

Dendrogeomorphic Evidence and Dating of Recent Debris Flows on Mount Shasta, Northern California

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By CLIFF R. HUPP, W. R. OSTERKAMP, *and*
JOHN L. THORNTON

DEBRIS-FLOW ACTIVITY AND ASSOCIATED HAZARDS 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:

<i>Multiply metric unit</i>	<i>by</i>	<i>to obtain inch-pound unit</i>
millimeter (mm)	0.03937	inch (in)
meter (m)	3.281	foot (ft)
kilometer (km)	0.621	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 per square kilometer per year ((Mg/km ²)/yr)	2.87	ton, (short) per square mile per year ((ton/mi ²)/yr)

DEBRIS-FLOW ACTIVITY AND ASSOCIATED HAZARDS ON MOUNT SHASTA,
NORTHERN CALIFORNIA

**DENDROGEOMORPHIC EVIDENCE AND DATING OF RECENT
DEBRIS FLOWS ON MOUNT SHASTA, NORTHERN CALIFORNIA**

By CLIFF R. HUPP, W.R. OSTERKAMP, and JOHN L. THORNTON

ABSTRACT

Evidence of debris flows is common along the glacially fed streams of the Mount Shasta volcano, California. These streams are Whitney Creek, Bolam Creek, Mud Creek, Ash Creek, Gravel Creek, and Inconstance Creek. Debris flows since 1580 can be documented by studying trees damaged by or growing on debris flows. Dates obtained from tree-ring analysis proved consistent with documented records of debris flows. Debris-flow dates in conjunction with geomorphic evidence permit the development of magnitude and frequency relations over a period of about 400 years.

Dendrogeomorphic evidence shows that debris flows are a common occurrence on many Mount Shasta streams. Debris flows traveling at least 2 kilometers have occurred at a frequency of about 10.5 debris flows per century; certain basins are more active than others, the Gravel Creek and Mud Creek basins are among the most active, and Inconstance Creek basin is the least active. Small debris flows are more frequent and usually do not move as far downslope as large debris flows. Cyclic scouring and filling by debris flows, in and adjacent to stream channels and on debris fans, is suggested by dendrogeomorphic evidence and seems to be related to event magnitude and frequency. Distinct periods of heightened debris-flow activity and quiescent periods occur in individual basins and are apparently related to glacial and valley wall stability and meltwater supply. Debris flows of all magnitudes appear to be the major surficial geomorphic agent during noneruptive times that sculpture the channels and develop large alluvial fans.

INTRODUCTION

Dendrochronological analyses are means of obtaining dates of occurrence of many important geomorphic events. Magnitude and frequency information are useful in the prediction of floods, landslides, debris flows, and most other hydrogeomorphic hazards. Where historic records are short or lacking, tree-ring study is the most accurate method for obtaining magnitude and frequency data over the past several hundred-year period. Botanical evidence in combination with geomorphic evidence allows for the interpretation and determination of the relative importance of various geomorphic processes.

Debris flows—a process at the fluid end of the mass-movement spectrum—are poorly sorted slurries of rock, soil, and water. These flows, also termed “lahars” when they occur on volcanoes, may originate from a variety of mechanisms (Mullineaux and Crandell 1962; Pierson 1980a, b; Costa and Jarrett 1981; Janda and others 1981; Costa 1984). Debris flow velocities range from less than 1 m/s to more than 40 m/s (Janda and others 1981), and they can flow down stream channels for many tens of kilometers (Crandell 1971; Janda and others 1981). Deposits may be preserved as overbank deposits, as terraces within channels, or as lobate sheets on debris fans (Curry 1966; Pierson 1980b; Costa and Jarrett 1981). Impact on trees from debris flows depends on flow velocity, thickness, and size of transported clasts. Effects of the impact on trees can range from tranquil burial of lower trunks to complete destruction of large areas of forests (Janda and others 1981; Hupp and Sigafos 1982; Hupp 1984; Costa 1984). Despite the coarse, sometimes bouldery texture of debris-flow sediments (Pierson 1980a, b; Costa and Jarrett 1981), woody vegetation may readily establish on these deposits.

Debris flows are common along many streams draining the Mount Shasta volcano, particularly those streams which head at alpine glaciers. These flows may represent the major surficial geomorphic agent during noneruptive periods on the mountain. During eruptive periods, debris flows may affect large portions of the Mount Shasta area. Deeply sculpted valleys, overlapping depositional terraces, and broad alluvial fans have developed downslope, respectively, in many Mount Shasta basins largely through debris-flow activity. Cyclic scouring and filling by debris flows, in and adjacent to the stream channels and fans, are suggested by dendrogeomorphic evidence and appears to be related to magnitude, frequency, and channel gradient.

The purpose of this report is to present the result of the studies to develop a debris-flow history (magnitude and frequency) for several streams on Mount Shasta over the past several centuries. The dating of Mount Shasta debris-flow activity from the 1500's is based on combined geomorphic and botanical evidence. Secondary purposes were to show that botanical evidence allows geomorphic characterizations of debris-flow deposition and scour, through time and for inference on the relative effects of debris flows of various magnitudes and frequencies.

DENDROCHRONOLOGICAL ANALYSIS

Woody vegetation grows along most streams except in very arid regions. In relatively humid areas, trees are usually the dominant vegetal cover over most of the landscape. Woody species are perennials, living through the harsh portion of a year, usually winter, by becoming dormant. When conditions conducive to growth recur, woody plants break dormancy and begin growing again. Seasonal growth results in the production of an annual increment of wood, called a tree ring.

Trees grow in height only at the tips of branches. Growth in girth is from a vascular cambium (wood-producing tissue) that sheaths the entire plant just under the bark. Thus, an annual growth increment is a cone of new wood overtopping that of previous years. Cones viewed in cross section are a series of concentric rings. Trees produce annual increments throughout their lives, which can be over 1000 years but more commonly a few years to several hundred years.

Scientists use tree-ring dating (dendrochronology) for determining the age of geomorphic surfaces or events simply by counting the number of rings since germination or damage. A count of tree rings from an increment core taken from the base of a stem yields the age of the stem so long as each year is represented by a single ring. The dendrochronological technique of cross dating (Stokes and Smiley, 1968; Cleaveland, 1980) is used to ensure that dating errors are not introduced by the possible occurrence of missing and multiple rings. Sigafos (1964) and Phipps (1967) describe tree growth in relation to hydrogeomorphic studies.

Dendrochronologic methods have been widely used in dating the occurrence of hillslope and fluvial geomorphic events and in determining rates of processes (LaMarche, 1968; Alestalo, 1971; Sigafos and Hendricks, 1972; Shroder, 1978; Hupp, 1983). Woody vegetation physically damaged by geomorphic events or growing on deposits provides a means for dating past events. The basic principles of tree-ring dating have been outlined extensively by Sigafos (1964), LaMarche (1968), Alestalo (1971), Helley and

LaMarche (1973), and Yanosky (1983). Floods, mudflows, debris flows, and debris avalanches can have numerous effects on woody vegetation, including partly felling tree trunks, scarring stems, and creating bare areas where plants can become established (Sigafos, 1964; Shroder, 1978; Butler, 1979; Hupp, 1983).

Published studies centering on the use of dendrogeomorphic evidence for estimation of debris-flow frequency and magnitude have not been extensive. However, some notable studies have either suggested the use of botanical evidence in debris-flow study or used botanical evidence to study other forms of mass wasting. In California, Jackson (1977) gives an over 500-year account of mudflows near Big Sur. Additionally, he developed a mudflow stratigraphy along streams using tree-root zones to age mudflow strata. This method also estimates relative magnitude. Other similar studies in the California Mountains include Stewart and LaMarche (1967), LaMarche (1968), Helley and LaMarche (1973), and Hupp (1984). In the Pacific Northwest, Mullineaux and Crandell (1962) have suggested the use of botanical evidence in dating recent debris flows on Mount St. Helens. The age and effects of mass wasting on woody vegetation has been studied by Swanson and others (1981) and Miles and others (1984). Currently, several scientists are using dendrochronology in their studies of debris flows on volcanoes in the Cascade Range (R.J. Janda, U.S. Geological Survey, oral commun., 1984). In the Colorado Rocky Mountains, the use of botanical evidence has been suggested by Sharpe (1974), Costa and Jarrett (1981) and Costa (1984). Several debris flows on Mount Elbert, Colo., have recently been tree-ring dated by C.R. Hupp, and J.E. Costa (U.S. Geological Survey, written commun., 1984). Langenheim (1956) used vegetation to interpret a large debris flow in the Elk Range of Colo. Shroder (1978) conducted a dendrochronological analysis of mass wasting in Utah. In the Mackenzie Mountains of Canada, Parker and Jozsa (1973), Butler (1979), and Gardner (1982) have used dendrochronology to date landslides. Sauchyn and others (1983) have evaluated botanical methods other than dendrochronology, for determining debris-flow dates in the central and the southern Canadian Rocky Mountains. In the Eastern United States, debris avalanches have been dated through tree-ring analyses by Flaccus (1959), White (1979), Kochel and other (1982), and Hupp (1983). The importance of mass wasting and botanical evidence in the Eastern United States, has been stressed by Hack and Goodlett (1960) and Hack (1965). In Scandinavia, Rapp (1963), and Rapp and Nyberg (1981) have studied debris flows and suggested the use of dendrochronological analysis. Alestalo (1971)

and Schweingruber (1983) review European studies of dendrochronology in relation to mass wasting.

TYPES OF BOTANICAL EVIDENCE OF DEBRIS FLOWS

Debris flows can damage or destroy trees in or adjacent to their paths. Trees that survive a debris flow provide the most accurate dates for a particular event. When the trees are not killed, the effects of a debris flow can be manifested in several ways, usually as some deformation of the stem with subsequent changes in wood anatomy or serial tree-ring pattern. These deformations have been categorized into four basic types (Hupp, 1983: 1984): (1) eccentric annual growth, (2) suppression and release sequences, (3) tilting and adventitious sprouting along the parent stem, and (4) corrosion of the stem by transported debris. The analysis of cross-dated cores and cross sections of stems having one or more of these deformations usually yields several confirmations of a date for a particular event.

Eccentric annual growth and suppression-release sequences both involve serial ring-width measurements. Eccentric annual growth (fig. 1A) is produced by growth of the stem in an inclined position. One side of the stem, depending on species, will produce a thicker ring relative to the opposite side after the stem has been tilted. For example, conifers will produce thicker rings on the downslope side of the tilt (compression wood) and thinner rings on the upslope side of the tilt (tension wood). The overall appearance of a cross section exhibiting eccentric growth is a period of relatively concentric rings prior to tilting, followed by an abrupt shift to eccentric ring growth after tilting (fig. 1). The date of the event which tilted the tree is within 1 year of the onset of eccentric growth. In areas subjected to prolonged and deep snow cover, trees growing on slopes may be tilted due to snow push. This type of eccentric-ring production is, however, a gradual shift to eccentricity rather than an abrupt shift associated with episodic events such as a debris flow. Many tilted trees have debris piled on the upstream side deposited during a debris flow; furthermore they grow in flat valley bottoms which makes snow push rather unlikely.

Suppression and release sequences (fig. 1C) appear as a period of relatively narrow rings followed by an abrupt shift to wide rings. This type of sequence can be caused by any number of events that would remove nearby trees that compete for required resources (water, light). When these competitors are removed, the tree is "released" and a period of greater growth (wide rings) often follows. Trees growing adjacent to the path of a debris flow that removed neighboring trees may be released after the debris flow. Conversely,

should a slow-moving debris flow deposit a substantial layer of sediment around the tree, a period of suppression may ensue. Regardless, release or suppression related to debris-flow activity generally occurs abruptly. Gradual shifts in ring width, which resemble suppression and release, are more typically associated with climatic variability (Fritts, 1976). This line of evidence for a particular date must be used with a measure of caution and substantial replication of the date must be found in other specimens. Furthermore, trees near the site and unaffected by debris-flow activity should be analyzed to rule out particular ring patterns which may be climatically induced. Suppression and release sequences are the least accurate dating technique. One to a few years may be required for a tree to begin released or suppressed growth owing to inherent lag times associated with ring width patterns (Fritts, 1976).

Severe tilting or partial burial can cause adventitious sprouting along the parent stem. These sprouts begin growing within one year after tilting and provide an excellent line of evidence (Hupp, 1983) when replicates are found for a particular date of an event. Tilt sprouting is easily recognized in the field owing to the distinctive growth form produced. However, adventitious sprouting is uncommon in gymnosperm plants (conifers), which form the bulk of the tree species on Mount Shasta.

The corrosion of tree stems by debris flows (fig. 1D) damages the cambium. This corrosion can result in termination of radial growth where the tree was struck. In subsequent years the scar will be increasingly covered by callus growth until the damaged area is completely covered and the cambium is once again continuous around the trunk. Cross sections through the scarred portion of the trunk can yield the exact year of damage. Often the season of occurrence can be determined by the location of earlywood or latewood at the outside edge of the scarred wood. Increment cores taken at different angles on either side of a scar and small wedges of wood through the side of the scar make dating possible without destroying the tree.

In areas where a debris flow removed vegetation and created sites for vegetation establishment, an approximate age for the debris flow may be obtained by coring the base of trees growing on the new surface (fig. 1) to their biological center (pith). Tree age may be used to date surfaces, although not necessarily as accurately or with as much confidence as other dating techniques. The time between the cessation of the debris flow and ecesis (plant establishment) is variable (Sigafos and Hendricks, 1969), therefore only a minimum age may be estimated. However, because of the nature of regeneration of vegetation on debris-flow deposits, it is rea-

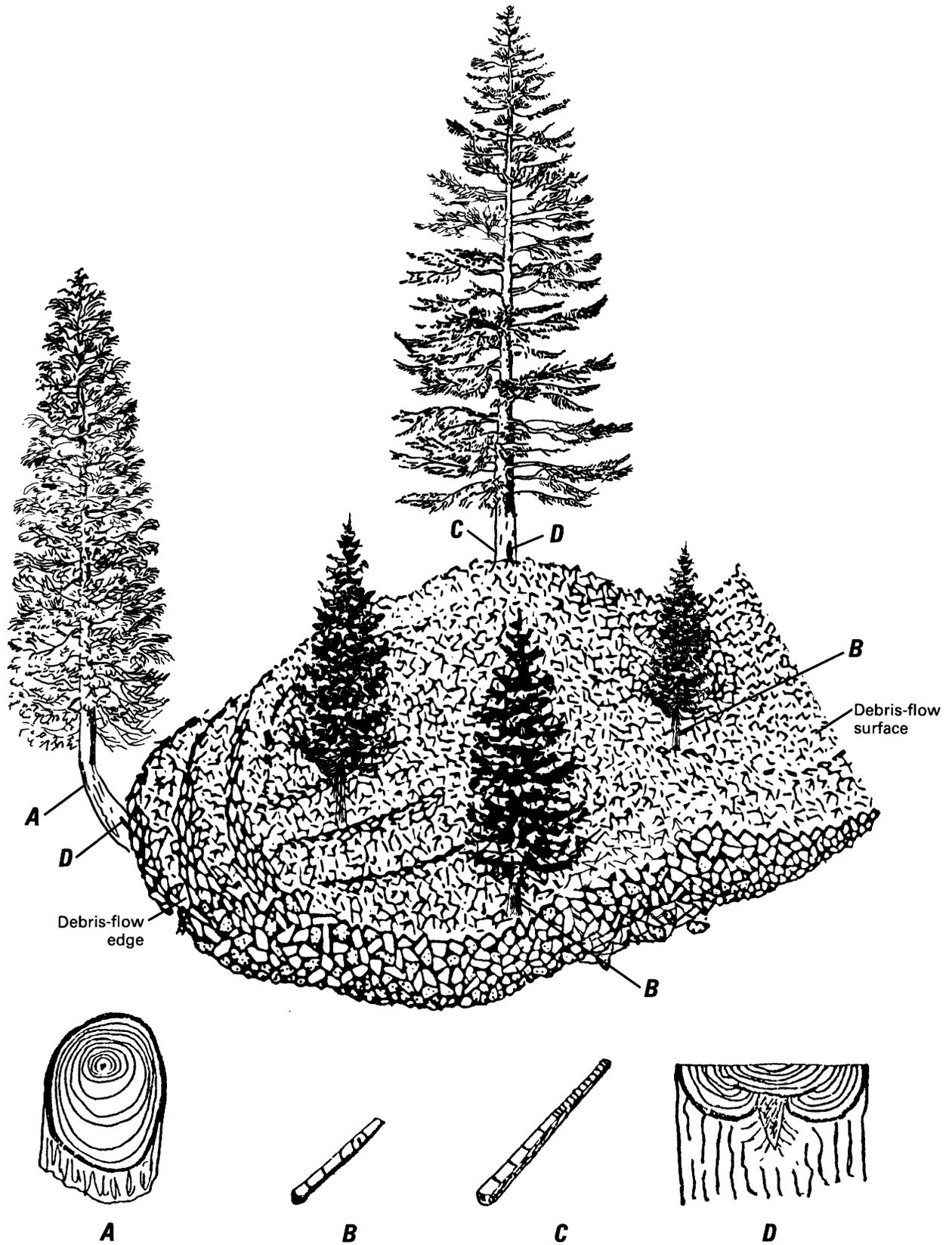


FIGURE 1.—Types of botanical evidence of debris flows. A, eccentric growth; B, age of surface; C, suppression and release; D, corrosion scar.

sonable to assume that the deposit is not significantly older than the trees when many trees (cohorts) on a deposit are about the same age (even-aged stand). Preliminary studies on Mount Shasta indicate that from 1 to 5 years elapse after the cessation of the debris flow before tree species begin ecesis (Hupp unpublished observations, 1982 through 1985; Sigafos and Hendricks, 1969).

Between 1982 and 1985, about 1,100 trees were analyzed for evidence of debris-flow activity on Mount Shasta. Specimens from these trees included cores, cross sections, and wedges. Examples of these specimens after sanding and interpretation are shown in figure 2.

PREVIOUS STUDY

The earliest study to use tree-ring dates on Mount Shasta debris flows was conducted by Beardsley and Cannon (1930). They studied a site along Mud Creek for 4 years following the 1924 debris flow. They also found geobotanical evidence for a debris flow in the late 1500's and another in about 1900. Beardsley and Cannon (1930) also found that, although many trees were not immediately killed by the debris flow, death of trees continued for 4 years probably as a result of burial and subsequent suffocation and desiccation of roots. Some trees were buried to a depth of about 5 m.

Dickson and Crocker (1953) used tree ages on the Mud Creek debris-flow area to confirm soil chronosequence dates. They found botanical evidence for four debris flows including the 1924 event. The three other dates were about 1388, 1747, and 1892; these are minimum ages and do not allow for period of vegetation establishment. Glauser (1967) determined that trees growing on the 1892 surface, determined by Dickson and Crocker (1953; 1954), to have an average age of 68 years in 1964. This would suggest that two years were necessary for vegetation establishment. Sollins and others (1983), also working on the Mud Creek debris-flow area, used tree rings to determine fire dates and apparently confirm the dates of debris flows suggested by previous studies.

Miller (1980) studied debris-flow activity on several streams around Mount Shasta. Specific dates of recent flows are not given. However, Miller reports that at least three debris flows occurred since about 1770 on Inconstance Creek; more than five debris flows on Gravel Creek in the last several hundred years; at least five debris flows on Ash and Cold Creeks in the last 200 years; more than seven debris flows in the vicinity of Mud and Squaw Valley Creeks since about 1880; and many debris flows on Whitney and Bolam Creeks in the last several hundred years. Although details of the den-

drochronological analysis are not given, Miller (1980) suggests that botanical evidence of debris flows is common along many of the mountain's streams.

