LAHARS AND LAHAR-RUNOUT FLOWS IN THE TOUTLE-COWLITZ RIVER SYSTEM, MOUNT ST. HELENS, WASHINGTON--MAGNITUDE AND FREQUENCY

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CONTENTS

NOTE: Ignore marginal hand-written notations (instructions to printer for release as Professional Paper

ILLUSTRATIONS

TABLES

CONVERSION FACTORS

For use of readers who prefer to use inch-pound units, conversion factors for terms used in this report are listed below.

Multiply SI	By	To obtain inch-pound
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
square kilometer (km^2)	0.3861	square mile (mi^2)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)

ABSTRACT

The recurrence interval of a lahar or lahar-runout flow at least large enough to inundate flood plains 50 kilometers from Mount St. Helens is less than 100 years. Lahars are volcanic debris flows and their deposits; lahar-runout flows are the hyperconcentrated streamflow evolved from distal lahars. The recurrence interval is conditional on eruptive state and is based on the most recent 4,500 years of the volcano's approximately 40,000-to-50,000-year history; it applies to the Toutle-Cowlitz River system that drains the northwest sector of the mountain and the modern crater. Lahars of the last 4,500 years have multiple origins, any one of which may cause lahars in the future. For a flow of 100-year recurrence interval, the flood plain would be inundated to a depth of 2 meters or more in the Toutle River valley between 30 and 50 km from the volcano. The recurrence interval is within a normal time frame for long-term planning.

Engineering works in the Toutle River system are best designed for lahars, rather than floods, of a particular frequency. This is true with regard to inundation levels and peak discharges, as well as impact force and shear stress on structures such as dam spillways and bridge piers.

Lahars large enough to inundate flood plains may be viewed as hazards like floods, but lahars differ from floods both in frequency distribution through time and in their effects at a particular depth of inundation. They are subject to separate and different statistical analyses. For example, lahars tend to cluster in time within eruptive periods, in effect increasing the present short-term potential. Unlike a water flood, a lahar flow depth of more than 1 m on flood plains can cause a significant part of the maximum possible damage. Trees are killed, many

structures are inundated and made unusable even if they are not crushed by timber floating in the lahar, and agriculture is not feasible for periods of as much as several years. On the positive side, the dead timber can be harvested, regrowth of some species is rapid, and the impacted watershed may be stimulated economically by reconstruction and tourism.

The largest lahar in the history of the watershed was formed by the bulking of sediment in a flood surge that originated from breaching of a natural dam of ancestral Spirit Lake. The entrained sediment is mainly stream alluvium, and megaclasts of an ancient debris avalanche are abundant in the flow unit. The flow had a peak discharge of 200,000 to 300,000 m^3/s at a distance of 30 to 50 km from the volcano, and is one of four lake-breakout lahars that occurred during a span of several years near the end of Pine Creek time. The third in the series is the second largest in the history of the watershed. The series of lahars is interpreted as an analog of the events that would have happened, without engineering intervention, after the 1980 eruption. In 1980, a debris avalanche catastrophically raised Spirit Lake more than 60 m and created new lakes in blocked tributaries.

The risk of a lahar with a peak discharge similar to that of the Amazon River at flood stage, like the huge flow of Pine Creek age, is reduced substantially, but only temporarily, by engineering works that have lowered and stabilized the level of Spirit Lake. Even with these works, however, a lahar is possible that is large enough to inundate flood plains and, locally, older lahar terraces throughout the river system. The large source of readily entrained sediment in stream channels and in the debris avalanche, combined with the potential for lahars of multiple origins in both the North and South Forks of the Toutle River, calls for continuing and conservative concern about lahar hazards in the system.

INTRODUCTION

PURPOSE, SCOPE, AND LOCATION OF STUDY

The purpose of this report is to analyze the magnitude and frequency of lahars and lahar-runout flows in the Toutle-Cowlitz River system by means of paleohydraulic and paleohydrologic approaches. The study encompasses the entire 40,000-to-50,000-yr history of Mount St. Helens but is focused particularly on the more recent eruptive periods. A companion report (Scott, 1985a) describes the origins and behavior of both modern and ancient lahars, based in part on observations and textures of the 1980 and post-1980 flows, and extension of those results to the many ancient lahars in the river system.

