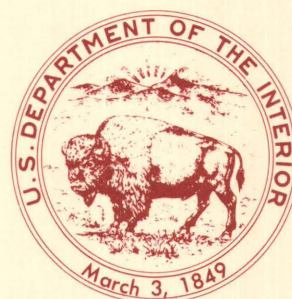


Gigantic Debris Avalanche of
Pleistocene Age From Ancestral
Mount Shasta Volcano, California, and
Debris-Avalanche Hazard Zonation

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Gigantic Debris Avalanche of Pleistocene Age From Ancestral Mount Shasta Volcano, California, and Debris-Avalanche Hazard Zonation

By DWIGHT R. CRANDELL

U.S. GEOLOGICAL SURVEY BULLETIN 1861

DEPARTMENT OF THE INTERIOR
DONALD PAUL HODEL, Secretary



U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

UNITED STATES GOVERNMENT PRINTING OFFICE: 1989

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Library of Congress Cataloging-in-Publication Data

Crandell, Dwight Raymond, 1923-
Gigantic debris avalanche of Pleistocene age from ancestral Mount Shasta volcano, California, and debris-avalanche hazard zonation.

(U.S. Geological Survey bulletin ; 1861)

Bibliography: p.

Supt. of Docs. no.: I 19.3:1861

1. Debris avalanches—California—Shasta, Mount, Region. 2. Geology, Stratigraphic—Pleistocene. 3. Geology, California—Shasta, Mount, Region. I. Title. II. Series.

QE75.B9 no. 1861 [QE599.U5] 557.3 s 88-600286
[551.2'1'0979421]

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UNITS OF MEASURE AND THEIR EQUIVALENTS

To convert metrics	Multiply by	To obtain
Micrometers	0.00003937	Inches (in.)
Centimeters (cm)	.3937	Inches (in.)
Meters (m)	3.28	Feet (ft)
Kilometers (km)	.62 (about 2/3)	Miles (mi)
Square kilometers (km ²)	.3861	Square miles (mi ²)
Cubic kilometers (km ³)	.2399 (about 1/4)	Cubic miles (mi ³)
Kilometers/hour (km/h)	.62	Miles/hour (mi/h)

Gigantic Debris Avalanche of Pleistocene Age From Ancestral Mount Shasta Volcano, California, and Debris-Avalanche Hazard Zonation

By Dwight R. Crandell

Abstract

The deposits of an exceptionally large debris avalanche extend from the base of Mount Shasta volcano northward across the floor of Shasta Valley in northern California. The debris-avalanche deposits underlie an area of about 675 km², and their estimated volume is at least 45 km³. Radiometric limiting dates suggest that the debris avalanche occurred between about 300,000 and 380,000 yr ago. Hundreds of mounds, hills, and ridges formed by the avalanche deposits are separated by flat areas that slope generally northward at about 5 m/km. The hills and ridges are formed by the block facies of the deposits, which includes masses of andesite lava tens to hundreds of meters across as well as stratigraphic successions of unconsolidated deposits of pyroclastic flows, lahars, air-fall tephra, and alluvium, which were carried intact within the debris avalanche. The northern terminus of the block facies is near Montague, at a distance of about 49 km from the present summit of the volcano. The flat areas between hills and ridges are underlain by the matrix facies, which is an unsorted and unstratified mudflowlike deposit of sand, silt, clay, and rock fragments derived chiefly from the volcano. Boulders of volcanic rock from Mount Shasta are scattered along the west side of Shasta Valley and in the part of Shasta Valley that lies north of Montague, at heights of as much as 100 m above the adjacent surface of the debris-avalanche deposits. The boulders represent a lag that was formed after the main body of the avalanche came to rest, when much of the still-fluid matrix facies drained away and flowed out of Shasta Valley down the Shasta River valley and into the Klamath River.

The debris avalanche probably originated in a quick succession of huge landslides of water-saturated rock on the northwest flank of ancestral Mount Shasta, each of which cut progressively deeper into the volcano. Evidence is lacking of contemporaneous volcanic activity, and the cause of the landslides is not known.

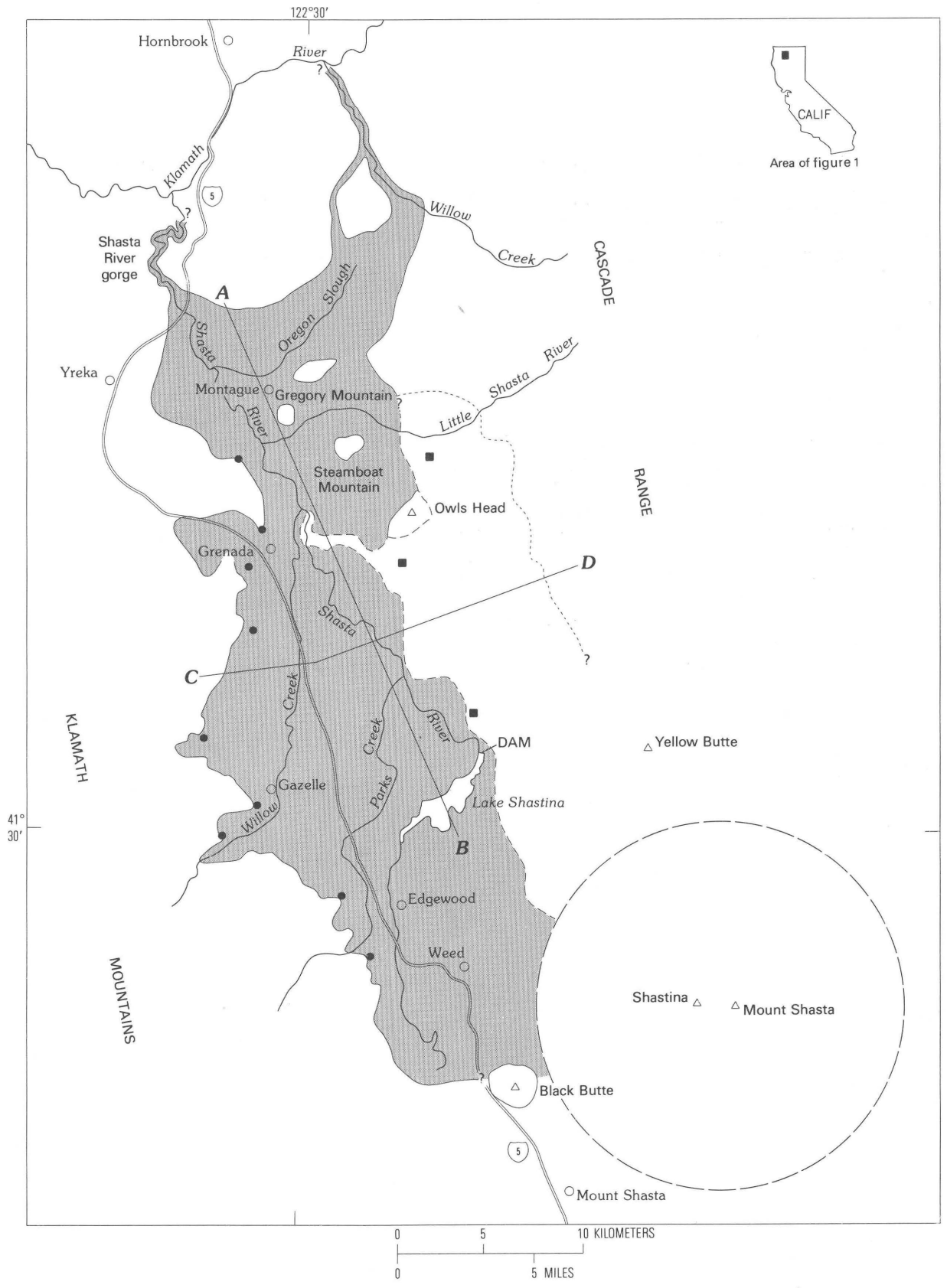
The possible lengths of future volcanic debris avalanches from Mount Shasta, as well as other volcanoes, with volumes of 1 km³ or more can be estimated from the equation $L = H/f$, where L is length, H is the altitude difference between the summit of the volcano and points 20 km downslope from it, and the value of f is 0.075. This value of f is based on the average height-to-length ratios of 11 representative volcanic debris avalanches with volumes of at least 1 km³. For the purpose of hazard assessment, a safety factor could be added to the calculated value that is commensurate with local conditions of topography, land use, and population at risk.

INTRODUCTION

The deposits of an exceptionally large prehistoric debris avalanche cover an area of at least 675 km² north of Mount Shasta in north-central California (fig. 1). Their lithology shows that the deposits were derived chiefly from an andesitic stratovolcano, which is presumed to be an ancestor of Mount Shasta. The absence of a landslide scar on the modern volcano implies that most of the ancestral volcano has been covered by products of later eruptions.

Some of the features of the avalanche deposits have been described previously (Crandell and others, 1984). My subsequent studies have revealed additional information, presented here, concerning the extent, volume, and mode of emplacement of the debris avalanche. A concluding section of this report discusses how the lengths of very large volcanic debris avalanches can be anticipated.

The term debris avalanche is used here to refer to the sudden and very rapid movement of an incoherent, unsorted mass of rock and soil mobilized by gravity (Schuster and Crandell, 1984). Movement is characterized by flowage in a dry or wet state, or both. Debris avalanches commonly originate in massive



2 Debris Avalanche, Mt. Shasta, California, Debris-Avalanche Hazard Zonation

rockslides which disintegrate during movement into fragments ranging in size from small particles to blocks hundreds of meters across. If the avalanche has a large content of water and fine material, this material may continue to flow downslope after the coarser parts of the avalanche come to rest. Thus, the texture and behavior of a debris avalanche may change between its inception and the final stages of emplacement.

TOPOGRAPHIC AND GEOLOGIC SETTING AND AGE OF THE DEBRIS AVALANCHE

The debris-avalanche deposits underlie the western two-thirds of Shasta Valley, which is a broad depression between the Klamath Mountains on the west and the Cascade Range on the east (fig. 1). The valley is drained by the Shasta River, which flows northward across the avalanche deposits and younger basaltic lava flows. The river enters a bedrock gorge in the Klamath Mountains northwest of Montague and joins the Klamath River about 10 km farther downstream. The floor of the southern part of Shasta Valley slopes northward from an altitude of a little over 900 m near Weed to about 760 m near Montague, and the part of the valley that lies north of Montague slopes gently southward. Mount Shasta volcano, which has a summit altitude of 4,316 m and an estimated volume of about 335 km³ (Williams, 1932), lies at the south end of the valley.

Shasta Valley is flanked on the west and north by complexly folded and faulted metamorphic, sedimentary, volcanic, and ultramafic rocks of Paleozoic age and by eastward-dipping marine sandstone and conglomerate of the Upper Cretaceous Hornbrook Formation (Peck and others, 1956; Hotz, 1977; Nilsen, 1984). A recent geologic map (Nilsen and others, 1983), which includes the northern part of Shasta Valley, shows the Hornbrook to dip 5–17° generally easterly in the area east of Yreka.

Volcanic rocks of Tertiary age border the north and east sides of Shasta Valley and also form a few hills that rise above the central part of the valley floor, such as

Figure 1 (facing page). Inferred minimum extent of debris-avalanche deposits (shaded) in Shasta Valley. Dashed circle, which represents the approximate base of Mount Shasta, is at about the 4,400-ft contour on the northwest side of the volcano. Short-dashed line along east margin of deposits is the western edge of post-avalanche lava flows; dotted line farther east is at an altitude similar to the maximum inferred height of the debris avalanche on the west side of Shasta Valley. Solid squares are mounds of avalanche deposits surrounded by lava; solid circles are blocks of Mount Shasta andesite along west side of Shasta Valley (see text). Lines A–B and C–D show locations of topographic profiles across the avalanche deposits.

Steamboat Mountain and Owls Head. Gregory Mountain at Montague is a cylindrical neck or plug of hornblende andesite (Hotz, 1977).

Steamboat Mountain (fig. 1) is shown on the geologic map of Nilsen and others (1983) to be underlain by volcanic rocks of Tertiary(?) age. However, sedimentary rocks of the Hornbrook Formation crop out on the eastern slopes of the mountain topographically lower than the volcanic rocks, which cap the mountain. At one point on the eastern side of Steamboat Mountain these sedimentary rocks strike nearly due north and dip about 15° east. The presence of the Hornbrook near the center of Shasta Valley suggests that the valley south of Montague is largely underlain by that formation.

The avalanche deposits are overlain on the east by basaltic lava flows and on the south by andesitic lava flows, lahars, and alluvium from Mount Shasta.

Modern Mount Shasta is made up of at least four overlapping cones, the oldest of which is more than 100,000 yr old and forms the south flank of the volcano (Christiansen and others, 1977). Even this oldest cone, however, probably postdates the debris-avalanche deposits in Shasta Valley and may itself represent more than one “evolutionary cycle” in the growth of Mount Shasta (Christiansen and others, 1977, p. 15; oral commun., 1986). Volcanic rocks that evidently are older than this cone, and that predate the debris avalanche, crop out at the west base of the volcano (Crandell and others, 1984). A sample of these rocks collected by R.L. Christiansen and potassium-argon dated by G.B. Dalrymple of the U.S. Geological Survey had an age of 593,000±41,000 yr.

