event were to occur. Because of its position, however, the probability of such an event affecting lower Squaw Valley seems remote.

MUD-ASH DEBRIS FAN

Much of the Mud Creek and Ash Creek drainage basins, on the southeast flank of Mount Shasta, is formed from andesitic lava flows and pyroclastic, debris-flow, glacial, and fluvial deposits. Mud Creek is headed by Konwakiton Glacier, and Ash Creek flows from Wintun Glacier. Other streams on the fan that do not receive glacial meltwater directly include the lower reaches of Squaw Valley Creek, Pilgrim Creek, and Cold Creek. The fan, which covers an area of nearly 300 km^2, is bounded roughly on the west by upper Mud Creek and lower Squaw Valley Creek, and on the north by exposed volcanic rocks north of the Ash Creek valley (pl. 1). Roughly 40 percent of the fan area exposes pyroclastic flows and lavas that show no evidence of having been covered by debris-flow deposits.

Debris deposits appear thickest in the upper parts of the Mud-Ash fan and thin to a featheredge in some parts of the lower slopes. Within 7 km of the peak of Mount Shasta, Mud Creek and Ash Creek incise, respectively, nearly 200 and 100 m of fan deposits, mostly pyroclastic flows. Bedded lavas are exposed locally in the gently sloping areas between lower Mud Creek and Ash Creek and are covered elsewhere by generally thin deposits of glacial, fluvial, and debris-flow material. Normally, all surface runoff on the southeast flank of Mount Shasta infiltrates the lower-fan deposits and is discharged to the McCloud River through fractures in the bedded volcanic rocks. Hence, only unusually large fluvial or debris-flow events are sufficient to discharge sediment directly to the McCloud River.

MUD CREEK

From Konwakiton Glacier, Mud Creek flows southeasterly before curving to the south and entering the McCloud River about 8 km southeast of the town of McCloud. A series of debris flows in the summers of 1924, 1925, 1926, and 1931 resulted in transport and deposition of sediment along the entire length of Mud Creek and prompted various studies of the history of debris flows along Mud Creek (see Hill and Egenhoff, 1976). The flows threatened, but did not reach, the town of McCloud. Subsequent investigations indicated that, in addition to the recent flows, at least four other debris flows during the last 1,200 years have covered large areas from McCloud eastward about 9 km and have extended southward into the McCloud River (Dickson and Crocker, 1953). The descriptions, causes, and effects of the 1924 to 1931 Mud Creek flows are well documented by various newspaper and engineering reports of the time, as well as by later studies of the soils and vegetation of the affected area (Beardsley and Cannon, 1930; Cooke, 1940; Dickson and Crocker, 1953).

The pre-1924 episodes of extensive Mud Creek debris-flow deposition identified by Dickson and Crocker (1953) occurred approximately 104, 245, 600, and 1,200 years ago. Abundant dendrochronological evidence is available for dating the two most recent flows; the earliest date was estimated from soil-development studies and could be considerably in error. Based on mapping of deposition from the five debris-flow episodes (Dickson and Crocker, 1953), the two earliest events (600 and 1,200 years ago) may have deposited significantly more debris than the later three. The 1924 to 1931 series of flows may have deposited the smallest volume of debris. Surveys by Wood (1931) suggested that the total volume of debris-flow material transported, 1924 to 1931, was about 23×10^6 m^3. An estimated 15 percent of that volume entered the McCloud and Sacramento Rivers, the rest having been deposited on the lower and middle parts of the fan. Larger flow events presumably would have transported a larger percentage of the debris volume into the McCloud River.

In addition to the five large episodes of debris-flow activity along Mud Creek during the last 12 centuries, numerous dendrochronological data indicate that smaller debris flows have occurred frequently during recent centuries. The smaller flows (1) resulted, more likely, from discharges caused from rapid releases of glacial meltwater, (2) resulted from bulking of fan and channel material relatively high in the basin, and (3) deposited material in the Mud Creek incisement that typically did not extend as far downslope as the Elk Spring area (pl. 1; T. 40 N., R. 2 W., sec. 16). In comparison, the large flows starting in 1924 appear to have added sufficient sediment from the gorge area of Mud Creek to form a slurry at a distance at least 6 km downstream from the water source at Konwakiton Glacier. A low terrace at that distance from the glacier, for example, was formed by debris-flow deposition in 1910. Parts of the terrace, and datable trees growing on it, survived the extensive overtoppings of 1924 to 1931, and the terrace surface showed no apparent deposition. The source of sediment for the 1924 to 1931 events appears to have been principally loosely consolidated beds of pyroclastic flows exposed as steep, bare valley sides in the deeply incised area (fig. 5). Furthermore, field evidence suggests that downstream from the preserved 1910 surface the combined processes of sapping along the valley walls and undercutting of the soft pyroclastic beds by the floodwaters caused periodic slope failures and slides, channel damming, and rapid conversion of the slide material and water into a slurry. The occurrence of successive episodes of slope failure, damming of streamflow, and breaching of the slide material offers an explanation for pulses of debris-flow movement that have been observed at Mount Shasta and elsewhere. Similar processes on a small scale were observed in Whitney Creek gorge in the summer of 1984.

FIGURE 5.—Mud Creek and valley wall, 6 km southeast of Konwakiton Glacier. View is upstream, to the northwest.

The most recent debris flow along Mud Creek for which tree-ring data are available occurred about 1964. Others of small to intermediate magnitude occurred in 1920 (Hill and Egenhoff, 1976), 1910, and about 1630 (fig. 2). Much earlier and larger flows, up to 8,000 years ago and possibly associated with eruptive events, are reported by Miller (1980) from carbon-isotope analyses. Evidence of a 1977 debris flow along Mud Creek (Miller, 1980) was not recognized during field surveys or on aerial photographs.

Since 1881, debris flows have occurred along Mud Creek in at least 8 years, suggesting a frequency during recent centuries of about one per decade (fig. 2). Assuming that only five large-magnitude flows (or flow episodes) have occurred during the last 1,200 years, a recurrence interval of about 250 years for those events, and a ratio with smaller events of roughly 1 to 25, is indicated. If nearly all sediment incorporated into the debris flows is derived from the upper basin and gorge area of Mud Creek (above Mud Creek dam; T. 40 N., R. 2 W., sec. 5, SW1/4; pl. 1), and if most or all debris moved by the smaller flows is bulked into the large-magnitude flows, sediment yields as great as 11,000 $Mg/km^2/yr$ for the source areas are indicated.