Other researchers on Mount Shasta have employed tree-ring methods incidentally to confirm an age of a recent deposit for soil chronosequences (Jenny 1980). No systematic dendrochronological effort has been conducted around the mountain except along Mud Creek. Even on Mud Creek, except for fire scars (Sollins and others, 1983), the bulk of the dates came from tree-age dating which is the least accurate type of botanical evidence. All of the previous studies give little or no details of their dendrochronologic methodology.

SITE DESCRIPTION

HYDROGEOMORPHOLOGY

Mount Shasta is a massive stratovolcano located at the southern end of the Cascade Range in northern California. Four volcanic centers have produced lava flows, pyroclastic flows, and domes, since Pleistocene time (Christiansen 1982). Both hot and cold debris flows have occurred relatively frequently on most major streams draining the mountain (Miller, 1980; Hupp, 1984). Basins which head at alpine glaciers have had the largest and most frequent debris-flow activity (Hupp, 1984); these include Whitney, Bolam, Mud, Ash, Cold, Gravel, and Inconstance Creeks (fig. 3).

Mount Shasta is surrounded by broad fans which begin relatively short distances away from the peaks. Deep stream valleys, which continue for long distances away from most Cascade Volcanoes (Crandell and others, 1979), are restricted on Mount Shasta presumably because of pronounced fan development. A result of fan development is the rapid spreading of debris flows on fans at relatively short distances away from the mountain. On other volcanoes in the Cascade Range, with deep radiating stream valleys, debris flows tend to travel considerably farther (Crandell and others, 1979). No streams directly draining Mount Shasta are gaged. Thus, detailed gaging station records are unavailable. Peak flows generally occur in the warm months as a result of snowmelt or glacial runoff. The glacial meltwater streams have little or no discharge during winter months. The greatest amounts of discharge and fluctuation in discharge occur in mid-summer. Aside from glacial floods (jokulhlaup), the midsummer diurnal fluctuation in streamflow accounts for a large part of discharge variations; the maximum daily discharge is about four times that of the minimum discharge (Meier, 1964). The slope of the daily streamflow hydrograph is consistent from day to day, season to season, and glacier to glacier (Meier,

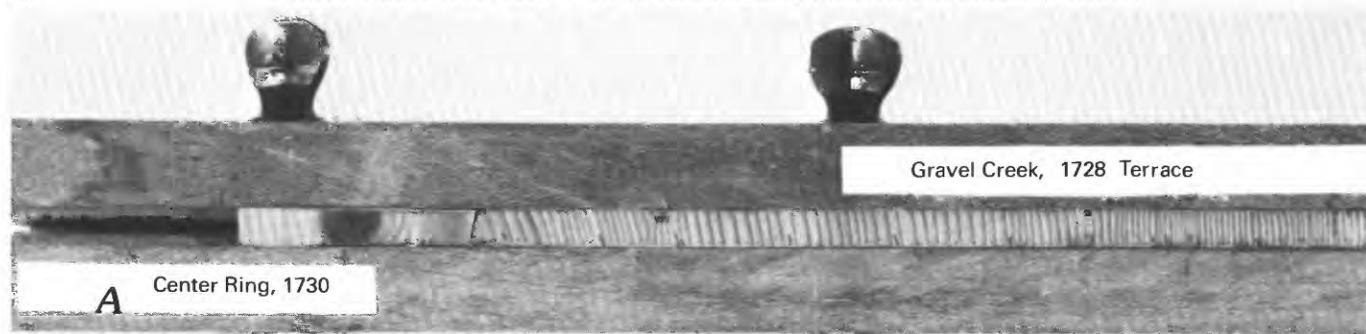


FIGURE 2.—Examples of botanical specimens in dendrogeomorphic study. *A*, increment core of tree indicating minimum age of terrace on Gravel Creek; *B*, cross section of red fir (cohort) on debris lobe along Gravel Creek; *C*, wedge through scar in tree near Whitney Creek; *D*, eccentric growth after the 1962 Ash Creek debris flow; *E*, scarring and eccentric growth from tree near Whitney Creek; *F*, scar cross section from tree affected by the historic 1924 debris flow on Mud Creek.

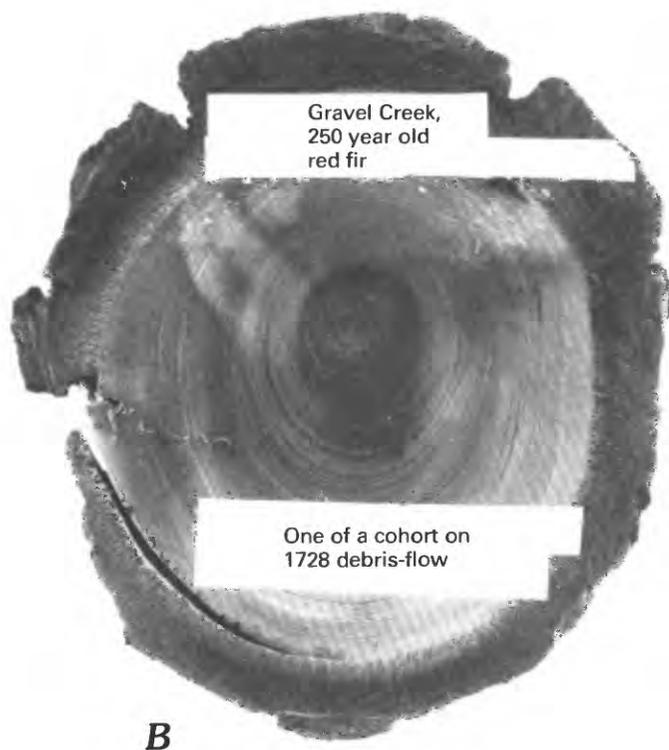


FIGURE 2.—Continued.

1964). There is no direct relation between precipitation and runoff except during late summer (Meier and Tangborn, 1961). However, the correlation between temperature and runoff can be significant if temperature measurements are made a number of days prior to the discharge measurement (Meier, 1964).

Glacier-streamflow records indicate periodic high discharges of water are usually associated with temporarily dammed meltwater under the glacier or near an unstable glacier tongue (Meier, 1964). Some outburst floods are minor and recognizable only on streamflow

records, others are large enough to destroy roads and bridges, the largest can be truly catastrophic (Meier, 1964). Outburst floods can occur at periodic intervals with no direct relation to meteorologic conditions, while others appear to be directly related to unusually warm temperatures or volcanic activity (Meier, 1964; Janda and others, 1981).

Sudden outbursts of water can rapidly accumulate (bulk) large amounts of sediment from bed, banks, and valley wall failures and ultimately form a debris flow. This hydrogeomorphic scenario may be the principal cause of debris flows on Mount Shasta. The most recent debris flow on Mount Shasta occurred on July 6, 1985, along Whitney Creek; fresh calving at the lowermost glacial tongue of Whitney Glacier was observed and is thought to have created an outburst flood and the subsequent debris flow (W.R. Osterkamp, oral commun., 1985).

Some generally related observations can be made that are apparent along all studied streams: (1) Small debris flows occur frequently and usually do not travel as far downstream as medium to large flows; (2) large debris flows occur less frequently than small flows and usually travel farther downstream; (3) debris flows tend to degrade (bulk) high on the slope and aggrade (debulk) low on the slope, and large debris flows may degrade in areas where subsequent small flows aggrade, producing overlapping strata in the channel incision; (4) subsequent debris flows may remove dendrogeomorphic evidence of previous flows; (5) debris-flow terrace deposits are usually lobate in plan morphometry and discrete in distribution, a feature more pronounced in upstream reaches; (6) channel gradient appears to exert substantial control on the depositional characteristics of debris flows; and (7) high-cut banks have stratigraphic evidence of many large prehistoric flows

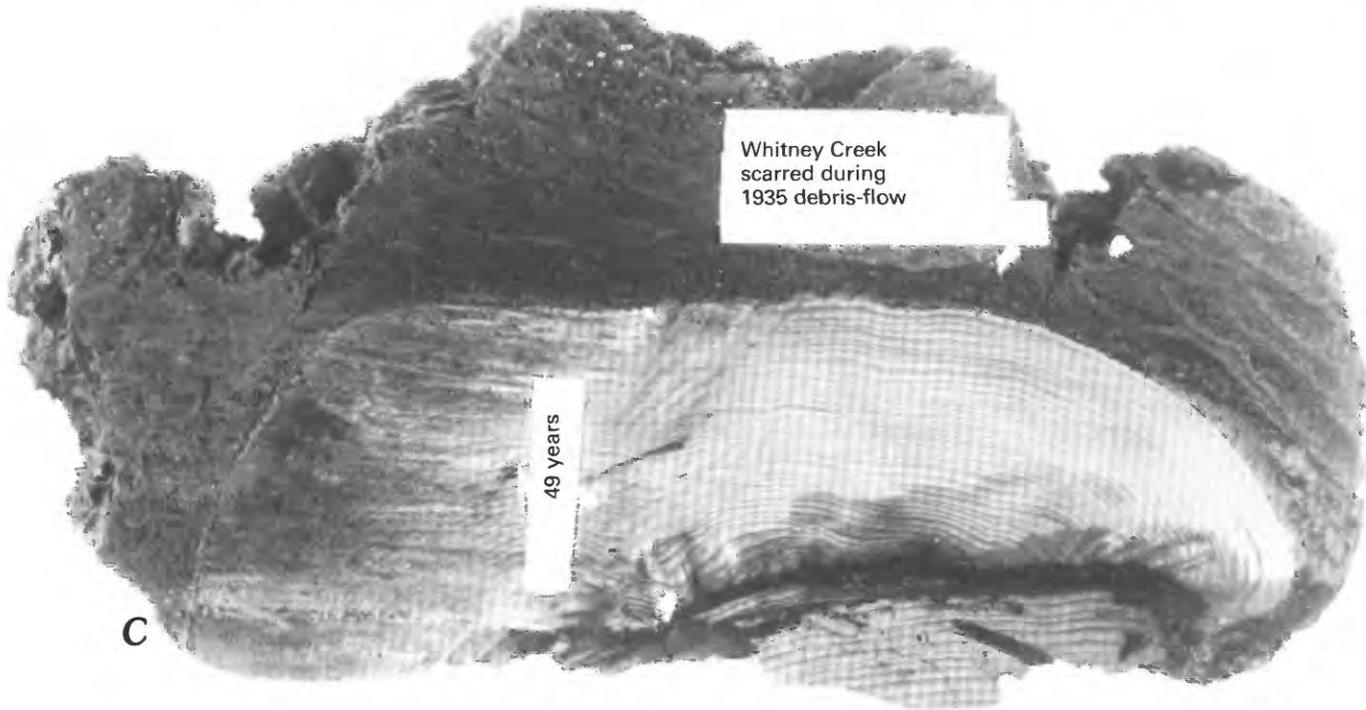


FIGURE 2.—Continued.

The first two observations are characteristics shared with water floods; and, except that both floods and debris flows tend to flow in stream channels, the similarities between the two are limited. The viscous nature of debris flows (Pierson, 1985) permits the development of geomorphic features precluded in fluvial activity—for example, perched stream channels, super elevated levee deposits, relatively high-relief lobate debris splays indicative of flow stagnation, and overlapping surge deposits formed during the same event. The valley sections of upper reaches are deeply incised into pyroclastic slopes which probably served as a source for debris through landsliding. Valley bottoms of these upper reaches are usually dominated by frequent small debris-flow lobes and terraces or are highly degraded from a recent large event. The valley sections in lower reaches have much less local relief and are dominated by large, infrequent debris-flow deposits, commonly forming part of a broad fan. Evidence of small debris flows in the lower reaches appears relatively minor, often wholly in-channel benches.

A consequence of periodic large debris flows is the development of large debris fans (Pierson, 1980a) which characterize the lower Mount Shasta slopes in the vicinity of major streams. The debris fans begin about midway on the mountain depending on gradient and length of time of debris-flow activity. Likewise length of deep incisement appears to be related to the length of debris flow history.

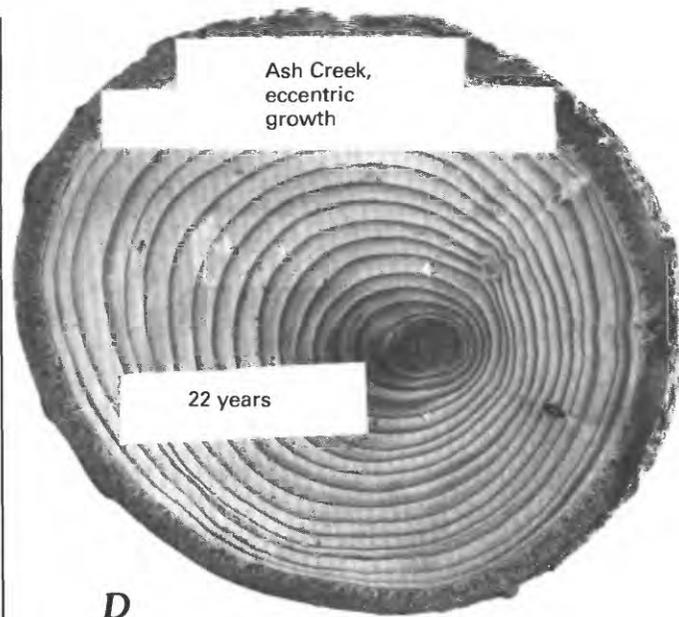


FIGURE 2.—Continued.

The reader is directed to other chapters in this series (Blodgett and others, in press; Osterkamp and others, 1986) for detailed accounts of the physical environment of Mount Shasta streams and adjacent areas.

VEGETATION

The forests of the Mount Shasta area fall into two major types: Coniferous Forest and Desert Woodland



FIGURE 2.—Continued.

(Munz, 1959). The Desert Woodland is restricted to the lower west-facing slopes in the area of the Whitney-Bolam alluvial fan. Munz (1959) describes the Northern Juniper subdivision of the Desert Woodland as an open forest of trees 3 to 18 m tall on brush covered slopes. The principal species are western juniper (*Juniperus occidentalis*), Jeffrey pine (*Pinus jeffreyi*), and basin sagebrush (*Artemisia tridentata*).

Most of the mountain (75–80 percent of area) is of the Coniferous Forest Type, within this type five subdivisions grow on Mount Shasta: Douglas Fir Forest, Yellow Pine Forest, Red Fir Forest, Lodgepole Forest, and Subalpine Forest (Munz, 1959). The boundaries of these subdivisions are generally determined by elevation and grade from one forest to another. The lowermost forest, Douglas Fir Forest, occurs up to 1375 m in elevation on the northern, eastern, and southern slopes. Common species include Douglas fir (*Pseudotsuga menziesii*), Tanbark-oak (*Lithocarpus densiflora*), and sugar pine (*Pinus lambertiana*). Trees in

this forest grow up to 60 m high and may form dense, nearly pure stands of Douglas fir. The Yellow Pine Forest is a common, diverse forest growing at a land elevation of from 1,100 to 1,675 m. Trees range in size from 23 to 60 m tall in extensive continuous forests; common species include Ponderosa pine (*Pinus ponderosa*), sugar pine, incense cedar (*Libocedrus decurrens*), white fir (*Abies concolor*), Douglas fir, and California black oak (*Quercus kelloggii*). The Red Fir Forest grows at a land elevation of from 1,675 and 2,300 m. Trees form dense stands and range from 30 to 50 m tall; common species include: California red fir (*Abies magnifica*), sugar pine, western white pine (*Pinus monticola*), white fir, Jeffrey pine, and lodgepole pine (*Pinus contorta*). The Douglas Fir, Yellow Pine, and Red Fir Forests form the bulk of the forest within the study area on the northern, eastern, and southern three-quarters of the mountain. The Lodgepole Forest occurs at elevations above 2,000 m and at slightly lower elevations on the northern quarter of the mountain in the

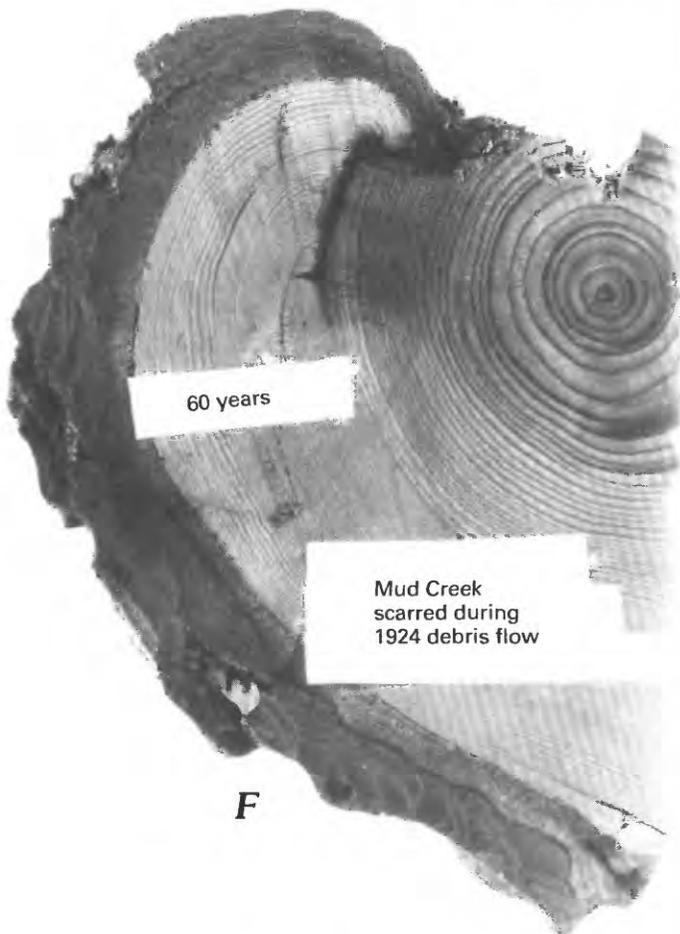


FIGURE 2.—Continued.

vicinity of Gravel and Inconstance Creeks. Trees grow in open stands 15 to 21 m tall, composed largely of lodgepole pine. The Subalpine Forest occurs at tree line and grows downslope for a few hundred meters at land elevations from 2600 to 2900 m. No study sites were located at these elevations, although some of the species of this forest were occasionally found at the uppermost study sites. Principal species of this forest include: Whitebark pine (*Pinus albicaulis*), limber pine (*Pinus flexilis*), lodgepole pine, and alpine willow (*Salix petrophila*). Nomenclature follows that of Little (1979).

Fires and lumbering have created extensive patches of open areas in most of these forests. Dense thickets of manzanita (*Artostaphylos patula* and other spp.), mountain misery (*Chamaebatia foliolosa*), California lilac (*Ceanothus* spp.), mountain-mahogany (*Cercocarpus betuloides*), madrone (*Arbutus menziesii*), and saplings of forest-tree species occur in disturbed areas. Cooke (1940) provides a description of the flora of Mount Shasta within the framework of a now dated lifeform classification.

The tree species that occur on or near debris flows at Mount Shasta include: California red fir, California black oak, Canyon live oak, Douglas fir, incense cedar, lodgepole pine, Ponderosa pine, sugar pine, western juniper, western white pine, and white fir. All of the above species were used in the dendrochronological analysis. Willows (*Salix* spp.) are common along streambanks but were rarely used in the dendrochronological analysis. Several species of shrubs grow on older debris-flow surfaces (cf. Dickson and Crocker, 1953 and 1954; and Sollins and others, 1983).

The northwest-facing quarter of Mount Shasta is noticeably drier than other parts of the mountain owing to a rain-shadow effect. Vegetation on this side of the mountain reflects the more xeric conditions by being relatively sparse, with a greater dominance of Ponderosa pine and xeric shrubs. Western juniper (largely absent on other parts of the mountain) occurs on the lower fan slopes here.

Relatively recent debris-flow deposits typically support noticeably younger forests; very recent deposits may be largely devoid of woody vegetation or with sparse seedlings or saplings. Forests growing on deposits less than 400 years old are generally the same age except for scattered older trees not killed by debris-flow passage of those affected by subsequent events. However, in many places, fire and lumbering (over the last century) have complicated the picture.