].1 here

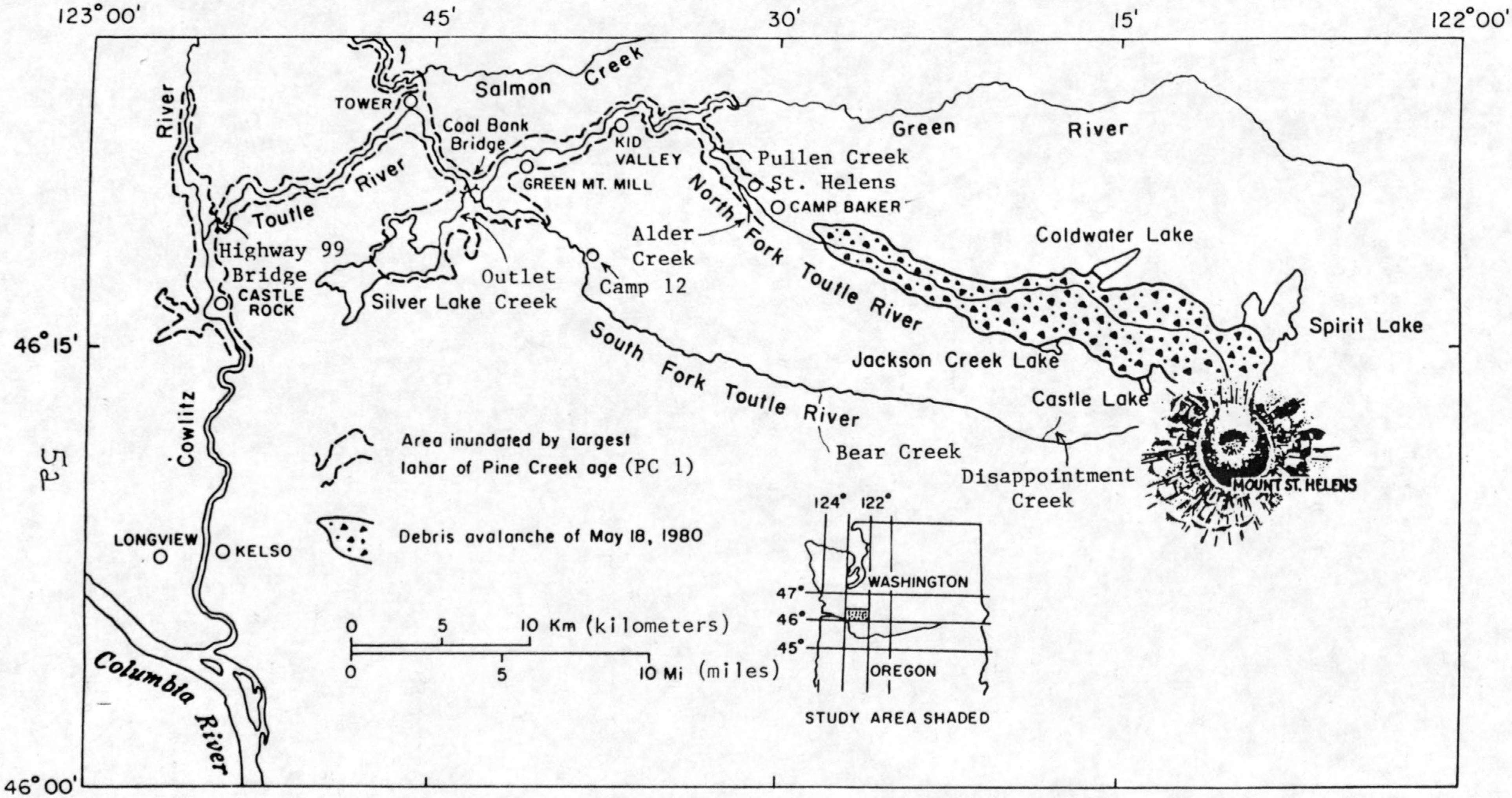
The Toutle River flows into the lower Cowlitz River (fig. 1), the headwaters of which drain part of Mount Rainier, the largest Cascade Range stratovolcano and one presently in a quiescent state. All observed lahars and lahar-runout flows affecting the lower Cowlitz River were identified (from their contained rock types) as originating in the Toutle River with volcanic activity at Mount St. Helens.

METHODS OF STUDY

The record of flows reaching long distances from Mount St. Helens can be treated like a flood-frequency analysis to calculate the probability of similar future flows. Such an analysis involving lahars will be most applicable to relatively long-term planning (involving at least several tens of years), whereas shorter-term hazards are best assessed from monitoring of the volcano and comparisons with the history of similar volcanoes (for example, Newhall, 1983). A basic difference is between the statistics of a long-term time series, in which the magnitude and

Figure 1.--Index map of Toutle-Cowlitz River system showing localities mentioned in text. The area inundated by lahar PC 1 is also shown and reflects its occurrence as the medial part of a flood wave beginning and ending as a flood surge.

Figure 1


123°00'
45'
30'
15'
122°00'
46°15'
46°00'
Salmon Creek
TOWER
Coal Bank Bridge
KID VALLEY
Green River
Pullen Creek
St. Helens
CAMP BAKER
GREEN MT. MILL
Toutle River
North Fork Toutle River
Alder Creek
Camp 12
Highway 99 Bridge
CASTLE ROCK
Outlet
Silver Lake Creek
Coldwater Lake
Spirit Lake
Jackson Creek Lake
Castle Lake
South Fork Toutle River
Bear Creek
Disappointment Creek
MOUNT ST. HELENS
Cowlitz River
Area inundated by largest lahar of Pine Creek age (PC 1)
Debris avalanche of May 18, 1980
LONGVIEW
KELSO
0 5 10 Km (kilometers)
0 5 10 Mi (miles)
Columbia River
124° 122°
WASHINGTON
47°
46°
45°
OREGON
STUDY AREA SHADED

frequency of events are in part inferred, and a case-history approach in which the appropriate examples are not yet completely known. The approaches are complimentary; the farther the horizon of the planner, the more useful will be the probabilities based on the flow record.

In addition, the magnitude, transformations, and the rates of attenuation of the ancient flows are a better guide to these aspects of the behavior of future lahars and lahar-runout flows than any model developed to date (see Scott, in press). The most typical lahar in the river system has consisted of the middle segment of a flood wave beginning and ending as streamflow (Scott, 1985a). The proximal flood surges are progressively bulked with sediment, and the distal flood waves progressively lose sediment, evolving into lahar-runout flows. Once the magnitudes of the input hydrographs and the observed rates of attenuation can be quantified in models (with both these aspects based on the actual behavior of large lahars), modeling will serve as an useful adjunct to the study of real-life lahars. Even then, however, a volcano's detailed flow history must be relied upon to indicate the most probable type and behavior of lahar.

