Downloaded from gsabulletin.gsapubs.org on August 28, 2013

Geological Society of America Bulletin

Recent Lahars from Mount St. Helens, Washington

D. R MULLINEAUX and D. R CRANDELL

Geological Society of America Bulletin 1962;73, no. 7;855-870
doi: 10.1130/0016-7606(1962)73[855:RLFMSH]2.0.CO;2

Email alerting services	click www.gsapubs.org/cgi/alerts to receive free e-mail alerts when new articles cite this article
Subscribe	click www.gsapubs.org/subscriptions/ to subscribe to Geological Society of America Bulletin
Permission request	click http://www.geosociety.org/pubs/copyrt.htm#gsa to contact GSA

Copyright not claimed on content prepared wholly by U.S. government employees within scope of their employment. Individual scientists are hereby granted permission, without fees or further requests to GSA, to use a single figure, a single table, and/or a brief paragraph of text in subsequent works and to make unlimited copies of items in GSA's journals for noncommercial use in classrooms to further education and science. This file may not be posted to any Web site, but authors may post the abstracts only of their articles on their own or their organization's Web site providing the posting includes a reference to the article's full citation. GSA provides this and other forums for the presentation of diverse opinions and positions by scientists worldwide, regardless of their race, citizenship, gender, religion, or political viewpoint. Opinions presented in this publication do not reflect official positions of the Society.

Notes

Copyright © 1962, The Geological Society of America, Inc. Copyright is not claimed on any material prepared by U.S. government employees within the scope of their employment.

THE GEOLOGICAL SOCIETY OF AMERICA

Downloaded from gsabulletin.gsapubs.org on August 28, 2013

D. R. MULLINEAUX
D. R. CRANDELL } *U. S. Geological Survey, Denver, Colo.*

Recent Lahars from Mount St. Helens, Washington

Abstract: Late Recent eruptions of Mount St. Helens volcano in the Cascade Range of southern Washington have caused numerous lahars; some extend more than 40 miles down valleys west of the volcano. These lahars typically consist of poorly sorted and unstratified detritus derived almost wholly from the volcano. The lahars and interbedded fluvial gravel commonly form valley fills; such a fill in the valley of the North Fork of the Toutle River contains at least three lahars.

Lahars from Mount St. Helens are composed mainly of nonvesicular rock fragments; thus, their great distance of transport is attributed to mobility provided by water rather than by gas emitted from particles in the matrix. Near the volcano, some of the lahars contain charred wood, proving that they were hot and resulted directly from eruptions.

Wood from within a lahar in the fill in the North Fork of the Toutle River valley has a radiocarbon age of about 2000 years. The lahar consists of material derived from a Mount St. Helens volcano that existed before the present cone was built; thus, the present cone must be less than 2000 years old. In addition, interpretation of soil profiles younger than the dated wood suggests that the modern cone may have been built within the last thousand years.

CONTENTS

INTRODUCTION

Mount St. Helens is a Recent volcano on the western flank of the Cascade Range in southern Washington (Fig. 1). Thick deposits of eruptive detritus, including coarse and fine pyroclastic deposits and lahars[1], form much of the slopes of the volcano and extend over older rocks. Construction of the volcano has extensively deranged previously established westward drainage in its vicinity, and valley fills of lahars and alluvium from it extend for many miles down old valleys west of the volcano.

This paper examines criteria for the recognition of lahars and describes a 40-mile fill of alluvium and lahars in the valley of the North Fork of the Toutle River. Two shorter flowage deposits, probably Mount St. Helens lahars, were also examined. These are similar to those in the Toutle River valley and are especially significant, as they contain charred wood that shows they resulted directly from volcanic eruptions.

The lahars were studied as part of a U. S.

[1] Lahar is an Indonesian word that describes mudflows and debris flows originating on volcanoes (van Bemmelen, 1949, p. 191).

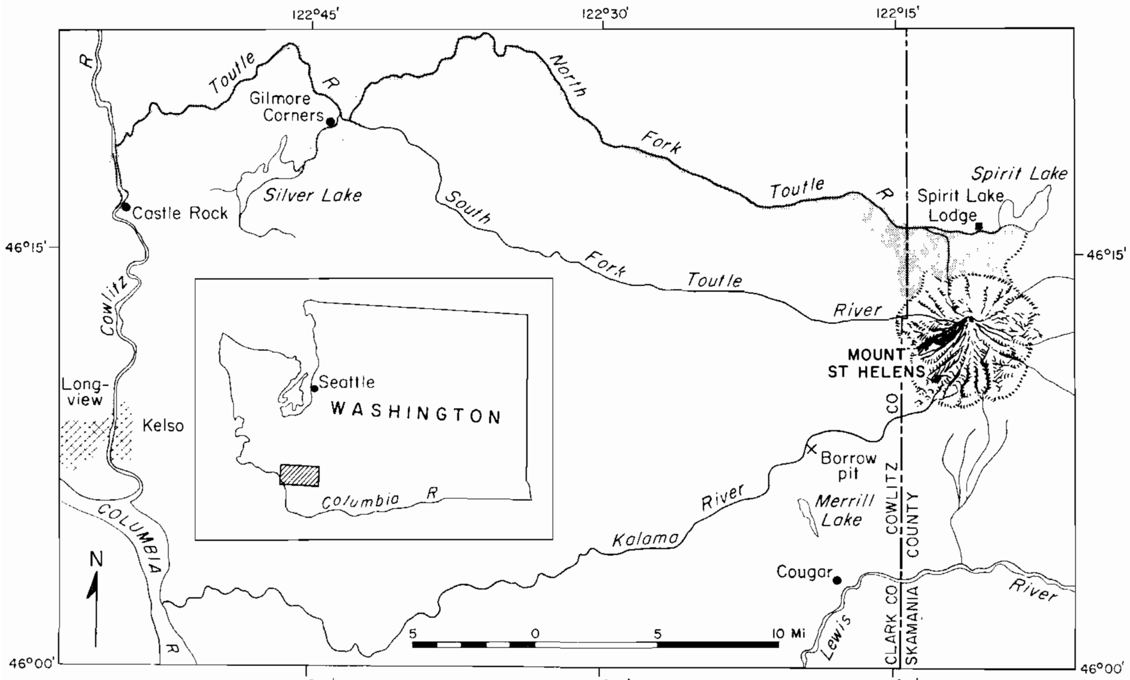

Figure 1. Index map of vicinity of lahars studied. Silver Lake lahar assemblage shown by stipple pattern

Downloaded from gsabulletin.gsapubs.org on August 28, 2013

Geological Survey investigation of volcanic mudflows and debris flows in the Cascade Range of the Pacific Northwest. Field work in the Toutle River valley and at Mount St. Helens was done during the summers of 1957, 1958, and 1959.

Explorers and geologists who visited the Pacific Northwest in the 19th century (Fremont, 1845, p. 193; Gibbs, 1854, p. 497) reported eruptive activity of Mount St. Helens. Diller (1899) discussed pieces of coniferous charcoal collected in the Kalama River valley by botanist Frederick Colville. Although Diller noted that no such wood had actually been seen in tree casts in lava, he concluded that Colville's specimens must have come from logs eroded from lava and redeposited in gravel.

Verhoogen (1937) described the volcanic stratigraphy and structure of Mount St. Helens and distinguished the hornblende-hypersthene andesites and hornblende dacites of an "older Mount St. Helens series" from the olivine basalts and pyroxene andesites that form most of the present cone. Verhoogen also recognized volcanic mudflows in deposits of both the older and present volcanoes. Later, Erdmann and Warren (1938) investigated damsites along the North Fork of the Toutle River and described a volcanic mudflow at the outlet of Spirit Lake. Lawrence (1938, 1939, 1954) discussed the pyroclastic deposits on the north flank of Mount St. Helens.