METHODS

SAMPLING DESIGN

Ten streams draining Mount Shasta were investigated for dendrogeomorphic evidence of debris flows. These streams are (counterclockwise from Whitney-Bolam Creek, fig. 3) Whitney and Bolam Creeks, Diller Canyon, Cascade Gulch, Panther Creek, Mud Creek, Cold Creek, Ash Creek, Gravel Creek, and Inconstance Creek. Sites for intensive study on most of the streams were selected to facilitate determinations of down-valley extent of any particular debris flow. Only one site each was investigated on Inconstance Creek, Panther Creek, and Cascade Gulch (fig. 2). These streams were judged to pose little threat to human activity after initial reconnaissance because of relative debris-flow inactivity or rapid dispersion of debris flows high on the mountain.

Most intensive study sites are located along reaches relatively easily accessed by roads. However, during the course of 4 years of study, on streams with more than one study site, nearly all reaches between the uppermost and lowermost study sites have been investigated. No sites were above tree line or more than 22 km from Mount Shasta peak. Seven sites were in-

DEBRIS-FLOW ACTIVITY AND ASSOCIATED HAZARDS, MT. SHASTA, CALIF.

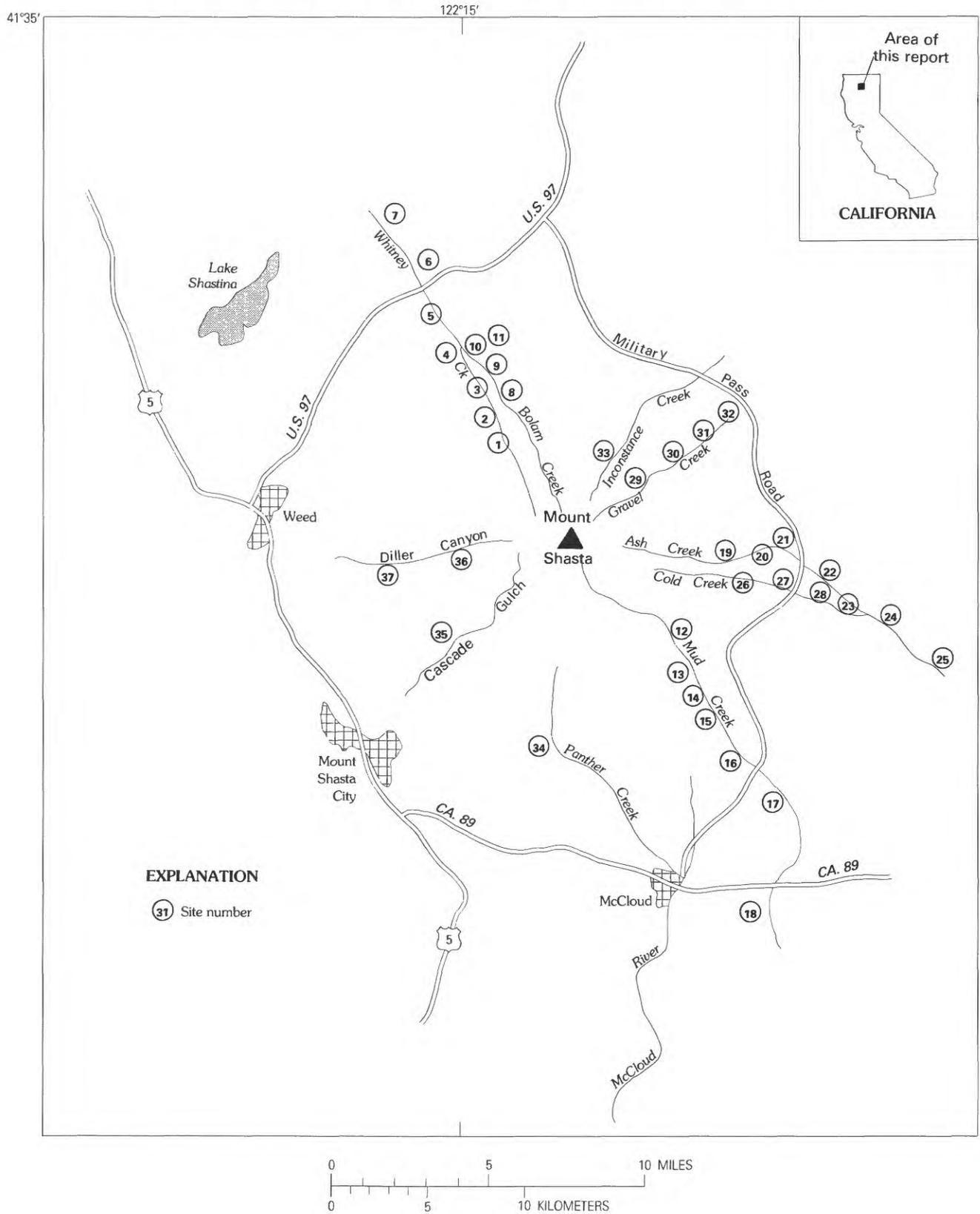


FIGURE 3.—Study area in northern California. Study sites are numbered 1 through 37, beginning with Whitney Creek.

vestigated on Whitney Creek, four sites on Bolam Creek, two sites on Diller Canyon, seven sites on Mud Creek, three sites on Cold Creek, seven sites on Ash Creek, four sites on Gravel Creek, and one site each on Inconstance Creek, Cascade Gulch, and Panther Creek (fig. 3). Generally, each site consists of a reach 1 to 2 km long and as wide as the alluvial valley bottom which is rarely more than 0.5 km wide.

FIELD AND LABORATORY ROUTINE

Field routine at each site consisted of (1) determination and extent of debris-flow deposition, scour, or both, through ground traverses, topographic maps, and aerial photography; (2) removal of increment cores, cross sections, and wedges from trees growing on or near the debris-flow surfaces using increment borers and handsaws; and (3) field analysis of wood samples for age and ring pattern. Trees sampled for age of surface were cored as near to the base of the tree as possible. Young trees of certain species can be aged by counting branch whorls, thus avoiding coring or cross sectioning. Trees sampled to obtain age of a scar or other deformation were cross sectioned or had a wedge removed at the point of scarring or deformation. Old or deeply imbedded scars can be aged by coring on either side of the scar, although the possibility of missing some of the rings formed since scarring is distinctly increased. The quality of information gained from scarred trees usually warrants a cross section or wedge.

Trees selected for dendrochronological analysis were either growing on debris-flow deposits with their root collars indicating germination after surface deposition or bearing obvious deformations indicative of debris-flow damage or both. Detailed field notes were taken that described the character and location of the debris-flow deposit, the location and type of botanical evidence for each tree sampled, and age of deposit (when known). Data, by site from each stream, were tabulated, noting amount and type of evidence for each possible debris-flow date. The location, extent, and age of each investigated debris flow were recorded and mapped where possible. A debris-flow stratigraphy is revealed in exposed streambanks on many of the studied streams. Thicknesses of some recent, dated debris flows were estimated from the amount of depositions above root zones exposed along cut banks.

Most cores and cross sections were returned to the laboratory in Reston, Va., for microscopic examination and cross dating. Cores are typically placed in holders and sanded with increasingly fine grit. Cross sections and cores are sanded to facilitate ring boundary determinations under microscopic observation. A few cores are then standardized (Fritts, 1976) and plotted. These

were measured for serial ring width. Ring width values data were then used to pinpoint suppression and release sequences not associated with debris-flow activity to rule out climatic variation. Probable dates of debris flows from field and laboratory analysis were tabulated. Depending on the type and amount of botanical evidence for a particular date, it is either included in the debris-flow history or considered questionable and not retained for later magnitude and frequency analysis. Generally, a date was kept if at least five specimens substantiated the date, or an obvious corrosion scar could be found that coincided with other types of botanical evidence.

ANALYSES OF MAGNITUDE AND FREQUENCY OF DEBRIS FLOWS

Frequency of past debris flows is relatively easy to determine from tree-ring data over the past 200 years or so. However, owing to removal of geomorphic and botanical evidence by subsequent debris flows, increasingly older events become more difficult to date. Small debris-flow deposits are particularly susceptible to removal by medium to large debris flows. Thus, the possibility of missing an old small event exists. Fortunately, fan deposits, owing to shifting channel positions, can be preserved for old medium-sized events. Large events are usually quite easy to detect with minimal field experience. Only the lifespan of the regional tree flora, fire, and lumbering limit dating of large events. Nevertheless, the minimum age for any surface with living woody plants can be determined.

Resolution of magnitude of a debris flow, like frequency, becomes more difficult with increasing age of the event. The bulk of botanical evidence for a particular event generally cannot be used as an estimation of magnitude. The elevation, distance downslope, and thickness of debris-flow deposits are, however, reasonable estimators of relative magnitude. The degree to which a flow was contained in the fan channel is also a reasonable estimate of magnitude.

The debris flows were separated into three magnitude categories—small, medium, and large. This separation is based primarily on distance along a stream for which there is evidence of passage or deposition of a debris flow and the degree to which it was confined to the channel incisement. All debris flows considered in this analysis traveled at least 2 km and were documented by tree-ring analysis. Small debris flows are those that were largely in-channel events. Medium debris flows are those that have limited downvalley extent but have some evidence of out-of-bank flow. Large debris flows are those that are traceable for several kilometers and usually have considerable over-bank scour or deposition.

This separation allows for the computation of frequency for the different magnitudes by stream. Frequency, by magnitude, was determined for each stream by adding the number of tree-ring dates for debris flows for each magnitude and dividing by the number of years since the oldest dated event.

AGE AND SPATIAL DISTRIBUTION OF DEBRIS FLOWS

About 1,100 trees provide evidence for at least 52 debris flows in 9 basins draining Mount Shasta (table 1). Table 1 summarizes the dates of debris-flow events and their magnitude in each of the study basins. Each stream is described and discussed similarly; the general vegetation and geomorphology, dates of debris-flow occurrence, frequency and downvalley distribution of debris flows, and magnitude and frequency of debris flows are presented. A site by site description of debris-flow activity in the Whitney, Bolam, Mud, and Ash Creek basins is detailed in the Appendix.

WHITNEY CREEK

Seven sites of intensive dendrogeomorphic study (fig. 3) in order of descending elevation are as follows: site 1, just above Whitney Falls; site 2, about 1 km above the gorge; site 3, in the gorge; site 4, fan near Bolam and confluence with Bolam Creek; site 5, above Southern Pacific Railroad; site 6, just below US 97; site 7, above Juniper Flat. Dated events range from about 1670 to 1985. A debris-flow stratigraphy in the gorge shows evidence of debris flows back as far as early Holocene times (Osterkamp and others, 1986). As will be shown to be true for most streams, discrete evidence for all debris flows (small, medium, and large) increases in the upstream direction up to the deep canyons typically found near tree line and above. The lower reaches of the fans tend generally to be dominated by less discrete, fine-grained deposits. Evidence of small debris flows in lower reaches, commonly consists of totally in-channel lag deposits barely distinguishable from fluvial deposits. Incised reaches tend to be narrow, with most medium to large debris flows being largely degradational. Reaches with shallow channel beds usually have many discrete overlapping debris-flow deposits. Incised reaches usually coincide with steep channel gradients, whereas shallow reaches coincide with more gentle gradients.

Woody plants readily establish on debris-flow deposits forming initially dense cohorts on the fine-grained parts of the surface. These cohorts usually begin growing 1 to 3 years after the debris flow. Trees

growing at the edge of and prior to a debris flow are often tilted and scarred as a result of the debris-flow passage. Where debris-flow velocities were apparently low the trees are relatively undamaged except for depositions at their bases. In general, depositional areas tend to have more botanical and geomorphic evidence of debris flow than degradational areas such as gorges. However, at downstream study sites, where deposits are thin and fine-grained, discrete geomorphic forms and botanical evidence is hard to find and difficult to interpret. This is partly a result of relatively low debris-flow velocities and infrequent occurrences and, particular to Whitney Creek, the dominance of western juniper. This species has obscure ring boundaries, a tendency for false and missing rings, and an apparent insensitivity to debris-flow deposition. Residents of the area, however, indicate that small, in-channel, debris flows are frequent under the U.S. 97 bridge (fig. 3).

THE 1985 DEBRIS FLOW

On the evening of July 6, 1985, a medium to large debris flow occurred along Whitney Creek. The flow was largely confined to the channel from near the toe of Whitney Glacier to just below the U.S. 97 bridge, from there the flow anastomosed and spread across the Whitney-Bolam fan down to Juniper Flat. This flow left usually thin bouldery levees along its course that indicated a depth of flow ranging between 5 to 10 m from the Falls to U.S. 97. Woody vegetation, mostly shrubs and pines, growing near the peak flow height was heavily scarred; virtually all vegetation growing a meter or more below the peak flow line was removed by the flow from the Falls to U.S. 97. Apparently slower velocities spared woody vegetation below U.S. 97 where the flow deposited around stems with little immediate damage evident, except near the main channel banks. Heights of scars on trees and levee placement indicate that this 1985 event was smaller than the 1935 event, although larger than any flow since 1935; botanical evidence of the small flows in 1952, 1960, 1974, and 1977 was removed between the Falls and U.S. 97.

EARLIER DEBRIS FLOWS

At least 14 debris flows have left dendrochronologic evidence of their passage along Whitney Creek. These debris flows are designated alphabetically beginning with the oldest. Age and distribution within the basin of each event within Whitney Creek basin are shown in figure 4.

Two categories of accuracy are inherent in this type of tree-ring dating: (1) dates based solely on cohorts of trees growing on deposits, and (2) more accurate dates

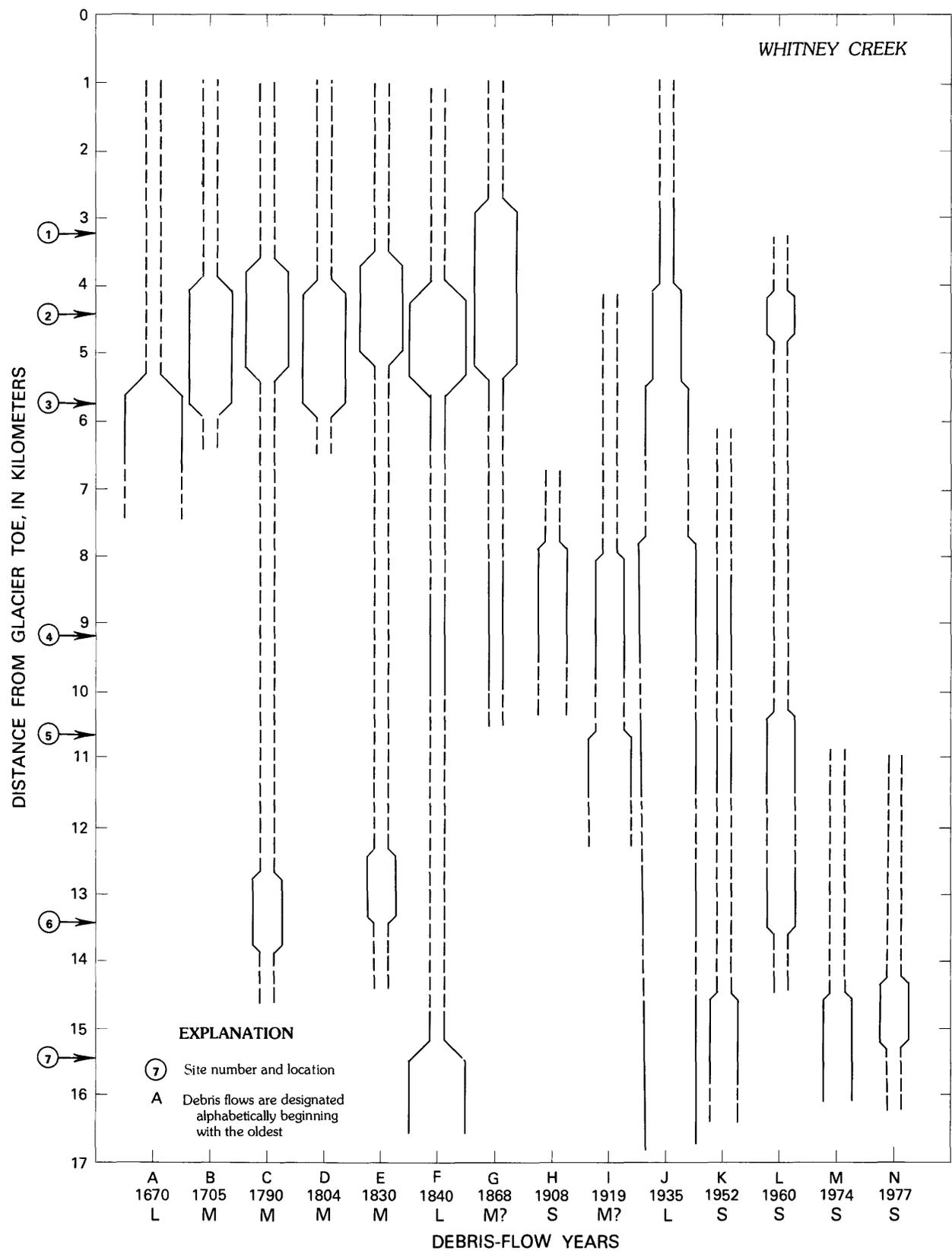


FIGURE 4.—Age and downvalley distribution of debris flows on Whitney Creek. Dashed lines indicate probable path of debris flow, solid lines outline reaches with dendrogeomorphic evidence of flow passage or deposition. Relative magnitude is indicated by width between lines. L, M, and S are large, medium and small debris flows, respectively.

based, in addition to tree age, on scars, eccentric ring patterns, and suppression and release sequences. The events including and prior to 1804 were dated primarily by ages of cohorts of trees growing on discrete deposits. Thus, these dates are approximate and include a 5-year maximum time for establishment of trees on deposits. The replicated age dates and growth form of trees strongly suggest, however, that the date indicated is within 10 years of the actual debris flow. Date of debris flows since 1804 may have tree-age evidence but is further substantiated by scars or eccentric growth patterns. These dates (more recent than 1804) are accurate to within 2 years of the debris flow, and many of the dates are accurate to the season and year of occurrence.

Contrary to other streams on the mountain affected by debris flows, most old deposits were found relatively high in elevation and recent deposits low in elevation (fig. 5). The alluvial fan of the Whitney and Bolam drainage (fig. 3) is more deeply incised at its apex and spreads farther downslope than other alluvial fans of the mountain. Most evidence of debris flows since 1868 in the upper reaches is degradational, whereas in the lower reaches these recent flows, even when small, aggrade quite low on the fan.

The valley cross sections on Whitney Creek (fig. 5) show that large debris-flow deposits are generally found high in the section and small debris-flow deposits are found low in the section. This is true for all studied streams on the mountain.

Position in valley cross sections and downvalley distribution suggest that all three magnitudes of debris flows (large, medium, and small) have occurred along Whitney Creek since 1670. Four large debris flows occurred in 1670, 1840, 1935 and 1985. Medium debris flows occurred in 1705, 1790, 1804, 1830, 1868, and 1919. The debris flows of 1908, 1952, 1960, 1974, and 1977 were apparently small. The absence of evidence of small debris flows prior to 1908 is probably the result of scour or deposition by subsequent larger debris flows.

The magnitude and frequency relation for Whitney Creek is depicted in figure 6. The frequency for all datable debris flows on Whitney Creek for the period 1670 to 1985 is 4.8 per century. Owing to removal of evidence of small debris flows their frequency is computed from the earliest date of a small debris flow rather than for the entire 3.1-century period. Medium debris flows, as defined, have some overbank deposition. Thus, the likelihood of their preservation is increased and their frequency is computed over the 3.1-century period. Likewise, frequency of large debris flows is computed over the 3.1-century period.