Multiple production of lahars in the Toutle River system (table 1) corresponds to virtually all of the eruptive stages and periods established by Mullineaux and Crandell (1981), Crandell (written commun., 1983), and Mullineaux (1986). Their chronology (table 1) is used as the time scale for the frequency analysis, but the concept of the eruptive period is discussed in a section dealing with the clustering of lahars in time. The use of "stage" as a designation for older eruptive periods and the group of several, more recent eruptive periods is after Crandell (written commun., 1983). Minor differences in chronology in Table 1 with

Table 1.--Lahar and lahar-runout occurrence and extent in the Toutle-Cowlitz River system. Eruptive history of Mount St. Helens after Crandell (written commun., 1983) and Mullineaux (1986); tephra units after Mullineaux and Crandell (1981) and Mullineaux (1986). The number of overbank flows inundating flood plains at the confluence of the forks of the Toutle River is indicated for each eruptive period.

Eruptive stages and periods, or dormant intervals	Approximate radiocarbon age, years before 1950	Tephra set
Spirit Lake eruptive stage		
Period beginning in 1980		1980
Dormant interval of 123 yr		
Goat Rocks eruptive period	[1]180-123	T
Dormant interval of about 200 yr		
Kalama eruptive period	[2]500-350	X W
Dormant interval of about 650 yr		
Sugar Bowl eruptive period	1,200	
Dormant interval of about 600 yr		
Castle Creek eruptive period	2,200-1,700	B
Dormant interval of about 300 yr		
Pine Creek eruptive period	3,000-2,500	P
Dormant interval of about 300 yr		
Smith Creek eruptive period	4,000-3,300	Y
Dormant interval of about 6,000 yr		
Swift Creek eruptive stage	13,700->9,200	J S
Dormant interval of about 5,500 yr		
Cougar eruptive stage	20,400-19,200	K M
Dormant interval of about 16,000 yr		
Ape Canyon eruptive stage	>40,000-50,000 to ~36,000	C

[1]Years before 1980, based on tree-ring dates and historic records.

[2]Years before 1980, based on tree-ring dates and radiocarbon dates.

Table 1 (cont.)

Lahar and lahar-runout occurrence and extent	Overbank flows (no.)
1980 lahar in South Fork Toutle River extending to confluence of forks (a second, non-overbank lahar also reached the confluence). Runout phase reached the Cowlitz River. 1980 lahar in North Fork Toutle River extending to Columbia River. 1982 lahar in North Fork extending to Kid Valley. Runout phase reached the Cowlitz River.	------2
Avalanches and coarse rubbly lahars buried forests in the upper South Fork and are possibly correlative with 2 downstream overbank lahars, extending to confluence. 3 lahars of probable Kalama age, at least 1 overbank and extending in North Fork to confluence.	------3
	------0
Lahar of probable Castle Creek age in North Fork extending in paleochannel at least to Camp Baker. Lahars of this period are unlikely to be represented in stratigraphic record because of the erosional regime probably existing after emplacement of the large volume of Pine Creek lahar deposits.	------0
At least 2 initial lahar-runout flows, 1 overbank, extending to confluence. 1 huge lahar followed by 3 smaller flows in North Fork extending to confluence. At least the first and third lahars in this sequence reached the Cowlitz River and probably extended to the Columbia River.	------5
3 lahars and at least 2 overbank runout flows extending at least to confluence. The youngest 2 lahars originated in the North Fork and the largest probably extended to the Columbia River.	------5
10 lahars and 1 overbank runout flow extending at least to confluence.	-----11
At least 1 large lahar extending to the Cowlitz River and probably to the Columbia River.	------1
At least 5 lahars and several overbank runout flows extending at least to the confluence. At least 2 lahars probably extended to the Columbia River.	---- >8

Table 1 of Scott (1985a) reflect some of the refinements of Mullineaux (1986). Of the radiocarbon dates from samples obtained by the writer, nearly all fit within the chronology of the established eruptive periods.

The recognition and correlation of the many lahars and associated flows in the river system (table 1) are based in part on the exposures produced by lateral erosion by the 1980 lahars and subsequent streamflow. By 1985, exposures of the older flow deposits in the river system were modified by channel aggradation, bank slumping, dredge spoils, and vegetation regrowth; and several older units were obscured. Nevertheless, the overbank deposits of lahars and lahar-runout flows many tens of kilometers away can continue to provide a detailed history of events not necessarily evident at or near the volcano. More importantly for the assessment of lahar hazards, it can reveal either the true magnitude or the relative magnitudes of the flows, as well as the type and behavior of a lahar and its probable origin.

The focus of the detailed analysis of the older flows is the vicinity of the confluence of the forks of the Toutle, over 50 km from the volcano, because that area is the most upstream part of the watershed that is well populated. Although the following record of older flows should be viewed as one in a series of successive approximations, it certainly is complete enough to indicate the continuing, long-term hazards of lahars in the system. No new stratigraphic terminology is proposed.

Radiocarbon dates with conventional one-sigma statistical counting errors less than ± 100 yrs are by I. C. Yang, and uncited dates with larger statistical error factors are by commercial labs. Dates of individual samples are in radiocarbon years unless otherwise stated.

Following Mullineaux and Crandell (1981), the ages of the eruptive episodes (Table 1) are in radiocarbon years, except for those of the Goat Rocks and Kalama periods which are in calendar years before 1950.

ACKNOWLEDGMENTS

Advice on pumice identifications by D. R. Mullineaux was invaluable. His identifications are cited as oral communications in the text and in the Coal Bank Bridge section in the Appendix. Uncited identifications at that section and at other localities were made by the writer.