ACKNOWLEDGMENTS

We are indebted to the Weyerhaeuser Timber Company for access to the Kalama River valley and to Ralph Sheppard of the Washington State Division of Forestry for guidance to the charred logs. Dr. Donald Clark, of the Forest Products Laboratory at the University of Washington, identified fragments of the charred wood and supplied information regarding the indicated conditions of burning. A. E. Roberts, U. S. Geological Survey, contributed background information on the geology of the lower part of the Toutle River valley. Meyer Rubin supervised the analysis of the radiocarbon sample in the laboratories of the U. S. Geological Survey, and W. E. Huff analyzed remanent magnetism of rock samples.

We express our appreciation to the following people for helpful criticism of the content and organization of the paper: R. W. Hay, John Verhoogen, and Howel Williams of the University of California at Berkeley, J. Hoover Mackin of the University of Washington, Laurence H. Nobles of Northwestern University, and Richard Q. Lewis, Howard A. Powers, Donald E. Trimble, and Ray E. Wilcox of the U. S. Geological Survey.

RECOGNITION OF LAHARS

The term, lahar, includes all of the broad textural range of debris flows and mudflows of volcanic origin. Sharp and Nobles (1953, p. 550) suggest that the term, debris flow, be used as a general designation for all types of rapid mass flowage involving debris of various kinds and conditions. They state that a mudflow is a variety of debris flow in which the mud, although not necessarily quantitatively dominant, gives to the mass the specific properties and modes of behavior that distinguish it from flows of debris in which a very fine-grained component is lacking. Varnes (1958, p. 37) suggests that the term, mudflow, be reserved for material with at least 50 per cent sand, silt, and clay-size particles; he uses the term, debris flow, to apply to material with a relatively high percentage of coarse fragments. As the flowage deposits described herein grade from a debris flow at the base to a mudflow at the top, the term, lahar, is used to designate any unsorted or poorly sorted deposit of volcanic debris that moved and was deposited as a mass and owed its mobility to water.

Lahars tend to follow pre-existing valleys and are commonly interstratified with nearly contemporary alluvium derived from the same source area. A deposit of two or more lahars, including interbedded alluvium where present, that is lithologically distinct and that lies in a given valley is here referred to as a lahar assemblage. The lahar assemblages from Mount St. Helens consist chiefly of lahars near the volcano but become progressively more diluted with alluvium downstream, as individual lahars thin and pinch out.

Lahars in the valleys heading at Mount St. Helens have several features in common: (1) they are poorly sorted, (2) unstratified, (3) have typically subangular component stones, (4) occur in valley fills interstratified with fluvial gravel, and (5) consist almost wholly of material derived from Mount St. Helens. Lahars share some of these features with deposits of other origins, such as till, colluvium, fluvial gravel, pyroclastic deposits, and dry volcanic avalanches.

Features that distinguish lahars from till are vertical grading from coarse material at the base to fine material at the top (Crandell,

Downloaded from gsabulletin.gsapubs.org on August 28, 2013

1957), flat tops, restriction to valley floors, and, in some lahars, the presence of wood that was charred in place. Vertical grading in lahars is widespread but is relatively uncommon in lahars on steep gradients near the source volcano. Farther from the volcano, vertical grading is probably the single most useful indication of origin; where this feature is present in deposits of coarse nonvesicular material far from the source, we believe it is a criterion of mass transport of the material in a flow mobilized by water.

The prevailing Mount St. Helens provenance of the lahars studied distinguishes them, down valley from the volcano, from colluvial deposits derived locally from older rocks.

As some lahars contain a small proportion of silt and clay, they may readily be confused with poorly sorted fluvial sand and gravel. Stones in the lahars from Mount St. Helens are noticeably more angular than those of the same rock types in fluvial gravel a comparable distance from the volcano. This angularity is probably a result of transport in a suspension, whereby stones are buffered by a viscous matrix that greatly reduces abrasion. In contrast, stones are rapidly rounded as they roll and bounce along the stream bed during fluvial transport.

The absence in lahars of structures characteristic of alluvium also aids in differentiating the two kinds of deposits. Individual lahars extend for considerable distances with little change in thickness and without significant lateral change in grain size. These features are not typical of beds of fluvial gravel. Bar or cut-and-fill structures typical of alluvium are absent. Gradual vertical change in grain size from coarse at the base to fine at the top is common in lahars, but the vertical alternation of grain sizes typical of alluvium is absent.

The presence of large boulders in lahars further serves to differentiate them from fluvial deposits. Some lahars studied contain boulders whose diameter is as much as a thousand times the median diameter of particles in the enclosing matrix. These large boulders are in an aggradational fill that is formed by a lahar assemblage. Their presence demands some agent other than fluvial transport, for unlike graded or degrading streams, aggrading streams tend to bury rather than rework the coarsest channel material, and the resulting deposits show a marked down-valley decrease in grain size (Mackin, 1948, p. 505; Pettijohn, 1957, p. 541). On the other hand, the ability of debris flows and mudflows to transport very large boulders for long distances is well known.

Where a lahar contains fragile wood that was charred in place or surrounds stumps charred by bombs in the deposit, the fact that it was hot or carrying hot material distinguishes it from alluvium.

The distinction of lahars from coarse, airlaid, volcanic material is difficult to make close to the source volcano. Restriction of lahars to valley floors, however, provides a useful criterion.

Differences in composition and evidences of mobility and heat are helpful in distinguishing lahars from deposits of hot, dry, volcanic avalanches. The extreme types of hot, dry, volcanic avalanches are (1) gas-rich, highly mobile, pumiceous avalanches and flows, usually referred to as glowing avalanches, glowing clouds, or *nuées ardentes* and (2) various types of gas-poor, less mobile, block-and-ash avalanches, some of which are referred to by these same terms.

Highly mobile, glowing, pumiceous avalanches and flows originate in an eruption of gas-rich magma. As the magma is expelled from the volcano, gas pressure causes it to froth, and as an avalanche of this material descends the slopes of the volcano, hot dense gas is emitted from incandescent particles of the erupted material, enveloping the particles and making them mobile (Perret, 1937, p. 84, 89). Because of their great mobility, individual gas-rich avalanches have traveled down valleys to distances of as much as 40 miles from the source volcano (Williams, 1942, p. 81). The most significant features of the resulting deposits are their length, abundance of constituent glass shards or vesicular glass, and evidence of very high temperature (Marshall, 1935; Gilbert, 1938; MacGregor, 1938; Williams, 1942, 1956; Hay, 1959). Deposits of glowing avalanches near Crater Lake, Oregon, which were formed during the climactic eruptions of Mount Mazama, contain from 41 to 85 per cent vesicular glass, as compared to 10 to 30 per cent lithic fragments (Williams, 1942, p. 84). The crystal-rich (50 per cent), glowing avalanche deposits of the Soufrière of St. Vincent, B. W. I., contain 36 per cent scoria and vitric ash, and only 14 per cent nonvesicular rock (Hay, 1959, p. 546). Great mobility and length are characteristic of both lahars and glowing avalanches; however, a scarcity of vesicular glass or evidence of low temperatures may distinguish one from the other.

Downloaded from gsabulletin.gsapubs.org on August 28, 2013

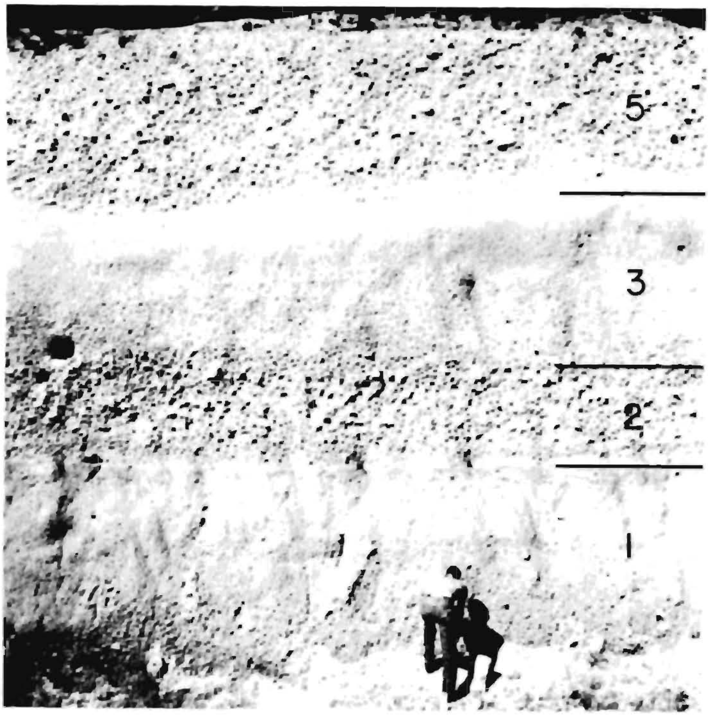

Figure 1. View of northeast side of borrow pit, Gilmore Corners, approximately at measured section; depositional units labeled as in measured section, except unit 4 (not visible). Crude stratification, imbrication of stones in unit 2 show that it is fluvial gravel and not coarse base of overlying lahar (unit 3).