The age of the avalanche is roughly bracketed by radiometric dates on rocks within the avalanche deposits and on a postavalanche lava flow. Charles Chesterman of the California Division of Mines and Geology collected samples for potassium-argon dating from two andesite blocks within the avalanche deposit. These rocks were analyzed by James Aronson of Case Western Reserve University, who reported ages of 360,000±40,000 and 380,000±60,000 yr (Crandell and others, 1984). A basalt lava flow that locally overlies the avalanche deposits was dated by Aronson as 300,000±100,000 yr old. Thus, the debris avalanche seems to be between roughly 300,000 and 380,000 yr old. This age is consistent with the presence, within the avalanche deposits, of clasts of a volcanic ash, described subsequently, that is about 400,000 yr old.

PREVIOUS INTERPRETATIONS OF THE GEOLOGY AND TOPOGRAPHY OF SHASTA VALLEY

The numerous mounds, hills, and ridges of Shasta Valley (figs. 2, 3, 4) have puzzled geologists for many

years. Diller and others (1915) noted that the hills consist of volcanic rock and stated that they “appear to be, in part at least, the products of minor and local eruptions that broke through the Cretaceous beds, each vent contributing its little pile of material.” Fenner (1923) subsequently proposed that a shallow sill had been intruded beneath Shasta Valley and that small bodies of magma rose from the sill to the surface to form the individual hills. These geologists evidently did not recognize the Mount Shasta provenance of the rocks that form the hills and their cogenetic relation to the mud-flowlike material that veneers the hills and underlies the flat surfaces between them.

Williams (1949, pl. 1) mapped the hills and ridges between the base of Mount Shasta and Lake Shastina as moraines formed by a glacier of Tioga age, which moved into Shasta Valley from the northwestern slopes of the volcano. His geologic map shows the northernmost moraine to coincide with the hills along the south side of Lake Shastina, and flat areas between the hills are shown as “fluvioglacial outwash” of Pleistocene age. The long ridge north of Lake Shastina is mapped as “Western Cascade flows and tuff-breccias” of Tertiary age, as are the hills and ridges to the north. Flat areas between these hills are shown as alluvium. The region north of Lake Shastina was aptly described by Williams (1949, p. 11) as “volcanic rocks eroded into a myriad of hillocks that range from a few feet to 200 and rarely to 300 feet in height. Most of these hillocks are domical, some are conical, others are mesas, and a few are long hogback ridges. Together they form a strange landscape, deceptively like the products of recent volcanic activity.”

Although Williams inferred that the Western Cascade volcanic rocks of Shasta Valley dip generally eastward, he (Williams, 1949, p. 53) noted that “the trouble is that the Western Cascade lavas [blocks in the debris-avalanche deposits] in the western half of Shasta Valley show no well-defined dips, and in the other half are buried by Recent flows.”

Williams’ interpretations were accepted by Mack (1960), whose geologic map shows the area south of Lake Shastina to be underlain by “morainal deposits” and the hills to the north to be “volcanic rocks of the Western Cascades.” Mack’s map shows most flat areas between hills and ridges as “younger alluvium” of “Recent” age, although terraces northwest of Weed are shown as “fluvioglacial deposits.” Mack (1960, p. 44) described an outcrop in the ridge bordering the northwest side of Lake Shastina as “deposits of stratified drift which were probably laid down in contact with the wasting glacial ice.” Mack’s “stratified drift” consists of the deposits of pyroclastic flows and lahars, alluvium, and beds of air-fall tephra (Crandell and others, 1984; this report, fig. 9).

Hotz (1977, p. 55–56) also agreed with Williams’ interpretation of the Shasta Valley landscape and stated, “The many small conical hills in Shasta Valley***are erosional remnants of an extensive blanket of andesitic tuff breccia” which apparently represent a continuation of the Western Cascade volcanic series of Tertiary age mapped by Williams (1949). Hotz noted that most outcrops in the hills reveal “a jumbled accumulation of blocks of volcanic rock as much as 1.5 m across,” and he went on to describe the lithology of the volcanic rocks. Hotz mapped the interhill areas as “alluvium of Shasta Valley,” and noted that the alluvium does not extend into the valleys to the west. He suggested that the alluvium is of glaciofluvial origin and was deposited by meltwater from glaciers in the Klamath Mountains southwest of Weed and on Mount Shasta.

Christiansen (1982) briefly mentioned the unusual topography of Shasta Valley and suggested that it originated from a large debris avalanche from Mount Shasta. Subsequent field studies by myself and my colleagues (Crandell and others, 1983, 1984) verified the debris-avalanche origin of the topography. Evidence that bears on this conclusion is as follows.

- (1) The unusual morphology of Shasta Valley is unlike that normally produced by stream erosion, and local closed depressions among the hills and ridges seem, in fact, to rule out this mode of origin.
- (2) The presence of stratigraphic successions of volcanoclastic deposits within hills and ridges, and their widely variable structure from place to place, suggest that these deposits are not in place.
- (3) Most rocks in the hills and ridges are pyroxene andesites similar to those of modern Mount Shasta volcano.
- (4) The presence between hills of a mudflowlike deposit that contains rocks of similar lithology to those in the hills suggests that all these deposits had a similar origin.
- (5) The morphology of the deposits on the Shasta Valley floor resembles that of known debris avalanches elsewhere.

DESCRIPTION OF THE DEBRIS-AVALANCHE DEPOSITS

The debris-avalanche deposits of Shasta Valley include two texturally distinct parts, which are referred to as the block facies and the matrix facies (Crandell and others, 1984). The block facies is responsible for the hundreds of mounds, hills, and ridges that dot the surface of the avalanche deposits; the matrix facies veneers these

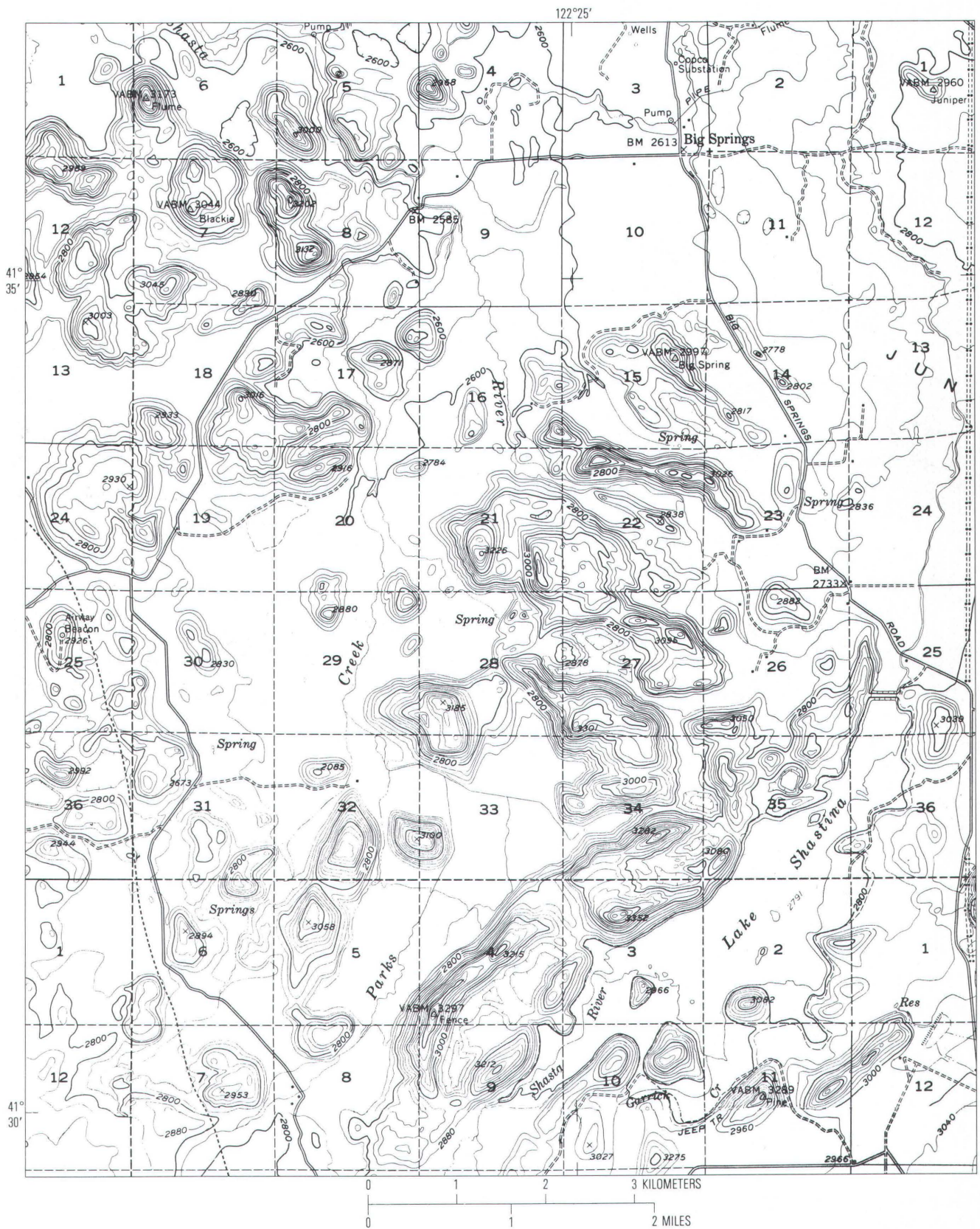


Figure 2. Topographic map of the southwestern part of the Lake Shastina 15' quadrangle and the northwestern part of the Weed 15' quadrangle, both published by the U.S. Geological Survey in 1954, showing the morphology of the debris-avalanche deposits. The hills are formed by the block facies, and flat areas are underlain by the matrix facies. The summit of Mount Shasta is about 20 km southeast of Lake Shastina. The approximate location of U.S. Interstate 5 is shown by the dotted line.



Figure 3. View southward from top of Gregory Mountain toward hills and flat areas formed by the debris avalanche. Black Butte, at the west base of Mount Shasta, is a volcanic dome formed about 9,500 yr ago (Miller, 1978).

landforms, underlies flat areas between them, and is inferred to enclose the lower parts of the blocks that characterize the block facies.

Matrix Facies

The matrix facies consists of an unsorted and unstratified mixture of pebbles, cobbles, and boulders in compact silty sand; texturally it resembles the deposit of a mudflow (fig. 5). A single sample of the matrix from a locality about 0.5 km west of Edgewood contained about 54 percent sand, 20 percent silt, and 12 percent clay, and the remainder consisted of material coarser than sand. Virtually all boulders and most cobbles in the matrix facies are pyroxene andesites similar to those that make up the present Mount Shasta volcano. At the Edgewood locality, nearly all clasts are angular to subangular regardless of their lithology.

At a locality about 32 km farther north, near Montague, most pebbles and cobbles of Mount Shasta

rocks are angular to subangular and have rough surfaces, whereas nearly all clasts of non-Shasta rocks are round to subround and have smooth surfaces suggestive of abrasion during stream transport. These non-Shasta clasts presumably were picked up by the avalanche from alluvium on the floor of Shasta Valley.

Pebbles in the matrix facies consist of rocks wholly or chiefly derived from ancestral Mount Shasta within a distance of 22 km from the summit of the present volcano, and include smaller percentages at greater distances (table 1, fig. 6). Samples 1, 3, and 4, which seem to contain only rocks derived from ancestral Mount Shasta, were each taken from the matrix facies on ridges near the base of the volcano. Sample 10 was obtained from the matrix facies at an outcrop in the Shasta River gorge; only 25 percent of the pebbles in it are of Mount Shasta rock types. I attribute the northward increase of percentages of non-Shasta rocks to scour and incorporation of preexisting deposits by the avalanche.



Figure 4. View southeastward from a hill about 6 km northwest of Lake Shastina, showing the morphology of the debris-avalanche deposits. The hills in the middle distance are formed by the block facies, and the valley floor of Parks Creek in the foreground is underlain by the matrix facies. The hill at the left is about 190 m high. Black Butte is at the far right.



Figure 5. Matrix facies of debris-avalanche deposits exposed in gully west of Edgewood (see fig. 7 for aerial view of location).

In addition to pebbles, cobbles, and boulders of volcanic rock from Mount Shasta, and a variety of rocks

from bedrock formations of Cretaceous and pre-Cretaceous age, the matrix facies of the debris avalanche in the Montague area locally contains clasts of compact but unconsolidated diatomite, laminated silt, and volcanic ash. A sample of volcanic ash taken from a clast within the matrix facies at a small quarry 1.3 km northwest of Montague was examined by Andrei Sarna-Wojcicki and his associates Charles Meyer and Robert Fehr, all of the U.S. Geological Survey (A. Sarna-Wojcicki, written commun., 1987) (see appendix "Volcanic Ash Analysis"). From their examination, Sarna-Wojcicki concluded that the ash is petrographically and chemically similar to an ash bed that was found at a depth of about 59 m in a core at Tule Lake, Calif. That ash is correlated with the Rockland ash, which was erupted from a vent in the Lassen Peak area of northern California, about 160 km southeast of Montague. The probable age of the Rockland ash is about 400,000 yr, based on fission-track dating of zircons in it (Sarna-Wojcicki and others, 1985).