PILGRIM CREEK

Pilgrim Creek heads on the Mud-Ash debris fan about 2 km downslope from Wintun Glacier (pl. 1) but does not directly receive glacial meltwater. Flows are ephemeral and are caused by snowmelt and precipitation. The channel of Pilgrim Creek typically incises 10 to 20 m of pyroclastic flows before transmission losses cause the stream channel to dissipate on the lower part of the fan about 7 km south-southeast of Sugar Pine Butte. Although debris flows restricted to the channel bottom may have occurred infrequently along Pilgrim Creek, there is no evidence of significant Holocene debris-flow activity. The lack of large supplies and discharges of water and mobile sediment from the headwater areas suggest that debris-flow activity along Pilgrim Creek will continue to be infrequent.

COLD CREEK

About a kilometer to the north of Pilgrim Creek, Cold Creek, also an ephemeral stream, drains part of the Mud-Ash debris fan before joining Ash Creek at Sugar Pine Butte (pl. 1). Cold Creek heads about a kilometer downslope from Wintun Glacier, has limited potential supplies of water and sediment, and shows no evidence of recent debris flows formed of material derived from its own drainage basin. The upper 6 km of the Cold Creek channel are cut into pyroclastic flows; the lower reaches of Cold Creek, to its confluence with Ash Creek, are bounded on the north by debris-flow deposits that moved down Ash Creek and blanketed an 8-km^2 area south of the creek. Thus, the lower reaches of Cold Creek were shifted southward as a result of debris-flow activity, whereas the position of upper Cold Creek apparently has been unaffected in recent centuries.

ASH CREEK

From Wintun Glacier, Ash Creek flows eastward, then curves to the southeast and enters the McCloud River from the north (pl. 1). Ash Creek has nearly perennial discharge, much of it meltwater. Most of the steamflow, however, infiltrates the volcanic rocks and overlying sediments of Coonrod Flat and Ash Creek Sink before reaching the McCloud River. Most sediment transported from the upper slopes of Mount Shasta by Ash Creek, therefore, is redeposited on the intermediate and lower parts of the Mud-Ash debris fan.

During recent centuries, deposition of Ash Creek debris flows has occurred on two well-defined parts of the Mud-Ash debris fan—portions of the Ash Creek basin above and below Sugar Pine Butte (pl. 1). Pleistocene basalt flows associated with Sugar Pine Butte (California Division of Mines and Geology, 1964) cause reduced channel and fan gradients immediately upslope of the butte. Thus, many smaller debris flows stall in this area. As Ash Creek flows into the relatively resistant basalt at Sugar Pine Butte, however, the channel gradient increases about 200 percent, and much of the debris-flow material reaching this stretch of channel is no doubt readily conveyed through and onto the again gentler slopes of the lower fan area. Debris-flow terraces are present on the fan below Sugar Pine Butte, but tree-ring dating of the flows is difficult owing to inferred low velocities of the flows and a general lack of clasts large enough to scar tree trunks and thereby date events.

Material of all the smaller flows has been deposited between the high gorge reaches and Sugar Pine Butte, whereas material of larger debris flows has been deposited both above and below the butte depending on the magnitude of the event and the debris-flow history. Where a series of small debris flows has partially filled the incisement of Ash Creek, spillage onto the upper fan has been likely. Conversely, dendrochronology studies show that, following a period of fluvial scouring, the larger flows have been conveyed beyond Sugar Pine Butte with little or no out-of-channel deposition on the upper fan area. Similar though poorly documented generalizations can be made for other streams of Mount Shasta, such as Whitney Creek and Mud Creek.

Debris flows along Ash Creek have been common in recent centuries, and possibly were frequent throughout Holocene time. Miller (1980, pl. 1) reports that a number of debris flows that may not have been associated with volcanic eruptions occurred during the period 9,400 to 3,100 years B.P.; evidence suggests that at least some of these flows occurred in the early part of that period. More recent flow episodes have been dated by Miller (1980) at about 2,800 years and 1,700 years B.P. Carbon-isotope data collected for the present study support the latter date and indicate that some deposition occurred at least as far downslope as Sugar Pine Butte. A single debris flow or series of flows spread an unknown distance downslope from Sugar Pine Butte about 800 years ago (roughly A.D. 1200). This event, which was dated by carbon-isotope analyses from wood collected in soil pits and from cutbanks along Ash Creek and which was also identified by Miller (1980), probably deposited debris over at least 6 km^2. Although evidence is very limited, it is inferred that deposition from the flow(s) may have extended onto Coonrod Flat (pl. 1) but, owing to gentle slopes, probably did not proceed further. Previous to this debris-flow episode, lower Cold Creek may have joined Ash Creek several kilometers upslope from the present confluence. Deposition from the A.D. 1200 (?) event appears to have shifted Ash Creek northward, and may have diverted the lower Cold Creek channel southward along the southern edge of the deposits. The volume of debris deposited is estimated to have been at least 10×10^6 m^3; it may have been substantially greater.

No known evidence remains of possible debris-flow activity along Ash Creek for the period A.D. 1200 to about 1725. Beginning about 1725, however, and extending through an approximately 44-year period to 1768, a series of Ash Creek flows deposited debris on top of and south of the deposits of A.D. 1200. This series of flows is well dated by dendrochronology and carbon-isotope data. Like the flows of about 800 years ago, the 1725 to 1768 events deposited debris at least as far down the mountain as Sugar Pine Butte, and possibly as far as Coonrod Flat. West of Sugar Pine Butte, rock debris of the 1725 to 1768 flows spread south of deposits from the previous episode of about A.D. 1200, causing another southward shift of the lowest 5 km of the Cold Creek channel. Thus, the lower part of the present Cold Creek channel marks the southern extreme of the 1725 to 1768 deposits, and the flow episode has been named the Cold Creek flows.