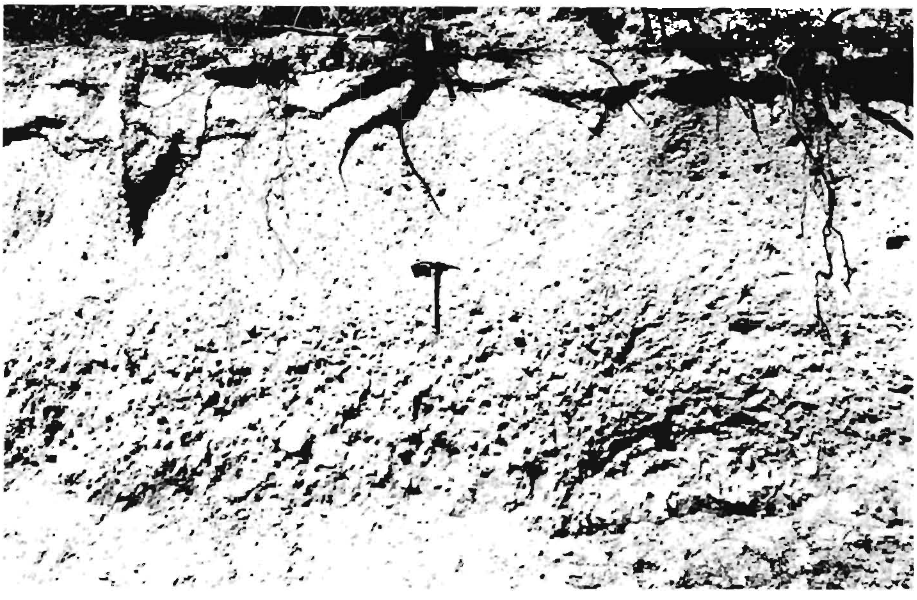

Figure 2. Upper lahar of Silver Lake assemblage in northern part of Gilmore Corners gravel pit, showing distinct vertical size gradation

SILVER LAKE LAHAR ASSEMBLAGE, MOUNT SAINT HELENS AREA, WASHINGTON

MULLINEAUX AND CRANDELL, PLATE 1
Geological Society of America Bulletin, volume 73

Downloaded from gsabulletin.gsapubs.org on August 28, 2013

Figure 1. Comparison of typical stones from upper lahar at Gilmore Corners (on sample sack) with gravel on bar of Toutle River near Gilmore Corners. Note meager abrasion on edges and faces of most stones from lahar. Well-rounded stones in bar gravel are lithologically like stones from lahar. Sack is 20 inches long.

Figure 2. Younger bomb-bearing lahar 50 yards east of Spirit Lake Lodge. Boulders are almost all breadcrust scoria bombs. Man points to completely charred small log. Large upright stump behind man, entwined in younger roots, is charred only where bombs lie against it.

COMPARISON OF STONES IN LAHAR AND ALLUVIUM, AND LAHAR NEAR SPIRIT LAKE LODGE, MOUNT SAINT HELENS AREA, WASHINGTON

MULLINEAUX AND CRANDELL, PLATE 2

Downloaded from gsabulletin.gsapubs.org on August 28, 2013

Block-and-ash avalanches, composed mostly of nonvesicular rock, are generally initiated by mild gas-poor eruptions, collapse of spines and parts of domes, or slides of rapidly accumulated pyroclastic deposits on the slopes of volcanoes. Perret (1937) reported that some block-and-ash flows are cushioned by gas emitted from constituent particles and regarded them as the feeblest type of *nuée ardente.* Avalanches of block and ash from accumulated hot pyroclastic debris on the upper part of Vesuvius during the 1906 eruption traveled a maximum of 2.5 miles from the vent and were confined to the slopes of the volcano, although the material did contain hot gas (Perret, 1924, p. 102). Although McTaggert (1960) suggests that the mobility of both gas-rich and gas-poor avalanches is chiefly due to heating of entrapped cold air and is a function of temperature rather than gas, the descriptions of Perret, Williams, and others indicate that block-and-ash flows characteristically are shorter than pumiceous flows. If so, relatively limited distance of travel and abundance of nonvesicular constituent rock are significant features of hot block-and-ash avalanches; their limited extent helps to differentiate them from lahars, which may travel tens of miles from the source volcano.

These criteria are useful in recognizing lahars but are not always diagnostic, as lahars commonly grade into some of the other types of deposits mentioned. For example, hot dry avalanches of all types may become hot lahars by accumulation of water, generally from snowfields or streams; hot lahars may cool as they travel down-slope or down-valley, and those that flow into relatively large rivers may grade imperceptibly into muddy streams whose deposits are texturally indistinguishable from those of other muddy streams. In this paper we discuss some lahars that are far from the volcano, interbedded with alluvium, and probably cold where we studied them; a hot lahar in which the largest fragments were hot enough to char adjacent wood; and a deposit that was hot enough at one time to convert entire logs to charcoal and may have been transitional between a hot dry avalanche and a hot lahar.

DESCRIPTION OF LAHARS STUDIED

Silver Lake Lahar Assemblage

Description. A fill terrace in the Toutle River valley near Silver Lake consists of lahars interbedded with fluvial sand and gravel; similar deposits underlie terraces along the whole length of the North Fork of the Toutle River from Spirit Lake to the Cowlitz River valley (Fig. 1). Fill terraces formed of this lahar assemblage west and north of Castle Rock indicate that the valley fill extended into and down the Cowlitz River valley to a distance of at least 40 miles downstream from Mount St. Helens.

On the north flank of Mount St. Helens, the surface of the Silver Lake lahar assemblage has a gradient of 300–500 feet per mile down toward the valley of the North Fork of the Toutle River and Spirit Lake. The surface of the assemblage in the valley just west of Spirit Lake has a gradient of about 150 feet per mile, which decreases to about 40 feet per mile near Silver Lake, 30 miles down-valley. A few terraces in the Cowlitz River valley between the mouth of the Toutle River and Castle Rock indicate a gradient there of a little less than 20 feet per mile.

The full thickness of the lahar assemblage is not exposed, because the Cowlitz and Toutle rivers have not yet cut below its base. In the Cowlitz River valley, 22 feet of the deposit crops out in the wall of a gravel pit northwest of Castle Rock (Fig. 1). The part of the assemblage exposed there consists of two lahars, 2 and 10 feet thick, respectively, and fluvial sand and gravel. The thickest known section crops out along the Toutle River near Silver Lake, where the depositional top of the assemblage is 60 feet above exposures at river level, although the maximum thickness exposed in any one outcrop is about 45 feet.

Near Gilmore Corners (Fig. 1), the top of the Silver Lake lahar assemblage forms a westerly sloping surface back into a broad tributary valley and is responsible for Silver Lake. The lahars are well exposed along the Toutle River east of Silver Lake, but the best outcrops are at Gilmore Corners (Pl. 1, fig. 1) in a gravel pit excavated in the assemblage between Silver Lake and the Toutle River. The following section was measured in the northeast side of the pit, the deepest part, in August 1959.