BOLAM CREEK

The four sites of intensive dendrogeomorphic study (fig. 3), in order of descending elevation are as follows: site 8, upper Bolam near trail switchback; site 9, below ford; site 10, above confluence with Whitney Creek; site 11, on Bolam fan. Evidence of debris flows is widespread along all reaches. Dated events range from about 1670 to 1974. No gorge reaches, as described for Whitney Creek, were investigated although deeply incised areas occur upstream of the uppermost site. Discrete debris-flow lobes and levees characterize the upper two sites, and they become only slightly less distinct at the confluence with Whitney Creek. Apparently, several debris flows left the present Bolam channel and flowed north over the fan above the confluence. This may explain a lack of evidence for some debris flows below the confluence that are present upstream. The documented 1935 event, which occurred on Whitney Creek, also occurred on Bolam Creek. However, the channel was considerably less scoured than Whitney Creek as a result of the 1935 event. Little deposition occurred along Bolam Creek in 1935 as is true on the upper reaches of Whitney Creek. The vegetational characteristics of Bolam Creek are essentially the same as that described for upper Whitney Creek. The valley bottoms tend to be broader than those for comparable reaches on Whitney Creek, at least up to site 8 (fig. 3). Locally extensive recent deposits have spread over these bottoms and now support cohorts of Ponderosa pine. Generally, the channel bed of Bolam Creek is shallow relative to top banks or debris-flow levees. Thus, even relatively small debris flows on Bolam Creek may have some overbank deposition.

No less than 10 debris flows have left dendrochronologic evidence of their passage along Bolam Creek. These debris flows are designated alphabetically beginning with the oldest. Age and distribution within the basin of event on Bolam Creek are shown in figure 7.

In addition to tree ages, most dates are confirmed by ring patterns of suppression and release or eccentric growth. The accuracy of the dates prior to 1897 is probably within 5 years of the event. Debris flows subsequent to 1897 are further documented by scars from corrosion and are accurate to within 2 years of the event and in most instances to season of occurrence.

The debris flow of 1670 (A, fig. 7) occurred only at site 9 and was dated by a cohort of three Ponderosa pines. It is tentative at best that this event is related to the 1670 debris-flow terrace in Whitney Gorge. The events of 1730, 1785, 1800, and 1845 (B through E, fig. 7) left discrete debris-flow lobes or terraces along the present Bolam Creek channel. The magnitude and frequency relation for Bolam Creek is shown in figure 8.

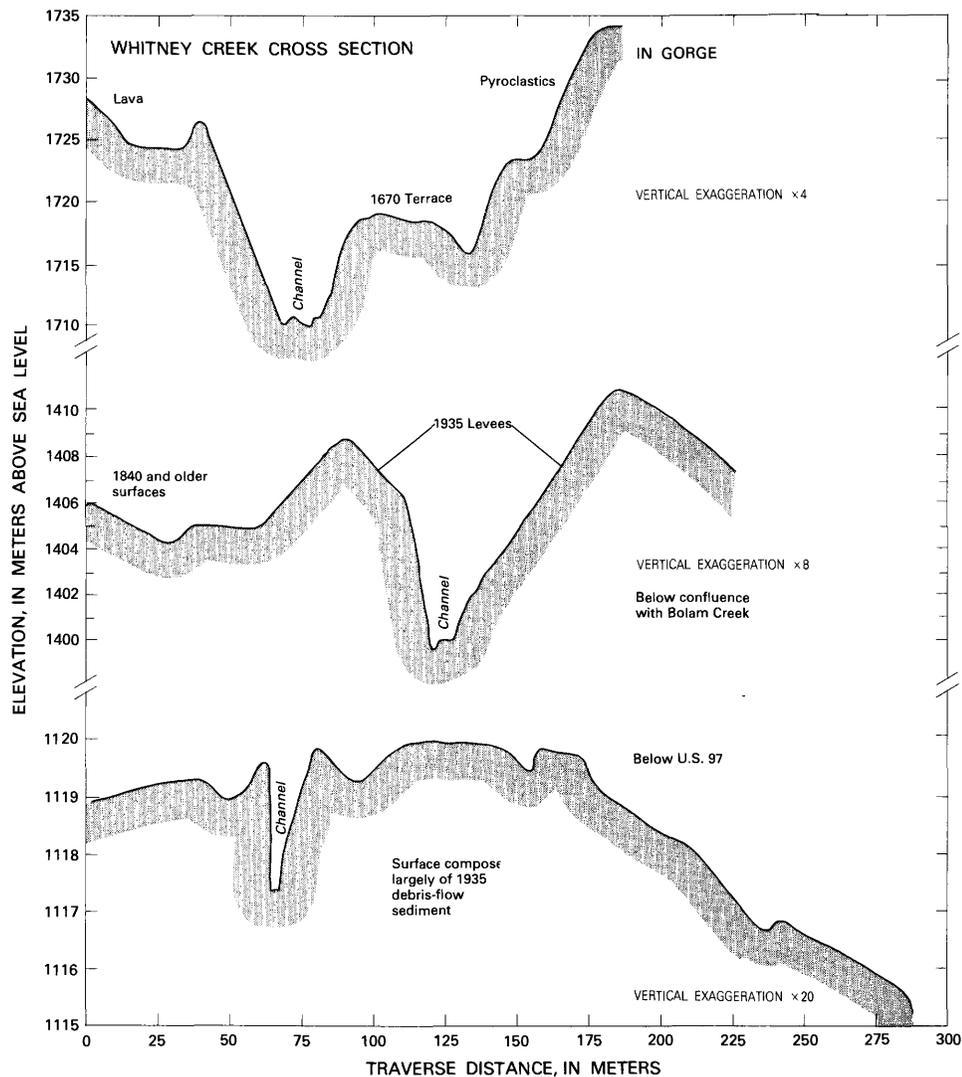


FIGURE 5.—Cross sections of Whitney Creek channel and depositions areas. Note fan development in the lowermost site. Vertical axis is variably exaggerated.

MUD CREEK

Mud Creek has received more attention historically than any other stream on Mount Shasta. The documented debris flows of 1924, 1925, 1926, and 1931 associated with the breakup of the Konwakiton Glacier, prompted scientific research which has persisted to the present (Beardsley and Cannon, 1930; Dickson and Crocker, 1953; 1954; Glauser, 1967; Hill and Egenhoff, 1976; Sollins and others, 1983; Hupp, 1984). Most previous work on Mud Creek deals with soil chronoserics. No systematic effort to reconstruct debris-flow history through tree-ring analysis has been conducted except for portions of Hupp (1984) and the present study. The Mud Creek basin represents the only basin which poses a serious threat to human life and interests because Mud Creek flows near the town of McCloud.

Mud Creek flows from the remnants of Konwakiton Glacier to the McCloud River (fig. 3). The stream rarely reaches the McCloud River, becoming influent on the lower reaches of the fan. The major incisement of Mud Creek extends farther downslope than any other stream on the mountain, which may explain the great

distances debris flows can travel along this stream. The length and depth of this incisement suggests a long history of debris-flow activity (Osterkamp and others, 1986). Mud Creek is probably the most mature stream on Mount Shasta and may be more typical of streams on other Cascade volcanoes (Crandall and others, 1979) than other streams on Mount Shasta.

Mud Creek flows on the humid southeastern face of Mount Shasta. Humid conditions favor a relatively diverse tree flora. The principal species along Mud Creek include Ponderosa pine, sugar pine, knobcone pine, white fir, Douglas fir, red fir, incense cedar, and, locally, California black oak. Douglas and white fir are common throughout the studied reaches and are associated with red fir in higher reaches and Ponderosa pine on lower reaches.

The deposits from debris flows become increasingly finer downslope without an abrupt shift in depositional environments that occurs on Ash Creek. Stream gradient and depth of channel incisement into terraces decrease gradually toward the McCloud River. Small and medium debris flows are recently less frequent than on

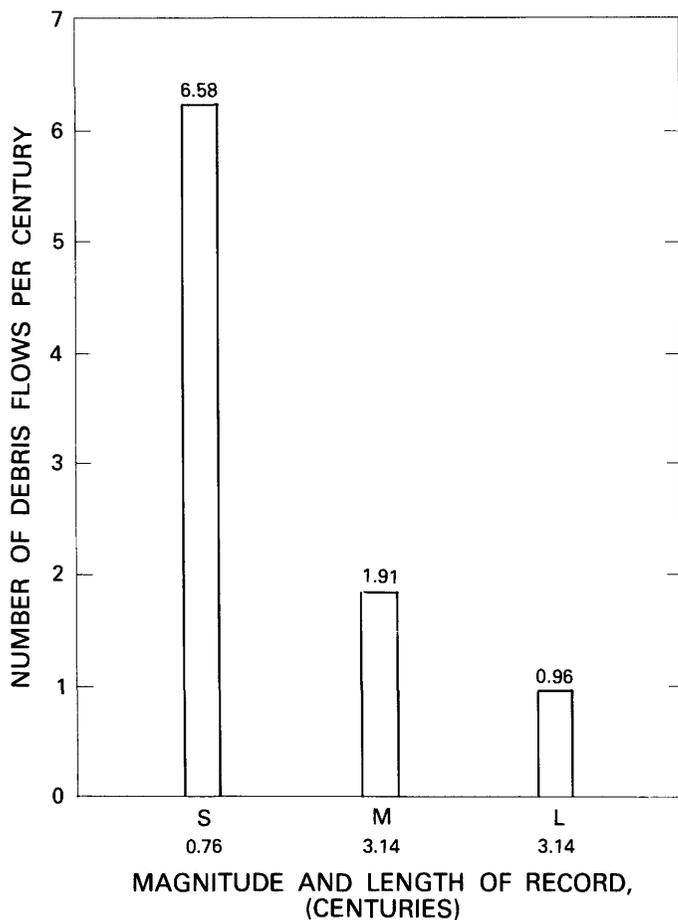


FIGURE 6.—Debris-flow frequency per century by magnitude class on Whitney Creek.

other major streams. The near channel terracing as described for other streams is apparent, although dominant features particularly below the major incisement were developed by debris flows between 1924 and 1931.

The seven sites for intensive dendrogeomorphic study (sites 12 through 18, fig. 3) range in elevation from 1,850 m to about 1000 m. Sites are numbered in order of descending elevation and are from 7.5 km to 22 km from Konwakiton Glacier. The upper four sites down to Mud Creek Dam (fig. 3) are located within the deep Mud Creek incisement; the lower three sites are on a broad fan.

A complex of terraces at site 13 (fig. 3) has well preserved dendrogeomorphic evidence of eight debris flows. The stream is entrenched deeply on the right bank and exposes a complex of terraces to a height of 10 m above the bed (fig. 9). The degradation of the channel probably occurred during the historic 1924–31 events; the lowest terrace is older than the historic events. Thus, the flows of 1924–31 were probably still bulking through this reach. Site 13 is geomorphically

similar to the Whitney Creek gorge reach. The complex of terraces is heavily forested, which allows for fairly accurate dating of four debris flows. The terrace complex contains debris-flow surfaces dated from 1630, 1740, 1881, and 1910 (fig. 9). Levees have been deposited on parts of this complex in 1840, 1924, 1931, and 1955.

At least 10 debris flows have left dendrogeomorphic evidence of their passages along Mud Creek. These flows are designated alphabetically beginning with the oldest (about 1630). Age and distribution of these events are shown in figure 10. Three (1881, 1924, and 1931) debris flows were of sufficient magnitude to reach the lowest study site on Mud Creek (fig. 10). Each event is historically documented (Hill and Egenhoff, 1976). Several debris flows associated with the breakup of Konwakiton Glacier, occurred during the period 1924 to 1931, but substantial dendrochronological evidence has been recovered only for events in 1924 and 1931. Events in 1881, 1924, and 1931 were largely degrading (bulking) in the upper three sites (fig. 10). The 1740 debris flow (B, fig. 10) may have traveled as far as site 17; Dickson and Crocker (1953) reported a surface in that vicinity of that approximate age. The only small debris flows for which there is dendrogeomorphic evidence on Mud Creek occurred after 1931, and are represented largely by small in-channel terraces.

Debris flows grouped into three magnitude categories with frequency per century are shown in figure 11. Distance downslope and overall downvalley length of deposition are the best estimators of magnitude. The frequency estimated for small debris flows is tentative owing to the short length of record (29 years). Frequency estimation for medium and large debris flows can be made in greater confidence because the dendrogeomorphic record is about 350 years.

In addition to cohort age dates, debris-flow activity since 1800 has been documented also by either scars or anomalous tree-ring sequences, or both. Debris-flow features older than 1840 were dated exclusively by the minimum age of cohorts. Except for the period 1924–31, debris-flow dates are apparently single events. This generalization becomes increasingly tentative with increasing age of a debris flow. Rapid melting of the glacier in conjunction with upstream slope failures appears to generate large debris flows clustered in time.

ASH CREEK

Ash Creek, like Whitney and Mud Creeks, received proportionately more attention than other studied streams owing to its size and frequency of debris-flow activity. Unlike Whitney or Mud Creeks, Ash Creek has not experienced a large debris flow in this century although small and medium debris flows occur fre-

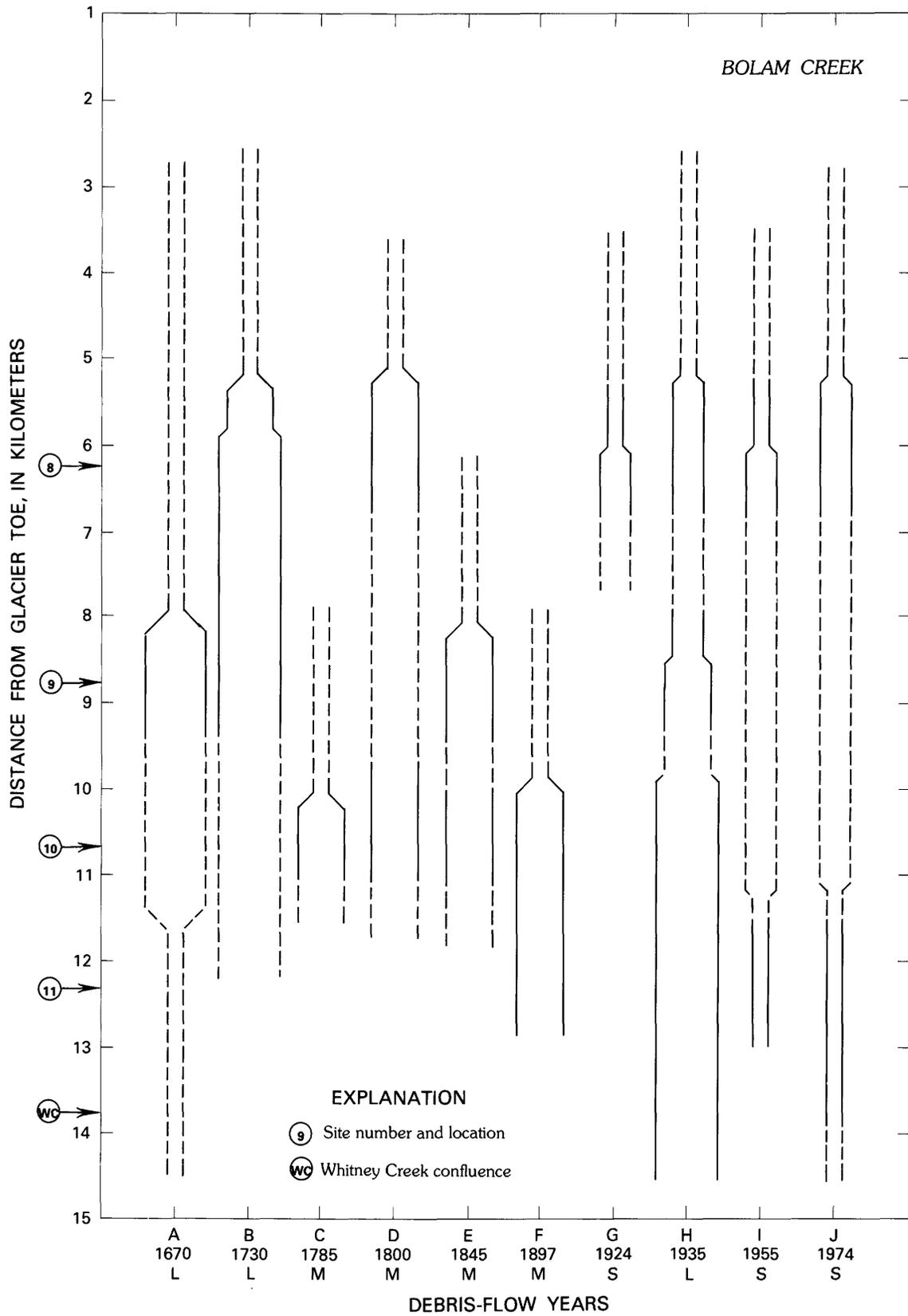


FIGURE 7.—Age and downvalley distribution of debris flows on Bolam Creek. Dashed lines indicate probable path of debris flow, solid lines outline reaches with dendrogeomorphic evidence of flow passage or deposition. Relative magnitude is indicated by width between lines. L, M, and S are large, medium and small debris flows, respectively.

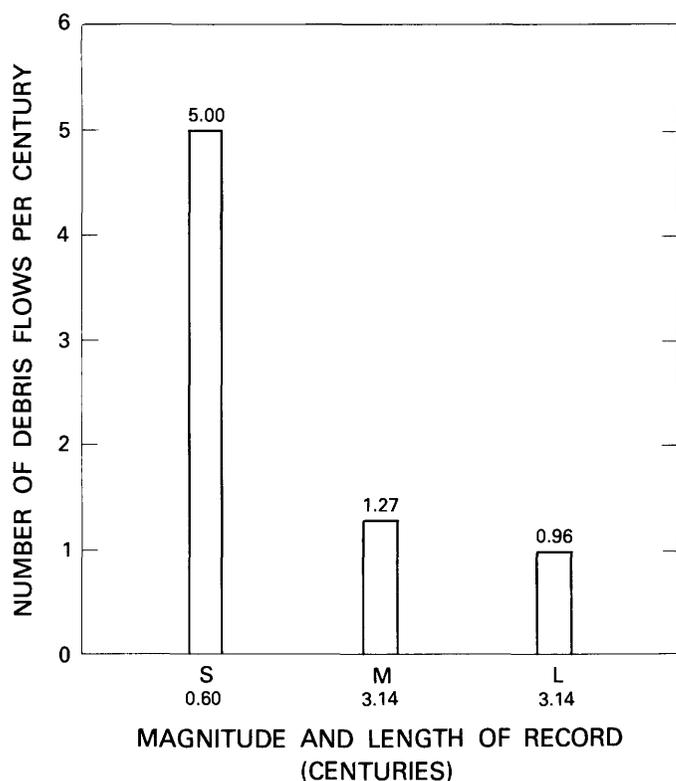


FIGURE 8.—Debris-flow frequency per century by magnitude class on Bolam Creek.

quently. This situation allows detailed investigation of small and medium debris flows which have not had their associated dendrogeomorphic evidence obliterated or reworked. Additionally, this stream shows how these intermediate-sized debris flows tend to fill the channel incisement and spread high on the fan in reaches where large debris flows typically degrade the channel. Data collected from Cold Creek are included in this section because Cold Creek is a tributary to Ash Creek.

Ash Creek flows nearly due east (fig. 3) and shares with Mud Creek the most humid face of Mount Shasta. The stream is fed by meltwater from Wintun Glacier and streamflow is usually constant during the summer at least down to the lowest study site. Streamflow occasionally reaches the McCloud River although much of the discharge becomes influent on Coonrod Flat (fig. 3).