Several local residents provided access to important exposures. Among these was N. B. Gardner, who had recognized that the tree molds penetrating the thick lahar sequence of Pine Creek age were evidence that the sequence had been emplaced within a relatively short time span.

I thank J. C. Brice, D. R. Crandell, R. J. Janda, and W. R. Osterkamp, U.S. Geological Survey, and J. H. Hubert, University of Massachusetts, for beneficial, constructive reviews of all or parts of the report. A draft of a paper by Crandell, describing deposits generally near the volcano as they existed before 1980, is referenced throughout this report as a written communication.

LAHARS AND LAHAR-RUNOUT FLOWS OF PRE-1980 ERUPTIVE STAGES AND PERIODS

The first part of this report consists of lahar and lahar-runout-flow stratigraphy, by eruptive stage and period. This, with the noted caveats, is the foundation of the subsequent discussion of lahar magnitude and frequency. Selected examples of many detailed stratigraphic sections appear in the Appendix, and these are mainly from the vicinity of the forks of the Toutle River. A glossary of many terms used in describing volcanic flow phenomena, lahars, lahar-runout flows, and volcaniclastic sediment is included in Scott (1985a).

That some lahars had moved long distances from Mount St. Helens in the Toutle River system was first recognized by Mullineaux and Crandell (1962). They defined a Silver Lake lahar assemblage near the confluence of the forks of the Toutle River, and noted that Silver Lake had formed behind the natural dam created by those lahars. The lahar sequence at that point was shown to include three lahars of Pine Creek age and a lower lahar of Smith Creek age (Crandell and others, 1981; Crandell, written commun., 1983).

APE CANYON ERUPTIVE STAGE (>40,000 or 50,000 to ~36,000(?) YEARS)

A valley fill containing at least five lahars and many lahar-runout flows is exposed near the confluence of the forks of the Toutle River, near Tower, and at the confluence of the Toutle and Cowlitz Rivers. At these localities the fill surface extends to a level as much as 30 m above the surface of the better preserved lahar-emplaced terrace of Pine Creek age. The older valley fill represents gradual valley-wide aggradation, in contrast to the brief series of catastrophic events that formed the younger terrace. Also unlike the younger terrace, which is underlain almost entirely by lahars and locally by lahar-runout deposits, the older fill includes a significant volume of pumice-rich alluvium, a part of which represents glacial outwash deposition.

The fill of Ape Canyon age is exposed near Tower at levels indicating that drainage during the eruptive stage was partially out of the Toutle River watershed and northward into Salmon Creek. Salmon Creek joins the Cowlitz River approximately 19 river kilometers upstream from the confluence of the Toutle and Cowlitz Rivers.

The lahars of Ape Canyon age are as much as 3.0 m thick but their correlation and detailed sequence could not be determined because of sporadic exposure. Areas of accessible exposure include the valley side slopes approximately 200 m upstream from the Coal Bank Bridge, and in valley side slopes short distances north and west of the Green Mountain Mill. Both forks of the Toutle River yielded multiple lahars during this stage. Deposits of Ape Canyon age occur sporadically both at channel level and at high levels (up to 60 m) in both forks, indicating the system-wide nature of the fill. The characteristically light-colored deposits form the basalmost parts of thick sections of pyroclastic flows, lahars, and volcaniclastic and glacial sediment near the base of the volcano in the upper South Fork.

Dacite and pumice clasts in the deposits are relatively highly weathered and impregnated with secondary clay. Meaningful size analyses for comparison with younger flow deposits consequently were not possible (as in table 5 of Scott, 1985a). Nevertheless, the textures of the lahars were similar to those of the younger flows in that the matrices are predominantly silty sand and have probably have relatively small amounts of primary clay-size sediment. Most are relatively fine grained compared to the flows of younger eruptive periods. In sections near the

Toutle-Cowlitz River confluence, lahar-runout flows are more abundant than lahars.

Soil development extends locally to depths of more than 3 m. Sufficient clay to cause a sticky consistency in the lower A and B horizons is characteristic, as is mottling of B and C horizons in irregular clay-rich zones. Silt loams of the Gee and Seaquest soil series (Call, 1974) occur on the surface of the fill. The red color locally present in the soil developed on Ape Canyon deposits, and less commonly on those of younger periods at lower levels, reflects upslope pedogenesis of volcanic rocks of pre-Mount St. Helens age. The lateritic pedogenesis also predates Mount St. Helens.

The dating of the sequence is based on several lines of evidence. The degree of weathering is significantly greater than that of deposits of Cougar age, the next youngest eruptive stage. At the Coal Bank Bridge section (Appendix) the fill occurs disconformably beneath lahars of Swift Creek age that can be seen to overlap a valley side slope cut in the older sequence. The pumice, the lahars, and the nonlaharic sediment of the sequence contain abundant biotite. Tephra set C (table 1) of the eruptive stage contains biotite as a characteristic ferromagnesian phenocryst (Mullineaux and Crandell, 1981, table 1). Pumice collected from the oldest deposits in the Coal Bank Bridge section is believed by Mullineaux (oral commun., 1982) to be of Ape Canyon age with 90 percent probability.

The range given for the start of the eruptive period is based on the thick and extensive deposits present in both the Toutle River and Lewis River systems. An unknown but probably lengthy period was necessary for accumulation of the sequence. The Lewis River drains the south and east sides of the volcano. A radiocarbon age (>35,800 yrs) from the lahar dated by Hyde (1975) in the upper Lewis River confirmed his date of >36,000 yrs. Both samples are radiometrically "dead," and thus represent minimum ages. Other field work with J. J. Major confirmed the distribution of Ape Canyon-age fill to high levels on valley side slopes throughout the lower reaches of the Lewis River system, like the system-wide deposits of the Toutle River.