Measured section

Location: SW¼NE¼ sec. 30, T. 10 N., R. 1 E., in northeast side of gravel pit at Gilmore Corners, Washington

	Feet	Inches
5. Lahar: pebbles and cobbles in a fine to coarse sand matrix, light gray with bluish cast; unstratified; few		

Downloaded from gsabulletin.gsapubs.org on August 28, 2013

	Feet	Inches
stones in basal 6–12 inches; material coarsest in lower middle part of deposit, becoming finer toward top; contains oxidized zone 1–3 feet thick at top	13–15	
4. Alluvium(?): lenticular silt and fine sand, pale brown, oxidized; contains scattered carbonized wood particles		1–9
3. Lahar: pebbles and granules in sand matrix, light gray with bluish cast; marked gradation from coarse material at base to fine material at top; locally oxidized in upper few inches	7–8	
2. Alluvium: pebble and cobble gravel, light gray, rudely stratified; overlies and locally lies within channel cut into unit 1; contact with unit 3 indistinct	5–14	
1. Lahar: Pebbles and granules in sand matrix, light gray with bluish cast; unstratified; grades from pebble and sand mixture at base to granule and sand mixture at top; upper 10–12 inches contains weathering profile and wood fragments. Base not exposed	9+	

The upper lahar (unit 5) in the assemblage exposed in the walls of the pit varies little in thickness. This lahar apparently forms the uppermost unit of the assemblage between Toutle River and Silver Lake and is exposed along the highway on the north side of Toutle River 2.5 miles northeast of Gilmore Corners. The area covered by this lahar is at least 5 square miles in the vicinity of Silver Lake alone.

The upper lahar is typical of those in the Silver Lake assemblage. It consists of unstratified poorly sorted material, which, although ranging in size from clay to boulders, is mainly of sand to pebble size (Fig. 2). Except for a basal zone of fine material several inches thick, the deposit in most places shows a gradual decrease in grain size from bottom to top (Pl. 1, fig. 2). At some places, however, the upward decrease in grain size may be limited to the upper half or third of the lahar or may even be missing. This change in grain size is marked; the median size of a sample from 7 to 10 feet below the top of the upper lahar is 16 mm, but the median size of a sample from 2 to 3.5 feet below the top at the same place is only 0.95 mm (Fig. 2). The graded top of the upper lahar is also somewhat better sorted than the rest of the deposit; samples from the basal and upper parts of the lahar have coefficients of sorting of 10.2 and 6.62, respectively. Similarly, the co-

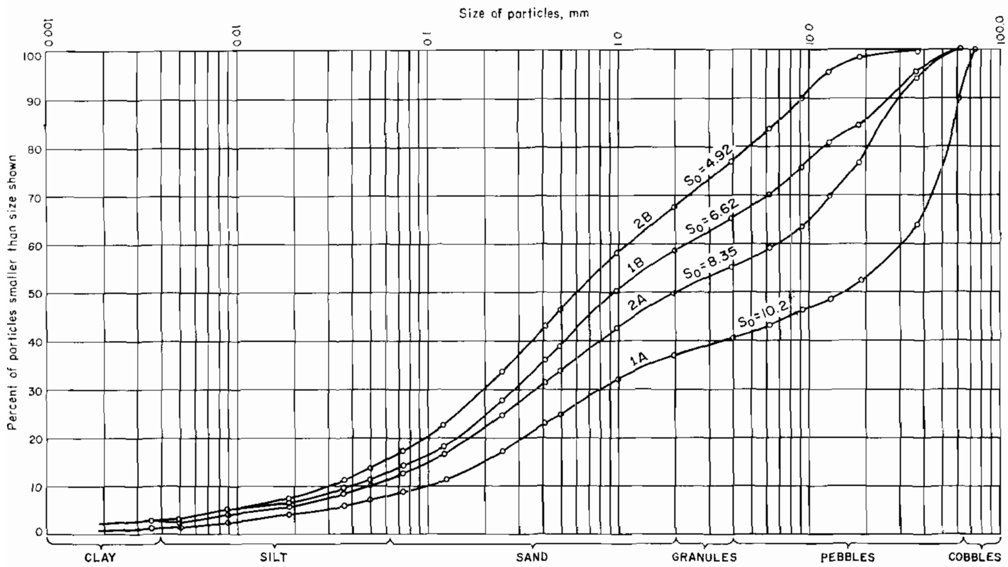

Figure 2. Cumulative curves illustrating grain size of lower (1A and 1B) and upper (2A and 2B) lahars at Gilmore Corners. Curve 1A based on sample from 7 to 10 feet below top of 14-foot thick upper lahar; curve 1B based on sample from 2 to 3.5 feet below top of upper lahar. Curve 2A based on sample from 5 to 7 feet below top of lower lahar; curve 2B based on sample from 1 to 3 feet below the top of the same lahar

Downloaded from gsabulletin.gsapubs.org on August 28, 2013

efficient of sorting in the lower lahar is 8.35 in a sample 5–7 feet below the top but is 4.92 in a sample 1–3 feet below the top.

Most pebbles in the lahars are subrounded or subangular; sand grains are subangular or angular. The angularity of rock fragments in the lahars contrasts markedly with the roundness of pebbles of the same rock types found in modern bars of the Toutle River near Gilmore Corners and in fluvial gravel interbedded with the lahars (Pl. 2, fig. 1). The long axes of elongate pebbles in each lahar show a preferred orientation parallel to the trend of the valley in which the deposits lie.

Large boulders are not abundant in the lahars near Silver Lake or farther downstream, but they become more abundant upstream. Many boulders of dacite and andesite from Mount St. Helens, concentrated by screening operations, lie on the floor of the gravel pit near Castle Rock. Dimensions of the largest boulder are 3.5 x 5 x 6.5 feet, and about a dozen other boulders are only slightly smaller. At the Gilmore Corners pit, a boulder about 2 x 3.5 x 4.2 feet was found in place, embedded in and extending about a foot above the top of the middle lahar. The presence of this boulder is noteworthy, for it lies in medium to coarse sand that makes up the graded upper part of the lahar.

Although on the whole the lahars at Gilmore Corners are unstratified, some structures of local extent suggest crude layering. Nearly horizontal, subparallel, light-brownish-gray zones, some of which split into two zones and others of which end abruptly at pebbles, are present in the upper few feet of the upper lahar in the northern corner of the pit. Some of these zones are caused by iron-oxide stains in the sand matrix of the lahar. In other zones, however, interstices of the matrix are filled with fine-grained iron oxide or iron oxide and clay. Apparently, the zones are not associated with vertical changes in grain size, and the staining and filling of the interstices probably are due to deposition from ground water.

In addition to the brownish zones, the upper part of the middle lahar at one place in the pit walls contains a poorly defined zone of material that is somewhat finer than the rest of the deposit. In cross section this zone is shaped like a small channel fill, but like the rest of the lahar, the material within the "channel" is unstratified. The finer grained material within the "channel" probably is a small part of the lahar that moved separately from and later than the main mass. Crude layering between slightly different masses of mudflow material in the Nirasaki mudflow in Japan has been attributed by Mason and Foster (1956, p. 78–79) to the overrunning or underrunning of some parts of the mudflow by other parts.

Stones in the Silver Lake assemblage are mostly pale-red, glassy, hornblende dacite and gray hornblende-hypersthene andesite (Verhoogen, 1937, p. 266; Roberts, 1958, p. 40) (Table 1); these stones are derived only from the older Mount St. Helens. No olivine basalt or pyroxene andesite from the modern cone were found in the lahar assemblage.

TABLE 1. LITHOLOGY OF STONES IN UPPER LAHAR AT GILMORE CORNERS GRAVEL PIT, in the SW¼NE¼ SEC. 30, T. 10 N., R. 1 E.

	Per cent
Gray, glassy, hypersthene-hornblende andesite	58
Pale-red, glassy, hornblende dacite	28
Sedimentary and volcanic rocks derived from formations of Tertiary age	14
	100

Although pumice pebbles and granules are scattered through the alluvium (unit 2 of the measured section) at Gilmore Corners and are abundant in thin alluvium at the top of the assemblage for several miles downstream from Spirit Lake, pumice is virtually absent in the lahars themselves. Vesicular glass and glass shards are sparse in the sand fraction of the lahars, which consists almost wholly of crystals of plagioclase, hypersthene, and hornblende and fragments of crystal-charged devitrified glass derived from the groundmass of the pale-red dacite and gray andesite.