Table 1. Percentages of pebbles from Mount Shasta in the matrix facies at various distances from the summit of the volcano, based on identification of 100 pebbles at each location

[The sample sites are shown on figure 6]

Sample site	Distance from summit (km)	Rocks from Mount Shasta	Other rocks	Not identified
1	17	100	0	0
2	21	84	11	5
3	21	98	0	2
4	22	98	0	2
5	28	35	62	3
6	42	40	60	0
7	44	41	50	9
8	47	47	53	0
9	50	45	53	2
10	55	25	71	4

At a road cut on the west side of the Shasta River, 5 km northwest of Montague, the matrix facies overlies an unconsolidated deposit of oxidized sand and gravel which seems to be part of an alluvial fan. Incorporated in the matrix facies here are masses several meters in diameter of similar sand and gravel. A few clasts consist of diatomite, laminated silt, and volcanic ash. Fossils of aquatic organisms, which are described subsequently, were noted in the matrix facies here and elsewhere in the Montague area.

A nearly horizontal 40 × 80 × 110-cm clast of volcanic ash in this road cut was examined in 1987. The clast lies 35 cm above the base of the avalanche deposit. Ash in the basal 19 cm of the clast is of fine to very fine sand size, whereas the upper part is of silt and possibly also of clay size. The upward decrease in grain size suggests that the basal part of the clast includes the lower part of the original ash bed. Faint bedding in the upper 10 cm of the ash indicates that the smallest dimension of the clast, 40 cm, represents a minimum thickness of the original ash layer. The ash is enclosed by the matrix facies, and its original base and top may not be present. Fossil gastropods are abundant along a horizon 1 cm below the top of the ash. In mineralogy and texture the ash resembles that from the quarry near Montague, and it probably is also correlative with the Rockland ash. The bedding and fossils in the ash suggest that it was deposited in a lake on the floor of Shasta Valley.

The fine-grained component of the matrix evidently is made up of several constituents, including pulverized volcanic rock as well as silt and sand derived from the Hornbrook Formation and alluvial and lacustrine sediments incorporated by the avalanche as it traversed the floor of Shasta Valley.

The matrix facies forms nearly flat surfaces which surround hills and ridges and which also extend westward beyond the hills to the side of Shasta Valley. These surfaces slope northward about 5 m/km in the western part of Shasta Valley, and represent the original depositional surface of the matrix facies rather than postavalanche stream erosion. Deposits of the matrix facies are inferred to be present along the east side of the avalanche but have been buried to depths of 20–90 m in that area by postavalanche lava.

The surface of the matrix facies locally displays areas of circular mounds, the most prominent of which is 1–2 km west and northwest of Edgewood (fig. 7). In that area, mounds roughly 10–30 m in diameter and as much as 60 cm high cover the nearly flat surface of the matrix facies in an area adjacent to and some 22 m higher than the Shasta River. Few large clasts are present on the mounds, but accumulations of cobbles and boulders occur around the perimeter of each mound. Masson (1949) attributed the formation of the mounds to the freeze and thaw of water-saturated soil; they probably were formed during a climate colder than that of the present.

Block Facies

The block facies of the debris-avalanche deposits occurs in a band as much as 12.5 km wide which extends north-northwestward to the vicinity of Montague (fig. 6), where the northernmost large block from Mount Shasta is at a distance of about 49 km from the present summit of the volcano. The block facies includes individual andesite blocks ranging in size from tens to hundreds of meters in maximum dimension, many of which are shattered, and masses of similar size of coherent but unconsolidated volcanoclastic deposits. Chemical analyses reported by Hotz (1977, p. 57) of rocks in blocks at seven localities near Montague show a range of 61–62.8 percent SiO₂.

Some hills are formed by one or more large blocks of a single rock type, and other hills are formed by lithologically dissimilar blocks. Continuous stratigraphic successions of lava flows can be recognized on the flanks of some hills (fig. 8). Other hills and ridges contain unconsolidated volcanoclastic deposits which are in their original stratigraphic succession and which remained coherent during transportation despite their low shear strength.

One such succession, exposed in a pit on the east side of the north-trending ridge adjacent to the west abutment of Lake Shastina dam (fig. 9), includes the deposits of pyroclastic flows, lahars, air-fall tephra, and alluvium. Buried soils in these units are right side up (fig. 10). Most units in the succession exposed in the pit dip

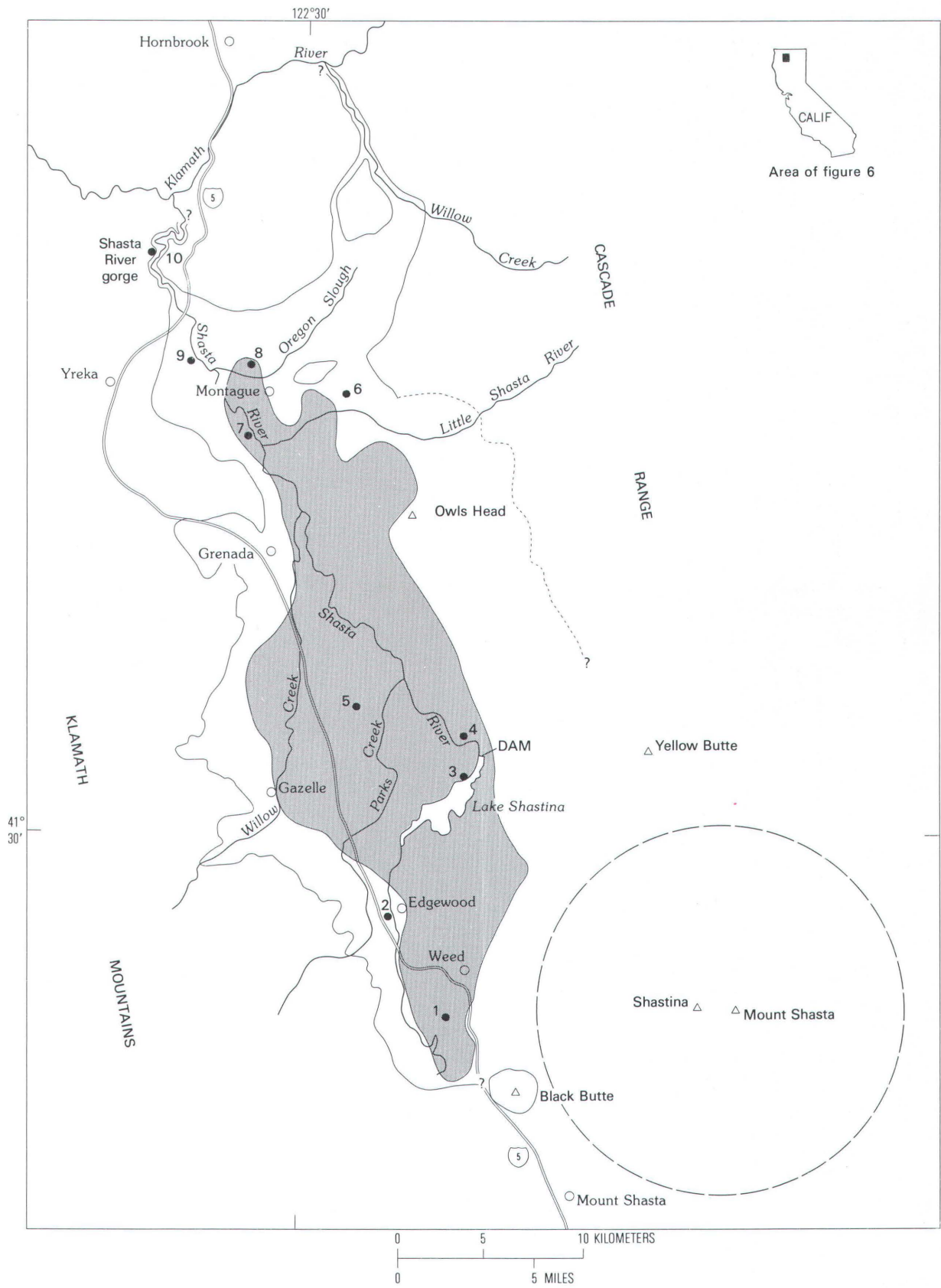


Figure 6. Map showing localities (numbered dots) at which pebbles in the matrix facies were identified (table 1) and the inferred extent (shaded) of the block facies.



Figure 7. Aerial view eastward of mounds on the surface of the matrix facies, 0.5 km west of the community of Edgewood, which is at upper right. U.S. Interstate 5 is in the center of the photograph, and the gully at right center is the location of figure 5.

20–25° westward. They are displaced as much as 20 m by normal faults which strike roughly parallel to the northward trend of the ridge. Most faults that are east of the axis of the ridge dip steeply eastward, and those that are west of the axis dip 50–60° westward. The northerly strike of most of the faults, parallel to the ridge crest, and the dips and downward displacements toward the flanks of the ridge suggest that the faulting occurred after the ridge-forming block was emplaced. Faulting may have resulted from adjustment of the settling block to the underlying surface.

Similar successions of unconsolidated deposits are exposed in road cuts through ridges west of Weed along U.S. Interstate 5. Most units exposed in the westernmost cut are east-dipping lithic pyroclastic-flow deposits which are broken by steeply west dipping normal faults (fig. 11). The deposits in the next road cut to the east are of similar origin but dip westward.

Individual hills formed by the avalanche deposits become smaller northward, probably as a consequence of the progressive disaggregation of blocks during

transport. The northernmost part of the block facies is represented by scattered large blocks of gray andesite in the area near Montague. Some of these blocks are more than 100 m across and more than 10 m thick, and some have been used as sources of crushed rock.

Blocks of andesite enclosed by matrix facies were exposed prior to 1987 in the walls of the quarry 1.3 km northwest of Montague (fig. 12). Some of these blocks were broken by cracks less than one to several tens of centimeters wide, which were filled with material of the matrix facies. From their study of cracks within blocks of the Shasta Valley avalanche deposits, Ui and Glicken (1986) concluded that most cracks like these did not result from transport within the avalanche, but had been formed primarily on or near the volcano, and were then progressively opened during transport.

This quarry is near the terminus of the block facies of the debris avalanche, in an area where the matrix facies of the avalanche had been at least 50 m deep before most of it drained away. An outcrop of pre-avalanche gravel a few hundred meters east of the pit

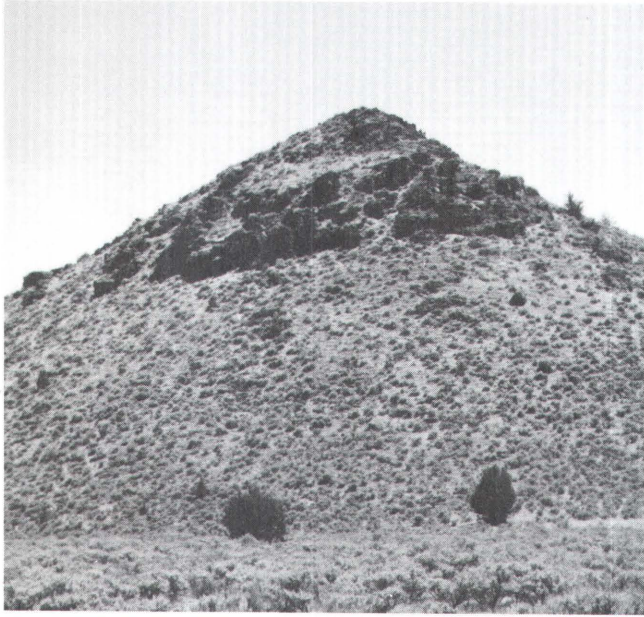


Figure 8. View of north side of a hill 7.5 km northwest of Lake Shastina. A succession of three lava flows crops out high on the hillside. The hill is about 100 m high.

indicates that the matrix facies between mounds in that area is now locally less than 1 m thick.

The transportation of intact stratigraphic successions of lava flows and volcanoclastic deposits has been described in other volcanic debris-avalanche deposits. Internally coherent blocks as much as 2.5 km long and 1 km wide are present in the deposit of a debris avalanche from Socompa volcano in northern Chile, which occurred about 7,500 yr ago (Francis and others, 1985; Francis and Self, 1987). These blocks apparently slumped and rotated without internal disruption during their movement from near the summit of the volcano 5–10 km to its base and now lie at the mouth of the amphitheater produced by the debris avalanche. Likewise, some blocks in a very large debris-avalanche deposit at Popocatepetl in Mexico are formed by lava flows in their original stratigraphic succession (Robin and Boudal, 1987). Megablocks also were transported intact in the prehistoric Nirasaki debris avalanche in Japan for distances of more than 20 km (Mimura and others, 1982). Measurements of remanent magnetism on units within these blocks indicate that the blocks had rotated in a horizontal, but not vertical, plane during transport. Sketches of outcrops of these blocks show that they are broken by many vertical faults of small displacement (Mimura and others, 1982, fig. 3). Many blocks in the May 18, 1980 debris avalanche from Mount St. Helens display fragile stratigraphic or structural features that had been formed on or within the volcano, and their preservation during avalanche transport has been attributed to laminar “plug” flow (Voight and

others, 1981, p. 360). Davies (1982) postulated that the main zone of shearing in a moving sturzstrom (debris avalanche) is close to its base; consequently, rocks shattered during the initial fall from the source can be carried in the main body of the avalanche long distances without becoming widely separated.