COUGAR ERUPTIVE STAGE (20,400 to 19,200 YEARS)

A thick lahar of Cougar age is exposed in a small quarry developed during 1981 in the Cowlitz River valley west of Castle Rock (NE 1/4 sec. 4, T.9N. R.2W.). The deposit is at an elevation similar to that of the subsequent huge flow of Pine Creek age, but the two lahars cannot be compared in size because of the unknown configuration of the valley in Cougar time. The deposit is at least 1.3 m thick and the included clasts are dominated by rock types from Mount St. Helens. Abundant pumice from the uppermost part of the unit is probably of Cougar age from tephra set K or M (table 1) but possibly of Smith Creek age, according to Mullineaux (oral communication, 1982). The original exposures showed that the flow deposit is overlain by at least 15 m of cyclically bedded, silt-rich sediment probably correlative with backwater deposits of major Channeled Scabland flooding of about 13,000 years ago. Consequently, a Cougar age for the lahar is a near certainty.

Although this flow was large enough to have reached the Columbia River, at least in its runout phase, its deposits were not definitely identified elsewhere within a long distance from the volcano in the Toutle River system. Its deposits, and those of any other large lahars of the eruptive stage, are probably covered by an inset younger assemblage. A probable Cougar-age lahar is present in the South Fork Toutle River as far as 10-12 km from the volcano (see Disappointment Creek section in Appendix), but is unlikely to represent the proximal phase of the lahar seen in the Cowlitz River. Other Cougar age deposits are present in the Bear Creek section (Appendix).

Sections near Tower may contain Cougar-age flows. Those deposits are definitely post-Ape Canyon and pre-Pine Creek in age but most are more probably of Swift Creek age, as discussed in the following section.

SWIFT CREEK ERUPTIVE STAGE (13,700 to >9,200 YEARS)

The lower 7 units of the post-Ape Canyon part of the Coal Bank Bridge section, 6 of which are lahars, are of probable Swift Creek age. Unit 3 was the oldest pumice-bearing unit in the section and yielded pumice regarded by Mullineaux (oral communication, 1982) as probably set J of Swift Creek age. Unit 8 is a rubbly lahar that is locally disconformable with older units, suggesting the possibility of change in the valley erosional regime. That lahar, and overlying units 9 through 14 (including 3 lahars and a lahar-runout flow), are more certainly of Swift Creek age. In general, the certainty of a Swift Creek age increases throughout the sequence of 14 units.

The upper part of a soil developed on unit 14 contained tiny charcoal fragments yielding in aggregate a radiocarbon date of 3,760 ± 180 yrs. Based on the date alone it is not clear if the soil represents (1) the approximately 5,000-yr interval between the Swift Creek and Spirit Lake stages, (2) the approximately 300-yr interval between the Smith Creek and Pine Creek periods, or (3) an interval between eruptions within the Smith Creek period. The type and extent of weathering process (in comparison to soil formation on the uneroded terrace of Pine Creek age, representing a 2,500-yr period) shows the soil to represent the earlier and longer dormant period. Thus the conformably underlying units (8-14) are of Swift Creek age. This conclusion is supported by the presence of pumice with phenocrysts of hypersthene and hornblende from units 8, 11, and 12. Pumice with that mineralogy is characteristic of Swift Creek age, but not exclusively so. It is, however, definitively different from set Y of Smith Creek age.

Cutbank exposures at the north side of the modern flood plain upstream from Tower reveal a sequence of lahars and lahar-runout deposits with marked facies change. The sequence is nearly lacking in pumice, but almost all the few pumice clasts that were gleaned from talus at the cliff base contain hypersthene and hornblende and probably represent set J. The extensive soil development to a depth of as much as 1.0 m is highly compatible with a probable Swift Creek age for most of the sequence. The possibility of Cougar-age flows low in the section should be evident from soil development within the section. No evidence of a hiatus was observed, however. The runout flows in the sections near Tower are the likely downstream transformations of the Swift Creek lahars in the Coal Bank Bridge section. The high cut banks on the south side of the valley near Tower contain flows of Pine Creek age downstream, but are composed of deposits of probable Swift Creek age upstream.