Above Sugar Pine Butte, Ash Creek closely approximates the northern extreme of the Cold Creek flows. The area of deposition, therefore, is well defined—about 8 km^2. Thicknesses of known Cold Creek deposition measured in a soil pit and at various exposures along stream channels suggest an average depth of burial of about 2 m, and hence a minimum deposit volume of 16×10^6 m^3. Total volume of the Cold Creek flows, assuming that significant deposition occurred downslope from Sugar Pine Butte, could easily have been an order of magnitude greater than the calculated minimum.

For the period 1768 to 1898, tree scars and other dendrochronological evidence suggest that several relatively low intensity debris flows occurred along Ash Creek. A larger flow, however, as indicated by tree-ring and carbon-isotope dates, resulted in deposition to an undetermined distance beyond Sugar Pine Butte about 1898 (Hupp, 1984). This flow was largely contained within the Ash Creek channel upslope from and adjacent to Sugar Pine Butte, but botanical and stratigraphic evidence along Ash Creek near its confluence with Cold Creek suggests that significant overbank deposition of fine-grained material occurred below the butte.

Following the 1898 flow, no significant debris flows occurred along Ash Creek until 1937, when flows extending into 1939 resulted in overbank deposition at least from the western part of section 16, T. 41 N., R. 2 W., to the Ash Creek incisement at Sugar Pine Butte (pl. 1). The 1937 to 1939 flows scarred many trees in the upper fan area but were not otherwise destructive; the area of deposition included relatively narrow strips adjacent to Ash Creek, and aerial photographs show that the flows caused substantial channel filling in a reach 5 to 7 km upstream from Sugar Pine Butte. A subsequent debris flow in 1962, therefore, spilled from the channel incisement through the same reach, as did a much smaller flow in 1977. The areas of deposition for each of the very recent events, 1937 to 1939, 1958, 1962, and 1977, are identifiable on aerial photography. Corresponding volumes of deposition for the four flows are small relative to the Cold Creek flows, the largest (the 1937 to 1939 episode) having an estimated volume less than a third that of the Cold Creek flows—about 5×10^6 m^3.

BREWER CREEK

Brewer Creek, an ephemeral stream that dies out before joining Ash Creek above Sugar Pine Butte, currently does not directly receive glacial meltwater. Incisement of the channel about 25 m into the pyroclastic beds of the upper fan shows that erosion is active upslope from T. 41 N., R. 2 W., sec. 4 (pl. 1). In that part of Brewer Creek there has been minor debris-flow activity in recent decades, but none of the flows has spilled from the stream incisement or progressed as far downslope as the Sugar Pine Butte area. Because the Brewer Creek basin does not appear to have the potential to accumulate and then rapidly convey large amounts of water, and because field inspection shows that no significant events have occurred along Brewer Creek, only minor, in-channel debris-flow activity is anticipated in the future.

GRAVEL CREEK FAN

Meltwater from Hotlum Glacier is discharged by Gravel Creek toward a topographic depression about 9 km to the northeast. The depression, nestled among the volcanic rocks of Mount Shasta, Ash Creek Butte, and The Whaleback, is a sink for water and sediment that move along Gravel Creek from the upper slopes of Mount Shasta (pl. 1). All streamflow of lower Gravel Creek is lost in the alluvial, debris-flow, and underlying volcanic deposits, and the lower part of the Gravel Creek fan therefore is strongly aggradational. Botanical studies along lower Gravel Creek (T. 42 N., R. 2 W., sec. 21), for example, indicate that up to 1.5 m of fluvial and possibly debris-flow deposition has occurred during the last 26 years.

Much of the lower half of the Gravel Creek debris fan merges with the Mud-Ash fan to the south. For the purposes of this report, however, deposits of the Gravel Creek basin are treated individually because (1) the upper Gravel Creek basin is separated from the Brewer Creek basin (of the Mud-Ash fan) by andesite flows, (2) only pyroclastic flows, not debris flows, appear to be continuous between the two basins, and (3) unlike streams of the Mud-Ash fan, which maintain a continuous drainage net to the McCloud River, all water of Gravel Creek is lost to infiltration and evapotranspiration.

Gravel Creek, as do other streams of Mount Shasta that head at a glacier, periodically conveys large amounts of meltwater that maintain and further erode a deep and locally bare-walled gorge in the upper part of the fan. When sufficient sediment is mobilized to form debris flows, coarse material may be transported and deposited as far as 11 km northeast of Mount Shasta peak. Stratigraphic, geomorphic, and botanical evidence of Holocene, particularly relatively recent, debris-flow activity along Gravel Creek is extensive. Miller (1980, pl. 1) recognized two poorly dated debris-flow episodes for the Gravel Creek valley, both possibly having occurred between 8,000 and 10,000 years ago. Dates of other debris flows older than about 400 years have not been determined (fig. 2).

Geomorphic and dendrochronologic observations show that the latest period of extensive fan development by debris-flow activity along Gravel Creek began no later than about 400 years ago below the gorge. Flows that have eroded pyroclastic debris from the steep walls of the gorge (upslope from about the middle of section 36, T. 42 N., R. 3 W.; pl. 1) have redeposited the material over the fan in a generally north-to-south direction through the 400-year period.

The earliest debris flow for which tree-ring data are available occurred in the year A.D. 1580 or slightly earlier, when a flow of unknown but large volume may have traveled to the topographic depression 9 km northeast of Hotlum Glacier. Flows of probable smaller size occurred in 1728 and 1836, followed by a large event in 1902 that caused tree damage on the Gravel Creek debris fan 7 km from the glacier. A series of flows from 1937 to 1939 is recorded by abundant botanical and geomorphic evidence, as well as by extensive deposits of 1939 within 0.5 km of the depression at the lower end of Gravel Creek (pl. 1). Another flow occurred in 1958, and possibly in 1959, but it was of smaller magnitude than those 20 years before and was confined largely to the channel entrenchment. The last known debris flow of Gravel Creek traveled at least 6 km from Hotlum Glacier in 1971, but it also appears to have been contained by the channel.

