Catastrophic debris avalanche from ancestral Mount Shasta volcano, California

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ABSTRACT

A debris-avalanche deposit extends 43 km northwestward from the base of Mount Shasta across the floor of Shasta Valley, California, where it covers an area of at least 450 km^2. The surface of the deposit is dotted with hundreds of mounds, hills, and ridges, all formed of blocks of pyroxene andesite and unconsolidated volcaniclastic deposits derived from an ancestral Mount Shasta. Individual hills are separated by flat-topped laharlike deposits that also form the matrix of the debris avalanche and slope northwestward about 5 m/km. Radiometric ages of rocks in the deposit and of a postavalanche basalt flow indicate that the avalanche occurred between about 300,000 and 360,000 yr ago. An inferred average thickness of the deposit, plus a computed volume of about 4 km^3 for the hills and ridges, indicate an estimated volume of about 26 km^3, making it the largest known Quaternary landslide on Earth.

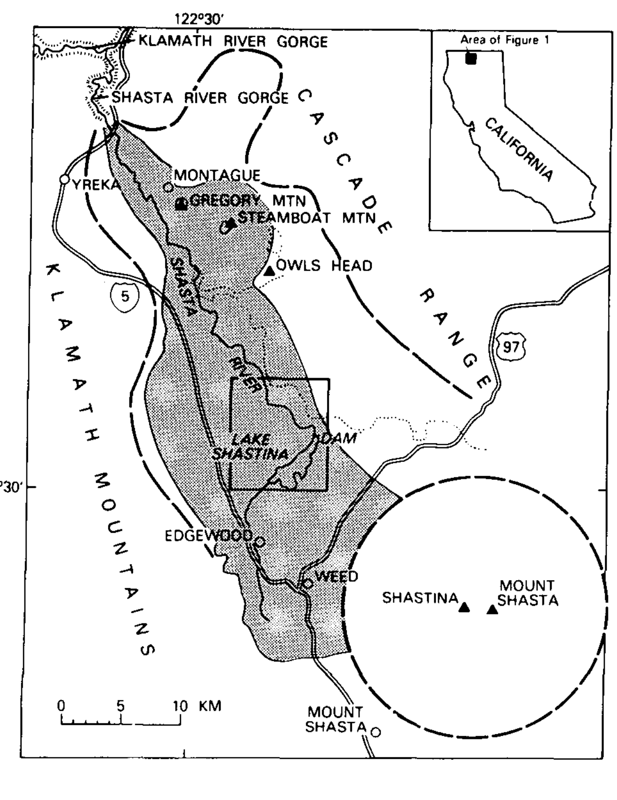

Figure 1. Sketch map of Shasta Valley debris-avalanche deposit (shaded). Heavy dashed lines show approximate margins of Shasta Valley and base of Mount Shasta volcano; dotted line indicates western edge of Quaternary basalt.

INTRODUCTION

The deposit of an exceptionally large volcanic debris avalanche underlies the southwestern part of Shasta Valley in north-central California (Fig. 1). The lithology of the deposit shows that it was derived chiefly from a large andesitic volcano at the site of, and presumed to be an ancestor of, the present Mount Shasta volcano. The surface of the deposit is marked by hundreds of mounds, hills, and ridges and closely resembles the topography of debris avalanches from other volcanoes (Fig. 2).

The mounds and hills of Shasta Valley have puzzled geologists for more than half a century. Diller and others (1915) noted that the hills consist of volcanic rock and stated they 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) proposed that a shallow sill had been intruded beneath Shasta Valley and that small bodies of magma from the sill rose to the surface to form the individual hills. Williams (1949) mapped the hills and ridges between the base of the volcano and Lake Shastina as moraines left by a glacier of Tioga age that moved into Shasta Valley from the slopes of Mount Shasta, and his geologic map shows a flat area to the west as glaciofluvial deposits. Williams believed that the hills and ridges north of Lake Shastina are products of stream dissection in volcanic rocks of Tertiary age, the "Western Cascade Series."