The study reaches on Ash Creek can be divided into two distinct depositional environments. These environments are separated by the Ash Creek gorge where all fluvial and debris-flow activity is constricted to a narrow passage between hard-rock hillslopes. A broad fan occurs above the gorge and gradually narrows upslope to the major alpine incisement at about 1,830 m in elevation. This fan is characterized by stepped, generally coarse-grained terraces and lobes left by debris

flows. The most recent debris-flow deposits are near the channel; older deposits lie south of the present channel. The left bank in the upper fan reaches is composed locally of pyroclastic material that suggests a general channel shifting to the north.

The second depositional environment is a broad fine-grained fan below the Ash Creek gorge, and, except immediately below the gorge, clasts rarely exceed 10 cm. The channel below the gorge is rarely more than 2 m below the fan surface. The channel above the gorge vertically undulates over the steplike channel deposits and can be incised several meters below the fan surface near the upstream end of a stepped channel deposit.

Woody plants rapidly establish (within 1 to 5 years) on the debris-flow surfaces of Ash Creek. Common tree species are Ponderosa pine, sugar pine, Douglas fir, white fir, incense cedar, and red fir. Cohorts of these species on older deposits facilitate minimum age determination throughout the upper fan. Trees near the present channel show damage from several recent debris flows and permit more accurate dating in addition to cohort ages.

The seven sites for intensive study on Ash Creek range in elevation from about 1,775 m down to about 1,281 m. These sites are numbered in order of decreasing elevation from site 19 to site 25 (fig. 3). The upper five study sites, (19 through 23) are located on the upper fan. Site 24 is located in the Ash Creek gorge reach. The lowest study site (site 25) is located at an old mill site on the lower fan. Most intensive tree-ring work was conducted in and above the gorge owing to the lack of discrete dendrogeomorphic evidence on the lower fan. Most debris flows on the lower fan probably occur as slow-moving sheets of fine-grained sediment slurries. Furthermore, only the largest flows deposit significant amounts of sediment over the lower fan but the large flows occur infrequently. As a result, botanical evidence of debris flows is scarce.

At least eight debris flows or debris-flow episodes have left dendrogeomorphic evidence of their passage along Ash Creek (fig. 12). The debris flows are designated alphabetically beginning with the oldest, the Cold Creek episode (1725 to 1768). Debris flows older than the Cold Creek episode (A, fig. 12) were not detected by dendrochronological analysis. Thus, the Cold Creek episode may have contained the largest debris flow on Ash Creek during the past several centuries. The 1939 and 1962 debris flows (E and G, fig. 12) may have removed in-channel evidence of smaller debris flows, those about the size of the 1977 debris flow (H, fig. 12).

The debris flows were divided into three magnitude categories as described for Whitney Creek. However, owing to relatively shallow channel incisement even at the highest study site, small debris flows may overtop

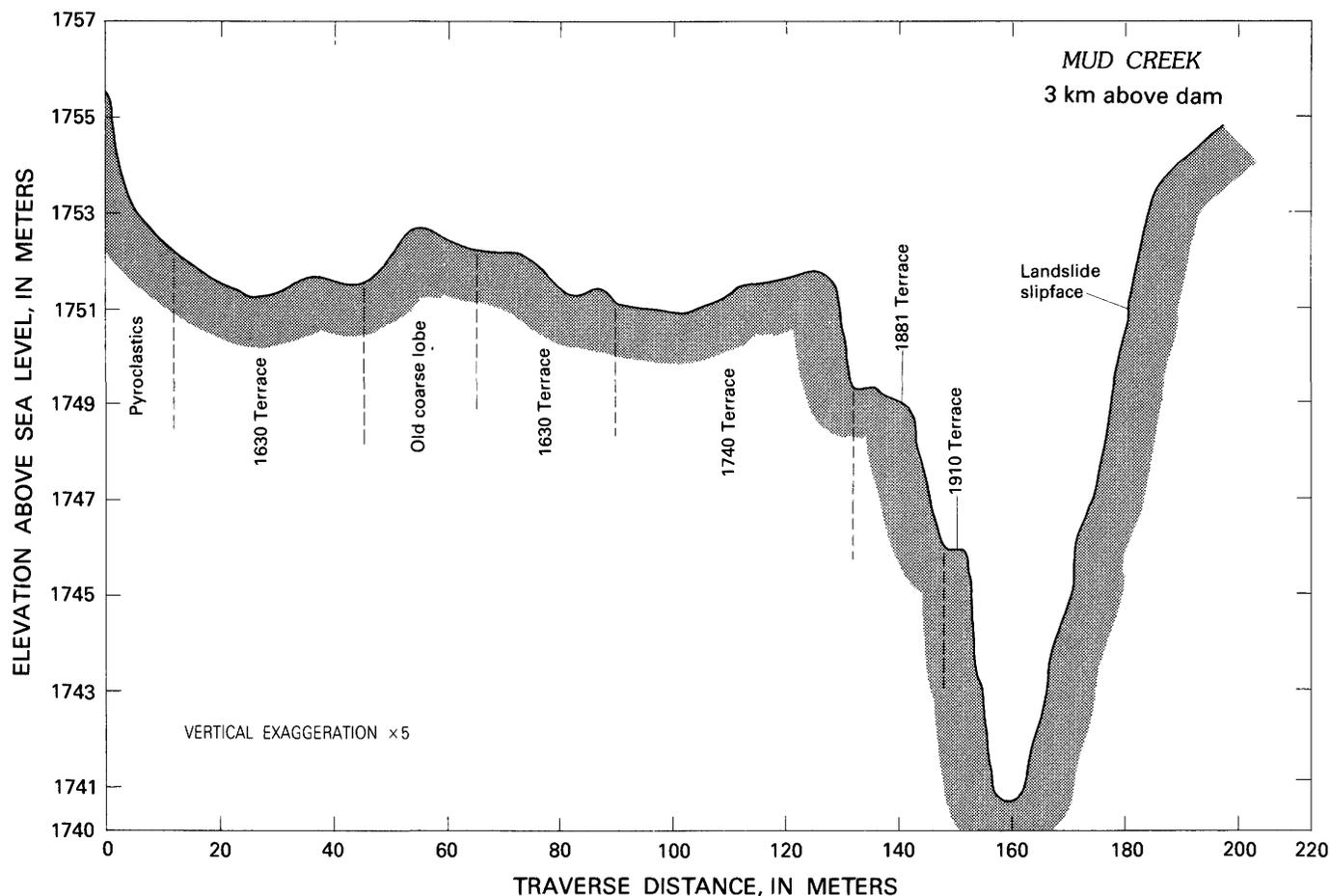


FIGURE 9.—Cross section of Mud Creek 3 km above dam. Multiple debris-flow terracing and dates are shown. Note lack of evidence of historic 1924 to 1931 debris flows (bulking in this reach). Landslides on right bank may contribute sediment to debris flows.

the bank in some locations. As for most Mount Shasta streams affected by debris flows, distance downslope of overbank deposition seems to be the best estimator of debris flow magnitude on Ash Creek. Only large debris flows (A and D, fig. 12) are capable of substantial deposition on the lower fan. These trends support the generalization that large debris flows degrade and bulk up high on the mountain, whereas smaller debris flows tend to aggrade high on the mountain and are largely in-channel events farther downslope (fig. 12). Thus, small debris flows fill channels degraded by larger debris flows, which suggests an overall cyclic process of channel filling and scouring controlled by the magnitude and frequency of debris flows. There seems to be a directional trend during the last several decades for medium and small events to build the fan in the upstream direction.

The frequency per century of debris flows in Ash Creek is shown in figure 13. The substantial debris flows of 1939 and 1962 (E and G, fig. 12) probably obscure evidence of most small flows prior to 1939. Thus, only a conservative estimate of small debris-flow

frequency may be made. At least three small flows have occurred since 1873. Medium and large debris-flow frequency (fig. 13) is computed for the entire dendrochronologic length of record (260 years).

Each proposed date of a debris flow on Ash Creek is substantiated by cohort age and either ring-pattern anomalies or scars or both. Thus, accuracy prior to 1898 is probably to within 3 years of the event and to within 1 year from 1898 to present. It should be noted, however, that the Cold Creek episode is composed of a series of at least three major and numerous smaller events. The anastomosing and reworking nature of these flows over the upper fan makes further dating difficult. The major debris flows probably occurred about 1728, 1747, and 1768. There is some dendrochronologic evidence of a small event on the upper fan about 2 years prior to the 1939 debris flow. The remaining debris-flow dates are probably single events. The tendency for debris flows to cluster in time may be related to periods of heightened bank slope instability in alpine reaches of Mount Shasta streams. Bank slope instability in conjunction with anomalously

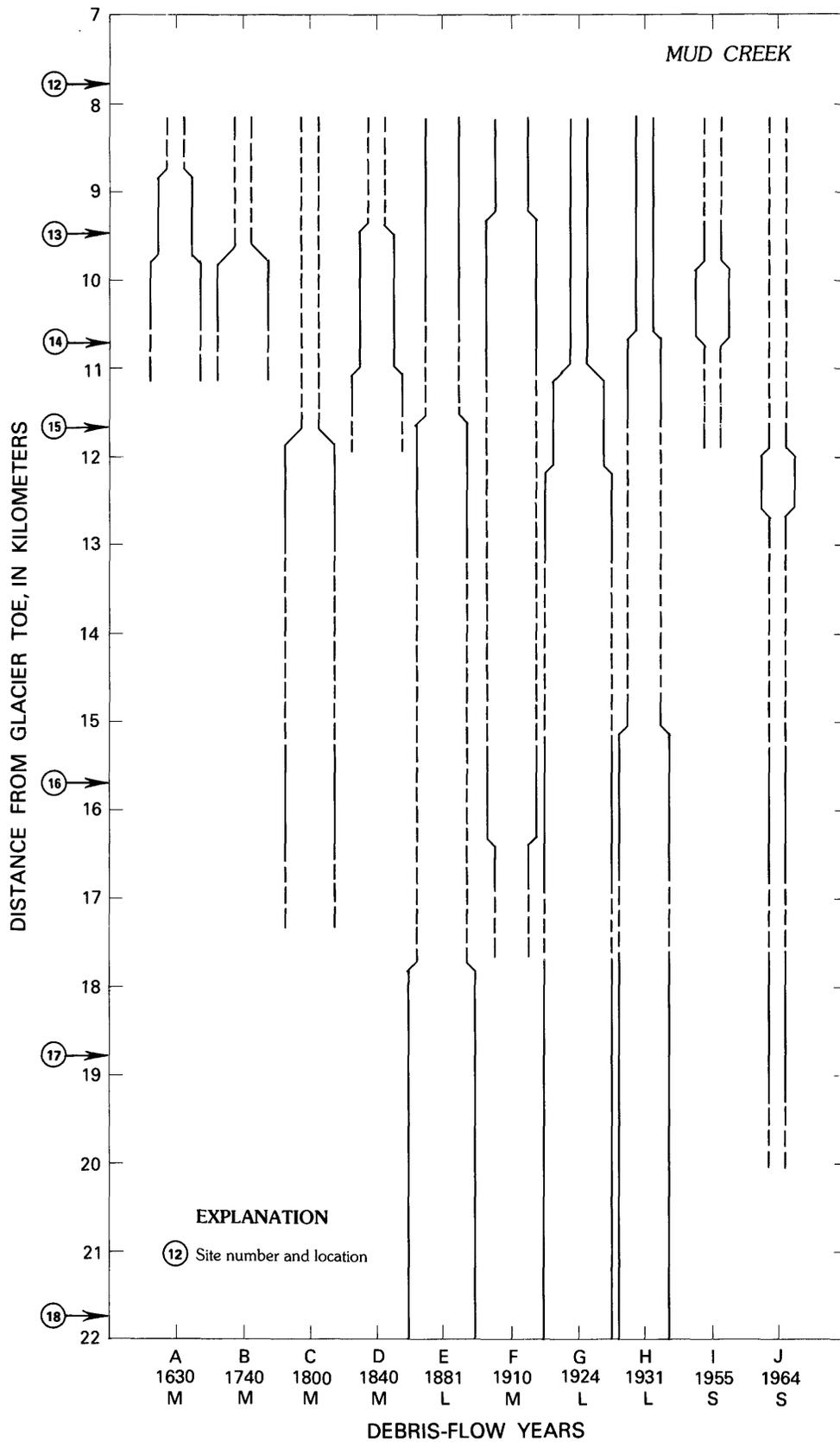


FIGURE 10.—Age and downvalley distribution of debris flows on Mud Creek. Dashed lines indicate probable path of debris flow, solid lines outline reaches with dendrogeomorphic evidence of flow passage or deposition. Relative magnitude is indicated by width between lines. L, M, and S are large, medium and small debris flows, respectively.

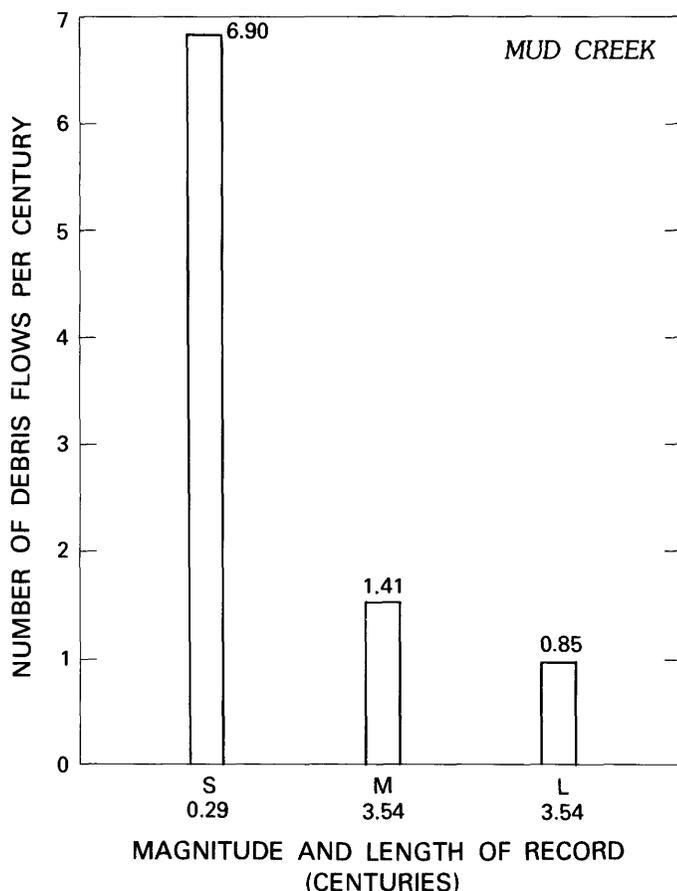


FIGURE 11.—Debris-flow frequency per century by magnitude class on Mud Creek.

high summer temperatures appears to be correlated with debris-flow activity (Osterkamp and others, 1986).

The upper site (19, fig. 3) is a good example of the different types of deposition that can result from the viscous nature of debris flows. The 1939 event left the channel at site 19 and scarred trees on the fan surface for hundreds of meters downslope and adjacent to the channel; most deposition from this event occurred farther downstream from site 19. A plan view of site 19 is shown in figure 14. The debris flows of 1962 and 1977 were depositional throughout the site, leaving distinct levees in the upper part and spreading into a broad sheetlike lobe (fig. 14). The 1962 event was substantially larger than the 1977 event and it deposited lobate sheets farther downslope and over a broader area (fig. 14). The channel is perched on the surface of the 1977 deposit (fig. 15) before it shifts to the right side of the 1962 surface downslope. Perched channels are indicative of recent events, where levees confine the channel to the higher central part of the deposit (fig. 15). Typical terracing of debris flows occurs about 2 km downstream near Military Pass Road (fig. 3). The incisement abruptly becomes deeper off the 1962 sur-

face. Here the typical terracing (fig. 16) begins and continues to the gorge. The 1939 event deposited an intermittent sheet of fine-grained material on the top bank near the channel. Roots growing before 1939 show the thickness of the 1939 deposit (fig. 17). Evidence from tree rings was determined for events in 1898, 1873, and about 1800. The 1898 event left a continuous sheet of fine-grained material at the top bank and immediately below the 1939 deposit.

COLD CREEK, SITES 26, 27, AND 28

Cold Creek (fig. 3) has been included in the Ash Creek section because it is a tributary to Ash Creek and has no direct glacial connection. Additionally, prior to the Cold Creek episode this stream probably joined Ash Creek substantially farther upstream. All debris-flow activity on Cold Creek is directly related to flows originating in the Ash Creek basin and discharges from Wintun Glacier.

Owing to similarity among the three sites on Cold Creek this discussion applies to all three sites. The study sites are evenly spaced between 1,700 m and 1,460 m in elevation. The right bank of Cold Creek is composed of pyroclastics through most of its reach. The left bank is composed of deposits from the Cold Creek episode. Tree-ring evidence suggests that the greatest periods of debris-flow activity during the Cold Creek episode occurred in 1728 and in the late 1740's. The 1898 debris flow apparently had a small arm of deposition along the upper Cold Creek site. Red staining in the rings of a few riparian trees suggests that floods may have occurred in conjunction with the 1962 and 1977 debris flows on Ash Creek (red staining in rings produced during flood years has been observed in trees affected by documented floods). Thus, recent debris flows rarely affect the Cold Creek channel but concomitant flooding may occur.

GRAVEL CREEK

Gravel Creek flows on the northeast face of Mount Shasta draining the Hotlum Glacier. Four sites of denrogeomorphic study were established along Gravel Creek (fig. 3). These sites were located at the intersections of the stream with road crossings. The uppermost site (site 29) is located at an elevation of about 2,135 m (fig. 3) and is the site of most intensive debris-flow dating. Sites 30, 31, and 32 are located progressively downstream (fig. 3) and were visited briefly to determine the downvalley extent of major debris flows identified at site 29. The lowermost site (site 32) is located in a saddle situated among Mount Shasta peak, the Whaleback, and Ash Creek Butte (fig. 3). Site 32 is

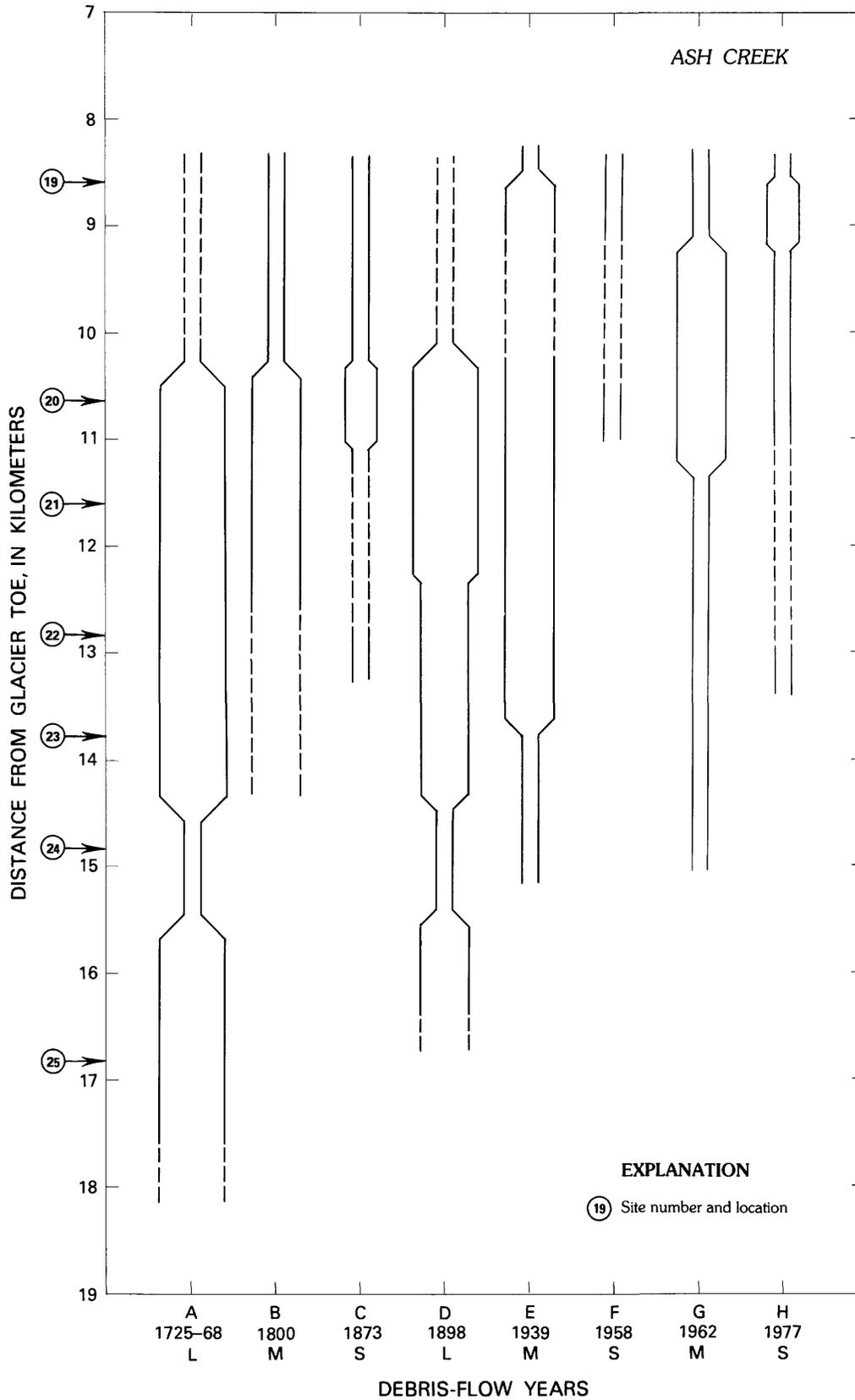


FIGURE 12.—Age and downvalley distribution of debris flows on Ash Creek. Dashed lines indicate probable path of debris flow, solid lines outline reaches with dendrogeomorphic evidence of flow passage or deposition. Relative magnitude is indicated by width between lines. L, M, and S are large, medium and small debris flows, respectively.