Field evidence and inspection of aerial photographs indicate that late Holocene debris flows have traveled along two well-defined channels, about a kilometer apart in places, on the upper part of the Gravel Creek fan (upslope, or southwest of the middle of section 29, T., 42 N., R. 2 W.; pl. 1). The more southeasterly of the channels is currently occupied by Gravel Creek and has had the more recent debris-flow activity. The two pathways merge on the lower parts of the fan, where lower slopes permit spreading of sediment over large areas and into the depression west of Ash Creek Butte. The potential for inundation by debris flows is moderate to high over large parts of the Gravel Creek debris fan, and parts of the lowest fan area are expected to continue to aggrade rapidly by fluvial processes (pl. 1). Although few quantitative data are available, geomorphic and botanical observations suggest that sediment yields from the upper Gravel Creek basin may be at present the highest on Mount Shasta.

INCONSTANCE CREEK FAN

A northern tongue of Hotlum Glacier provides the headwaters for Inconstance Creek, which drains much of Mount Shasta north of Gravel Creek (pl. 1). Like the other glacier-fed streams of the mountain, Inconstance Creek cuts deeply into soft pyroclastic beds and shows abundant evidence of late Holocene debris-flow activity. Much of its upper basin is covered by andesite flows (Christiansen and others, 1977), however, and, relative to other glacial basins of Mount Shasta, Inconstance Creek has a limited sediment supply and a less developed lower fan. The lower portion of the Inconstance Creek debris fan merges with that of Gravel Creek (pl. 1). All water and sediment conveyed by Inconstance Creek move toward the northwest part of the topographic depression into which Gravel Creek drains, and none leaves the area by fluvial processes.

Recent debris flows extending as far as 8 km or slightly more from Hotlum Glacier have been common and are well dated, but occurrences of earlier events are not well documented. Miller (1980, pl. 1) reports extensive debris-flow movement associated with volcanic activity along Inconstance Creek, possibly in middle Holocene time, and one or more large flows in the period 1,000 to 1,500 years B.P. Fan deposits of the lower Inconstance Creek drainage net suggest that numerous other early to middle Holocene debris flows occurred, but magnitude and frequency data for such flows are not available.

Dendrochronological evidence of debris flows along Inconstance Creek provides dates of events as early as A.D. 1683; other dates suggested by eccentric tree growth following tilting by a debris flow include 1693, 1728 (which conforms with a similar date from the adjacent Gravel Creek basin and from the Ash Creek basin), and 1881. Various scars and suppression–release sequences in trees indicate debris flows extending along Inconstance Creek at least 5 km from Hotlum Glacier in 1918 and 1939.

Very well formed debris-flow levees, particularly for the 1918 and 1939 events, are coarse in the upper part of the Inconstance Creek fan (fig. 6) but grade into finer debris and mostly fluvial deposits as the stream bends eastward 2 km south of Military Pass (pl. 1). Although few debris flows of Inconstance Creek appear to extend farther from Hotlum Glacier than about 6 km, reworking and deposition downslope of debris by fluvial processes are causing significant aggradation between the northeast flank of Mount Shasta and the southern margin of The Whaleback (pl. 1). Volume estimates and related sediment yields are not available for Inconstance Creek debris flows, but yields for recent centuries are inferred to be comparable to those for the Whitney, Mud, and Ash Creek basins.

FREQUENCY AND CAUSES OF DEBRIS FLOWS

In figure 2, dates of debris flows are plotted on a logarithmic time scale because the frequency of known debris flows decreases with age. At least three possible causes of this pattern can be suggested: (1) Because of their freshness, recent events are more easily identified in the field than are older flows; (2) evidence is

FIGURE 6.—Debris-flow levees of 1918 and 1939, Inconstance Creek. View is up the channel, to the southwest.

easily obliterated by larger and more recent events; especially in the case of relatively small, in-channel debris flows; and (3) debris-flow activity during recent centuries may have been more intense than it was during earlier parts of Holocene time. The first cause is, perhaps, self-evident. Botanical evidence is largely limited by the ages of the trees, and relatively old debris-flow deposits, where preserved, are sometimes difficult to date and are generally buried by more recent deposits. Likewise, the second cause of more infrequent dates of events with increasing age seems obvious: The deposits and botanical evidence of small, in-channel events are easily destroyed when a larger, more erosive debris flow occurs along the same channel reach.

The third possible cause is less obvious and certainly the most speculative. Evidence that debris flows now occur more frequently than they did earlier in Holocene time is provided by patterns of deposition on several debris fans of Mount Shasta. Surveys at Gravel Creek (pl. 1; sec. 36, T. 42 N., R. 3 W.), for example, show that during the last 400 years the channel has shifted progressively in a southeasterly direction. The oldest debris-flow deposits of the area (405 years) rest unconformably on an undated pyroclastic layer at the northwestern extreme of the modern fan incisement. All other surfaces overlying the pyroclastics are younger than 300 years, and all were datable by botanical techniques (fig. 2). Debris-flow deposits estimated to be about 1,200 years old occur along Mud Creek (Dickson and Crocker, 1953), and deposits of roughly the same age have been dated at Inconstance Creek by Miller (1980), presumably by carbon-isotope analysis. No debris flows, however, have been identified on Mount Shasta older than about 1,200 years and younger than 1,800 years—the approximate carbon-isotope age of the most recent relatively widespread pyroclastic flow.

Further evidence of accelerated late Holocene incisement and debris-flow activity is available from Whitney Creek gorge (fig. 4). Stratigraphic relations, carbon-isotope dates, and botanical evidence of debris-flow deposition and erosion suggest that rates of incisement by Whitney Creek during the last 500 years may have been as great as during any part of Holocene time. Datable andesite, pyroclastic, debris-flow, and fluvial deposits of the Whitney Creek gorge area show that the upper fan surface has been stable for the last 9,200 years, but the oldest terrace surface within the gorge has been dated botanically at 315 years. The oldest trees found on stable, unlumbered sideslopes do not significantly exceed 430 years in age, and numerous unvegetated, steep, and highly unstable slipfaces along the valley walls demonstrate that incisement is occurring.