FOSSILS IN THE MATRIX FACIES

Fossils of aquatic organisms were found in the matrix facies of the debris-avalanche deposits at eight localities in the Montague area. A sample of this facies obtained from about 0.5 m above the base of the deposit at a road cut on the west side of the Shasta River valley 5 km northwest of Montague contained ostracodes, gastropods, bivalves, bones and scales of fish, and diatoms. According to Richard M. Forester, U.S. Geological Survey, the diatoms are present both in the matrix of the debris avalanche and in fragments of diatomite within the sample. Forester reported identifying the following ostracode taxa: *Candona patzcuaro* Tressler, *Limnocythere itasca* Cole, *Limnocythere sappanensis* Stapin, and *Candona candata*?. In addition, *Cytheromorpha*, sp. undetermined, was identified; this is an estuarine or shallow-marine ostracode of unknown age. Forester reported that the first four ostracode taxa are common inhabitants of shallow, often ephemeral, lacustrine environments. The species are not usually found in fluvial environments but could live in a low-energy fluvial setting. They have a broad tolerance for temperature differences and could exist in temperate continental climate. These fossils, as well as those of gastropods, fish, and bivalves, probably were present in soft lacustrine and fluvial sediments on the floor of Shasta Valley and were incorporated when the debris avalanche moved across these deposits.

The presence of these fossils in the matrix facies suggests that when the debris avalanche occurred, the floor of Shasta Valley was of low relief and locally occupied by small lakes and low-gradient streams. The valley floor then, as now, probably was flanked by alluvial fans debouching from adjacent bedrock hills.

DISTRIBUTION OF THE DEBRIS-AVALANCHE DEPOSITS

The debris-avalanche deposits were initially recognized only in the central part of Shasta Valley upstream from the Shasta River gorge, although it was inferred that the matrix facies of the avalanche moved downstream to the Klamath River (Crandell and others, 1984). Subsequent investigations have revealed avalanche deposits in three additional areas: along the



Figure 9. Block of volcaniclastic deposits exposed in the south side of a borrow pit west of Lake Shastina dam. The block includes the deposits of pyroclastic flows, lahars, air-fall tephra, and alluvium. These units dip 20–25° west (toward the right), and are displaced by faults (dashed lines) that dip toward the east and west sides of the ridge. Arrows show the direction of displacement along the faults.

lower west flank of Shasta Valley, within the Shasta River gorge, and in the part of Shasta Valley that lies north of Montague.

Boulders of volcanic rock from Mount Shasta from less than a meter to several meters in diameter are scattered along the west side of Shasta Valley in areas adjacent to and upslope from the main body of the avalanche deposits. These boulders were noted at 17 sites at heights of as much as 95 m above the adjacent Shasta Valley floor, which is underlain by the matrix facies of the avalanche, but the matrix facies was not found in conjunction with any of the boulders. Although some blocks could have been carried to their present location by man, others obviously were not, inasmuch as they weigh many tons. The boulders are not a lag left by stream erosion and mass-wasting processes that removed a deposit that was originally tens of meters thick; evidently the boulders were left when the matrix facies that transported them drained away downslope.

The altitudes of the highest boulders at 13 localities along the west side of Shasta Valley, projected eastward to the axis of the debris-avalanche deposits, form a reasonably straight north-sloping longitudinal profile from a point northwest of Weed to a point northwest of Montague (fig. 13, profile *A–B*). The slope of this profile roughly parallels the present surface slope of the matrix facies of the debris-avalanche deposits. North of the position of the Shasta River indicated on the profile, the tops of hills formed by the block facies are no higher than the crest of the moving debris avalanche, but to the south some hills and ridges extend as much as 90 m above the profile (fig. 13, profiles *A–B* and *C–D*). Profiles *A–B* and *C–D* were constructed by assuming that the top of the moving debris avalanche was flat; however, it may have been somewhat convex. The heights of the profiles imply that many blocks were carried completely submerged, whereas others were only partly submerged and “floating” in the matrix facies.



Figure 10. A buried soil (behind the pick) is represented by yellowish-brown oxidation in the upper part of a pyroclastic-flow deposit exposed in the borrow pit west of Lake Shastina dam. The deposit contains abundant breadcrusted bombs.

Profile *A–B* seems to record the crest of the matrix facies during flowage. The profile probably does not represent a static condition—that is, a time when the entire valley was simultaneously filled with mud and rock debris to that height. Instead, the profile probably marks the crest of a wave which left behind a veneer of matrix or scattered boulders, or both, after it passed downvalley. Such deposits are analogous to those left tens to hundreds of meters high on valley walls after the down-valley flowage of very large lahars at Mount Rainier, which originated in debris avalanches from the volcano (Crandell, 1971, p. 7).

Although the block facies of the debris avalanche from ancestral Mount Shasta reached only to the vicinity of Montague, two lobes of the matrix facies continued farther. One extended northwestward into the Shasta River gorge, and the other moved into the northern part of Shasta Valley. A remnant of the matrix facies was found in a road cut on the west side of the Shasta River gorge about 3.5 km downstream from the upper end of

the gorge. Upslope from the road, boulders of Mount Shasta rocks litter the side of the gorge to a height of about 43 m above the Shasta River. About 1 km farther downstream, similar boulders on the east side of the gorge extend from near river level up to a maximum height of about 88 m above the river. At this height, the gorge is about 500 m wide. The boulders here, some of which are as much as 1 m in diameter, veneer the inside of a U-shaped bend in the gorge.

The presence of these remnants of the matrix facies within the Shasta River gorge indicates that the gorge was virtually as deep when the debris avalanche occurred as it is today, and that the matrix facies was locally at least 88 m deep as it flowed down the gorge. The absence in the gorge of a fill terrace formed by the matrix facies suggests that after the crest of the flow passed, most of it drained on downstream, leaving behind only bouldery veneers on the gorge walls.

The northern lobe of the matrix facies moved into the part of Shasta Valley that lies north of Montague, crossed a low divide, and drained into a tributary of the Klamath River. The avalanche in this area is represented by abundant scattered boulders of volcanic rock from Mount Shasta. Although outcrops of the matrix facies were not recognized in that part of Shasta Valley, drillers' logs of water wells record the presence of 6–20 m of deposits which seem to represent that facies. No mound- or hill-forming blocks of the avalanche were recognized in that area. The highest boulders in that part of Shasta Valley are at an altitude of about 823 m (2,700 ft), which is 15–30 m higher than the valley floor and about 8 m lower than the inferred maximum crest height of the moving matrix facies near Montague (fig. 13). At the north end of Shasta Valley, the matrix facies crossed a divide at an altitude of about 808 m (2,650 ft) and spilled into the north-trending valley of Willow Creek. Scattered boulders are present along Willow Creek at least as far as downstream as a point about 2 km from the Klamath River. At that point, boulders of volcanic rock from Mount Shasta are as high as 17 m above Willow Creek. This location is about 52 km from the northern base of Mount Shasta and about 64 km from its summit; the boulders are at an altitude of about 670 m (about 2,200 ft), which is about 3,600 m lower than the present summit of the volcano.

The vertical distribution of the boulders in the northern part of Shasta Valley and the deposits encountered in drill holes indicate that the matrix facies was at least 50 m deep when it flowed northward across that area. Northward flowage ceased when the crest of the matrix facies progressed down Shasta Valley beyond Montague and moved into the Shasta River gorge; some of the matrix facies in the northern part of the valley then drained back to the southwest. North of Montague, the floor of Shasta Valley now slopes about 4 m/km



Figure 11. Block of volcaniclastic deposits exposed in a road cut along U.S. Interstate 5 west of Weed. The deposits dip east and are displaced along west-dipping faults. The pinkish-gray zone in the left center of the photograph is the thermally altered top of a pyroclastic-flow deposit.

southwestward, which is a slightly lower gradient than that in the valley south of Montague (about 5 m/km).

Although the matrix facies must have moved into the Klamath River along Willow Creek as well as the Shasta River, a road reconnaissance of the Klamath River valley between the mouth of the Shasta River and the Pacific Ocean failed to identify any deposits that contain rocks from Mount Shasta.

EXTENT, THICKNESS, AND VOLUME OF THE DEPOSITS

The area covered by the debris-avalanche deposits was initially estimated to be at least 450 km² between the base of Mount Shasta, at an assumed altitude of 1,220 m (about 4,000 ft), and the head of the Shasta River gorge (Crandell and others, 1984). Subsequent investigations, however, show that the debris-avalanche deposits underlie a total area of at least 675 km².

No remnants of the debris-avalanche deposits have been recognized on the lower slopes of the volcano

northeast of Weed. The last blocks of the debris avalanche probably had so much kinetic energy that they moved to or beyond the foot of the volcano. However, postavalanche lava flows, domes, and deposits of pyroclastic flows and lahars blanket areas upslope from the southernmost blocks and may cover avalanche deposits in those areas.

The eastward extent of the avalanche deposits is poorly known because of the presence of one or more postavalanche lava flows. Although hummocks of the debris avalanche protrude through the lava at a few places, none of these are more than a few kilometers from the boundary between the avalanche deposits and the lava. Nevertheless, the deposits are inferred to extend beneath the lava for two reasons. First, the scattered boulders of rock from Mount Shasta along the west side of Shasta Valley indicate that the avalanche was thicker during movement than it is now, and should have spread eastward to a height roughly similar to that on its west side (fig. 1). Second, logs of water wells drilled through the lava describe deposits, discussed subsequently, that



Figure 12. Blocks of andesite from Mount Shasta enclosed within and resting on matrix facies (yellow). Note the pervasive shattering of the blocks of red and gray andesite. This outcrop in a small quarry 1.3 km northwest of Montague was destroyed during quarrying operations in 1987.

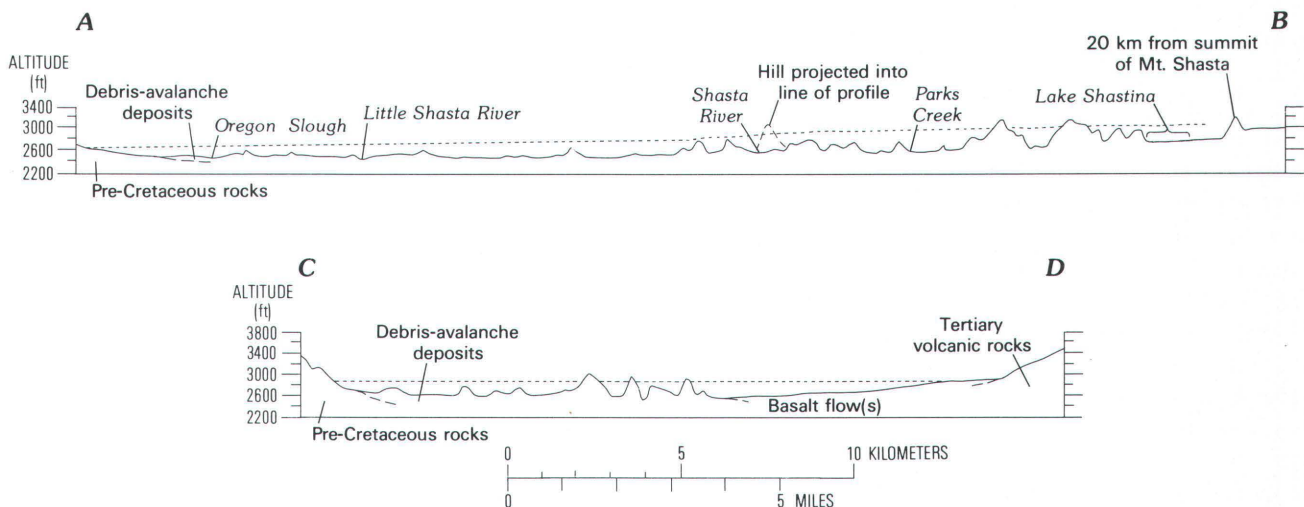


Figure 13. Longitudinal (A–B) and transverse (C–D) topographic profiles of the debris-avalanche deposits, and profile of the inferred upper surface of the avalanche (dotted line) during emplacement. The profiles are located on figure 1 and have a vertical exaggeration of 5x. On profile A–B, note that the tops of hills north (to the left) of the Shasta River are all below the dotted line, but some to the south are above the line.

Table 2. Extent and thickness, inferred from well logs, and estimated volume of the debris avalanche in seven areas

Area	Extent (km ²)	Maximum thickness (m)	Average thickness (m)	Volume (km ³)
A	118.3	> 120	75	8.87
B.....	146.3	> 105	100	14.63
C.....	100.2	> 77	75	7.52
D	132.1	> 61	50	6.61
E.....	8.0	> 26	25	0.45
F.....	127.3	> 26	25	3.18
G	34.0	> 21	15	0.51
Totals.....	676.2			41.77

are inferred to represent the debris avalanche. Boulders derived from Mount Shasta were not found on surfaces east of the lava flows.

An average thickness of 50 m was originally estimated from logs of water wells reported by Mack (1960), and the volume of the deposits was calculated to be at least 26 km³ (Crandell and others, 1984). This figure included a volume of 4 km³ that is represented by the hills and ridges of the avalanche.

In 1985, I inspected more than 200 drillers' logs of water wells in Shasta Valley at the Red Bluff office of the California Department of Water Resources. Most of these wells were completed after 1960, so they supplement those reported by Mack. Each well log was examined for possible deposits of the debris avalanche, and the well site was plotted on a base map of Shasta Valley. The debris avalanche is recorded in these logs by such terms as clay and gravel, clay and boulders, clay and rock, and lava and clay, and in some logs by interbedding of these materials with "lava rock." The "lava rock" recorded in some drill holes probably consists of blocks from Mount Shasta which are suspended in the matrix facies.