Mack (1960) agreed with Williams's interpretations; his geologic map shows the southern part of the debris-avalanche deposit as "morainal deposits," and the hills to the north as "volcanic rocks of the western Cascades." The 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 immediately west of Lake Shastina dam as "deposits of stratified drift which were probably laid down in contact with the wasting glacial ice."

Christiansen (1982) briefly mentioned the unusual topography of Shasta Valley and suggested that it resulted from a large debris avalanche from Mount Shasta. During field work in 1982, we (Crandell et al., 1983) verified the debris-avalanche origin of the topography and discovered details that are described here.

TOPOGRAPHIC AND GEOLOGIC SETTING OF THE DEBRIS AVALANCHE

The debris-avalanche deposit underlies 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. The valley is drained by the Shasta River, which meanders northward across the surface of the avalanche deposit and basaltic lavas of Quaternary age. The floor of Shasta Valley slopes northward from an altitude of a little over 900 m near Weed to about 760 m near Montague. Mount Shasta volcano, which has a summit altitude of 4,316 m and an estimated volume of about 335 km^3 (Williams, 1932), lies at the south end of the valley.

Shasta Valley is flanked on the west and north by ultramafic and metamorphic rocks of pre-Cretaceous age and by eastward-dipping marine sandstone and conglomerate of the Upper Cretaceous Hornbrook Formation (Peck et al., 1956). Volcanic rocks of Tertiary age border the valley on the north and east and also form a few hills that rise above the central part of the valley floor, such as Gregory Mountain, Steamboat Mountain, and Owls Head. The avalanche deposit is overlain on the east by basaltic lavas.

MORPHOLOGY OF THE DEBRIS AVALANCHE

The most conspicuous features of the debris avalanche are hundreds of scattered mounds, hills, and ridges that are separated by flat areas. Although most of the hills are of round or irregular shape in plan view, prominent ridges are present near Lake Shastina and southwest of Weed. The largest ridge borders the northwest side of the lake (Fig. 3) and has a sinuous northeasterly trend transverse to the direction in which the avalanche moved. This ridge is 8–9 km long and as much as 1.5 km wide, and its highest point is about 210 m above the adjacent flat area to the north.

The hills decrease in number as well as in basal area and height toward the northwest. Hills 2–10 km northwest of Lake Shastina include some with basal areas of as much as 2 km^2 and heights of as much as 180 m. Near Montague, in contrast, most hills have basal areas of less than 0.06 km^2 and heights of less than 30 m.

The Shasta River has cut down only 9 m into the debris-avalanche deposit near Edgewood, and less than 30 m west of Montague. The lack of deep dissection of the deposit is largely due to a resistant bedrock threshold near the upper end of the Shasta River gorge (Fig. 1).

DESCRIPTION OF THE DEBRIS-AVALANCHE DEPOSIT

The debris-avalanche deposit consists of two lithologically distinct parts, which we refer to as the matrix facies and the block facies. The matrix facies consists of an unsorted and unstratified mixture of pebbles, cobbles, and boulders in compact sandy silt; texturally it resembles a mudflow. Virtually all boulders and most cobbles are pyroxene andesites similar to rocks that make up the present Mount Shasta volcano. At one locality northwest of Montague, the matrix facies overlies an unconsolidated deposit of oxidized sand and gravel that probably is part of an alluvial fan along the west flank of Shasta Valley. At this locality, the matrix facies contains masses several metres in diameter of similar sand and gravel. Smaller fragments in the matrix facies include sandstone and conglomerate derived from the Hornbrook Formation as well as metamorphic rocks. A few clasts at this and other localities consist of diatomite and laminated silt. The matrix facies at this locality and some others contains fossils of aquatic organisms, described below.

The fine-grained component of the matrix evidently is made up of several constituents, including sedimentary rock from the Hornbrook Formation, volcanic rock that was pulverized during movement of the debris avalanche, and fine-grained alluvial and lacustrine sediments incorporated by the avalanche as it traversed the floor of Shasta Valley.

The matrix facies underlies flat areas between hills and extends beyond the outermost extent of the hills and mounds to the west side of Shasta Valley. The flat areas slope northwestward about 5 m/km and border the Shasta River as far as the upper end of the Shasta River gorge.