The large number of known debris flows on Mount Shasta during the last 500 years, relative to those earlier than about A.D. 1500, therefore, may in part be actual rather than fully a result of poor preservation and of more difficult identification with increasing age. During the last 500 years, at least 70 documented debris flows have occurred on the slopes of Mount Shasta; fewer than a fourth of that number have been documented for earlier parts of the Holocene, although numerous currently undated deposits may ultimately increase that number significantly. If indeed the frequency of debris-flow occurrence on Mount Shasta has been relatively high in recent centuries, a possible cause is climatic change. The culmination of the Little Ice Age, a time of expansion of many alpine glaciers, occurred roughly 100 to 300 years ago, and it was followed by general climatic warming and glacial retreat (M.F. Meier, U.S. Geological Survey, oral commun., 1984). Glacial expansions represent periods of increased storage of ice and snow; perhaps summer ablation during periods of increased storage produces releases of meltwater sufficiently often to cause a high frequency of debris flows.

Regardless of how debris-flow frequency may have changed on Mount Shasta during Holocene time, there is no doubt that geomorphic and botanical evidence of most small-magnitude events generally persists for only a relatively short amount of geomorphic time. Only known debris flows of the last century, therefore, are inferred to be representative of actual frequencies for recent geomorphic time, or to be indicative of future debris-flow frequency. Figure 2 indicates that at least 37 debris flows have occurred on Mount Shasta during the last 100 years—a rate of more than one per 3-year period. This rate may be indicative of the frequency at which debris flows will occur on the mountain in coming decades, although it should also be noted that only six known flows have occurred since 1962, and none since 1977. Whether this quite recent reduced frequency will continue over a longer term cannot be evaluated.

FREQUENCY OF LARGE-MAGNITUDE DEBRIS FLOWS

As geologic or hydrologic hazards, only the large debris flows are capable of causing significant damage to cultural developments on the flanks of Mount Shasta. For the purposes of this chapter, a large debris flow is defined in terms of areal damage potential and is any event of a magnitude sufficient to spill from a channel confinement and produce a tabular, mappable deposit on a fan surface. Excluded, therefore, are all flows restricted to valley or incisement bottoms as well as flows that locally deposit material on a fan surface owing to excessive within-channel turbulence or roughness, splattering, or head variations at incisement bends.

Table 1 lists all known and currently dated large-magnitude debris flows at Mount Shasta. For possible reasons already mentioned, the majority of the known large-magnitude flows have occurred during the last five centuries. Many of the older flows are exposed in scarps of incisements or were identified in a sequence of several or many debris-flow beds. These observations are consistent with the previous suggestion that much of the fan incision by streams and debris-flow activity may be of late Holocene age. Large-magnitude debris-flow deposits in the Squaw Valley Creek and Graham Creek basins (Miller, 1980) are of uncertain source (table 1) and may be indicative of a poorly developed drainage network in early to middle Holocene time.

As for Mount Shasta debris flows in general, the known large flows listed in table 1 are concentrated in the last century, again suggesting that older flows are difficult to identify. Part of this apparent concentration is that dendrochronology of recent flows, such as the Mud Creek series of 1924 to 1931, documents individual events, but that earlier flow sequences, the Cold Creek series of 1725 to 1768, for example, are difficult to identify as other than a succession of flows representing periods of years to decades. As a final approach to anticipating future debris-flow activity, therefore, table 1 shows that a minimum of 12 large-magnitude or potentially damaging flows have occurred on Mount Shasta during the last century. It is reasonable to expect that this rate may continue in the future, but it should be noted that no flows of relatively high yield have occurred for nearly 50 years. If smaller flows are at least 10 times as numerous as large flows, a rate of more than 120 events per century, or an average of more than 1.2 flows per year, is indicated; observations suggest that debris flows have not occurred at this rate during recent decades.

CAUSES OF LARGE-MAGNITUDE DEBRIS FLOWS

A variety of causes and processes by which debris flows may occur on Mount Shasta has been described previously, but a more specific set of circumstances may be applicable to the occurrence of large-magnitude flows. Although the 1935 flow of Whitney Creek may be an exception, the amount of water needed to cause the observed sediment yields listed in table 1 is generally too great to be explained by individual storm events or single cases of slipface collapse, damming, and conversion of the debris to a slurry. The 1931 debris flow of Mud Creek, for example, deposited an estimated 29×10^6 Mg of sediment (table 1). Based on 17

TABLE 1.—*Large-magnitude Holocene debris flows of Mount Shasta, Calif.*

[Mg, megagrams; km, kilometer; km^2, square kilometer; yr, year]

Stream	Age (years B.P.)	Comments
Ash Creek	8	Small; confined to upper fan.
Ash Creek	23	------------------------
Gravel Creek	46–48	Large but unknown yield.
Ash Creek	46–48	Yield $\sim10\times10^6$ Mg.
Whitney Creek	50	Area of deposition ~8 km^2; yield $\sim4.0\times10^6$ $Mg/km^2/yr$.
Mud Creek	54	Yield $\sim29\times10^6$ Mg/km^2/yr[1].
Mud Creek	59	Yield $\sim3.0\times10^6$ Mg/km^2/yr[1].
Mud Creek	60	Yield $\sim0.45\times10^6$ Mg/km^2/yr[1].
Mud Creek	61	Yield $\sim13\times10^6$ Mg/km^2/yr[1].
Gravel Creek	83	Length of travel ≥7 km.
Ash Creek	87	------------------------
Bolam Creek	87–89	Area of deposition ~3 km^2; yield $\sim3.0\times10^6$ $Mg/km^2/yr$.
Mud Creek	105	
Whitney Creek	195	
Ash Creek	217–260	Cold Creek series of ≥3 flows; yield $\geq32\times10^6$ $Mg/km^2/yr$.
Mud Creek	245	
Gravel Creek	405	Large but unknown yield.
Whitney Creek	420±60	Age by carbon-isotope analysis.
Mud Creek	600[2]	Age by dendrochronology.
Ash Creek	800	Area of deposition ~6 km^2; age by carbon-isotope analysis.
Mud Creek	1,200[2]	Age determined by soil development, may be subject to considerable error.
Inconstance Creek	1,000–1,500[3]	Age poorly known.
Ash Creek	1,700	Age by carbon-isotope analysis.
Inconstance Creek	1,800[3]	
Ash Creek	2,800[3]	Age by carbon-isotope analysis.
Squaw Valley Creek	4,000[3]	Two or more very large flows that may have been derived from Mud Creek basin.
Ash Creek	3,100–9,400[3]	Poorly documented and dated.
Inconstance Creek	5,900[3]	Poorly dated.
Graham Creek	6,700[3]	Source area may have been Whitney Creek Basin.
Gravel Creek	~8,000–10,000[3]	Two episodes; poorly dated.