A sample of fine silt and clay from the upper lahar several miles up the North Fork of the Toutle River from Gilmore Corners was identified by X-ray methods by Arthur J. Gude, 3d, of the U. S. Geological Survey. The fraction smaller than about 37 microns and larger than 2 microns contains, in order of relative abundance, feldspar, alpha cristobalite, and quartz; the fraction smaller than 2 microns contains alpha cristobalite, feldspar, quartz, and halloysite.

Origin. In the Silver Lake assemblage interpretation of deposits as lahars is based on lithology, vertical grading, poor sorting, absence of stratification typical of fluvial deposits, angularity of stones, and the presence of large

Downloaded from gsabulletin.gsapubs.org on August 28, 2013

boulders in a fine matrix. The very small content of pumice, scoria, or glass shards indicates that the deposits were not formed by gas-rich hot avalanches; their length indicates that they are not the products of dry, gas-poor, block-and-ash avalanches from Mount St. Helens.

The lahars in the Silver Lake assemblage probably originated in eruptions of Mount St. Helens. The erupted material probably fell in large masses on the upper slopes of the volcano and then slid or flowed down-slope as either wet or dry block-and-ash avalanches, collecting enough additional water from melting snow and ice and from the North Fork of the Toutle River to form wet slurries that traveled far down-valley. Downstream, the lahars presumably were progressively more diluted with water, until they became little more than a very muddy stream; some, in the absence of excessive water, retained their identity for many tens of miles from the volcano. During intervals between the formation of lahars, streams reworked the deposits on the volcano and lahars on the valley floors to form fluvial gravel found in the lahar assemblage.

The lahars themselves give little evidence as to the kind of eruption that caused them or whether they were wet or dry high on the volcano. Their similarity to block-and-ash flows suggests that they probably originated from mild explosive eruptions or from collapse of spines or domes (Williams, 1956, p. 60).

Weathering profiles and age. Two weathering profiles and dated wood within the Silver Lake assemblage suggest that emplacement of the assemblage continued until late in Recent time. The weathering profiles are in the upper parts of the lower and upper lahars. The profile in the lower lahar consists of an oxidized zone as much as 12 inches thick overlain by a humified zone 1–2 inches thick that contains small carbonized wood fragments. In places, just below the humified zone, there is a light-brownish-gray zone about 1 inch thick that is conspicuously lighter in color than either the oxidized or unoxidized part of the lahar. The light-colored layer probably is a bleached horizon (the A_2 horizon of pedological terminology) of a podzolic soil. Where the lahar has been channeled, the weathering profile follows the bottom of the channel, proving that the channel was formed prior to the weathering.

The profile in the upper lahar, at the present ground surface, consists of an oxidized zone overlain by a layer of duff 1–2 inches thick. The oxidation extends to an average depth of about 18 inches but locally to a depth of as much as 36 inches.

A zone of oxidation 4–12 inches thick occurs in the silty sand alluvium that overlies the middle lahar, and in places it extends a few inches down into the underlying lahar. This oxidation may be part of a profile resulting from surface weathering, but it could have been produced by aerated ground water moving along the contact between a permeable material above and a less permeable material below.

The only direct evidence of age of the lahar assemblage was obtained from wood in the lower lahar at Gilmore Corners. Most wood in this lahar is almost completely replaced by iron oxide, but one wood fragment from it was identified as part of a stem and branch of a conifer by Dr. Donald Clark (oral communication). As the fragment was found about 1 foot below the top of the lahar, it must have been transported by the lahar. It has a radiocarbon age of 2030 ± 240 years (W-811).

The weathering profile in the lower lahar is nearly as thick as the profile at the top of the assemblage and apparently includes a leached horizon; it probably required about as much time for its development as did the profile at the top. If this is true, accumulation of the fill probably continued until perhaps a thousand years ago, thus implying that the volcano continued to erupt the hornblende dacite and hornblende-hypersthene andesite of older Mount St. Helens for at least a thousand years after the dated wood was incorporated. The known thickness of the deposits near Silver Lake and the possibility that there are weathering profiles in unexposed parts of the fill below the dated wood suggest that the assemblage may have been emplaced over a period of several thousand years.

The flat-topped fill formed by the Silver Lake assemblage in the Toutle and Cowlitz River valleys is banked against rounded, silt-covered, fluvial terrace deposits of Pleistocene age. A short distance north of Castle Rock, the facial bone of a mammoth recovered from such a terrace deposit (Roberts, 1958, p. 39) was assigned an age of late Pleistocene.

Lahar at Spirit Lake Lodge

A younger lahar lies within a valley cut into the Silver Lake lahar assemblage in the valley of the North Fork of the Toutle River near

Downloaded from gsabulletin.gsapubs.org on August 28, 2013

Spirit Lake Lodge (Fig. 1), 4.5 miles from the summit of Mount St. Helens. This lahar originated at the summit or somewhere on the north slope of the volcano and moved northward down to the valley of the Toutle, where its nearly unmodified flattish surface is several tens of feet below the upper surface of the Silver Lake assemblage. The younger lahar presently forms the south bank of the Toutle River for about a quarter of a mile in the vicinity of Spirit Lake Lodge. The gradient of the lahar there is about 300 feet per mile.

The lahar near Spirit Lake Lodge is an unstratified mixture of pebbles, cobbles, and boulders in a friable matrix of angular sand (Fig. 3). At the only outcrop where it is exposed in cross section, it is about 15 feet thick and shows neither a size gradation from base to top nor any imbrication of the stones (Pl. 2, fig. 2). The boulders and many of the smaller stones are breadcrust bombs of medium- to dark-gray scoria; the surface of the deposit is dotted with large boulders of the scoria, some having a maximum dimension of 5–6 feet. Other stones in the deposit are mostly light- or medium-gray hornblende and pyroxene andesite. The matrix of the lahar is composed predominantly of nonvesicular rock fragments. Red and dark-gray scoria makes up 10–20 per cent of the medium sand size, but colorless vesicular glass or pumice is rare. Both brown and colorless vesicular glass and glass shards are more common in the finest sand size but are minor constituents.

Wood fragments are abundant in the lahar, and an upright tree stump extends from the underlying fluvial sand and gravel through the lahar. Some of the wood fragments are completely converted to charcoal, but others are charred only on the outside. Some fragments of charcoal are fragile twigs, and others are long slender branches with bark still present; all are brittle. The stump that protrudes into the lahar still has bark and is charred only where large bombs rest against it; no charring was observed where only matrix material is adjacent to the stump.

The lahar at Spirit Lake Lodge contains abundant large bombs and other fragments of scoria, but the stump, uncharred except where adjacent to bombs, rules out the possibility of an incandescent gas-emitting matrix. In addition, the breadcrusted exteriors of the bombs indicate that they began to solidify prior to incorporation in the deposit. The presence of wholly charred wood, as well as only partly