The debris-avalanche deposits were divided into seven areas (fig. 14), and the extent, maximum and average thicknesses, and volume were estimated for each area (table 2). The area of greatest uncertainty is area F, much of which is directly underlain by postavalanche lava. One driller's log of a well in the northern part of area F records the debris avalanche ("Volcanic cong. and boulders") overlying Hornbrook Formation ("brown sandstone") at a depth of 143 ft (43.6 m), and other wells in area F, after penetrating 100–359 ft (30.5–109.5 m) of lavas, evidently bottomed in debris-avalanche deposits more than 85 ft (26 m) thick. Some of the "lavas" penetrated in these wells probably are blocks within the debris-avalanche deposit. An average thickness of the deposit of 25 m in this area probably is a conservative estimate. Some drill holes in area F ended in "clay and gravel" or "clay and rock," terms that are inferred to represent debris-avalanche deposits. Other drill holes

ended in "clay," but it is not known whether this term refers to the matrix facies of the debris avalanche or to lacustrine deposits on the floor of the preavalanche Shasta Valley.

The estimated volume of the debris-avalanche deposits beneath the present floor of Shasta Valley is 41.77 km³, to which is added a calculated volume of 4 km³ represented by the hills and ridges formed by the block facies; thus, the total volume of the debris-avalanche deposits is estimated to be at least 45 km³. This is the largest of the volcanic debris avalanches tabulated by Siebert and others (1987) and is also larger than a debris avalanche (described as a debris flow) from Popocatepetl, which has recently been described by Robin and Boudal (1987). That deposit, which is inferred to be 30,000–50,000 yr old, has an estimated volume of about 28 km³, similar to that of the Socompa debris avalanche in Chile (Francis and Self, 1987).

ORIGIN OF MORPHOLOGY AND DRAINAGE ON THE DEPOSITS

The morphology of the Shasta Valley debris-avalanche deposits evidently has changed little since their formation at least 300,000 yr ago. The Shasta River has cut down about 22 m into the flat-topped matrix facies near Edgewood, and a similar amount northwest of Montague. The lack of a well-integrated drainage system and absence of deep and widespread dissection of the deposits are due to the gently sloping surface of the matrix facies and to the presence of resistant rock in the bed of the Shasta River at the head of the gorge 8.5 km northwest of Montague. This bedrock threshold is the base level for the upstream part of the Shasta River drainage basin. The relatively dry climate of the area, with average annual precipitation ranging from about 51 cm at Edgewood to about 30 cm at Montague (Mack, 1960, p. 14), also inhibits erosional modification of the deposits.

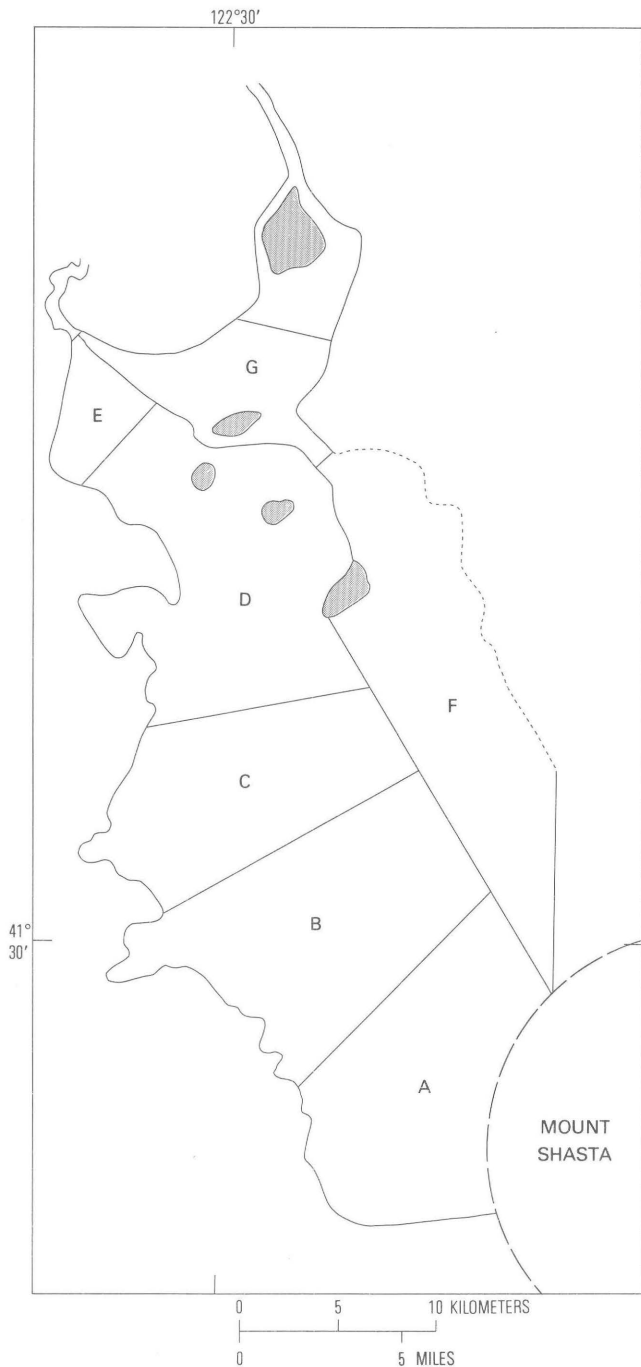


Figure 14. Subdivisions used in estimating average thickness and volume of debris-avalanche deposits. The long dashed line is the approximate base of Mount Shasta; the dotted line is the approximate eastern margin of the avalanche deposits inferred from an eastward projection of maximum altitudes of boulders on the west side of Shasta Valley (see text). Shaded areas were not covered by the debris avalanche.

The hundreds of hills and ridges of the debris avalanche are its most conspicuous morphologic

features. Many hills and ridges seem to occur in clusters whose long axes are transverse to the direction of avalanche movement (fig. 15). The clusters are distributed along the axial part of the debris avalanche and are partly or wholly bordered by flat areas underlain by the matrix facies. Ridges within some clusters have trends that are transverse to the direction of avalanche movement, ridges in other clusters are mostly aligned in the direction of movement, and those in still other clusters seem to have random trends.

A cluster of hills and ridges southwest of Weed seems to be an avalanche-marginal feature (fig. 16). Although most ridges in the cluster trend northward, a northeast-trending ridge borders the south edge of the cluster. The crest of this ridge is a little higher than 1,292 m and is the highest point anywhere on the avalanche deposits. Drillers' logs indicate that the debris-avalanche deposits are about 67 m thick adjacent to the ridge. This cluster at the southwest margin of the debris avalanche may have been formed by part of the initial slide block from the volcano. A similar cluster of hills and ridges is not present near the base of the volcano at the northeast margin of the debris avalanche.

The presence, within ridges, of intact stratigraphic successions of unconsolidated volcanoclastic deposits as well as large blocks of andesite indicates that the hills and ridges were not formed by the bulldozing up of accumulations of rock debris, but are masses that remained reasonably coherent as they moved downslope from the volcano. The local presence of veneers of the matrix facies on these blocks indicates that they were partly or wholly enclosed in matrix when the blocks were emplaced. The blocks now stand in relief not because of postavalanche erosion, but because after they came to rest, the more mobile matrix facies drained away from them.

The drainage pattern on the surface of the debris-avalanche deposits in Shasta Valley probably originated during the final stages of emplacement as the matrix facies drained northward. One drainage route is represented by the flat, north-sloping surface of the matrix facies along the west side of Shasta Valley north of Gazelle, which has been modified locally by alluvial fans at the mouths of some east-flowing streams. A similar north-sloping surface is inferred to exist beneath postavalanche lava along the east side.

The Shasta River flows northward along the west side of the block facies as far as a point about 3 km north of Edgewood, then turns and follows a northeastward course between parallel ridges formed by the block facies, as does Parks Creek. Beyond Lake Shastina, the Shasta River probably originally flowed northward along a matrix-drainage channel, perhaps joining Little Shasta River east of Steamboat Mountain. The Shasta River probably was diverted from this northward course by the

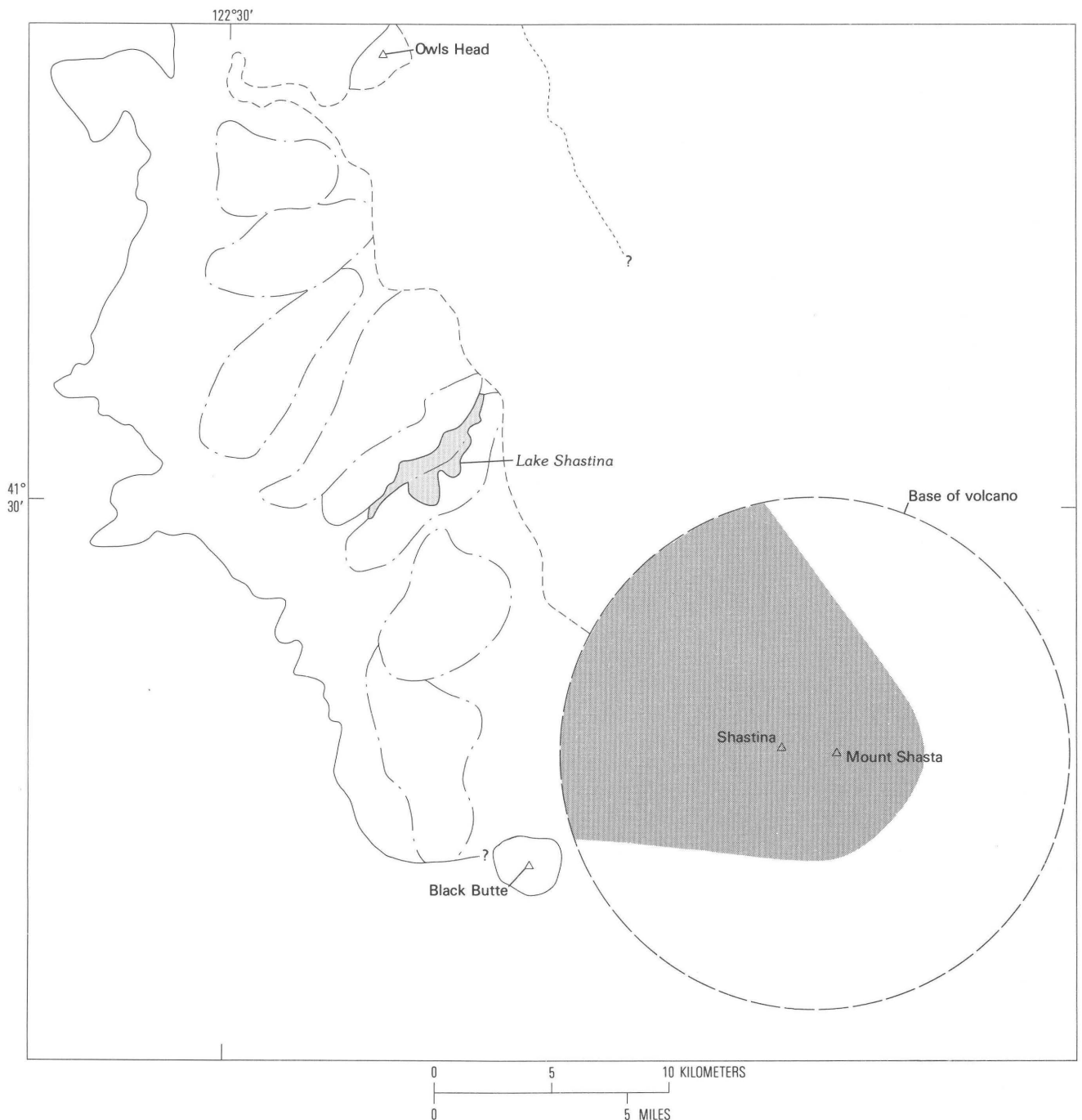


Figure 15. Clusters of hills and ridges, indicated by dash-and-dot lines, in the proximal part of the debris-avalanche deposits. The short-dashed line indicates the western edge of post-avalanche lava flows, and the dotted line is at a height similar to the inferred maximum height of the debris avalanche on the west side of Shasta Valley. The shaded part of Mount Shasta represents a possible source area of the debris avalanche on an ancestral volcano.

post-avalanche lava flows, which caused the river to find a new course diagonally back to the northwest across the block facies. East of Grenada, a matrix-drainage channel was followed by a northwesterly trending lobe of post-avalanche lava. Farther north, Little Shasta River follows a

westerly course that apparently also was established during the draining away of the matrix facies.

Closed depressions locally are present on the surface of the debris-avalanche deposits. At least five of these that occur along the ridges that border the

northwest side of Lake Shastina are shown on the U.S. Geological Survey topographic map of the Lake Shastina 15' quadrangle. Some of these depressions have closures of more than 20 m and are as much as 2 km long and 0.5 km wide. Only one contains a lake. Other basins, some of which contain lakes, are present 3–11 km north and 6 km west of Lake Shastina. Lakes farther north and northwest are in man-made reservoirs or in depressions on the surface of a postavalanche lava flow.

The origin of the closed depressions is problematic. Debris avalanches that move in a dry or nearly dry state typically form deposits that have very rough surfaces, and closed depressions are common as part of the original constructional topography of the deposits. Thus, the presence of closed depressions in the deposits north and west of Lake Shastina would not be considered unusual except for evidence that the matrix of the avalanche was fluid and very mobile. Such a matrix seemingly should have filled depressions that are lower than the crestal height of the avalanche.