[1]Modified from Wood (1931).
[2]From Dickson and Crocker (1953).
[3]From Miller (1980).

laboratory analyses of estimated minimum water content of Mount Shasta debris flows and a contributing drainage basin of about 16 km^2, the 1931 event required a water content equaling at least a fourth of the estimated 2,000-mm mean annual precipitation for that part of Mount Shasta (U.S. Department of Commerce, 1968, p. 114). Only a very rapid release of glacial meltwater appears to be a plausible explanation for the half-meter average runoff that resulted in the summer of 1931 debris flow from the upper Mud Creek basin. Weather records from McCloud and Mount Shasta City show that precipitation was deficient in the summer of 1931 but that temperatures were higher than normal. Discharges of this magnitude may be necessary to cause a sufficiently rapid succession of undercuts and slope failures leading to debris-flow pulses. Although the mechanism by which sediment is mobilized to form large-magnitude debris flows of Mount Shasta is based on indirect evidence, the rapid releases of glacial meltwater have been well documented as the principal hydrologic causes of the 1924 to 1931 series of Mud Creek flows (Hill and Egenhoff, 1976). It appears likely that similar processes are responsible for large debris flows in other glacial-meltwater basins of Mount Shasta. This explanation seems particularly appropriate for the Whitney and Bolam Creek basins, which, owing to rainshadow effects, have much lower precipitation rates than do those basins of the eastern and southeastern parts of the mountain.

A large supply of easily mobilized sediment is a second requirement for large-magnitude debris flows. Bulking of channel alluvium may be sufficient to cause some small, in-channel flows, but much larger volumes of material are required to produce the debris flows listed in table 1. The steep, highly unstable, and barren incisement scarps of the upper-fan gorges are the obvious sources of most sediment forming Mount Shasta debris flows. The depths of the incisements or the surface areas of the slipfaces within the gorges therefore provide indications of the amount of sediment potentially available to form debris flows.

Figure 7 presents data and a line of relation between gorge depths (within geologic sections of pyroclastic and related deposits) and known debris-flow frequency during the last 500 years for various drainage basins of Mount Shasta. Disregarding Cold Creek, which is largely determined by Ash Creek flows, the data yield a relation suggesting a strong influence (r=0.91) on debris-flow frequency by depth of incision. This relation provides compelling evidence that the principal sediment source areas of Mount Shasta debris flows are the unvegetated valley walls within the various gorges; glacial debris and channel alluvium are probably secondary sediment sources. For most large-

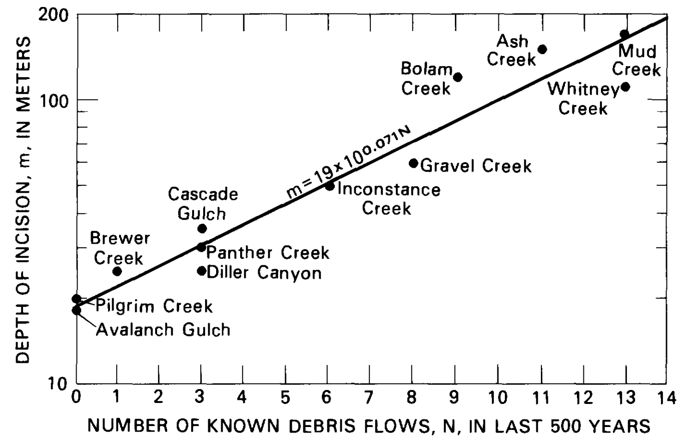


FIGURE 7.—Graph relating depth of stream-channel incision on Mount Shasta to known number of debris flows, by stream, during the last 500 years.

magnitude flows, if not smaller debris flows as well, therefore, almost all sediment mobilized is derived from small parts of the upper drainage basins—those areas where stream incision is actively occurring. Other parts of the upper fan surfaces are relatively stable, show low rates of fluvial and eolian erosion, and contribute insignificant amounts of sediment to depositional areas of the lower fan surfaces.

An indirect cause of debris flows on Mount Shasta is the effect that sustained periods of warm summer temperatures have on melting rates of glacial ice and snow. Fragmentary weather records from California and Oregon (Roden, 1966) for the last 165 years show that unusually warm summer temperatures often have accompanied large-magnitude debris flows on Mount Shasta, including those of Mud Creek from 1924 to 1931 (Hill and Egenhoff, 1976). Similarly, occurrences of debris flows in two or more basins during the same year can sometimes be related to warm summer temperatures; examples are the years 1840, 1881, 1897 to 1900, 1939, 1958, and 1977 (fig. 2). Small, single-occurrence debris flows may be related to a variety of conditions and do not necessarily indicate rapid melting of glacial ice and snow.

AREAS OF DEBRIS-FLOW HAZARD

Plate 1 presents interpretations of areas of Mount Shasta currently subject to debris-flow hazard. The three degrees of inferred hazard shown on the map are based principally on late Holocene debris-flow activity. Thus, the term "hazard" is used without regard to distribution of human activity and is nearly synonymous with likelihood of occurrence. Within the "high-hazard" areas, the likelihood of impacts by debris flows changes markedly in the downslope direction. The upper reaches of incised stream channels, such as those of Whitney, Bolam, Mud, and Gravel Creeks, are very likely to be modified by debris flows during the next few decades. Downslope, the probability of debris-flow impacts steadily decreases to lower fan areas, where deposition seems possible but unlikely during the next century. As previously defined, the "medium-hazard" and "low-hazard" areas have correspondingly lower likelihoods of being affected by debris flows during the next 100 years.

BASINS OF GLACIAL-MELTWATER STREAMS

Potential damage by debris-flow activity on Mount Shasta is much greater in basins headed by a glacier than in basins that do not directly receive glacial meltwater. Hence, the inferred hazard in those basins, again in a counterclockwise direction around the mountain, are summarized first.