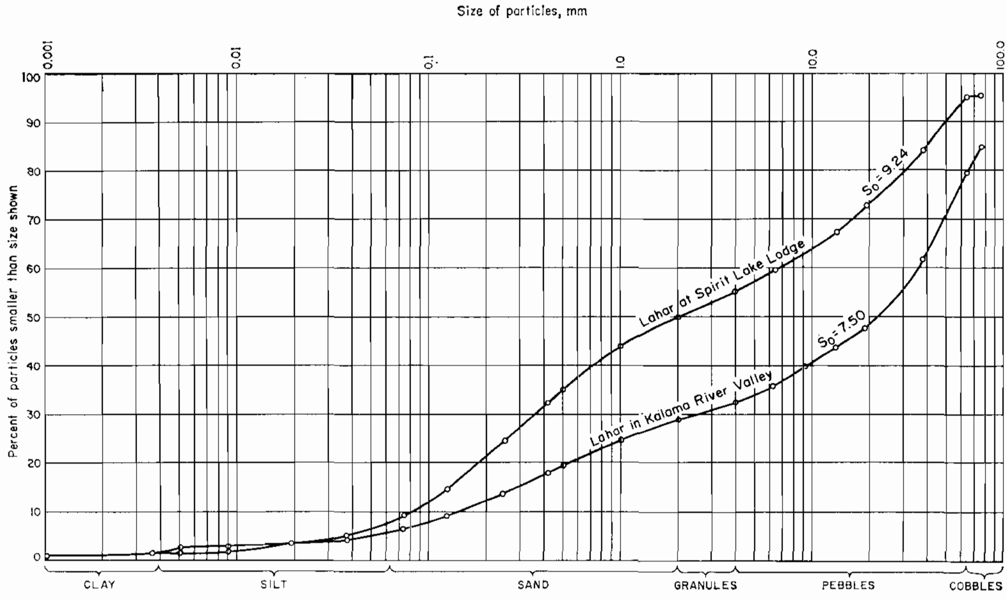

Figure 3. Cumulative curves illustrating grain size of lahar at Spirit Lake Lodge and lahar in Kalama River valley. Boulder- and cobble-size bombs excluded from lahar sample at Spirit Lake Lodge. Sample in Kalama River valley taken from 1 to 4 feet above base

Downloaded from gsabulletin.gsapubs.org on August 28, 2013

charred and uncharred wood, suggests that the matrix was first very hot, but that it cooled during transport and was not hot enough to char wood by the time the mass reached the Toutle River. Preservation of fragile branches in the deposit suggests relatively gentle transport, more gentle than expected in a dry avalanche of tumbling blocks and ash. The low temperature of the matrix, the apparent gentle transport, and the mobility that enabled the mass to flow on a relatively low gradient suggest that water was the mobilizing agent, and that the mass moved as a viscous lahar.

The surface of the lahar at Spirit Lake Lodge is covered by only a thin layer of organic matter; large rotten logs are absent, and most of the largest standing trees are less than 3 feet in diameter. In contrast, some trees are more than 6 feet in diameter on the Silver Lake assemblage nearby, and many large rotten logs lie on its surface. Tree-ring counts of some of the largest trees on the lahar at Spirit Lake Lodge suggest an age of about 330 years. Observation of the 1947 Kautz Creek debris flow at Mount Rainier and a study by Dickson and Crocker (1953) of lahars from Mount Shasta indicate that reseeding takes only a year or two on the surface of lahars in environments similar to that at Spirit Lake Lodge; thus, the lahar there is probably very little older than 330 years.

Probable Lahar in Kalama River Valley

A deposit of volcanic debris that extends 10 miles down the Kalama River valley southwest of Mount St. Helens exhibits characteristics of both lahars and glowing avalanche deposits. Although we are not certain that water in the fluid state was responsible for its mobility, it seems certain that water was involved, and for convenience we refer to the deposit as a lahar.

The lahar overlies fluvial sand and gravel and, 10 miles from the volcano, underlies the surface of a rather wide flat floor in the valley that contrasts markedly with the narrow V-shaped valley a few miles downstream. However, outcrops of a lava flow from Mount St. Helens, underlying or surrounded by the lahar, suggest that the Kalama River valley owes its flat floor to a valley-filling lava flow or to a combination of lava flows, lahars, and alluvium. The gradient of the wide valley floor decreases from 200 or 300 feet per mile near Mount St. Helens to less than 100 feet per mile near its western end.

The lahar is best exposed about 8 miles from the summit of the volcano in a narrow part of the Kalama River valley in sec. 33, T. 8 N., R. 4 E. and in a deep trench cut by the river about a mile farther upstream. In section 33, the exposures are in road cuts and in a borrow pit (Fig. 1) near the point where the old trail from Merrill Lake to Mount St. Helens and the present logging road cross the Kalama River. Here the lahar is 15–20 feet thick and is overlain by local deposits of pumice gravel.

The lahar consists of an unstratified and poorly sorted mass of pebble-and cobble-size rock fragments in a friable sandy matrix (Fig. 3). Most fragments are angular or subangular, and no size gradation is apparent from base to top in the borrow-pit exposure. The over-all color of the deposit is light gray, but the upper 6 feet has a faint reddish cast. The rocks are mostly light- and dark-gray andesites and basalts, a few of which are scoriaceous. Reddish-gray andesites are a minor constituent. Most were derived from the modern Mount St. Helens volcano. Pumice gravel is abundant only in the basal 1–2 feet of the lahar that overlies pumice in channels. The coarse-sand size components are dominantly fragments of crystal-charged devitrified glass, and crystals that are found as phenocrysts in the larger stones. Scoria and pale-brown vesicular glass make up about 10–15 per cent, and rounded white pumice and clear glass shards constitute another 10–15 per cent of the coarse-sand size. In the finest sand size, about half is glass shards, clear vesicular glass, or crystals with vesicular glass clinging to them. Euhedral crystals of plagioclase, hypersthene, and clinopyroxene are abundant in the sand matrix.

Near the borrow pit, the lahar contains many logs that have been converted to charcoal, and it probably was here that Colville (Diller, 1899, p. 639) found the charcoal logs in the "Kalama River gravels." Colville reported partly charred logs, but none were seen during this investigation. In the borrow-pit exposure, a log of Douglas fir (*Pseudotsuga taxifolia*) 3 feet in diameter lies in a nearly horizontal attitude about 10 feet below the top of the deposit and is converted to charcoal equally from outside to inside, including well-preserved bark. The log is fragile and light in weight, and the grain of the wood is perfectly preserved. According to Doctor Clark (oral communication), the condition of the charcoal indicates that the log was heated to a temperature of at least 200° C, and the ab-

Downloaded from gsabulletin.gsapubs.org on August 28, 2013

sence of ash indicates that oxygen was excluded. Within 6 inches of the top and sides of the log, much of the silt and fine sand has been removed from the enclosing lahar, leaving an openwork gravelly sand. The remaining stones are coated with a soft, dark, sooty material, which apparently is an organic product expelled during destructive distillation of the log. Above the log, spiral "pipes" of openwork gravelly sand, also coated with sooty material, lead toward the surface of the deposit. The fragility of the log and the presence of bark suggest that the log was not reworked in its present state from an older deposit; the coating on stones around the log and in the "pipes" clearly shows that the wood was converted to charcoal where it now lies.

In a nearby road cut, several dozen logs of charcoal at or near the base of the lahar are mixed with fragments of pumice. A mile and a half upstream from this exposure, where more than 50 feet of the lahar is exposed in a cutbank of the Kalama River, no wood was seen.

Because the charcoal logs indicate a high temperature in the deposit, 10 stones were collected for remanent magnetism tests, to determine if the temperature was higher than the Curie point of the contained magnetic minerals (Aramaki and Akimoto, 1957). The orientation of the north-seeking poles in the stones (Fig. 4) is distinctly not random, and although stability tests have not been made, the temperature of most of the stones tested was probably near or above the Curie point after the mass came to rest. Nevertheless, the grouping of the magnetic directions is definitely more scattered than groupings obtained by Aramaki and Akimoto on hot dry avalanches, and the directions in stones 2 and 7 vary from the present direction of the earth's magnetic field by more than 45°. The temperature of most of the larger stones was probably near or above the Curie point when the lahar came to rest, but some included stones and the mass, as a whole, probably were at a lower temperature.