If, as I believe, these depressions were formed after the bulk of the avalanche came to rest and the still-fluid matrix facies drained away, they probably originated in one or more ways. Some could have been formed by differential compaction of the avalanche deposits, although if this was an important process, the depressions seemingly should be more numerous and widespread than they are. Other closed depressions may be kettles left by the melting of blocks of glacier ice transported from the slopes of the volcano as part of the debris avalanche. In addition, some depressions could have been formed when blocks shifted apart from one another as they adjusted to local conditions of basal and lateral support after the matrix facies drained away.

SOURCES OF WATER IN THE DEBRIS AVALANCHE

Several lines of evidence indicate that the matrix facies of the debris avalanche was wet during movement. The amount of water required to mobilize this facies is suggested by a liquid limit of 22.5 percent, which was determined on a sample of matrix obtained from an outcrop 0.5 km west of Edgewood (fig. 5). If it is assumed that a water content of 22.5 percent was necessary for the matrix to move as a fluid, and that half of the debris-avalanche deposits is made up of the matrix facies, at least 5 km³ of water would have been required to mobilize the mass. This figure may be correct only within an order of magnitude, but it does suggest the involvement of a very large amount of water.

Rock debris in the avalanche probably was wet from the start, and as the avalanche moved across the floor of Shasta Valley it could have incorporated bodies

of surface water as well as saturated fluvial and lacustrine sediments. The ridges formed by the avalanche deposits adjacent to Lake Shastina are veneered with matrix facies, which locally surrounds blocks of coherent rock tens of meters in diameter. The presence of the matrix facies on those ridges, which include some of the last material to move from the volcano, implies that the source material was wet when the debris avalanche occurred.

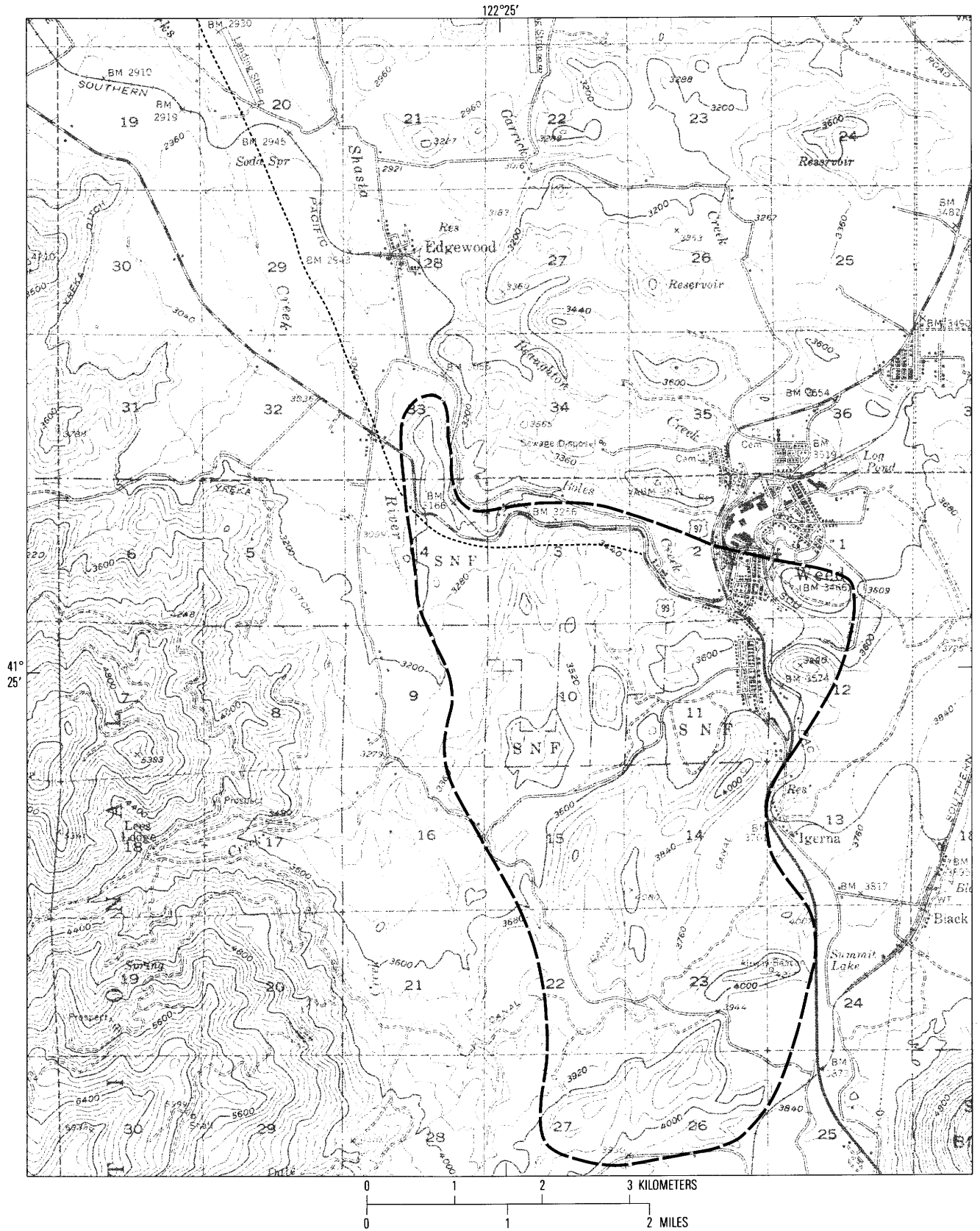
Several sources of water presumably existed on and within the pre-avalanche volcano. Probably the most important was subsurface water of meteoric origin, some of which could have been part of an active hydrothermal system. Water also could have been contributed by snow and ice to the parts of the avalanche that originated on the flanks of the volcano. If ancestral Mount Shasta had a crater lake, it also could have provided water to the initial part of the avalanche. However, a crater lake seemingly would have been drained during or shortly after the initial failure of the volcanic edifice, and therefore would not have contributed water to rock masses involved in subsequent failures. The presence of matrix facies on the proximal parts of the avalanche and evidence that much of this facies drained away at a late stage of avalanche emplacement suggest that the proximal parts were just as wet as the distal parts. If so, a crater lake evidently was not the only source of water.

A large water content may not have been essential to the initial landslides from the volcano, or to the movement of the debris avalanche beyond the base of the volcano, but it clearly was instrumental in determining the distance of movement and the draining away of much of the matrix facies during the final stages of avalanche emplacement.

CAUSE OF THE DEBRIS AVALANCHE

Slope failures on volcanoes can be triggered by steam or magma explosions and by earthquakes, and such failures can trigger eruptions if magma is present within a volcano. Rocks representing juvenile magma were not recognized in the avalanche deposits, and no evidence has been found that the debris avalanche was associated with magmatic activity. The summit of Yellow Butte, at the north base of the volcano, was searched without success for the presence of directed-blast deposits that might have been genetically associated with the formation of the debris avalanche.

The avalanche at Mount Shasta could have been triggered by one or more steam explosions within the volcano, like those that have triggered debris avalanches at other volcanoes during historic time. For example, at Bandai-san volcano in Japan, laterally directed steam explosions in 1888 caused a massive slope failure which



resulted in a debris avalanche with a volume of 1.5 km^3 (Nakamura, 1978). At Shiveluch volcano, U.S.S.R., a debris avalanche of similar volume in 1964 probably was caused by either an earthquake or volcanic explosion (Miller and Bogoyavlenskaya, 1983; Siebert, 1984).

It is also possible that the debris avalanche at Mount Shasta was caused by an earthquake. At Mount St. Helens, a magnitude-5.2 quake was the direct cause of a debris avalanche in 1980, but the stability of the north flank of the volcano had been greatly reduced during the preceding two months by the intrusion of a dacite cryptodome. The north flank of ancestral Mount Shasta could have become unstable for a similar reason, but evidence is lacking.

The stability of ancestral Mount Shasta could also have been affected by glacial erosion. The debris avalanche originated on the north flank of the volcano, where glaciers would have been largest, but this relation may only have been fortuitous. The extent of glaciers on ancestral Mount Shasta is not known, nor is it clear whether the debris avalanche occurred during a glacial or an interglacial period. The age limits of the debris avalanche are so broad that it could have occurred either during isotope stage 10 of the marine stratigraphic record (glacial, between 356,000 and 336,000 yr ago) or stage 9 (interglacial, between 336,000 and 276,000 yr ago) (Hays and others, 1976).

INITIATION OF THE DEBRIS AVALANCHE AND EMPLACEMENT OF DEPOSITS

The debris avalanche probably started as a rockslide or quickly spaced series of rockslides on the northwest flank of ancestral Mount Shasta. As the rock masses disintegrated during downslope movement they were transformed into one or more debris avalanches. Beyond the base of the volcano, the debris avalanches seem to have merged into a single very large mass which moved northward along the floor of Shasta Valley. Deceleration of this mass led to emplacement of the block facies, but the wet matrix continued to move downslope as a mudflow.

A gradual transition probably occurred from rockslide to debris avalanche and from debris avalanche to

mudflow. Such transitions occurred in the debris avalanche at Mount St. Helens in 1980, which originated in three large slump blocks on the north flank of the volcano. These broke up during downslope movement to form debris avalanches. Even though the rock debris was wet, it was emplaced as a closely spaced series of debris avalanches, and the muddy matrix did not drain away immediately. Five hours after the debris avalanche came to rest, however, water began flowing from the deposits and, cutting down through and remobilizing the incoherent material, formed a very large mudflow which extended more than 120 km farther downvalley (Janda and others, 1981). At Mount St. Helens, less than 30 seconds elapsed between the first and second collapses (Voight and others, 1981, 1983) and all the retrogressive collapses may have taken place within no more than a few minutes. The rockslides left a broad deep depression in the center of the volcano, open to the north, which resembles the so-called avalanche calderas (Siebert, 1984) created by similar events at many other volcanoes.

The debris avalanche at Mount Shasta probably also originated in a rapid succession of rockslides, each of which extended progressively deeper into the volcanic edifice as lateral support was removed. The northernmost blocks probably originated on the north flank of the ancestral volcano, and the blocks that are now near the base of the volcano may include parts of the southern flank. If so, the block facies of the avalanche deposits, from Montague to the base of the volcano, probably includes a north-to-south cross section through ancestral Mount Shasta.

The clusters of hills and ridges that characterize the avalanche surface may each represent the collapse of a very large landslide block which subsequently broke up during downslope transport. An especially large block that remained almost intact is represented by the ridge 9 km long that borders the northwest side of Lake Shastina (fig. 2). The slightly sinuous trend of this transverse ridge seems to indicate that velocity distribution in this part of the debris avalanche was almost uniform, despite an overall transport distance of more than 20 km from its probable source area on the volcano. The ridge may represent one of the last large collapses of the succession and probably came from what was then the south side of the volcano. The length of the ridge seems to be a minimum figure for the linear extent of the headwall left by the landslides. It is not known whether the slight sinuosity of the ridge reflects the shape of the headwall or was caused by deformation of the long slide block during movement. The proximity of the ridge to the base of the volcano implies that this part of the debris avalanche had less kinetic energy than preceding parts, perhaps because it did not descend from as great a height as the parts of the avalanche that preceded it.

Figure 16 (facing page). Topographic map of the northwestern part of the Weed 15' quadrangle, published in 1954 by the U.S. Geological Survey, showing the morphology of the southwesternmost cluster (dashed line) of hills and ridges of the debris avalanche. Note that most ridges in the cluster trend northerly, whereas those in the adjacent cluster, north of Boles Creek, trend westerly. The summit of the volcano is about 16 km east of Weed. The location of U.S. Interstate 5 west of Weed is shown by the dotted line.

The avalanche moved initially northwestward from the base of the volcano and thence generally northward along the floor of Shasta Valley in a massive wave consisting of water-saturated matrix carrying huge blocks of rock and poorly consolidated sediments. Volcaniclastic deposits that form ridges northwest of Lake Shastina and west of Weed are tilted and faulted but are right-side up, which suggests that these blocks were not overturned during transport. The avalanche slowed as it moved northward across the gently sloping valley floor, and the blocks were dropped as the carrying ability of the avalanche decreased, or when they became "grounded" on the underlying surface. The more mobile matrix facies continued northward along two routes into the Klamath River. Further drainage of the matrix downvalley lowered the surface of the debris avalanche in Shasta Valley, locally by at least as much as 95 m, so that blocks were left standing higher than the adjacent deposits of the matrix facies.

No unequivocal evidence was found that, because of its velocity, the debris avalanche ran up onto topographic obstacles in its path. The maximum height of boulders along the west side of Shasta Valley, about 95 m, could have been reached by run up if the avalanche had been traveling at a speed of 43 m/sec (about 155 km/h). Those boulders, however, cannot be identified specifically as products of avalanche run up, and the fact that the highest of them seem to form an even, north-sloping profile suggests that they probably represent the crest of a northward-moving wave. Furthermore, the principal direction of movement of the debris avalanche evidently was northward, coincident with the axis of the block facies, and velocities should have been greatest in this direction. The southern slope of Gregory Mountain was searched for topographically high boulders of Mount Shasta rock, which would constitute evidence of high run up and thereby a high speed. The highest boulders of Mount Shasta rock found on this slope, however, are only about 33 m above the adjacent surface of the matrix facies and are lower than the inferred maximum height of the matrix facies in this area during movement.