The incisements of Bolam Creek and Whitney Creek above their confluence are subject to frequent debris flows, but the adjacent fan areas currently can be covered only by high-magnitude events. The area directly north of lower Bolam Creek was covered by a large flow in 1897, but this area is not regarded as a high-hazard area because no other debris-flow deposits have been identified in the area. About 2 km below the confluence, Whitney Creek changes from a generally degrading stream incisement to a depositional or aggrading fan surface. The upper portion of the aggrading surface, within 2 km of U.S. 97, is prone to deposition by any debris flow large enough to extend beyond the Southern Pacific Railroad tracks west of Bolam. Most of the remainder of the Whitney–Bolam debris fan is subject to significant debris-flow hazard, but only by infrequent, large-magnitude events. The lowest part of the fan, within 2 km of the Shasta River, is not highly susceptible to debris-flow deposition, but fluvial reworking of debris-flow material may at times result in rapid aggradation of the lower fan surface.

Mud Creek is incised deeply into fan deposits to Mud Creek Dam (pl. 1) and slightly below, and hazards due to debris flows in this upper part of the basin are confined to the area of stream incisement. Several kilometers below Mud Creek Dam, the creek becomes depositional and debris flows can overflow the Mud Creek channel and spill onto a large fan area. In the intermediate and lower parts of the Mud Creek basin, inferred debris-flow hazard on the Mud-Ash debris fan is based largely on depositional areas of the 1924 to 1931 flows and the four previous large-magnitude flows (table 1). Most areas designated as low hazard have not had late Holocene debris-flow deposition, but they could be susceptible if large discharges from Konwakiton Glacier again occur. Much of the town of McCloud and lower Squaw Valley are within potential debris-flow areas, but the threats to these areas appear small. In both cases, potential hazard by debris flows is principally from the upper Mud Creek basin, not from the Panther Creek basin.

No debris-flow hazard currently appears present over a large area of the Mud-Ash debris fan separating the Mud Creek basin from the Pilgrim Creek and lower Ash Creek basins. Large areas of the Ash Creek basin, however, are subject to possible blanketing by debris-flow deposits downslope from the western part of section 16, T. 41 N., R. 2 W. (pl. 1). The fan area above Sugar Pine Butte is the most likely part of the basin to sustain out-of-channel deposition in future decades, but a substantial area extending to the lower end of Coonrod Flat also appears to be vulnerable to debris-flow deposition. Significant aggradation is occurring as far south as the Ash Creek Sink area as fluvial deposition of reworked debris-flow deposits. Debris-flow activity as far downslope as Ash Creek Sink appears unlikely.

Unlike those of Mud Creek and Ash Creek, debris flows of Gravel Creek move only a few kilometers before the channel ends in a broad zone of deposition and rapid aggradation. Much of this zone is considered a high-hazard area and could be covered by debris flows if rapid melting of Hotlum Glacier were to occur; an area of similar size appears to have lower or medium hazard potential. Even if large-magnitude debris flows along Gravel Creek do not occur in the next century, fluvial erosion of channel alluvium, pyroclastic beds, and older debris-flow deposits is expected to result in rapid aggradation in the low area west of Ash Creek Butte. Regardless of the magnitude of future debris flows originating in the Gravel Creek basin, none is expected to flow distances greater than 6 km. Owing to the relative remoteness of the lower Gravel Creek fan, debris flows present little threat to human activities except to unpaved roads and logging operations.

Inconstance Creek drains toward the same depression as does Gravel Creek. It, too, is likely to exhibit debris-flow activity in future decades, but the threats to life and property are regarded as minimal. No debris flows of Inconstance Creek are expected to travel farther than the low area west of Ash Creek Butte.

BASINS LACKING GLACIAL-MELTWATER CONTRIBUTIONS

The geology of the upper Graham Creek basin, a tributary to Whitney Creek, is dominated by lava flows. Because precipitation readily infiltrates the volcanic rocks, which also provide a limited source of sediment, debris flows originating in the Graham Creek basin are considered unlikely. There appears to be virtually no hazard along Graham Creek owing to debris flows.

The channel of Diller Canyon incises soft pyroclastic beds that can supply sufficient sediment to initiate debris flows. A supply of water limited to runoff of precipitation events and spring melting of the snowpack, however, is normally insufficient to cause other than small-magnitude debris flows. The likelihood of significant out-of-channel debris-flow deposition resulting from extraordinary runoff in the upper Diller Canyon drainage basin appears remote. Debris flows from Diller Canyon currently cause no hazard to Weed or nearby communities (pl. 1).

Cascade Gulch, Avalanche Gulch, Panther Creek, and upper Squaw Valley Creek (north of McCloud) have limited sources of both water and sediment. Although small-magnitude debris flows have been documented along Cascade Gulch and Panther Creek, the probability of spillage onto fan surfaces by flows from any of the four channels seems small. There appears to be no debris-flow hazard to the Mount Shasta City area from Cascade Gulch, or to the McCloud area from Squaw Valley Creek. Local damage to Everitt Memorial Highway by debris flows along Cascade Gulch is possible, but the drainage appears to present no debris-flow hazard to McBride Springs Campground (T. 41 N., R. 4 W., sec. 35, SW1/4). A debris flow moving along Panther Creek could conceivably affect parts of McCloud, but no debris flows of recent decades are known to have traveled as far south along Panther Creek as the Signal Butte area (pl. 1).

In the Ash Creek area on the east side of Mount Shasta, Pilgrim Creek drains and incises a fan area sufficiently large that small-magnitude debris flows seem possible. No evidence of activity along Pilgrim Creek, however, has been obtained, and the possible hazard is therefore considered low. Similarly, no debris flows are known to have originated in the Cold Creek basin. As discussed previously, however, much of the Cold Creek basin and drainage network has been heavily modified by debris flows from Ash Creek, and therefore are included in areas interpreted to be of medium or high hazard. In-channel debris flows have occurred along Brewer Creek, on the north side of the Ash Creek drainage, but limited sources of water and sediment preclude significant debris-flow hazard.