The block facies forms the mounds, hills, and ridges of the debris avalanche. The block facies includes individual andesite blocks ranging in size from tens to hundreds of metres in maximum dimension, many of which are brecciated, as well as masses of coherent but unconsolidated volcaniclastic deposits of similar size.

Some hills consist of one or more large blocks of a single rock type, although the slopes of most such hills are veneered with smaller rock fragments of varied rock types, mostly derived from ancestral Mount Shasta but locally including pebbles and cobbles of metamorphic rock. Other hills are formed by lithologically dissimilar blocks, some of which are parts of continuous stratigraphic successions and probably were transported by the avalanche in the same relative positions that they had within the volcano. Still other hills and ridges contain unconsolidated volcaniclastic deposits that are in their original stratigraphic succession. One such

Figure 2. View southward from top of Gregory Mountain toward hills and flat areas formed by Shasta Valley debris avalanche.

sequence, exposed in a pit directly west of Lake Shastina dam and thought by Mack (1960) to be of glacial origin, includes alluvium, beds of airfall tephra, and the deposits of pyroclastic flows and lahars. Soils in the upper parts of some of these units indicate that the units are right side up. The succession exposed in the pit dips as much as 60° northwestward and is displaced by vertical to steeply southeast-dipping normal faults that strike roughly parallel to the trend of the ridge, and by vertical faults that strike northwestward.

Similar successions of unconsolidated deposits crop out in two roadcuts through ridges crossed by Interstate 5 west of Weed. Most units exposed in the westernmost roadcut are eastward-dipping lithic pyroclastic-flow deposits that are broken by numerous steeply west-dipping normal faults. The deposits in the next roadcut to the east are similar but dip westward.

The genetic relation of the matrix facies to the block facies is demonstrated by the following: (1) Some blocks several to tens of metres across are entirely enclosed by matrix, and clastic dikes of the matrix facies penetrate narrow cracks and joints in the blocks. Other blocks are surrounded by the matrix facies in plan view, but their bases are not exposed. (2) Some clasts of Mount Shasta rock types in the matrix facies are identical to some rock masses of the block facies tens to hundreds of metres across. (3) The matrix facies veneers the slopes of some hills formed by the block facies, and most other hills are veneered with rock fragments that are inferred to have been left as a lag when finer parts of the matrix drained downslope.

FOSSILS IN THE MATRIX FACIES

Fossils of aquatic organisms were found in the matrix facies of the debris avalanche at six localities near Montague. A sample from a roadcut on the west side of the Shasta River valley 5 km west-northwest of Montague contained ostracodes, gastropods, bivalves, scales and bones of fish, and diatoms. Richard M. Forester, U.S. Geological Survey (1982, written commun.) identified the following ostracode taxa: *Candona patzcuaro* Tressler, *Limnocythere itasca* Cole, *Limnocythere sappaensis* Staplin, and *Candona candata?*. In addition, *Cytheromorpha,* sp. undetermined, was indentified. This is an estuarine or shallow-marine ostracode of unknown age that probably was derived from the Hornbrook Formation. According to Forester, the first four taxa com-