The shape, size, and height of ancestral Mount Shasta either before or after the debris avalanche are not known. However, the altitude of the ancestral volcano can be approximated by making certain assumptions. It is pointed out in a subsequent section that representative debris avalanches with volumes of at least 1 km^3 have an average height-to-length ratio of 0.075. If it is assumed that the end of the avalanche proper was at a distance of 49 km from the summit, use of this ratio to calculate height indicates that the altitude of the ancestral volcano would have been about 4,453 m, only 39 m higher than that of today.

The approximate altitude of the source of the ridge-forming block at Lake Shastina can be calculated if

it is assumed that this block is 25 km from its source, and that the base of the ridge is at an altitude of 723 m (the topographic base of the ridge, less 100 m for the inferred thickness of the avalanche deposit at that site). A calculation based on these values suggests that the source area of the block was at an altitude of about 2,600 m.

COMPARISON OF WET AND DRY VOLCANIC DEBRIS AVALANCHES

A wide variety in the proportion of water to rock debris probably exists among debris avalanches. At one end of the scale, some debris avalanches seem to have been virtually dry; with the addition of hot rock debris, these grade into pyroclastic flows. For example, a quick succession of three avalanches occurred about 300 yr ago at the Chaos Crags dacite domes in Lassen Volcanic National Park, Calif. (Crandell and others, 1974). The local presence of abundant prismatic jointed blocks of dacite in those debris-avalanche deposits, as well as rock debris that was thermally altered after it came to rest, suggests that some of the source material was hot (Crandell, unpub. data, 1972). Likewise, Kawachi (1983, p. 173) inferred that the A.D. 170 Ohtsukigawa volcanic debris avalanche from Mount Tengudake in Japan moved as a "low temperature, dry particulate flow."

A debris avalanche in 1984 from Ontake volcano in central Japan was triggered by an earthquake. Matsuda and Ariyama (1985) described the avalanche as "dry" and specified that "the interspace of blocks during movement was not water but air." A prehistoric debris avalanche from Lastarria volcano in Chile apparently was also dry but was highly mobile due to the entrainment of air (Naranjo and Francis, 1987).

The 1888 debris avalanche at Bandai-san volcano in Japan contained water but probably was not saturated (Sekiya and Kikuchi, 1889). Nakamura (1978) referred to it as a volcanic dry avalanche and noted that the water present in the avalanche was not essential to movement. The 1980 debris avalanche at Mount St. Helens also contained water, but it, too, was not saturated (Voight and others, 1981, 1983). Wet debris avalanches like these can grade directly into lahars at their distal ends, as at Bandai-san; or the rock debris in them can be eroded and remobilized by water expelled after the avalanche comes to rest, as at Mount St. Helens.

Other debris avalanches seem to have been so wet that water was an important factor in determining their behavior and mode of emplacement. The role of water in the debris avalanche from Mount Shasta has been discussed in earlier sections of this report. Another debris avalanche in which the fluid matrix drained away after the coarse component was emplaced occurred at Galunggung volcano in Indonesia. Jagger (1930) quoted Escher (1925) as follows:

“The hillocks represent the fixation of the last material of the slide, clots that remained standing higher, the principal mass having slowed down because of increasing bottom friction as it spread out fanwise and lowered, and as it lost part of its water. The finer mud and surface material flowed on down the slope, leaving the clots in relief where irregular clusters of boulders clothed with mud made the remnant hills. The largest of these were in the middle of the landslide fan and opposite the middle of the crater valley.”

Mounds on the Pungarehu lahar from Mount Egmont volcano on the North Island of New Zealand (Neall, 1979), which is now regarded as the deposit of a debris avalanche (Uj and others, 1986), also seem to have been left in relief when the wet matrix drained away (V.E. Neall, Massey University, New Zealand, written commun., 1987).

Debris avalanches typically form hummocky-surfaced deposits, but avalanches in which large blocks are absent may result in deposits with flat surfaces. The absence of such blocks may be due to pervasive fragmentation of rock during movement as a result of its low strength. In addition, some debris avalanches that originated in saturated rock, or became saturated during movement, have transformed directly into lahars whose deposits now have flat or nearly flat surfaces. The Osceola and Electron lahars, which originated at Mount Rainier, have such surfaces. Both are thought to have originated in avalanches of saturated, hydrothermally altered weak rock from the summit and upper slopes of the volcano (Crandell, 1971). Other lahars probably have formed in the same way, such as many of those at Mount Baker volcano (Hyde and Crandell, 1978) and at Mount Adams volcano (Vallance, 1986).

Wet debris avalanches may be no more mobile than dry ones during their initial emplacement, but wet avalanches have the potential for extending as wet flows (mudflows) far beyond the end of the debris avalanche proper. Thus, debris avalanches from volcanoes in which rocks are saturated endanger larger areas than do those in which rocks are not saturated. Stratovolcanoes of the Cascade Range that bear glaciers and extensive snowfields are all presumed to be capable of producing wet debris avalanches, and such events have indeed occurred at some of these volcanoes in the past.

HAZARD ZONATION FOR VOLCANIC DEBRIS AVALANCHES

Debris avalanches are potential hazards at most if not all high, steep-sided volcanoes. The great height at which a falling or sliding rock mass can originate provides tremendous kinetic energy, which can cause the resulting debris to move far beyond the base of a volcano so swiftly

that areas in its path can not be successfully evacuated after the debris avalanche begins. Some such events in the past evidently were not preceded by recognized warning signs or accompanied by volcanism. Likewise, future debris avalanches may occur without warning during intervals of volcano dormancy.

The need to identify and evacuate threatened areas before debris avalanches occur suggests that these potential hazards should be assessed at volcanoes where they may occur. Hazard zonation for volcanic debris avalanches seemingly can best be accomplished by making analogies with similar events in the past. Scheidegger (1973) found a correlation between the volumes of 33 debris avalanches of nonvolcanic origin and their so-called “coefficients of friction” (f), which are derived from their height-to-length (H/L) ratios. Hsü (1975) subsequently referred to these ratios as “equivalent coefficients of friction.” If an estimated volume is plotted on Scheidegger’s curve, the corresponding value of f can be found and used in the equation: $L = H/f$. A disadvantage of this approach is that the maximum volume of a potentially unstable rock mass on a volcano is rarely possible to determine.

A more convenient approach to determining possible avalanche length is based on the vertical distance through which a rock mass can be expected to drop, because length is proportional to this distance (Hsü, 1975; Schuster and Crandell, 1984; Siebert and others, 1987). On the basis of the H/L ratios of 11 debris avalanches with volumes greater than 1 km^3 , Schuster and Crandell suggested that the length of an anticipated debris avalanche can be estimated by dividing its potential vertical drop (H) by an f value of 0.075.

Siebert and others (1987) tabulated the volume, distance, and vertical drop of all reported volcanic debris avalanches and found that f values of avalanches with volumes greater than 1 km^3 are 0.05–0.13 and average 0.09. They proposed that the value of 0.05 be used for hazard zonation for a “worst case scenario” for “very large avalanches,” but they did not discuss how the potential for such avalanches could be recognized. Their tabulation shows that only two reported volcanic debris avalanches in the world have so low a value of f . Subsequently, an f value of 0.03 was reported by Francis and Self (1987) for a debris avalanche from Socompa volcano. They attributed its unusually high mobility to reduction of friction caused by seismic ground shaking while the avalanche was moving.

Most volcanic debris avalanches are quickly channeled into the heads of valleys that drain the volcano or extend into basins beyond the foot of the volcano. The distances to which debris avalanches can move down these depressions can be estimated from the equation $L = H/f$, in which H is the difference in altitude between the summit of a volcano and a point at an arbitrary

Table 3. Potential lengths of debris avalanches in three directions from the summit of Mount Shasta, which has an altitude of 4,316 m

[Values for height are the differences in altitude between the summit and points 20 km from it. Potential lengths shown in columns A, B, and C are based on f values of 0.05, 0.075, and 0.09, respectively]

Direction from volcano	Height (m)	Potential avalanche lengths (km)		
		A	B	C
Northwest.....	3,462	69	46	38
South.....	3,316	66	44	37
Southwest.....	3,487	70	46	39

distance of 20 km downvalley or downslope. This distance is the median length of the 41 debris avalanches tabulated by Siebert and others (1987) that have volumes greater than 1 km³. Various values of f can be used. As noted above, a value of 0.05 is that recommended by Siebert and his colleagues for a “worst-case scenario;” a value of 0.075 was recommended by Schuster and Crandell (1984); and the value of 0.09 is the average of a group of 11 representative debris avalanches chosen by Schuster and Crandell, all of which have volumes greater than 1 km³. The value of 0.09 also is the average of the 41 known debris avalanches of Quaternary age (Siebert and others, 1987). Siebert and his colleagues noted that the average f value of 20 volcanic debris avalanches with volumes under 1 km³ is 0.13. This value is not used here because a conservative approach to hazard assessment would dictate the assumption that the volume of an anticipated debris avalanche will be at least 1 km³, unless a smaller potential volume could be unequivocally determined. The desirability of such a conservative approach is illustrated by the 1980 debris avalanche at Mount St. Helens, which had a volume at least two orders of magnitude larger than that anticipated (Miller and others, 1981, p. 798; Schuster and Crandell, 1984).

In this connection, a practical problem in anticipating the volume of a debris avalanche is in determining not only the size of an initial slope failure but also the possible sizes of closely following failures that could result from removal of support by the initial collapse. For example, the initial failure at Mount St. Helens on May 18, 1980, was immediately followed by two more debris avalanches whose combined volume was more than double that of the first one (Glicken, 1986).

Examples of Debris-Avalanche Hazard Zonation

The approach used here to anticipate lengths of debris avalanches is applied, for the purpose of illustration, to Mount Shasta, Mount Rainier, and the pre-1980 Mount St. Helens.

Table 3 shows the distances to which future debris avalanches could travel at Mount Shasta, based on three values of f and on heights determined from the altitude difference between the summit and points 20 km down-slope to the northwest, south, and southwest. The only previous debris avalanche recognized at Mount Shasta is the one described here. It is assumed that the length (49 km) of that debris avalanche from the present summit of the volcano is represented by the most distant mound of rock debris from the volcano, which is 2.2 km northwest of Montague, even though the fluid matrix of the avalanche extended far beyond this point. The distance of 49 km is 3 km greater than the predicted length of a debris avalanche if an f value of 0.075 is used (fig. 17), but is 23 km shorter than the predicted distance based on an f value of 0.05.

Possible lengths of future debris avalanches at Mount Rainier, determined in the same way as that explained above, are shown in table 4. Debris avalanches in the past at Mount Rainier have quickly transformed to lahars which have been funneled down one or more of the deep canyons that head on the volcano, and the avalanche deposits themselves have not been identified. Although Siebert and others (1987, Appendix B, p. 455) listed the Greenwater lahar from Mount Rainier as a debris avalanche 70 km in length, I (Crandell, 1971, p. 18) believe the deposits to have been emplaced by a lahar.

At Mount St. Helens, the debris avalanche of May 18, 1980 traveled 29 km from the summit of the volcano down the valley of the North Fork Toutle River (fig. 19). Table 5 shows that an f value of 0.075 predicts a debris-avalanche length in that valley of 33 km, assuming pre-1980 topography. Table 5 indicates that a debris avalanche with a volume of at least 1 km³ moving from the pre-1980 volcano southeastward down the Pine Creek valley could have extended into Swift Reservoir, and one moving southward down the Swift Creek valley could have reached both Swift Reservoir and Yale Lake. Although this approach would have permitted us to anticipate the length of the 1980 avalanche in the valley of the North Fork Toutle River, this distance is no longer

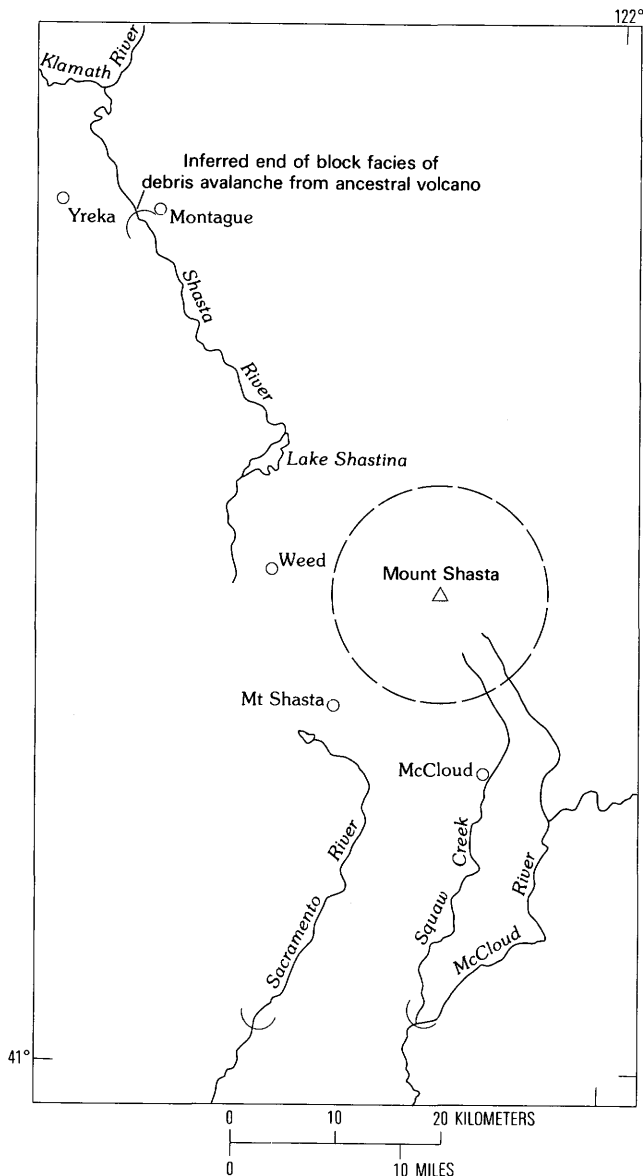


Figure 17. Map of Mount Shasta volcano and adjacent area. Semicircles show the distal ends of possible future debris avalanches, which have volumes of at least 1 km^3 , in three valleys heading on the volcano. The lengths are based on differences in height between the summit and points 20 km down each valley and on a height-to-length ratio of 0.075. The inferred end of the block facies of the debris avalanche in Shasta Valley is shown for comparison.

applicable because the summit of the volcano is lower. The present topography and geology of the volcano suggest that debris avalanches of very large volume will not descend its east, south, or west sides in the foreseeable future.