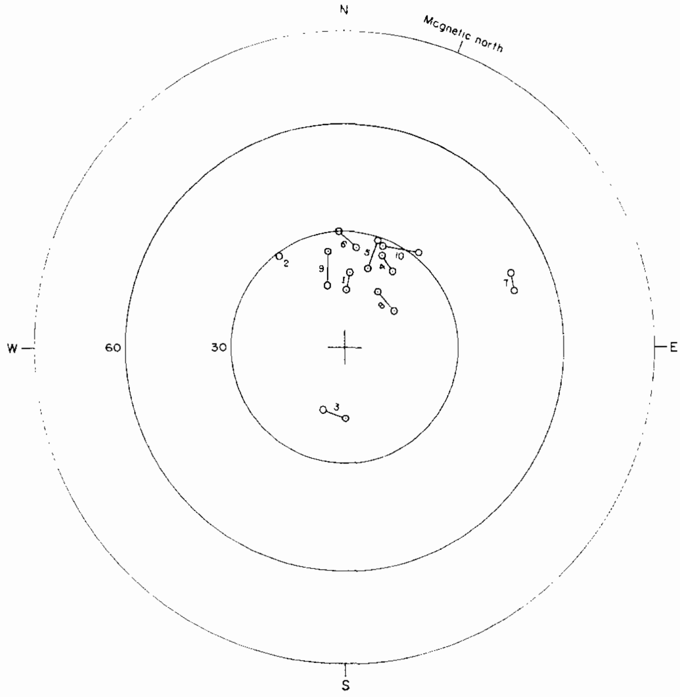

Figure 4. Point diagram of azimuth and dip of north-seeking poles in 10 stones from Kalama River lahar. Two points, representing two different samples from same stone, are plotted for each except stone 2. Stone 3 may have been turned end for end when collected.

As the Kalama River valley lahar evidently was of high temperature and contains pumice

Downloaded from gsabulletin.gsapubs.org on August 28, 2013

in the matrix, it somewhat resembles the deposit of a gas-rich glowing avalanche. The bulk of this deposit, however, is of nonvesicular rock. Moreover, the lack of lapilli-size pumice here is a noteworthy difference between this deposit and deposits of gas-rich glowing avalanches described elsewhere (Williams, 1942; Hay, 1959). The Kalama River valley deposit probably started either as an intermediate type of hot avalanche or as a gas-poor avalanche that incorporated fresh, vesicular, pyroclastic material. Its mobility, shown by its length and relatively low surface gradient, could be caused by gas-emitting particles in the matrix, heating of entrapped cold air, or water in the liquid or gaseous form. The discharge of the Kalama River at the time this deposit was laid down probably was comparable to that of the present river, and a large amount of water must have been incorporated by the time the mass reached the point where we studied it. Although we are not at all certain that water was essential to movement, a laharic origin is suggested by the length, the probability that much water was incorporated, and the absence of lapilli-size pumice. The evidence of a high temperature indicates that any incorporated water probably was expelled as steam during transit and after the mass came to rest.

DISCUSSION OF HOT LAHARS

Many features of the deposits studied at Spirit Lake Lodge and in the Kalama River valley suggest that they are the flowage products of hot, gas-poor, volcanic debris mobilized by water, but the presence of enough heat to carbonize wood seems anomalous. However, the nature of the carbonization of wood in the lahar at Spirit Lake Lodge suggests an answer. Before the lahar arrived at the Toutle River, it probably was hot enough to convert all contained wood to charcoal, and any water incorporated in the lahar at this stage must have been converted to steam. The formation of steam would have dissipated heat, caused turbulence, and added considerably to the mobility of the mass by decreasing internal friction. Gradual loss of heat probably lowered the temperature of the flow until newly incorporated wood was only slightly charred or left uncharred. Nevertheless, the included bombs, because of their low heat conductivity, apparently retained a high internal heat even after the matrix cooled. After the mass came to rest and the water either drained away or escaped as steam, the heat that had been retained in the bombs was sufficient to char adjacent wood.

In this way, water and steam in a lahar could mobilize the mass on a low gradient; yet, after the lahar came to rest, heat from included rock fragments could raise the whole mass above 100° C. Kemmerling (*in* Stehn, 1929, p. 12) reported a temperature of 360° C in gases streaming from a lahar from Keloet volcano in Java shortly after it came to rest. Temperatures of 100° C were measured in the same lahar a year after its formation.

Hot lahars are a common product of volcanic activity. A notable result of the 1929 eruption of Santa Maria volcano in Guatemala was the production of lahars hot enough to carbonize wood (Sapper and Termer, 1930). These were formed by the descent of glowing avalanches into streams; the interior of the deposits remained hot for 4 weeks. Extensive lahars resulted from the 1926 eruption of Tokachidaké volcano in Japan when a hot avalanche on the western slope of the volcano melted an accumulation of snow (Tada and Tsuya, 1927; Murai, 1960). Hot lahars also have been produced during eruptions of the Hibok Hibok volcano in the Philippines (Alcarez, 1956, p. 33) and Mt. Pelée in Martinique (Anderson and Flett, 1903, p. 481).

AGE OF MOUNT ST. HELENS

From the time of early exploration in the 19th century, the smooth slopes and lack of glacial features on Mount St. Helens have been interpreted to mean that the volcano is young. Verhoogen (1937) used topographic evidence and the absence of olivine basalt (the earliest rock type erupted by the present volcano) in the terrace deposits of the North Fork of the Toutle River to date it as of Recent age. He regarded the terrace deposits as glaciofluvial gravel derived from the older Mount St. Helens during Pleistocene time.

Not only is the present cone of St. Helens of Recent age, but the older St. Helens that provided the material in the terraces apparently existed until late in Recent time and may have been entirely of Recent age. The presence of only the older St. Helens is indicated at the time the 2000-year-old wood sample was incorporated in the Silver Lake lahar assemblage, for neither lahars nor alluvium in the assemblage contain rocks from the present cone. The present cone may have been formed within the last thousand years, for soil profiles in the assemblage above the dated wood sug-

Downloaded from gsabulletin.gsapubs.org on August 28, 2013

gest an interval of perhaps as much as a thousand years during which the volcano continued to erupt the hornblende dacite and hornblende-hypersthene andesite of the older St. Helens. A critical point in these estimates of age is Verhoogen's correlation of rocks in in a canyon below Goat Rocks, and in the canyon wall of the South Fork of the Toutle River (Fig. 5). Except in the canyon where the rock may be intrusive, the old St. Helens rocks at each locality consist mostly of unconsolidated volcanic debris composed of pale-red horn-

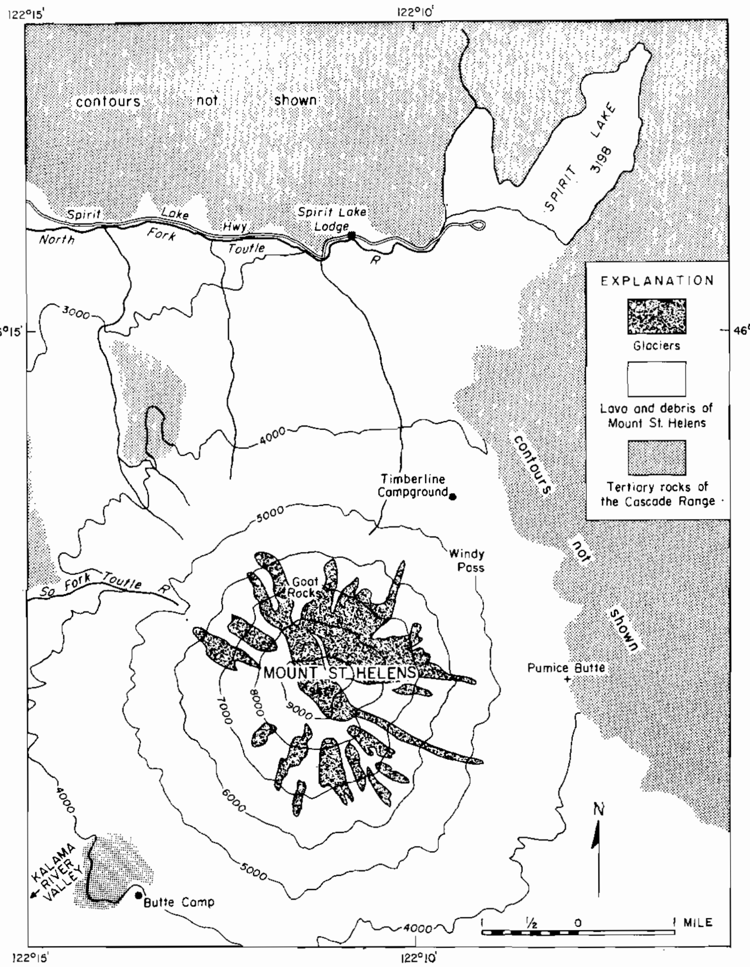

Figure 5. Index map of vicinity of Mount St. Helens and Spirit Lake

the Toutle River terrace deposits (the Silver Lake lahar assemblage) with rocks of the older Mount St. Helens. The northern and northwestern parts of the volcano were reconnoitered in an attempt to confirm Verhoogen's correlation of the two deposits.