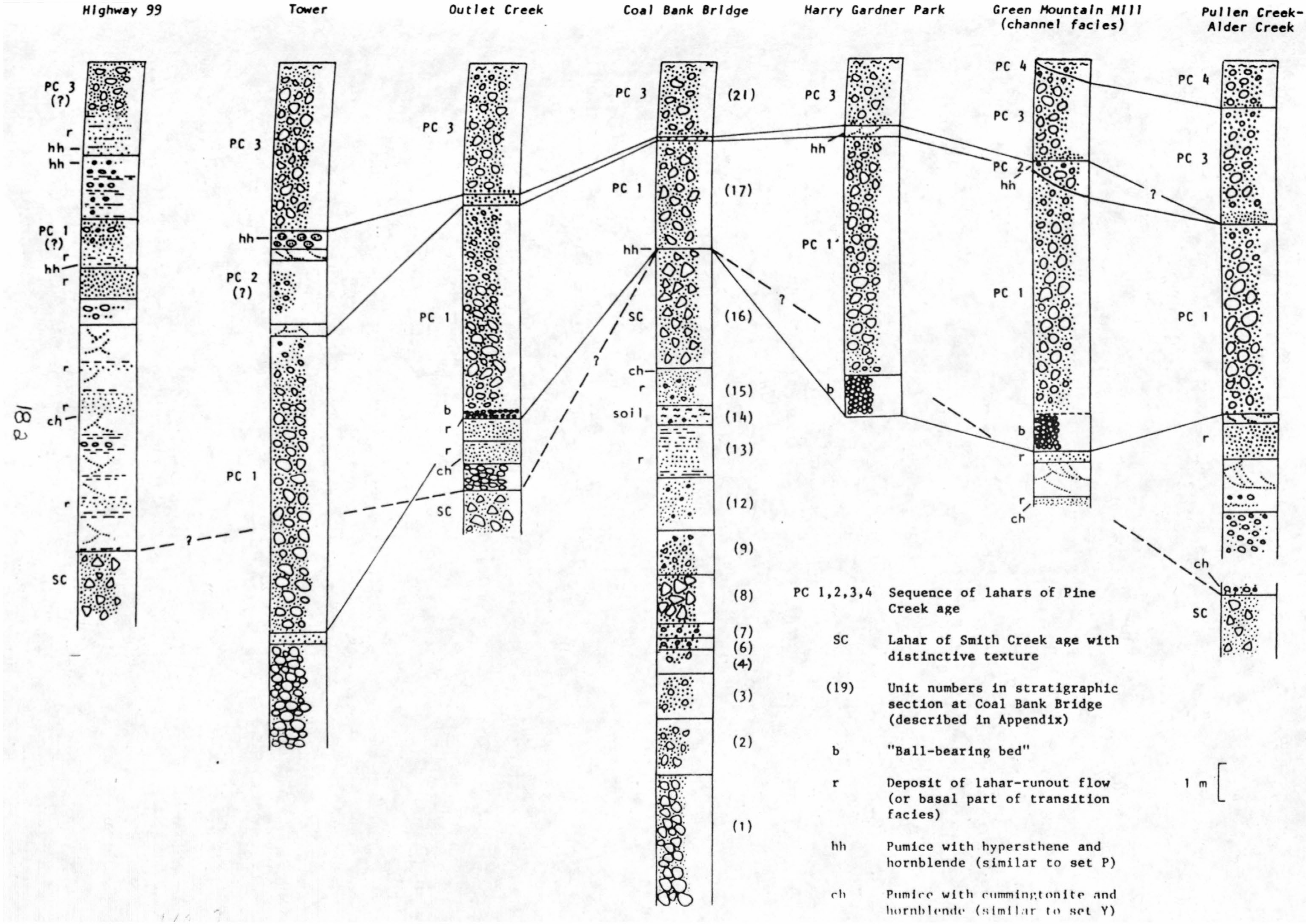
Near the volcano a sequence of pyroclastic flows and lahars of Swift Creek age forms part of an apron of flowage and alluvial deposits that extends into the headwaters of the South Fork of the Toutle River and locally inundated the valley bottom (see Bear Creek and Disappointment Creek sections in Appendix; Crandell, written commun., 1983). The extent (up to 20 km at the Bear Creek locality) and number of Swift Creek flows extending into the upper South Fork suggests that the numerous lahars of that period at the confluence of the forks could mainly reflect flow from that tributary. The largest flows of the subsequent two periods clearly were derived from the North Fork of the Toutle River.

SPIRIT LAKE ERUPTIVE STAGE

Smith Creek eruptive period (4,000 to 3,300 years)

Two flow units in the Coal Bank Bridge section represent the Smith Creek eruptive period with a relatively high degree of probability. A runout flow deposit just beyond the transition from a lahar overlies the soil of the preceding dormant period, and the uppermost part of the bed (unit 15) contains concentrated pumice identified by Mullineaux (oral commun., 1983) as from set Y of Smith Creek age. On a textural basis, the overlying large lahar (unit 16) is a highly probable correlative of the lowest lahar of the Outlet Creek section (Appendix) and is probably the lahar with a relatively high clay content seen beneath the Pine Creek deposits at several locations ranging from the community of St. Helens on the North Fork to the Highway 99 Bridge on the lower Toutle River (fig. 2). The lowest lahar at Outlet Creek was interpreted by Crandell (written commun., 1983) to be Smith Creek in age, as based on the the presence of pumice from set Y and wood fragments yielding a date of 2,810 $\pm$ 200 radiocarbon years in the overlying fluvial sequence. This overlying sequence is not present in the Coal Bank Bridge section but is widely distributed throughout the North Fork and main Toutle River. What is likely the same lahar occurs at Alder Creek beneath a soil containing wood fragments with a radiocarbon age of 2,900 $\pm$ 250 years (Crandell, written commun., 1983)). The extent, thickness, and texture of the lahar indicate that it probably reached the Columbia River. A much smaller but

Figure 2.--Selected columnar sections of lahars and lahar-runout flow deposits in the Toutle River system. Numbers assigned to units of the Coal Bank Bridge section correspond to those in the measured stratigraphic section at that locality described in the Appendix.



Highway 99
Tower
Outlet Creek
Coal Bank Bridge
Harry Gardner Park
Green Mountain Mill (channel facies)
Pullen Creek-Alder Creek
PC 1,2,3,4 Sequence of lahars of Pine Creek age
SC Lahar of Smith Creek age with distinctive texture
(19) Unit numbers in stratigraphic section at Coal Bank Bridge (described in Appendix)
b "Ball-bearing bed"
r Deposit of lahar-runout flow (or basal part of transition facies)
hh Pumice with hypersthene and hornblende (similar to set P)
ch Pumice with cummingtonite and hornblende (similar to set Y)
1 m

similar lahar overlies the main lahar at Kid Valley and probably reached the confluence of the forks of the Toutle River, but it is not recorded in the Coal Bank Bridge section. Both units have a relatively high primary clay content, the behavioral implications of which are discussed in Scott (1985a).