DISCUSSION

Factors that can be considered in choosing a value of f for hazard assessment at a volcano include the

number of lives and value of property at risk downvalley, the possible volume range of future debris avalanches, and the topography of areas beyond the base of the volcano. A very conservative approach to predicting avalanche length would be to use an f value of 0.05. A somewhat less conservative approach, but one that perhaps is more pragmatic for long-term planning, would be to use an f value of 0.075, plus a safety factor that is commensurate with local conditions. A debris-avalanche hazard zonation map of areas downslope from a volcano could show various degrees of hazard that are based on different values of f .

Factors that are not considered in this approach, but which will influence the lengths of debris avalanches, include width and shape of valleys and the volume and perhaps also the nature of the rock debris. The water content of the rock debris probably also will determine whether the debris avalanche (1) stops abruptly, (2) stops but is soon remobilized in part to form a mudflow that extends farther downvalley, or (3) becomes transformed directly into a mudflow as it moves downvalley. The length that can be anticipated from the $L = H/f$ formula represents only a downvalley distance that might be affected directly by a debris avalanche. For purposes of hazard assessment it should be assumed that a debris avalanche from a snow-covered stratovolcano will generate a mudflow, in one way or another, which will endanger valley floors tens if not hundreds of kilometers beyond the end of the debris avalanche proper.

Mudflows represent a different and less dangerous kind of hazard than debris avalanches. Mudflows typically travel down valley floors or other depressions at speeds ranging from a few kilometers to a few tens of kilometers per hour, and, with adequate warning, people on valley floors can avoid mudflows by moving to higher ground.

ACKNOWLEDGMENTS

I am indebted to Robert L. Christiansen and C. Dan Miller for their encouragement and advice during this study and to Robert L. Schuster for helpful consultation in the field. Personnel of the State of California Water Resources Division in Red Bluff kindly offered the facilities of their office while I was inspecting logs of water wells. I also appreciate the interest and hospitality of Mr. Don Meamber of Montague, Calif., who permitted my repeated access to a critical exposure on his property.

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Table 4. Potential lengths of debris avalanches from the summit area of Mount Rainier, which has an altitude of 4,392 m

[Values for height are the differences in altitude between the summit and points on valley floors 20 km from it. Potential lengths shown in columns A, B, and C are based on f values of 0.05, 0.075, and 0.09, respectively]

Valley	Height (m)	Potential avalanche lengths (km)		
		A	B	C
White River	3,438	69	46	38
Carbon River	3,779	76	50	42
Puyallup River.....	3,842	77	51	43
Nisqually River.....	3,718	74	50	41
Cowlitz River	3,779	76	50	42

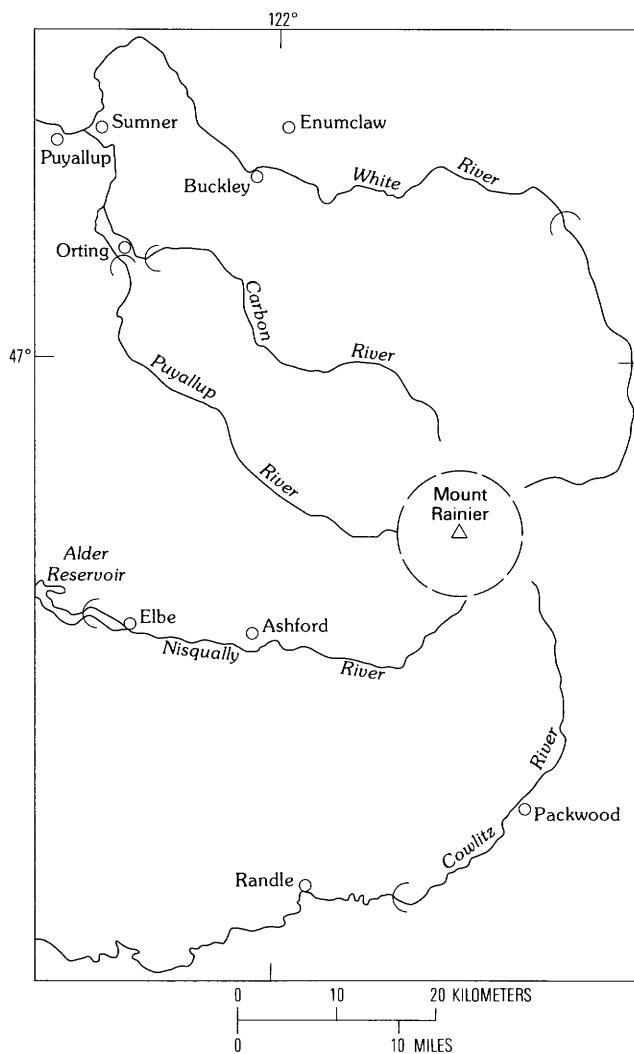


Figure 18. Map of Mount Rainier volcano and adjacent area. Semicircles show the possible lengths of debris avalanches that have volumes of at least 1 km³, in five valleys heading on the volcano. The lengths are based on differences in height between the summit and points 20 km down each valley and on a height-to-length ratio of 0.075.

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Table 5. Potential lengths of debris avalanches from the summit area of the pre-1980 Mount St. Helens volcano, which had an altitude of about 2,949 m

[Values for height are the differences in altitude between the summit and points 20 km downvalley from it. Potential lengths shown in columns A, B, and C are based on f values of 0.05, 0.075, and 0.09, respectively]

Valley	Height (m)	Potential avalanche lengths (km)		
		A	B	C
North Fork Toutle River.....	2,462	49	33	27
South Fork Toutle River	2,571	51	34	29
Kalama River.....	2,584	52	34	29
Swift Creek-Lewis River	2,797	56	37	31
Pine Creek-Lewis River	2,639	53	35	29

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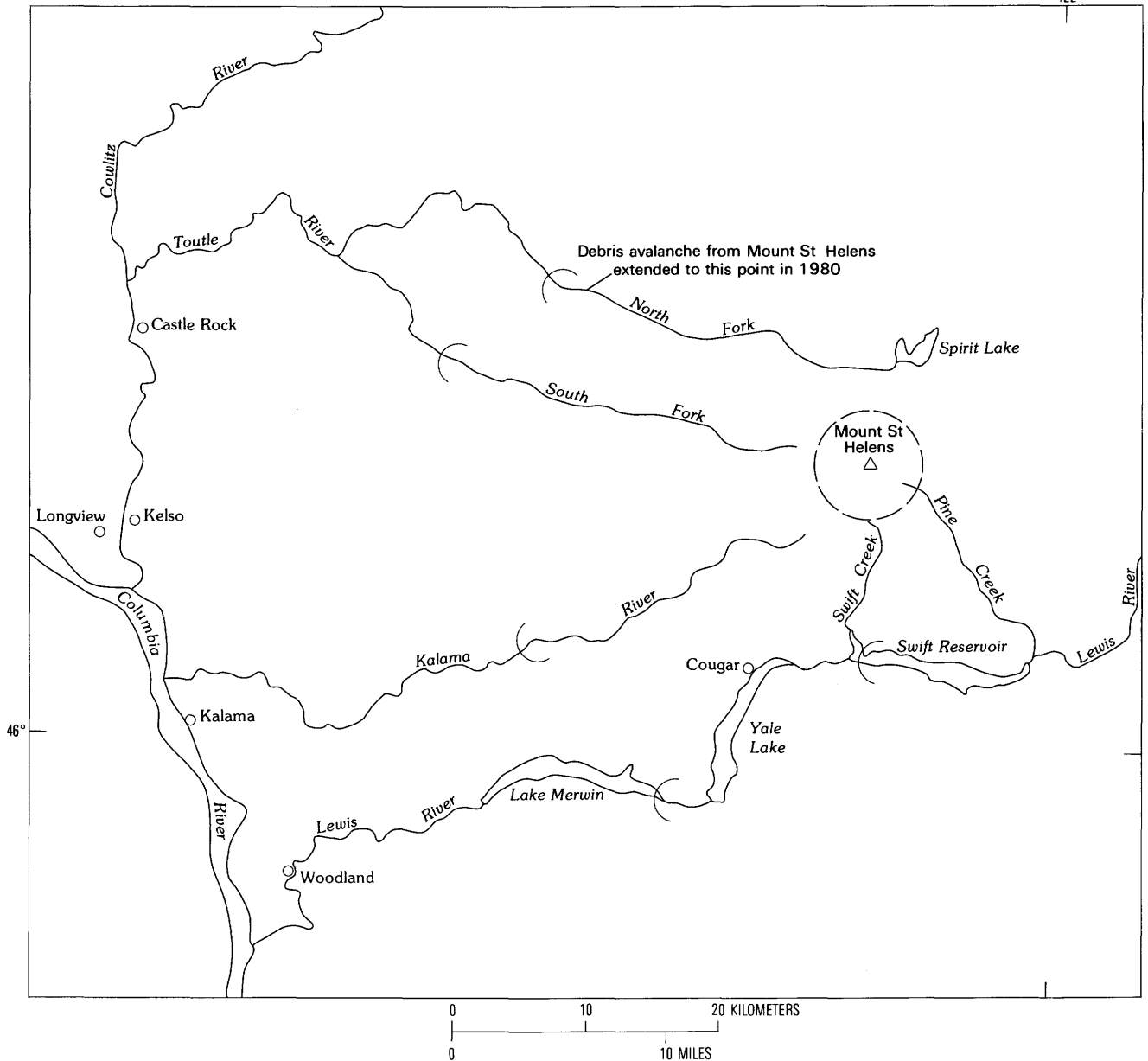


Figure 19. Map of the pre-1980 Mount St. Helens volcano and adjacent area. Semicircles in five valleys show the possible lengths of debris avalanches, with volumes of at least 1 km^3 , that could have originated at the volcano before the eruption on May 18, 1980. The lengths are based on differences in height between the summit and points 20 km down each valley and on a height-to-length ratio of 0.075. The end of the May 18, 1980 debris avalanche in the North Fork Toutle River valley is shown for comparison.

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VOLCANIC ASH ANALYSIS

VOLCANIC ASH ANALYSIS

A sample of volcanic ash from a clast within the matrix facies of the debris avalanche at a locality 1.3 km northwest of Montague was examined by Andrei Sarna-Wojcicki (written commun., 1987) and his associates Charles Meyer and Robert Fehr, who reported the following results. Minerals identified in the whole sample include green hornblende, green to brown pleochroic hornblende, oxyhornblende, hypersthene, apatite (small crystals within glass shards), brown to reddish-brown biotite, clinopyroxene (?), and plagioclase feldspar. The green hornblende, biotite, hypersthene, and plagioclase feldspar phenocrysts are partly coated with glass.

A heavy-mineral separate of the sample included the following:

	Percent
Hornblende	73
Hypersthene	24
Clinopyroxene	2
Total	99

Glass shards in the 30–80-micrometer fraction of the sample are mostly clear, with angular bubble walls and bubble-wall junctions and straight ribs. Shards in the 80–150-micrometer fraction are mostly tubular pumice

with cylinder-, capsule-, or spindle-shaped vesicles. Some spindle-shaped vesicles are partly filled with fluid. Some shards have equant or spherical vesicles, and one shard of brown glass was noted.

A probe analysis of the glass by Charles Meyer indicated the following chemical composition (recalculated to 100 percent):

	Percent
SiO ₂	78.35
Al ₂ O ₃	12.33
Fe ₂ O ₃	0.89
MgO	0.18
MnO	0.04
CaO	0.87
TiO ₂	0.14
Na ₂ O	3.69
K ₂ O	3.51
Total	100.00

Sarna-Wojcicki stated that the composition of the volcanic ash is closely similar to a sample of the Rockland ash bed obtained at a depth of about 59 m in a core at Tule Lake, Calif. He noted that samples of the ash have little or no biotite at most localities, but that a small amount of this mineral is present at the Tule Lake site. Sarna-Wojcicki suggested that the biotite is cogenetic and represents the most highly differentiated part of the magma that produced the Rockland tephra.

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