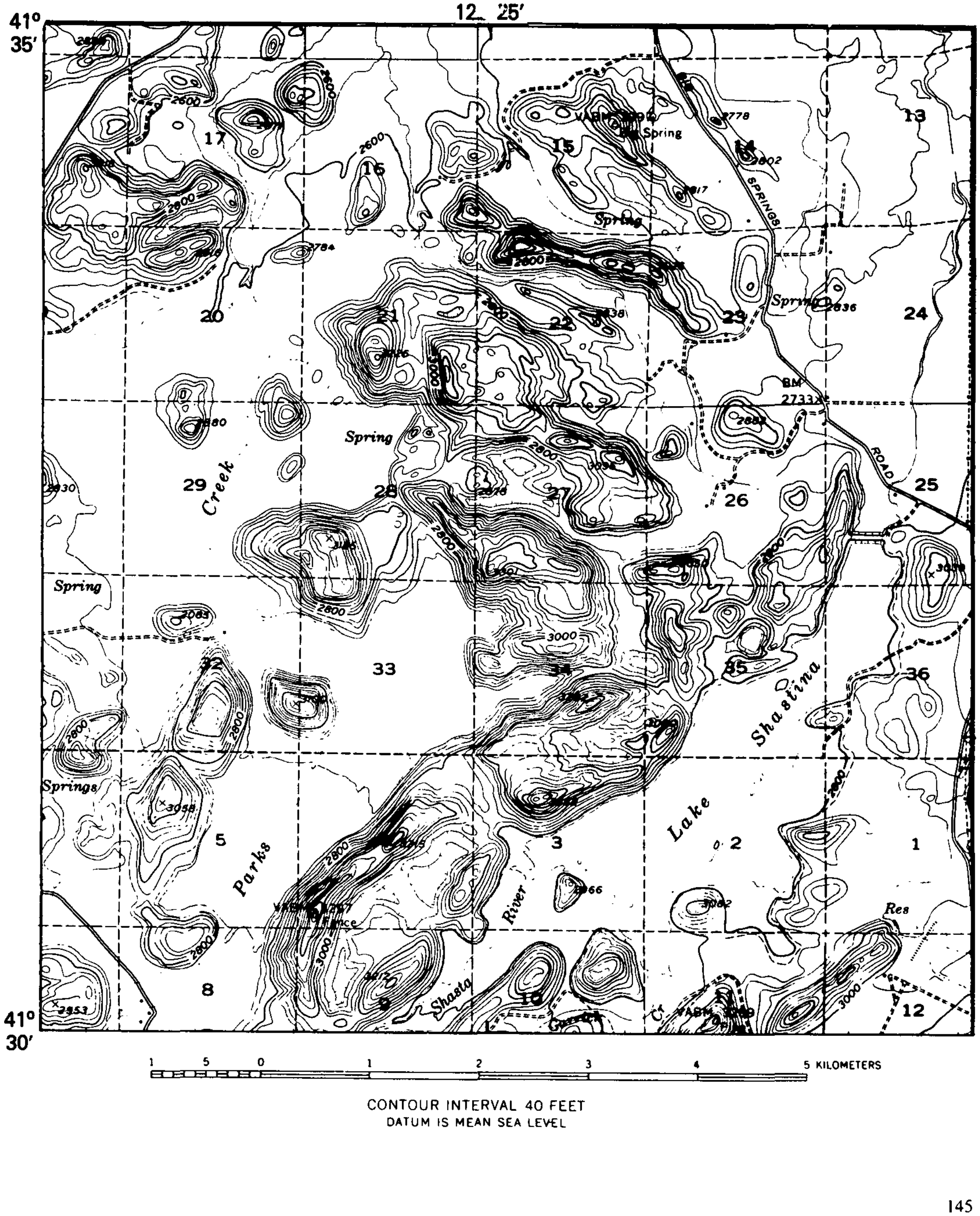

Figure 3. Topography of debris-avalanche deposit near Lake Shastina. Hills are formed by block facies and flat areas by matrix facies of deposit.

ably live in shallow or ephemeral lacustrine environments but could also live in a low-energy fluvial environment. The assemblage has a broad tolerance for temperature differences and is indicative only of a temperate continental climate. These fossils are believed to have been present in soft lacustrine and fluvial sediments on the floor of Shasta Valley and to have been incorporated when the debris avalanche moved across and eroded these sediments.

EXTENT AND VOLUME OF THE DEBRIS AVALANCHE

The debris-avalanche deposit covers an area of at least 450 km^2 between the base of Mount Shasta and the head of the Shasta River gorge. The length of the deposit between these points is about 43 km, and its maximum known width is about 13 km. Although the matrix facies moved into the gorge, its downstream extent is not known.