The overlying, mainly fluvial sequence includes at least six runout flow deposits, two of which are included in the Outlet Creek section (units 3 and 4). The sequence probably includes deposits of both Smith Creek and Pine Creek age, as well as the intervening dormant period. The upper part at the Green Mountain Mill section is probably of Pine Creek age. The lower part at the Highway 99 locality (fig. 2) contains pumice mineralogically similar to set Y and thus is probably Smith Creek in age; the upper part contains pumice like that of set P and thus is probably Pine Creek in age.

Near the volcano, lahars and pyroclastic flows of Smith Creek age compose a significant part of the apron of deposits extending north from the volcano into the valley of the North Fork Toutle River west of Spirit Lake (Crandell, written commun., 1983). These units are now covered by the 1980 debris avalanche.

Pine Creek eruptive period (3,000 to 2,500 years)

The Pine Creek age of the uppermost lahar-runout deposits in the mainly fluvial sequence beneath the largest Pine Creek lahar (PC 1) is also indicated by their local streambank inundation of old-growth forest, and the dating of that forest (Table 2). The forest grew during the preceding dormant interval and survived on flood plains throughout much of Pine Creek time until it was inundated by a series of four lahars late in the eruptive period (PC 1 through 4). That the lahars were confined

Table 2.--Radiocarbon dates indicating that the age of the largest lahar in the history of the watershed (PC 1) and three lahars closely related in time, was near the end of the Pine Creek eruptive period, about 2,500 years ago. Sequence of dates is from upstream to downstream.

Date	Location and Comments
2,510 ± 40	Green Mountain Mill section (see Appendix). Outermost wood from highest part of stump remaining at base of channel facies of lahar PC 1. Analysis by I. C. Yang.
2,550 ±145	Buried forest at distal end of gorge beginning below the Coal Bank Bridge. Outermost wood about 2 m above original ground surface. Analysis by Geochron Inc.
2,560 ± 155	Same as preceding sample.
3,290 ± 195	Same as preceding sample. The only significant difference was tree type--this stump was a cedar; the other two were probably Douglas firs. See text.

2,440 ± 40	Detrital limb immediately beneath lahar PC 1, 3.0 km upstream from confluence of Toutle and Cowltiz Rivers (lahar flowed upstream from confluence). Analysis by I. C. Yang
2,790 ± 245	Same sample (split) as preceding. Sample split by I. C. Yang; analysis by Geochron, Inc.

to Pine Creek time is indicated by the radiocarbon dates, as well as by the lack of rock types from the modern cone of Mount St. Helens in the youngest of the flows. Those rock types are present in the deposits of subsequent eruptive periods. The series of lahars late in the period is interpreted as of lake-breakout origin, and it includes the two largest flows in the history of the watershed (see subsequent discusssion of magnitude).

Lahar PC 1, the largest lahar from Mount St. Helens in the history of the Toutle River watershed, occurred about 2,500 yrs ago (table 2). The subsequent three flows occurred within several years thereafter, the evidence for which is discussed in the section on time clustering of lahars. The channelized parts of lahar PC 1 stripped the forest from areas marginal to channels; the flood plain flow surrounded standing trees and preserved their form as vertical tree molds. Facies of the series are shown in fig. 12 of Scott (1985a).

Radiocarbon dates relevant to the age of lahar PC 1 are summarized in table 2. The only aberrant date (3,290 $\pm$195 years) was from a cedar tree in growth position on a surface inundated by the lahar. The cedar was possibly dead at the time of inundation. Cedars are relatively well preserved in growth position at Old Maid Flat on Mount Hood about 200 years after death by lahar inundation (Crandell, 1980), based on observations by P. T. Pringle and myself. Some other species are nearly entirely decayed at Old Maid Flat, forming tree molds like those in the series of Pine Creek age at Mount St. Helens. Another possibility is that the sample was from the interior of the tree, on the premise that the outer layers were abraded by boulders, which were concentrated in the basal flow as energy was reduced in the expanding reach below the gorge (see Scott, 1985a). These explanations assume no laboratory error.

Near the volcano, the Pine Creek eruptive period was marked by many pyroclastic flows, compared to a relative paucity of such flows in the Smith Creek period (Crandell, written commun., 1983). Deposits of the period underlie large areas around the base of the volcano. In the headwaters of the Toutle River system they include several lahars of probable Pine Creek age in the upper South Fork that apparently did not reach the confluence in significant volume. Lahars of the period traveled at least as far as the Bear Creek section (Appendix) in the South Fork, however. Crandell also reports lahars interbedded with pyroclastic flows from the period on the north side of the volcano in the drainage area of the North Fork Toutle River and, in Castle Creek, a thick fill of pyroclastic flows and lahars.

Castle Creek eruptive period (> 2,200-1,700 years)

The dormant interval of less than 300 years, which followed emplacement of the huge volume of Pine Creek lahars, was marked by extensive reworking of lahar-emplaced sediment. A widespread terrace underlain by fluvial deposits up to 2.5 m in thickness illustrates the rapid response of a river system to laharic sedimentation. These deposits have little (1 to 2 percent at most) of the darker and more mafic rock types of the Castle Creek and subsequent eruptive periods. Field work with R. J. Janda likewise revealed only small amounts of these lithologies in a fill emplaced subsequent to the Pine Creek lahars in the Cowlitz River below its confluence with the Toutle River. Paleomagnetic data indicate that two lava flows with the changed, more mafic chemistry are of the same age as Pine Creek dacites on the south side of the volcano. (R. T. Holcomb, written commun., 1986). The lack of basic lithologies in the Pine Creek lahars and the low content in their subsequently reworked deposits can be explained by the lack of a significant volume of basaltic lava flows on the north side of the volcano at that time. It does not rule out the change in chemistry having occurred within the Pine Creek eruptive period, as suggested by the paleomagnetic data.