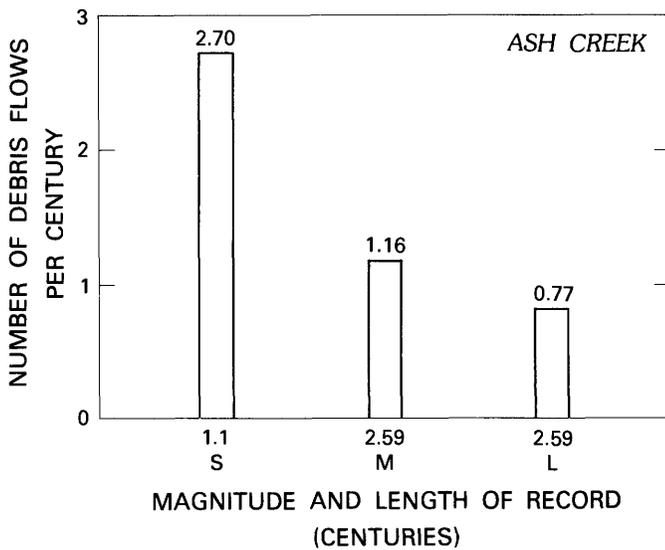


FIGURE 13.—Debris-flow frequency per century by magnitude class on Ash Creek.

highly aggradational, dominated by fine-grained sediments delivered by Gravel Creek which becomes influent in this reach.

Generally, there is much evidence of debris-flow activity along the upper reaches of Gravel Creek. In the vicinity of site 29, the stream has a distinct incisement with an anastomosing series of debris-flow levels on the left side of the valley. Since about 1580, the channel has been shifting from northwest to southeast (left to right). This prevailing directional shift has preserved depositional features of at least seven debris flows on the left side of the valley while cutting into older pyroclastic deposits on the right bank. In cross section, the channel at site 29 is perched higher than some of the area affected by debris flows on the left side of the valley. Thus, while shifting over the past four centuries the stream has become increasingly aggradational at site 29.

Gravel Creek exemplifies the trend found on most of the streams for discrete surficial dendrogeomorphic ev-

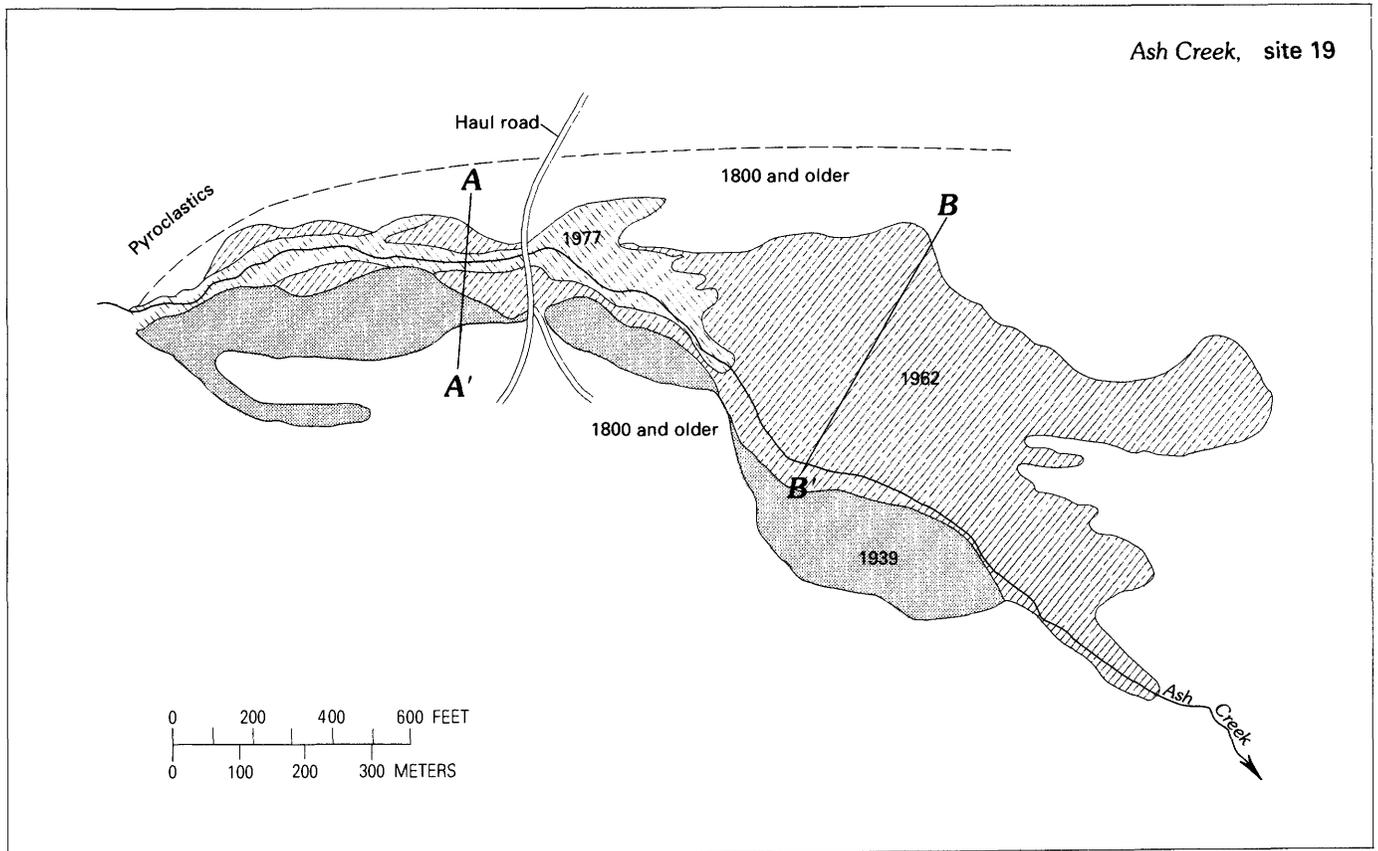


FIGURE 14.—Plan view of upper Ash Creek. Age and locations of three recent debris flows (1939, 1962, and 1977) are shown. Locations of cross sections A-A' and B-B' are shown in figure 15.

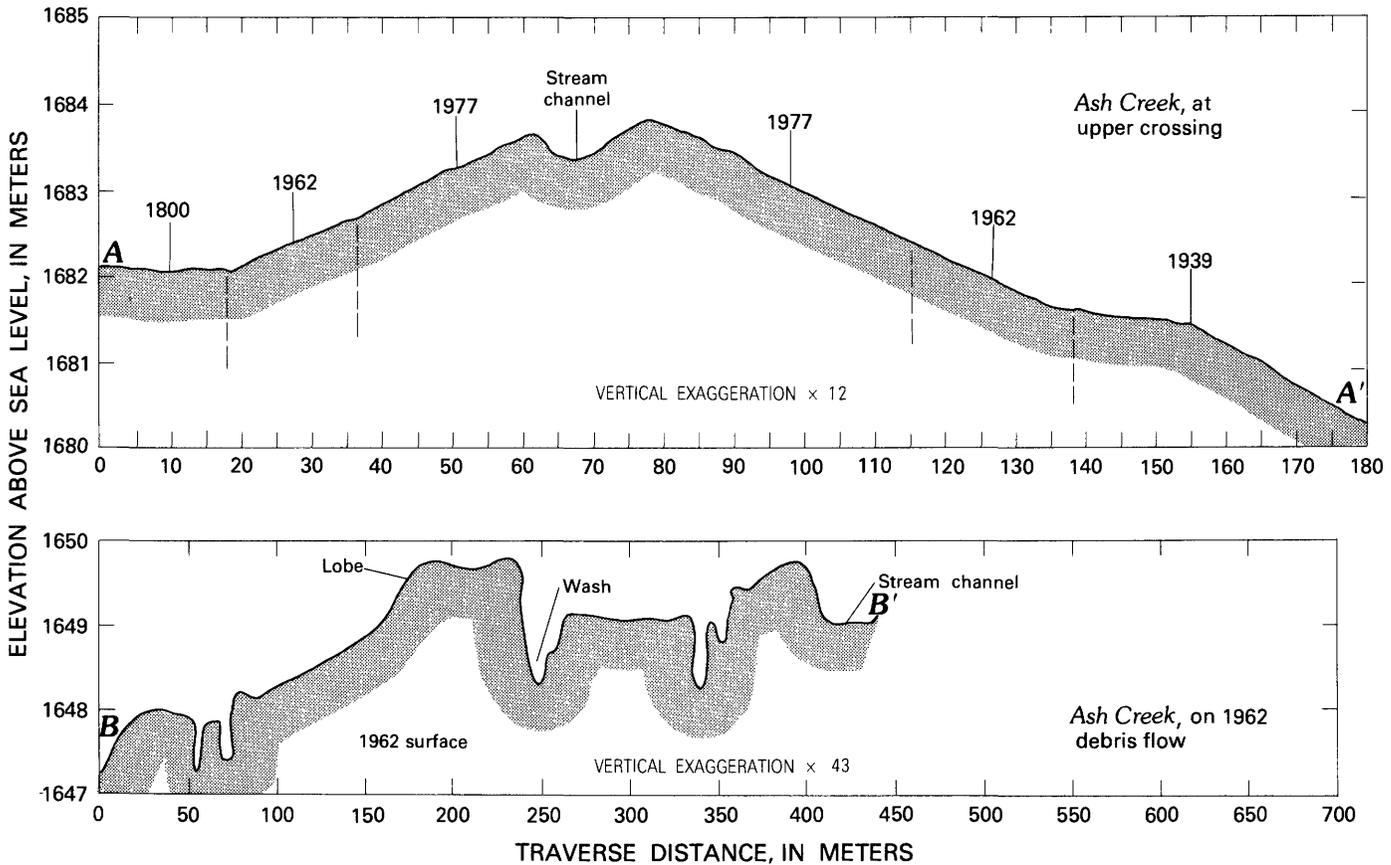


FIGURE 15.—Two cross sections on upper Ash Creek. Note perched condition of channel on the recent 1977 deposit. Cross section on 1962 deposit with areas of lobes and scour is shown at bottom of figure; note perched condition of channel, washes (scoured areas) to left are possible sites of stream capture.

idence of debris flows to increase in the upstream direction. Debris-flow deposits are thin below site 29 and are subject to fluvial reworking. Furthermore, only large debris flows appear to proceed downslope as far as site 32 and these may represent debris-flow runouts—fine-grained flood deposits associated with upstream debris flows.

The forests along Gravel Creek are dense and diverse reflecting the more humid conditions of the eastern side of the mountain. Ponderosa pine, prevalent on the northwest face, is present only sporadically. Western white pine, Douglas fir, lodgepole pine, and red fir are the prevalent tree species; the two latter species are particularly common at higher elevations. Red fir is the dominant species at site 29.

SITE 29

This site (fig. 3) is located just downstream from the area where debris flows have breached the channel incision. Above this area debris flows are contained entirely by steep pyroclastic banks. Site 29 thus marks

the beginning of the Gravel Creek debris fan which rapidly spreads laterally with decreasing gradient toward the saddle. The area of intensive study includes a reach about 0.75 km above the road crossing and an equal distance below.

The surface of the fan at this site is characterized by anastomosing and overlapping discrete debris-flow deposits and scour areas. The oldest debris-flow features are on the left side of the fan and generally decrease in age toward the right bank which is composed of pyroclastic deposits. Many of the deposits are coarse grained (boulders up to 1 m) and stand in high relief (up to 5 m) to adjacent scoured areas.

Site 29 supports many trees with damage from debris-flow passage. Many of the debris-flow lobes support cohorts of trees on the fine-grained interior lobe surface (fig. 18). Some of these lobes have dense cohorts of red fir that are only a few meters high but are hundreds of years old. More recent lobes came to rest against large trees which were scarred at time of impact and thus allow for accurate determination of debris-flow dates.

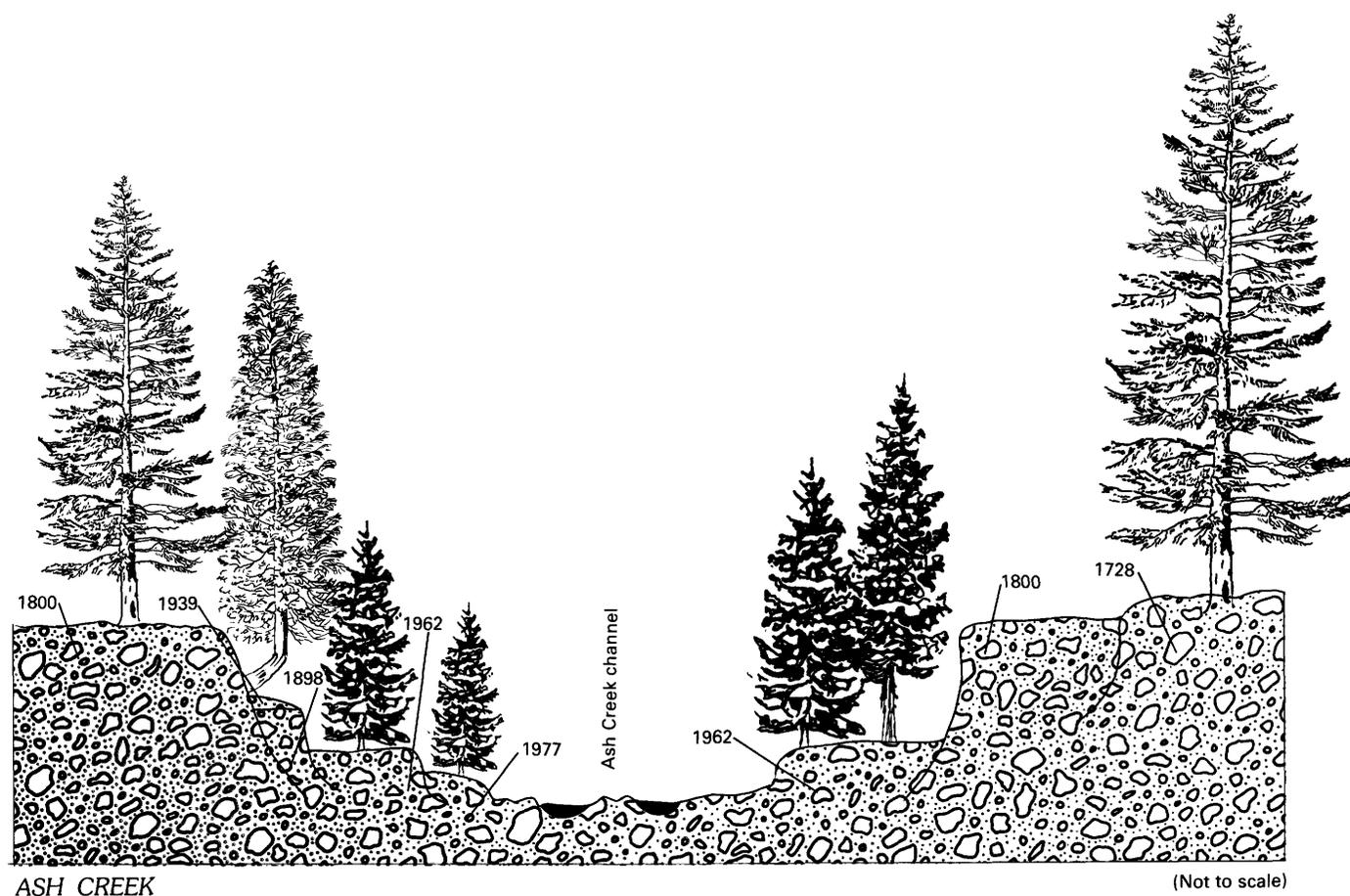


FIGURE 16.—Terracing by debris flows on Ash Creek near Military Pass Road.

Evidence of at least seven debris flows was recovered from site 29 (table 2). The earliest dated event occurred about 1580 and is preserved as a downvalley series of weathered lobes on the left side of the fan. Subsequent events occurred to the right of these surfaces and generally increase in elevation (in cross section) toward the present channel (fig. 19). Subsequent debris-flow events occurred in or about 1728, 1836, 1902, 1937–39, 1958–59, and 1971. The two most recent events were apparently small flows confined largely to the channel, which deposited coarse levees at the channel edge. The events in 1728 and 1937–39 were large debris flows approaching the 1580 event in magnitude. These two large events spread over parts of the fan surface scouring older deposits in places and depositing lobes which now stand in high relief (fig. 19). The remaining dated events (1836 and 1902) apparently were medium debris flows that breached the channel in only a few places. However, both events left discrete lobes over the 1728 surface that were not reworked by the 1937 and 1939 events. The events of 1937–39 and, to a lesser degree, 1958–59, appear to be a cluster of debris flows. This

tendency for two or more debris flows to occur within a few years of each other has been observed on several of the glacial-headed streams. Evidence for events in 1937 and 1939 suggests that the debris flows are two distinct events during the 3-year period.

The trend for small events to be preserved only if they are recent is evident in table 2. Evidence of earlier small events was most likely obliterated by the 1937–39 events, which precludes accurate frequency interpretations for small events on Gravel Creek. However, a fairly reliable frequency estimate may be calculated for combined medium and large events. Events such as that of 1902 (medium) and larger occur on Gravel Creek about once every 80 years. Large debris flows probably occur less frequently; small events are substantially more frequent, tentatively about once every 13 years. Relative to other mountain streams this is an active basin for debris flows. However, flows have limited downvalley extent relative to other streams perhaps owing to an abrupt shift in gradient and the lack of an entraining incisement below 2,135 m in elevation.



FIGURE 17.—View of Ash Creek channel banks above Military Pass Road. Sediment over exposed root zone (arrow) was deposited during the 939 debris flow. This deposit varies in thickness (up to 1.5 m) through sites 20 and 21.