Deposits, tentatively identified by Verhoogen as "old Mount St. Helens series" or which are lithologically indistinguishable from old St. Helens rocks, were observed near Windy Pass, near Timberline Campground, blende dacite and gray hornblende-hypersthene andesite, pumice, and ash. No basalt was found in any old St. Helens deposit, and the constituents of the unconsolidated debris are indistinguishable from those in the Silver Lake lahar assemblage. The old St. Helens rocks at each locality are overlain by thin basalt lava flows; thus, we believe Verhoogen's stratigraphy and correlation are correct.

Presumed block-and-ash flow deposits make up most of the canyon walls of the South Fork

Downloaded from gsabulletin.gsapubs.org on August 28, 2013

of the Toutle River where it is incised in the base of Mount St. Helens. The block-and-ash flows in the lower two-thirds of the canyon wall consist of the red and gray rocks of the older Mount St. Helens. These deposits are overlain by thin, basalt lava flows intercalated with block-and-ash flows containing basaltic stones and, near the top of the canyon, by block-and-ash flows of light- to medium-gray, dense, pyroxene andesite. No significant erosional unconformity was noted between the units, suggesting that eruptions of dacites and andesites of the old St. Helens and eruptions of the olivine basalts and pyroxene andesites of the present volcano were not separated by a long time interval.

The proportion of the present volcano that consists of olivine basalt and pyroxene andesite is not known. The highest outcrops of "old St. Helens series" described by Verhoogen, or found by us, are at an altitude of about 5000 feet near Windy Pass and below Goat Rocks. Because these rocks have not been found higher on the cone, the upper 3000–4000 feet of the volcano is probably composed of debris and lava flows that were erupted late in Recent time, perhaps within the past thousand years.

REFERENCES CITED

Alcarez, Arturo, 1956, Philippines, p. 32-34 *in* Symposium on volcanology of the Pacific with emphasis on *nuées ardentes:* Quezon City, Philippines, Natl. Research Council of the Philippines, Univ. of the Philippines, 8th Pacific Sci. Cong. Proc., v. 2, 573 p.

Anderson, Tempest, and Flett, J. S., 1903, Report on the eruptions of the Soufrière in St. Vincent in 1902, and on a visit to Montagne Pelée, in Martinique, Part I: Royal Soc. London Philos. Trans., ser. A, v. 200, p. 353–553

Aramaki, Shigeo, and Akimoto, Syun-iti, 1957, Temperature estimation of pyroclastic deposits by natural remanent magnetism: Am. Jour. Sci., v. 255, p. 619–627

Bemmelen, R. W. van, 1949, The geology of Indonesia, v. 1, General Geology: The Hague, Govt. Printing Office, 732 p.

Crandell, D. R., 1957, Some features of mudflow deposits (Abstract): Geol. Soc. America Bull., v. 68, pt. 2, p. 1821

Dickson, B. A., and Crocker, R. L., 1953, A chrono-sequence of soils and vegetation near Mt. Shasta, California, part I: Jour. Soil Sci., v. 4, no. 2, p. 123–141

Diller, J. S., 1899, Latest volcanic eruptions of the Pacific Coast: Science, n. s., v. 9, p. 639–640

Erdmann, C. E., and Warren, Walter, 1938, Report on the geology of three dam sites on Toutle River, Cowlitz and Skamania counties, Washington: U. S. Geol. Survey Open-File Report, 119 p.

Fremont, J. C., 1845, Report on the exploring expedition to the Rocky Mountains in the year 1842, and to Oregon and north California in the years 1843–44: 28th Cong. 2d sess., Senate Exec. Doc. 174, 693 p.

Gibbs, George, 1854, Report on the geology of the central part of Washington Territory: 33d Cong. 1st sess., House Doc. 129, v. 18, pt. 1, p. 494–512

Gilbert, C. M., 1938, Welded tuff in eastern California: Geol. Soc. America Bull., v. 49, p. 1829–1861

Hay, R. L., 1959, Formation of the crystal-rich glowing avalanche deposits of St. Vincent, B.W.I.: Jour. Geology, v. 67, p. 540–562

Lawrence, D. B., 1938, Trees on the march: Mazama, v. 20, no. 12, p. 49–54

—— 1939, Continuing research on the flora of Mt. St. Helens: Mazama, v. 21, no. 12, p. 49–54

—— 1954, Diagrammatic history of the northeast slope of Mt. St. Helens, Washington: Mazama, v. 36, no. 13, p. 41–44

MacGregor, A. G., 1938, Royal Society expedition to Montserrat, B.W.I.; The volcanic history and petrology of Montserrat: Royal Soc. London Trans., v. 229, p. 1–90

Mackin, J. H., 1948, Concept of the graded river: Geol. Soc. America Bull., v. 59, p. 463–512

Marshall, Patrick, 1935, Acid rocks of the Taupo-Rotorua volcanic district: Royal Soc. New Zealand Trans., v. 64, p. 323–366

Mason, A. C., and Foster, H. L., 1956, Extruded mudflow hills of Nirasaki, Japan: Jour. Geology, v. 64, p. 74–83

McTaggert, K. C., 1960, The mobility of *nuées ardentes:* Am. Jour. Sci., v. 258, p. 369–382

Murai, Isamu, 1960, On the mud-flows of the 1926 eruption of volcano Tokachidaké, central Hokkaido, Japan: Tokyo Univ. Earthquake Research Inst. Bull., v. 38, pt. 1, p. 55–70

Downloaded from gsabulletin.gsapubs.org on August 28, 2013

Perret, F. A., 1924, The Vesuvius eruption of 1906: Carnegie Inst. Washington Pub. 399, 151 p.

—— 1937, The eruption of Mt. Pelée, 1929–1932: Carnegie Inst. Washington Pub. 458, 126 p.

Pettijohn, F. J., 1957, Sedimentary rocks: New York, Harper and Brothers, 2d ed., 718 p.

Roberts, A. E., 1958, *Geology and coal resources of the Toledo-Castle Rock district, Cowlitz and Lewis* counties, Washington: U. S. Geol. Survey Bull. 1062, 71 p.

Sapper, Karl, and Termer, Franz, 1930, Der ausbruch des vulkans Santa Maria in Guatemala vom 2–4 November 1929: Zeitschr. fur vulkanologie, v. 13, pt. 2, p. 73–101

Sharp, R. P., and Nobles, L. H., 1953, Mudflow of 1941 at Wrightwood, southern California: Geol. Soc. America Bull., v. 64, p. 547–560

Stehn, C. E., 1929, Keloet: 4th Pacific Sci. Cong., Java, Excursion E. 2a., pt. 1, p. 1–23

Tada, Fumio, and Tsuya, Hiromichi, 1927, The eruption of the Tokachidake volcano, Hokkaido, on May 24, 1926: Tokyo Univ. Earthquake Research Inst. Bull., v. 2, p. 49–85

Varnes, D. J., 1958, Landslide types and processes, p. 20–47 *in* Eckel, E. B., *Editor,* Landslides and engineering practice: Highway Research Board Special Rept. 29, 232 p.

Verhoogen, Jean, 1937, Mount St. Helens; a Recent Cascade volcano: California Univ., Dept. Geol. Sci. Bull., v. 24, no. 9, p. 263–302

Williams, Howel, 1942, The geology of Crater Lake National Park, Oregon: Carnegie Inst. Washington Pub. 540, 162 p.

—— 1956 [1957], Glowing avalanche deposits of the Sudbury Basin: Ontario Dept. Mines, 65th Ann. Rept., v. 65, pt. 3, p. 57–89

MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, JULY 2, 1960
PUBLICATION AUTHORIZED BY THE DIRECTOR, U. S. GEOLOGICAL SURVEY