SEDIMENT YIELDS AND RATES OF DEPOSITION

Calculations of observed volumes of debris-flow or fluvial deposits with inferred rates of debris-flow frequency lead to estimates of sediment yields and denudation rates on Mount Shasta. Sediment yields are based on an assumed rock density of 2.65 grams per cubic centimeter and a porosity of 0.25 for debris-flow deposits. Volume and frequency data are adequate to permit calculations for four basins (table 2), but it is emphasized that the resulting yields and denudation rates are estimates that may be substantially in error.

The yields of table 2 for Whitney and Ash Creeks are based on debris-flow volumes calculated from areas of deposition and average thicknesses of the deposits estimated from cutbanks and soil pits. Volumes of the Mud Creek flows and resulting sediment yields were obtained from estimates and maps published by Wood (1931) and Dickson and Crocker (1953), and results for Gravel Creek are based on dendrochronological evidence of aggradation rates on its lower fan area. The yields for Whitney, Mud, and Ash Creeks are based only on sediment moved during large-magnitude debris-flow events, whereas the yield for Gravel Creek is determined from primarily fluvial deposits. Of the four streams in table 2, results for Mud Creek are probably the most reliable; those for Gravel Creek may represent too few data and too short a period of time to be considered trustworthy. All four sets of yields and degradation rates are regarded as conservative—more likely to underestimate than to overestimate average conditions of sediment transport and deposition.

The sediment yields estimated for Mount Shasta drainage basins (table 2) approach and exceed some of the highest yields and denudation rates that have been observed throughout the world (Li, 1976; Griffiths, 1982; Saunders and Young, 1983). Although the yield estimates given in table 2 are possibly less accurate than many previously published yields for other high-yield areas, they are based on longer time periods than are many yields computed from fluvial sediment loads or hillslope-erosion studies. Thus, the yields and denudation rates estimated for the upper slopes of Mount Shasta may be indicative of late Holocene erosion rates rather than rates possibly influenced by recent human activity.

TABLE 2.—*Estimated sediment yields and denudation rates in selected drainage basins of Mount Shasta, Calif.*

[yr, year; km^2, square kilometer; Mg, megagram; mm, millimeter][1]

Stream	Period (yr)	Area (km^2)	Yield ((Mg/km^2)/yr)[2]	Denudation rate (mm/1,000 yrs)
Whitney Creek	50	10	30,000	11,000
Mud Creek	1,200	16	11,000	4,000
Ash Creek	250	12	17,000	6,400
Gravel Creek	26	5.0	50,000	19,000

[1]Sediment yields are based on assumed bulk densities of 2.0 for debris-flow deposits; sediment yields and calculated denudation rates are averages of entire estimated subaerial contributing drainage basin.

[2]Equivalent to metric tons per square kilometer.

The denudation rates listed in table 2 seem supportive of the previous speculation that geomorphically recent debris-flow activity on Mount Shasta may have been more intense than it was in early to middle Holocene time. Field investigations of this study suggest that most sediment forming debris flows in the glacial-meltwater basins of Mount Shasta is derived from within the channel incisements; evidence is strong that other parts of the fan surfaces have experienced relatively minor Holocene erosion. The denudation rates listed in table 2, however, are averages for the entire subaerial basins above the lower gorge reaches, whereas the primary contributing areas for sediment discharge, that is, the gorge areas, probably account for less than 5 percent of the subaerial basin areas. The local denudation rates for the gorge areas, therefore, currently may range as high as 400 m per thousand years. Because the deepest incisements of Mount Shasta are generally less than 200 m (fig. 7), it seems apparent that the upper and middle fan areas would be much more extensively dissected had present rates of sediment yield and denudation prevailed throughout Holocene time.

Similar calculations for the deposition of sediment also lead to an inference of presently high rates of debris-flow activity and denudation. Lower Gravel Creek terminates in a topographic basin into which all sediment from the stream is deposited. Recent deposition of about 0.06 m per year (60 m/1,000 yr) has been restricted to an area estimated to be about 2 km^2. If a larger area of probable deposition, estimated to be perhaps 12 km^2, is considered, an aggradation rate for the lower Gravel Creek fan of 10 m/1,000 yr is calculated. For that rate of deposition to have occurred throughout Holocene time, the original depression would have had to have been in excess of 100 m in depth, even if it is assumed that no sediment was contributed by Inconstance Creek. There is no evidence that the original basin was as deep as 100 m, and predominantly late Holocene deposition, therefore, is indicated. Slightly southwest of the limit of currently rapid deposition (T. 42 N., R. 2 W. sec. 21, SW1/4; pl. 1), a radiocarbon date of a buried branch supports this conclusion. The date suggests an average rate of fluvial deposition of 0.84 m/1,000 yr during the last five centuries.

On a larger scale (and neglecting the relatively minor amounts of sediment presumably lost to the McCloud and Shasta Rivers), if an average sediment yield of 15,000 $(Mg/km^2)/yr$ is assumed for a total upper slope area of 60 km^2, a sediment yield of 9.0×10^5 Mg/yr is indicated. Also assuming a bulk density of deposited sediment of 2.0 and a total depositional area of 150 km^2, an aggradation rate of 3 m/1,000 yr is estimated. This rate, had it prevailed throughout Holocene time, would account for an average depth of burial of 30 m over all fan areas currently known to have received fluvial and debris-flow deposits. Casual observations of stream incisements, outcroppings of Pleistocene and early Holocene volcanic rocks, data from soil pits, and a small number of water-well logs suggest that the average depth of burial is much less than 30 m.

Debris-flow occurrence on Mount Shasta is an important late Holocene geomorphic process, both as a local geologic hazard to humans and as a more widespread mechanism by which material forming the mountain is redistributed at a very rapid rate relative to a geomorphic time scale. As indicated, debris-flow activity on Mount Shasta during recent centuries may have been as intense as at any time during the Holocene Epoch. At a time when alpine glaciers continue to retreat (Meier, 1984) and periodically release large amounts of meltwater, it seems probable that debris flows on Mount Shasta will occur frequently, continuing rapidly to modify the mountains' landscape. If, in the more distant future, glaciers of Mount Shasta continue to dwindle, debris-flow activity is likely to subside.

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