SITES 30, 31, AND 32

These sites (fig. 3) are almost entirely dominated by fine-grained deposits, most of which have been reworked through fluvial activity. The channel at the lower two sites (31 and 32) is shallow and usually less than a meter below the broad alluvial fan. These sites have undergone substantial aggradation of fine-grained sediments. Typical lobes and levees from debris flows is lacking, instead runoutlike deposits occur and may be associated with debris-flow activity upstream.

The event of 1902 is the oldest of the seven dated events below site 29. Eccentric growth beginning in 1902 was found in a specimen at site 31. Scars on a few trees at sites 30 and 31 document the debris flow in 1939, which suggests that the 1939 event was the larger of the two events in 1937–39. One tree with eccentric growth beginning in 1959 and a tree scarred in 1971 are the only evidence of small flows at site 31.

Several partially buried trunks at site 32 have an average minimum age of 26 years (possibly dating the 1958 flow). These young trees are the only datable dendrochronologic evidence of depositional activity at site 32. Fine-grained sediments up to 1.5 m thick occur above the root collars of the young trees at site 32; thus an aggradation rate of about 60 cm per year since 1958 is indicated.

INCONSTANCE CREEK

Inconstance Creek was studied at only one site (site 33, fig. 3) at an elevation of about 2,300 m. This site is characterized by a fairly deeply incised channel with a narrow terrace and an overlying series of debris-flow deposits on the right bank. Vegetation on the terrace and right bank shows the effects of periodic debris flows through scars, buried trunks, and ring patterns.

A stand of western white pines dates the terrace surface to about 1680. Subsequent eccentric growth pat-



FIGURE 18.—Sapling cohort on debris-flow lobe near site 29 on Gravel Creek. Saplings date a debris flow in 1939.

TABLE 2.—Summary of debris flows and magnitudes on Gravel Creek in the vicinity of site 29

[Asterisk indicates geomorphic evidence of the debris flow was also found at lower sites. S, M, and L are small, medium, and large debris flows, respectively.]

Date	Magnitude		
	S	M	L
1580			X
1728			X
1836		X	
1902*		X	
1937-39*			X
1958-59*	X		
1971*	X		

terns suggest debris-flow passage in 1693, 1728, and 1881. Coarse levees which dominate the channelward terrace edge were left by a debris flow in 1918 as dated from numerous scars and eccentric growth patterns (fig. 20). Boulders left as levees by the 1918 event ranged in size from 0.25 m to 1.5 m. A few surviving

white pines below the 1918 levees have scars from a smaller in-channel debris flow in 1939 which formed levees inside the 1918 levees. Small paired terraces adjacent to the channel have a minimum age of about 20 years as dated from a cohort of white pine saplings. A red intra-ring stain (possibly a layer of crushed cells) in these saplings suggests a flood event occurred in 1971. The well preserved nature of relatively old debris-flow deposits at site 33 suggests that debris flows are not as frequent as on other glacier headed streams of Mount Shasta. Channel, levees, and old terraces are shown in figure 21. Dendrogeomorphic evidence suggests that events in the late 1600's partly filled the channel incisement. Subsequent events have largely degraded the site as suggested by the lack of deposits on the terrace since about 1680 except for the 1918 levees. Events in the last 250 years, including the undoubtedly large debris flow in 1918, have bulked up at site 33 and were depositional farther downstream. Only small debris flows aggrade at this site.

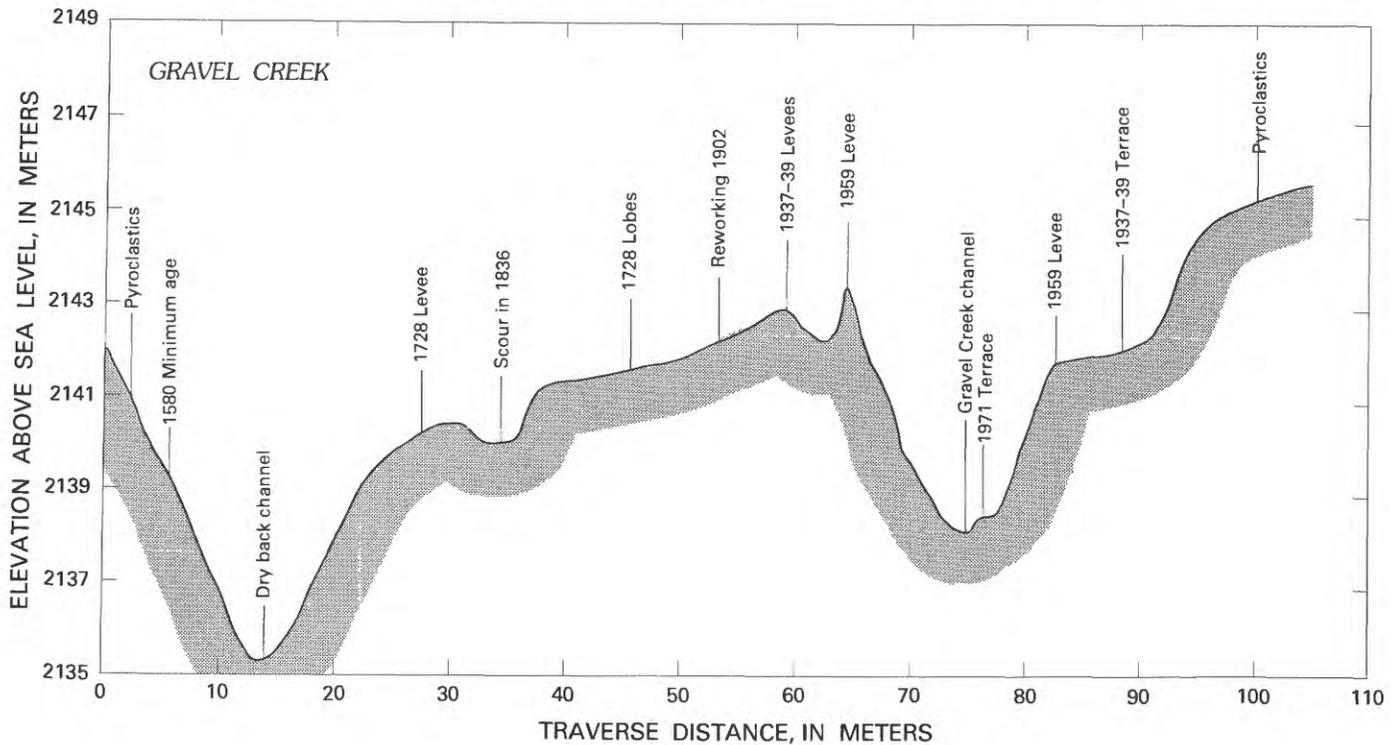


FIGURE 19.—Cross section of Gravel Creek near site 29. Note progressively increasing elevation of deposits and decreasing age of deposits toward the left bank.

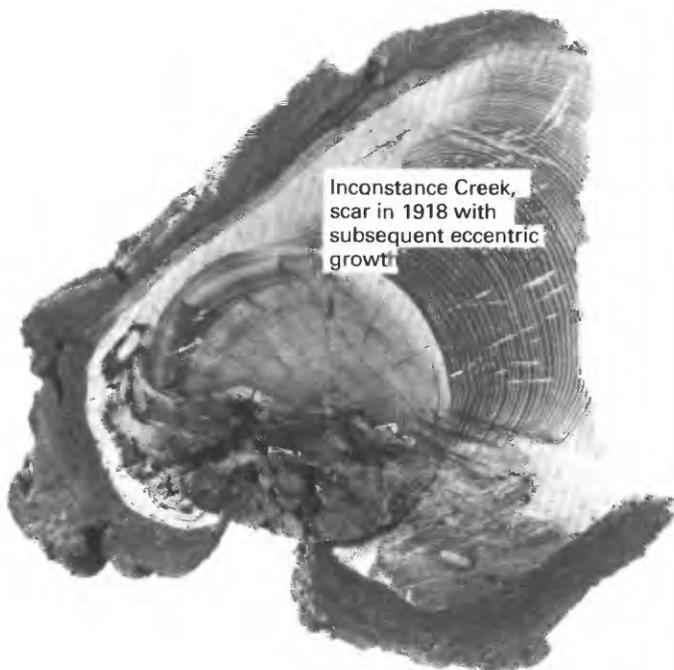


FIGURE 20.—Cross section of western white pine affected by debris flow on Inconstance Creek. Tree was scarred and tilted in 1918 resulting in eccentric growth after 1918.

Debris flows of all magnitudes are relatively infrequent on Inconstance Creek. Tree-ring data suggest that debris flows of any magnitude occur here only once every 38 years. Large debris flows occur substantially less frequently than once every 38 years, probably about once per century.

NONGLACIAL STREAMS

Panther Creek, Cascade Gulch, and Diller Canyon (fig. 3) are streams which are not presently draining glaciers. These streams have dendrogeomorphic evidence of debris flows; however, activity is much less than on streams previously discussed (table 1). The lack of a direct glacial connection probably precludes relatively frequent debris flows; and those that have occurred usually have been small.

PANTHER CREEK

Panther Creek flows on the south face of Mount Shasta. It is speculated that this stream may have had some connection to the Konwakiton Glacier in the past (J. Thornton, U.S. Geological Survey oral commun., 1982). Studies were made at only one site (site 34, fig. 3) near the old Mount Shasta-McCloud Road; elevation is about 1,685 m.



FIGURE 21.—View of Inconstance Creek near site 33. Note levees and terrace on left.

Dendrogeomorphic evidence indicates that four debris flows occurred since about 1804. Relatively small debris-flow terraces occur above the road. The two largest debris flows were dated to about 1804 and 1885 from cohorts of Douglas fir and incense cedar. Small in-channel terraces were deposited in 1924 and 1967, as dated from scars and anomalous tree-ring sequences.

CASCADE GULCH

Cascade Gulch is located on the southwest flank of Mount Shasta. (fig. 3). The stream within Cascade Gulch flows intermittently even during summer months and becomes totally influent a few kilometers above the city of Mount Shasta. Dendrogeomorphic evidence for debris flows was found at one site (site 35, fig. 3) above the intersection of the stream and Everitt Memorial Highway. Three deposits left by small debris flows were dated about 1770, 1928, and 1957.

DILLER CANYON

Diller Canyon lies on the west face of Mount Shasta, more specifically on the Shastina peak (fig. 3), and the stream within Diller Canyon becomes influent a few kilometers above Weed. There is geomorphic evidence of a historic glacier on Shastina, although Diller Canyon presently has no glacial connection. The relatively deeply incised canyon suggests sediment discharges were previously higher, possibly due to debris flows, but there have been no recent large flows datable by tree-ring sampling.

Diller Canyon was investigated at two sites for dendrogeomorphic evidence of debris flows. The highest site (site 36, fig. 3) is located at an elevation of about 2,300 m within the major incisement. One incised terrace was deposited in 1935 and may be meteorologically related to activity on Whitney Creek in that same year. Other older terraces were apparent but were not dated. The other site on this stream (site 37, fig. 3) is located on a fan developed in the lower reaches, at an elevation of about 1,500 m. Dendrogeomorphic evidence suggests that four small debris flows occurred in about 1886, 1921, 1947, and 1961. The 1935 event at the higher site did not proceed as far downslope as site 37.

DISCUSSION

Some coincidence of debris-flow dates is evident (table 1). Of the 52 events listed, 30 percent occurred on two or more streams in a given year; in 1728 and 1939 debris flows occurred on three streams. This would suggest a relation between weather patterns affecting the entire mountain and debris-flow activity.

Osterkamp and others (1986) have suggested that high summer temperatures are related to debris-flow activity for the period for which temperature data are available. Botanical evidence reveals most scarring from debris flows is within the interval of seasonal growth and, hence, formed during summer months. This observation supports the contention that high summer temperatures may, in part, initiate debris flows. It is also likely that local summer storms over individual basins may be responsible for some debris flows, particularly small events.

Debris-flow frequency since 1580 is shown in figure 22. It is apparent that small debris flows (shown as dashed vertical lines, fig. 22) are more easily detected if they occurred recently. Only 3 of 18 are more than 100 years old. The frequency of medium and large events also decreases with age (fig. 22), which is partly an artifact of tree-ring dating, because subsequent events remove evidence of previous events. However, Osterkamp and others (1986) present other lines of evidence that indicates heightened debris-flow activity in the last few centuries. Four periods of relatively high debris-flow frequency are apparent (fig. 22): (1) between 1898 and 1940, (2) between 1830 and 1845, (3) between 1780 and 1805, and (4) the Cold Creek episode from 1725 to 1770. The 1700's experienced heightened debris-flow activity relative to the 1800's and the last half of the present century (fig. 22), which may be related to the "little ice age" when anomalously large amounts of ice and snow accumulated.

The interval of years between debris flows of any magnitude on glacial streams has a mean value of 6.24 years. Years with more than one medium to large debris flow seem to be an indicator of periods of heightened debris-flow frequency rather than long strings of single-event years (fig. 22). This observation supports the premise that debris flows occur in clusters over a period of not more than a few decades. The mean gap between multiple-event years is 41.4 years ($n=7$, $s=\pm 26.8$). Relative debris-flow activity by basin may be estimated by calculating the mean age of small debris flows (fig. 23). Evidence of small debris flows is highly susceptible to obliteration by medium and large flows. Thus, the mean age of small debris flows should reflect the level of debris flow activity in a basin. Basins with recent evidence of small flows are probably active basins; conversely, substantial evidence of old small flows should indicate relatively low debris-flow activity. Geomorphic observations by Osterkamp and others (1986) suggest that Gravel Creek is one of the most active basins and that Inconstance Creek is the least active basin. These observations are supported by the calculated mean age of small flows depicted in figure 23.

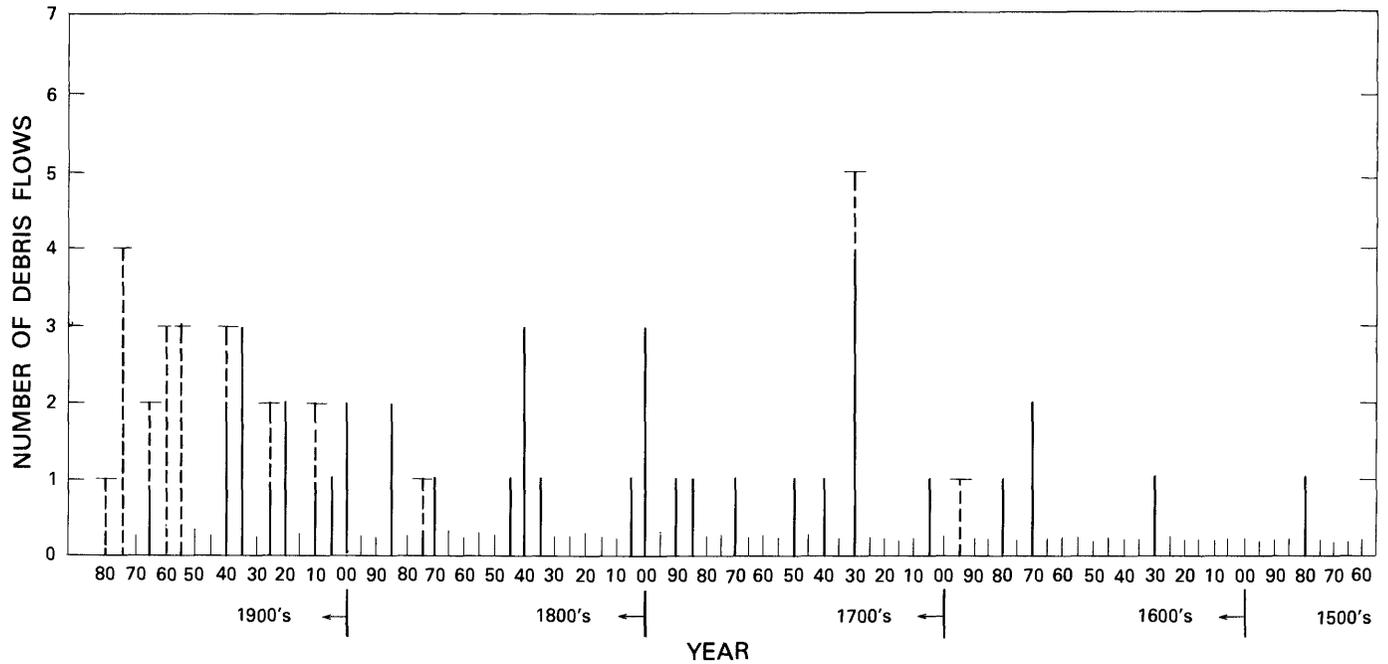


FIGURE 22.—Age and frequency of debris flows on Mount Shasta back to 1580, all dates from botanical evidence. Medium and large debris flows are indicated with solid lines, small flows with dashed lines. Note lack of evidence for small debris flows with increasing age.

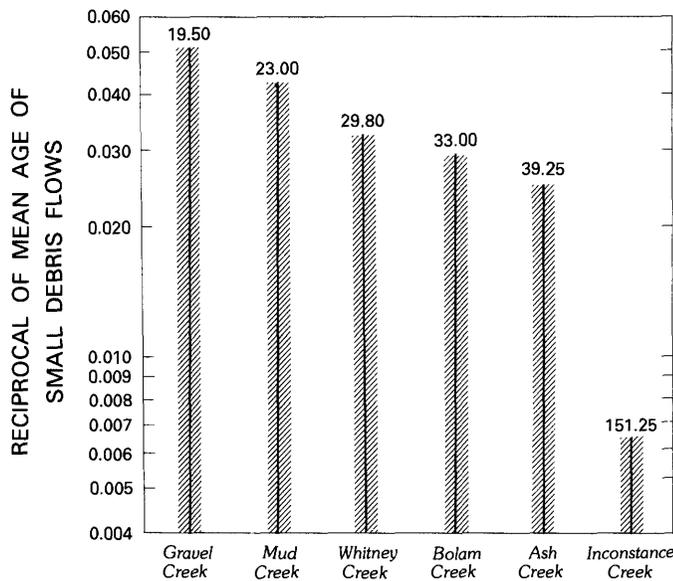


FIGURE 23.—Debris-flow activity by basin. Calculated as mean age of small debris flows, shown as reciprocal on vertical axis (log scale). Actual mean value shown at top of bar.

The glacial basins, in order of decreasing debris-flow activity, are Gravel Creek, Mud Creek, Whitney Creek, Bolam Creek, Ash Creek, and Inconstance Creek (fig. 23). Gravel Creek may be currently in a heightened phase of activity (Osterkamp and others, 1986). The recent breakup of the Konwakiton Glacier

may explain the high degree of activity on Mud Creek. The order-of-magnitude decrease in activity in the Inconstance Creek basin (fig. 23) may result from a small basin area, shallow channel incision in alpine areas (Osterkamp and others, 1986), and perhaps an inactive headwater glacier.

The evidence indicates a cyclic nature of sediment movement through glacially fed basins. Apparently during periods between major debris flows medium and small debris flows allow for storage of sediment relatively high on the mountain. These sediments are stored as lobes and terraces within the active channel incisement. The middle and upper reaches of Ash Creek provide a good example of the stepped channel fill associated with a relatively long period since a major event. Whereas, the middle and upper reaches of Whitney Creek reflect the scouring nature of large events. The cycle of channel filling and scour may be imbedded in a larger cycle of periods of heightened debris-flow activity and relatively quiescent periods. Examples of heightened periods of activity are the 1920's and early 1930's on Mud Creek and the Cold Creek Episode on Ash Creek. Inconstance Creek may represent a basin currently in a period of quiescence as evidenced by the good preservation of old medium and small debris flows. Conversely, Gravel Creek may be currently in a heightened period of activity, suggested by evidence of recent numerous small and medium debris flows.

Analysis of dendrogeomorphic evidence has allowed for the development of debris-flow histories for the streams draining Mount Shasta, Calif. Debris flows have been dated over a 400-year period back to 1580. No other methods are available which provide the degree of accuracy in the development of debris-flow histories beyond times of historic documentation as afforded through tree-ring analyses. Dates of debris flows and their downvalley distribution from botanical evidence when combined with geomorphic evidence provide a means for better estimation of magnitude and frequency of debris flows over a several hundred year period.