The thickness and volume of the avalanche deposit are poorly known. The maximum exposed thickness of the matrix facies is about 30 m in the west bank of the Shasta River 2 km northwest of Edgewood, where its base is below river level. Logs of some water wells in Shasta Valley (Mack, 1960) describe coarse clastic deposits beneath the valley floor that clearly are part of the debris avalanche. Some wells penetrate as much as 76 m of these deposits without reaching their base. If it is assumed that the deposit has an average thickness of 50 m beneath the level represented by the flat-topped matrix facies, its volume is about 22 km^3. The volume of the hills protruding above the matrix facies was computed to be an additional 4 km^3, resulting in a total volume of at least 26 km^3. Such a volume indicates that the debris-avalanche deposit is the largest reported Quaternary landslide on Earth.

AGE

Rocks that form the mounds of the debris-avalanche deposit have previously been thought to be of Tertiary age, but the constructional, little-dissected morphology of the deposit suggests that it is much younger, as is shown by radiometric limiting dates. Charles Chesterman of the California Division of Mines and Geology collected samples from two andesite blocks within the avalanche deposit and an overlying basalt, which were submitted to James Aronson of Case Western Reserve University for potassium-argon dating. The resulting ages of the andesite blocks are 360,000 $\pm$ 40,000 and 380,000 $\pm$ 60,000 yr; the postavalanche basalt yielded an age of 300,000 $\pm$ 100,000 yr (David L. Wagner, California Division of Mines and Geology, 1982, written commun.). Thus, the debris avalanche probably is between 300,000 and 360,000 yr old.

Although no scar is visible in the presumed source area of the avalanche, andesites older than those incorporated within the deposit are exposed low on the west flank of Mount Shasta. G. B. Dalrymple of the U.S. Geological Survey (1979, written commun.) has dated an andesite collected by R. L. Christiansen from the west base of the volcano as 593,000 $\pm$ 41,000 yr. Most of the visible part of the volcano consists of andesites lithologically similar to those of the block facies of the avalanche deposit, and younger than about 300,000 yr, as indicated by seven additional dates determined by Dalrymple on rocks collected by Christiansen.

ORIGIN OF THE DEBRIS AVALANCHE AND MECHANISMS OF MOVEMENT

No juvenile eruptive products were found associated with the avalanche deposit, and its cause is not known. Although a debris avalanche of this size perhaps is likely to be triggered by some kind of intrusive or eruptive activity, another possible cause is a strong earthquake.

Rocks forming the northwestern slope of an ancestral Mount Shasta may have moved downward in a closely spaced succession of slide masses, which became progressively more fragmented as they moved away from the volcano. The masses may have been so closely spaced in time and distance that the debris avalanche moved forward and came to rest essentially as a single unit. The great mobility of the debris avalanche may have been enhanced by a fine-grained matrix produced as the avalanche incorporated saturated sediments from the floor of Shasta Valley. The distribution of the matrix facies suggests that it was fluid and highly mobile and moved as a mudflow toward the margins of the Shasta Valley and northward down the valley after large blocks in the debris avalanche came to rest.

The initial parts of the avalanche on its southwest margin and the later parts of the main body of the debris avalanche may have moved beyond the base of the volcano as a succession of large coherent blocks on basal slip surfaces. The largest blocks, which are now in a zone just beyond the foot of the volcano, moved laterally at least 10 km, and possibly twice that distance, without being severely disrupted. Although some blocks rotated forward or backward, they remained right side up.

HAZARD IMPLICATIONS

Very large debris avalanches have been recognized at many volcanoes, and some relatively small ones have occurred during the past 100 yr, most recently at Mount St. Helens in 1980 (Voight et al., 1981). These catastrophic events are normal and expectable because of the heights and steep slopes characteristic of large stratovolcanoes and inherent structural weaknesses caused by the presence within them of unconsolidated deposits that may contain abundant water; this water, in turn, can increase the mobility of a debris avalanche or mudflow.

Debris avalanches from volcanoes are significant hazards because they may occur without warning, perhaps even without any precursory volcanic activity, and can move great distances at high speed and cover large areas. Although a debris avalanche might be anticipated at a volcano, its volume and extent probably could not. An extreme example like the Shasta Valley debris avalanche is useful in determining the possible maximum extents of such events in "worst case" scenarios. In this regard, it should be emphasized that the Shasta Valley avalanche traveled at least 43 km beyond the base of the volcano on a slope that probably was only about 5 m/km.

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