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APPENDIX: DETAILED SITE DESCRIPTIONS

WHITNEY CREEK

SITE 1, ABOVE WHITNEY FALLS

Site 1 (fig. 3) is largely degradational in character. The historic 1935 debris flow scarred several trees within the channel incisement but left few deposits. One older debris-flow levee just below the top bank was dated to about 1868. All overbank deposits were older than the existing trees. The predominance of pyroclastics near the channel incisement suggests that few recent debris flows have overtopped the banks at this site. The absence of scars or tilts after 1935 within the channel incisement suggests that nothing larger than the 1935 event has since passed through this site. The 1935 event was largely degradational throughout the upper reaches at least past the gorge. A recent event, 1985, left a debris line just below the 1935 levees, suggesting a magnitude slightly smaller than the 1935 event.

SITE 2, ABOVE THE GORGE

Site 2 (fig. 3) is a relatively narrow-bottom well within the major channel incisement. The channel itself is deeply incised into the bottom, lending a terraced appearance. The surface of this terrace is characterized by many overlapping and often steep, discrete debris-flow lobes. The oldest and farthest downvalley event on this terrace occurred about 1670. This flow may make up a considerable volume of the terrace with more recent, small debris flows deposited over the 1670 surface. The 1670 debris flow may have sufficiently filled the channel to allow for debris from several flows of smaller magnitude to be deposited on the terrace. Three debris-flow lobes on this surface were dated to about 1705, 1790, and 1804. The 1804 debris flow was at least partly responsible for a narrow, lower terrace on the left bank. At least two debris flows between 1830 and 1840 were of sufficient magnitude to scour much of the left bank and a back channel on the right side of the terrace. Two remnants of debris-flow levees inside the channel incisement of the main terrace were dated to about 1868 and 1981. The 1935 debris flow was entirely degradational in this area, leaving only scars on the few trees growing inside the channel just below the terrace. Considerable bulking of the 1935 event may have occurred in this reach and the gorge is suggested by the absence of trees older than 1935 more than 2 m

below the terrace edge. The channel in this reach and the gorge are as much as 10 m below the terrace edge. A recent datable event occurred about 1960 and appeared as a locally present, relatively low, small in-channel terrace. The 1960 evidence was removed by the flow in 1985.

SITE 3, IN THE GORGE

Site 3 (fig. 3) is partly described in the previous section (site 2). The reach is characterized by a deep, wide channel incisement with a substantial terrace $\frac{3}{4}$ of the way below the top of the incisement. The channel is deeply incised into this terrace on the left bank. The surface of this terrace is largely composed of the 1670 debris flow with a back channel on the right side formed during the passage of the 1830–1840 debris flows. A lobe of the 1841 debris flow occurs on the upper end of the 1670 terrace. Scarring of trees at the left edge of the terrace occurred in 1868 and 1935. No trees grow more than 2 m below the left terrace edge, which provides further support of the degradational nature of debris flows in this and upstream reaches since the mid 1800's. A flow in 1985 left a thin boulder line a few meters below the 1670 terrace.

SITE 4, FAN NEAR CONFLUENCE WITH BOLAM CREEK

Site 4 (fig. 3) covers the upper fan reaches of Whitney Creek. Generally, the stream is not as deeply entrenched as the reaches above. Pyroclastic deposits occur near the top bank with stratified debris-flow deposits nearest the channel. Some evidence of anabranching occurs near bends in the stream. Trees at site 4 and below are sparse probably owing to fire and lumbering. Two terracelike features are locally exposed along this reach: a lower one with young small trees and higher one with scattered older trees. Depositional patterns are complex and discontinuous along the reach. Botanical evidence exists for only relatively recent debris flows in about 1840, 1868, and 1908. Scars dating the 1935 event were found on some of the older trees as well as scars between 1952 and 1954. As will be shown for other streams, surficial geomorphic and botanical evidence becomes more difficult to interpret downvalley.

SITE 5, ABOVE SOUTHERN PACIFIC RAILROAD

Site 5 (fig. 3) is similar to that described above (site 4) in its geomorphic and botanical characteristics. A low terrace is common along the reach and higher terracing locally common. Few trees grow along Whitney Creek, although botanical evidence was found for flows between 1918 and 1921, and in 1935, 1950, between 1958 and 1962, and 1985.

SITE 6, JUST BELOW U.S. 97

Site 6 (fig. 3) is characterized by a shallow channel, rarely more than 2 m below topbank. It is apparent that many hydrologic events (floods, mudflows, and debris flows) begin to spread and anastomose from site 6 downslope as indicated by many shallow diversion channels. Except in the immediate vicinity of the main channel, the deposits are very fine grain relative to those upstream. Ponderosa and Jeffrey pines, which compose nearly all of the botanical evidence upstream (except alpine species above the falls), give way to increasing dominance of juniper downstream. The dendrochronologic limitations of juniper have been noted previously. Isolated stands of pines near the main channel indicate debris flows in about 1790 and 1830; more recent flows scarred trees in 1935, between 1960 and 1962, and 1985.

SITE 7, ABOVE JUNIPER FLATS

Site 7 (fig. 3) is the most downstream study site. Except for occasional rather coarse lobes, the surface is very fine grained. Debris flows appear to have moved from east to west across the fan. Junipers of various ages are locally partly buried by fine-grained deposits. The 1935 event apparently deposited fine sediments over large areas of the site. Subsequent debris flows have both deposited sediments upon the 1935 surface and, in other places, eroded it. Cores and cross sections from junipers indicate a debris flow in about 1840, which contributed substantially to the fan at site 7. Geomorphic evidence suggests that the 1935 event approximated the 1840 flow in magnitude. Smaller debris flows in about 1952, about 1960, 1974, 1977, and 1985 reached site 7.

BOLAM CREEK

SITE 8, UPPER BOLAM

Site 8 (fig. 3) is located in a fairly deep valley with side slopes overlain by pyroclastic material. The valley bottom is characterized by levees and lobes left by a debris flow in 1974. These levees and lobes are largely devoid of trees except for small stunted seedlings whose average age is about 8 years old. Another more recent

flow may have occurred within the levees of the 1973–74 event (Miller, 1980) but there is no known dendrochronologic evidence. These recent debris flows overlie older deposits dated to 1730, 1800, 1924, 1935, and 1955. Scars and eccentric growth patterns support all debris-flow dates at site 8 except for the two oldest (1730 and 1800), which are based on cohort age.

SITE 9, BELOW FORD

From site 9 (fig. 3) up to the lower reach of site 8, the valley bottom is broad with many debris- and pyroclastic-flow surfaces. The area immediately adjacent to the present channel is dominated by debris-flow deposits. The 1935 debris flow left substantial levees along the channel that may have been reworked by more recent flows in 1955 and 1974. Nearby debris-flow terraces have minimum formation dates of 1670, 1730, and 1845 from cohort ages. The channel from site 9 to the confluence with Whitney Creek is part of the Whitney-Bolam alluvial fan with a characteristic shallow channel bed relative to topbanks. Locally the banks may be cut and reveal a debris-flow stratigraphy similar to those described on Whitney Creek (Osterkamp and others, 1986).

SITE 10, ABOVE CONFLUENCE WITH WHITNEY CREEK

Site 10 (fig. 3) is similar to site 9 although the channel is wider and debris-flow terracing more common. Terrace surfaces provided minimum ages of 1730, 1785, 1800, 1845, and 1897. The 1935 event left substantial levees that have been reworked by numerous smaller debris flows that could not be dated. A recent event left a mud plaster still evident about 1.5 m above the present channel. This site and those upstream to a lesser degree suggest many small debris flows have occurred since 1935 at a greater frequency than on Whitney Creek. It is probable that either these recent events occurred with such frequency that tree establishment is prevented or altered; the last flow removed evidence of events and occurred so recently that seedlings have not yet become established. However, none of these recent events have overtopped the 1935 levees. Apparently these small, recent events stop flowing wholly within the channel above the confluence with Whitney Creek, as evidenced by steplike lobes within the channel. Some events may have proceeded into Whitney Creek but have been reworked by fluvial action in the main stem where greater discharges of water occur.

SITE 11, BOLAM FAN NORTH OF CHANNEL

Site 11 (fig. 3) is a broad fan with generally fine-grained deposits. Dendrogeomorphic evidence suggests

that at least some debris flows left the Bolam Creek channel and flowed north over the fan. Debris flows in this area appear to rapidly lose their coarse fragments, and thus leave sheets of increasingly fine-grained material downslope. Tree-ring dates from scattered buried trunks document recent debris-flow activity at site 11 in 1896, 1935, 1955, and 1973–1974. Shallow channel areas along the right bank just below site 9 indicate that debris flows may have left the channel in this reach. Unfortunately fires and lumbering have removed all but a few scattered trees, which is typical along the Whitney-Bolam fan.

MUD CREEK

SITE 12, IN DEEP INCISEMENT

Site 12 (fig. 3) is located in a steep, relatively narrow valley formed by the major Mud Creek incisement. The valley walls bear evidence of massive slope failures some going the whole height of the gorge (250 m). The valley floor is characterized by a locally present low terrace. Trees on this terrace predate the debris flows of 1924–31, although boulder levees on the channelward edge were left by flows in 1924 and in 1931. Thus, these recent large events were relatively small here and bulked through this reach and below. Trees on the terrace show evidence for events in about 1881 and 1910. Aggraded mounds on valley-floor areas across from valley-wall failures are possible evidence that landslides ran up the opposite bank and may have temporarily dammed Mud Creek. One of these mounds supports trees with minimum ages that suggest landsliding occurred in the early 1880's. Osterkamp and others (1986) discuss the significance of valley-wall failure in relation to debris-flow activity.

SITE 13, 3 KILOMETERS ABOVE DAM

Site 13 (fig. 3), although still in the major incisement, has a relatively broad valley bottom. The stream is entrenched deeply on the right bank and exposes a complex of terraces to a height of 20 m above the bed (fig. 11). The degradation of the channel probably occurred during the historic 1924–31 events; the lowest terrace is older than the historic events. Thus, the flows of 1924–31 were probably still bulking through this reach. Site 13 is geomorphically similar to the Whitney Creek gorge reach. The complex of terraces is heavily forested and allowed for fairly accurate dating of four debris flows. The terrace complex contains debris-flow surfaces dated to 1630, 1740, 1881, and 1910 (fig. 11). Levees have been deposited on parts of the terrace complex in 1840, 1924, 1931, and 1955. Immediately upstream of these high terraces the stream crowds the left

bank. Low levees on the right-upstream bank support trees that document the historic flows of 1924–31 and about 1955, the latter being the lowest levee.

SITE 14, 1 KILOMETER ABOVE DAM

From site 14 (fig. 3) to downstream the events of 1924–31 become increasingly depositional. Lobate surges of the 1924 and 1931 debris flows came to rest on midlevel terraces presently 15 m to 20 m above the channel. Site 14 is characterized by three distinct terrace levels on the left bank; the highest debris flow was deposited about 1840. The age of the midlevel terrace is probably about 1910, although deposits from 1924 and 1931 now cover the surface and have left pronounced levees at the channelward edge. Tree ages on the lowest terrace suggest the surface formed in about 1964. No trees below the highest terrace are older than the 1924–31 events. The lobate surge deposits probably occurred on the recessional limb of the debris-flow event.

SITE 15, DAM SITE

The dam at site 15 (fig. 3) was built in response to the destructive 1924 debris flow. Fluviation and subsequent flows, particularly in 1931, have filled the channel upstream of the dam, whereas the channel below the dam has been incised into terraces. The historic events of 1924–31 dominate much of the fan developed at and below site 15. Apparently these historic events occurred as anastomosing flows over the fan and killed many trees by root and stem burial (Beardsley and Cannon, 1930). However, higher portions of the fan where trees were not killed support older trees from which evidence was recovered for debris-flow activity in about 1800 and 1881. A small in-channel terrace supports vegetation which documents a small debris flow in 1964.

SITE 16, PIPELINE CROSSING

Site 16 (fig. 3) as well as the two sites downstream, reflects the highly aggradational nature of debris-flow activity on the lower reaches of Mud Creek. The channel is incised 2 m to 4 m into terrace deposits and the texture of deposits become increasingly fine grained. The fan supports a relatively sparse tree cover that documents five debris flows about 1800, 1910, the historic 1924 and 1931 events, and a small flow in 1964. Dendrochronologic evidence of the 1881 event was not found.

SITES 17 AND 18, BETWEEN ROAD 13 CROSSING (DEBRIS FLOW NATURAL AREA) AND CA 84 CROSSING

Sites 17 and 18 (fig. 3) are similar to Site 31 except for increasingly sparse tree cover and finer textured

deposits. The tree cover increases with distance from the channel which presumably reflects a gradual thinning of the 1924–31 deposits. Old trees typically 50 m to 75 m from the channel document the 1881 debris flow through minimum ages and anomalies in tree-ring sequences. For detailed descriptions of these and adjacent areas see Dickson and Crocker (1952; 1953), Hill and Egenhoff (1976), and Sollins and others (1983).

ASH CREEK

SITE 19, UPPER ASH CREEK CROSSING

Site 19 (fig. 3) is dominated by deposits left by recent debris flows in 1939, 1962, and 1977. These deposits are the highest in elevation occurring at the head of the upper fan. Above site 19 the stream is deeply incised to near its head at Wintun Glacier, as is typical of all major streams in their upper alpine reaches. The left bank above the recent deposits is composed of pyroclastics, whereas the right banks and areas south of the channel are debris-flow deposits. Debris flows appear to preferentially deposit on or overtop the right bank at the upper part of this site. The 1939 event left the channel at site 19 and scarred trees on the fan surface for hundreds of meters downslope and adjacent to the channel; most deposition from this event occurred farther downstream of site 19. A plan view of site 19 is shown in figure 14. The debris flows of 1962 and 1977 were depositional throughout the site leaving distinct levees in the upper part and spreading into a broad sheetlike lobe (fig. 14). The 1962 event was substantially larger than the 1977 event and deposited lobate sheets farther downslope and over a broader area (fig. 14). The channel is perched on the surface of the 1977 deposit (fig. 15) before it shifts to the right side of the 1962 surface downslope. Perched channels are indicative of recent events, where levees confine the channel to the higher central part of the deposit (fig. 15).

The 1977 debris flow is historically documented (Miller, 1980). Tree damage from the 1977 event, as well as from events in 1962 and 1939, is widespread. At the extreme left edge of site 19 large trees bear evidence of a debris flow about 1800. The 1977 debris flow was a small flow lying wholly on the 1962 surface and occupying about $\frac{1}{10}$ the area of the 1962 surface. Substantial overbank deposition from the 1939 debris flow downstream of site 19 suggests that it was larger than the 1962 event. However, most material in the 1939 debris flow was transported through site 19 (some bulking may have occurred here), whereas the site is dominated by the larger sheetlike deposit of the 1962 flow. A small debris flow also occurred in 1958, but evidence was found only at the highest part of site 19. Scarred

trees adjacent to the path of the 1939 event indicate passage of coarse material in 1931 and 1952 as well, although no geomorphic evidence could be found for these two events.

SITE 20

Site 20 (fig. 3) is located at and immediately below the lower part of the area devastated by the 1962 debris flow. The stream is incised into deposits from the 1962 flow only up to about 1.5 m. The incisement abruptly becomes deeper off the 1962 surface. At site 20 the terracing (fig. 16) begins and continues to the gorge. Stepped channel fill also begins along this reach. Deposits lateral to the channel are substantially more fine grained than those upstream. The 1977, 1962, and 1958 events were confined to the channel at site 20 and downstream, occurring as small relatively coarse-grained terraces within the major channel incisement. The 1939 event deposited an intermittent sheet of fine-grained material on the topbank near the channel. Roots growing before 1939 show the thickness of the 1939 deposit (fig. 17). Evidence from tree rings was determined for events in 1898, 1873, and about 1800. The 1898 event left a continuous sheet of fine-grained material at the topbank and immediately below the 1939 deposit. The 1873 debris flow is documented only at this site and site 22 and was undoubtedly a small event. Other evidence of the 1873 debris flow was obliterated upstream by subsequent flows, particularly the 1962 debris flow. Large trees on the right bank are a cohort that became established about 1800 (fig. 15).

SITE 21, MILITARY PASS FORD

The fan at site 21 (fig. 3) is broad and extends largely to the right or south of the present channel. Debris-flow deposits more recent than 1725 become increasingly more apparent from south to north toward the channel, which suggests that the channel has shifted northward since 1725. Deposits left by the mid-1700 event are the oldest and largest debris flows on Ash Creek for which there is tree-ring evidence (fig. 16). The fan above the gorge is dominated by these deposits except at the uppermost two sites. Laterally the 1725 and mid-1700 deposits extend from near the present channel south to the Cold Creek channel and may have contributed to the formation of the Cold Creek drainage (Osterkamp and others, 1986). The mid-1700 event is termed the Cold Creek episode (Osterkamp and others, 1986). The period between 1725 and 1768 had numerous flows on Ash Creek. The largest of these events occurred about 1725, 1728, and around 1740; subsequent events until 1768 were smaller and probably related to continued upstream channel instability initiated by the massive flows occurring during the early part of the Cold

Creek episode. The present channel configuration of both Cold Creek and Ash Creek above the gorge is largely a result of the Cold Creek episode (Osterkamp and others, 1986). The more recent events documented upstream in about 1800, 1898, 1939, 1962, and 1977 are represented by terraced deposits near the present channel (fig. 16). The 1977 deposit is only a small in-channel, barlike feature and may be a lag deposit of a sediment-rich flood associated with the upstream 1977 debris flow.

SITE 22

Site 22 (fig. 3) is quite similar to site 19 in overall appearance and the deposits left by events during the Cold Creek episode dominate the fan surface except near the channel. Dendrogeomorphic evidence occurs for the 1873, 1898, 1939, 1962, and 1977 events as described for upstream sites. A portion of the channel along this reach is underlain by lava that has apparently caused even small flows to spread locally over the fan. Otherwise, the channel becomes increasingly more incised in this lower part of the upper fan.

SITE 23, JUST ABOVE JUNCTION SPRING

Site 23 (fig. 3) is not located along the main stem of Ash Creek but is an area subject to debris flows which overtop the channel incisement. Site 23 is located in a valley just above the Ash Creek gorge, which heads at upslope debris-flow deposits. The valley, particularly upstream, has been subjected to fine-grained deposition. Most large trees have partly buried trunks, which

indicate that at least 30 cm of aggradation has occurred here since the Cold Creek episode. Cohorts of trees and suppression sequences document depositional events in 1728–1740, 1898, 1939, and 1962. The most recent event may represent the smallest magnitude necessary to affect this area.

SITE 24, ASH CREEK GORGE

The gorge site 24 (fig. 3) has small depositional areas compared to sites upstream or downstream. A narrow terrace supports trees which have been scarred by events in 1898, 1939, and 1962. The debris flows of the Cold Creek episode were largely transported through the gorge and probably destroyed most trees. However, the debris-flow strata exposed on the channelward terrace edge may have been laid down during the Cold Creek episode. Coarse materials are located to about 0.5 km below the gorge. Below this secondary fan at the gorge mouth, the lower fan spreads into a fine-grained apron that extends from lower Ash Creek to the confluence with the McCloud River.

SITE 25, AT OLD MILL SITE

Site 25 (fig. 3) is located on the fine-grained lower fan and typical debris-flow features are lacking. Site 25 has only a mildly undulating surface indicative of fluvial activity. Large trees with partly buried trunks often have suppression-release sequences which suggest depositional events in 1725–28, 1800, 1898, and 1962. As is the case on lower elevation sites along Mount Shasta streams, it is difficult to infer the relative magnitude of a series of depositional events from tree-ring data.