The sediment-transport regime in the Toutle River system during the dormant interval preceding the Castle Creek eruptive period was likely one of rapidly migrating braided channels, in which the vast influx of laharic sediment was reworked. Consequently, preservation of lahar deposits of Castle Creek age, inset against eroding cutbanks of the lahar-emplaced terrace of Pine Creek age, is unlikely.

A coarse rubbly lahar, probably from the Castle Creek period, was recognized in the basal part of the fill of a pre-Kalama-age paleochannel near Camp Baker. Based on relative soil development on the fill deposits and on a younger lahar of probable Kalama age at the same locality, the fill is probably of Castle Creek age. A significant content of modern-cone rock types establishes the basal channel fill as post-Pine Creek in age.

In the headwaters of the Toutle River system, Crandell (written commun., 1983) describes the deposits of the period as predominantly lava flows and pyroclastic flows accompanying a single lahar in the Castle Creek drainage. Several lahars of this eruptive period were recognized near the volcano in the upper South Fork, and numerous flows occur in other drainages outside the Toutle River system.

Sugar Bowl eruptive period (age: 1,200 years)

Lahars representing this brief eruptive period, the chief product of which was the Sugar Bowl dome on the north flank of the mountain

(Mullineaux and Crandell, 1981), were not seen in the downstream river system. Crandell (written commun., 1983) recognized apparently local lahars of this period that were formed by interactions between pyroclastic flows and snowpack at the base of the cone near Spirit Lake. Crandell and Hoblitt (1986) have recognized two northeastward-directed lateral blasts associated with formation of the Sugar Bowl dome.

Kalama eruptive period (500 to 350 years)

In both the North Fork Toutle River at Camp Baker and the South Fork at Weyerhaeuser Camp 12, similar lahars of probable Kalama age occur above soils containing wood dated at 1,250 ± 40 years at Camp Baker and 1,360 ± 215 years at Camp 12. All flow deposits are relatively fine-grained flood plain facies with granular matrices. A possibly correlative channel facies of the North Fork flow near Camp Baker consists of coarse cobbles locally with a clast-supported framework. Relative thicknesses of incipient soil development on the units in each fork are compatible with a Kalama age. Mature trees growing on the units establish a pre-Goat Rocks age for the flows.

The largest Kalama-age lahar in the North Fork Toutle River forms a low terrace level near Kid Valley, where it conformably overlies two smaller lahars that are also of Kalama age. Wood from an in-place stump overlain by the three units yields a date of 505 ± 155 years. Mature trees occur on the terrace surface. Near the Green Mountain Mill the largest flow contains a hypersthene-rich pumice that is mineralogically similar to set W.

The upper glaciated valley of the South Fork Toutle River is filled by a sequence of the deposits of avalanches that transformed to lahars extending at least 20 km from the crater. During and probably associated with part of this deposition was a major pyroclastic surge with many similarities to the 1980 blast deposit. Wood from the outermost part of a mature tree buried by the largest of the avalanche deposits yielded a date of 460 ± 40 years. That date corresponds to a calendar date of about 1440 A.D. on the tree-ring calibration curve of Suess (1970). Given the standard deviation of the date, and the presence of about 25 annual rings in the sample, that deposit may correlate with the eruption producing layer Wn of set W. That eruption has been dated as A.D. 1480 by Yamaguchi (1983).

The pyroclastic surge described here and in Scott (1985a) is almost certainly the pyroclastic flow dated by Yamaguchi and Hoblitt (in press) within the range of A.D. 1647-1668. The deposit contains abundant, generally surficially charred, wood and is locally dominated by the light-gray, fine-grained dacite of the summit dome, which formed the peak of the volcano prior to 1980. Mapping of the surge deposit during 1984 showed its deposits to include pebble-size, non-pumiceous clasts at elevations in excess of 300 m on valley side slopes at distances of 7 km from the crater. The surge entered both Sheep Canyon and the drainage of the North Fork Toutle River, and was strongly directed westward down the South Fork against the probable prevailing wind direction. The episode is marked by a fine-grained layer 1 cm or less in thickness that occurs within the grass-root zone at greater distances from the volcano. That unit is the deposit of the ash cloud associated with the surge (or flow; note the variety of terminology applied to the 1980 lateral blast).

Ilustrative of the spread in radiocarbon ages from young material (see Suess, 1970, and Stuiver, 1978), three wood fragments from the main surge deposit yielded dates of 485 ± 155, 435 ± 125, and 145 ± 125 radiocarbon years. A radiocarbon date of 145 years can correspond to various calendar year ages between approximately A.D. 1670 and A.D. 1810 (Stuiver, 1978, fig. 1). The tree-ring dating by Yamaguchi and Hoblitt (in press) more accurately defines the time of this event.

The locally thick valley-fill facies of the surge is locally overlain by a lahar closely, if not synchronously, related in time and also closely related in composition. At other locations the surge deposits are related to avalanche deposits having, in 1982 exposures, probable ground surge deposits at their bases. All these flows probably occurred slightly later than the Kalama time interval recognized by Mullineaux and Crandell, but are treated here as if they occurred during a brief extension of that eruptive period. Only the Kalama-age lahars that extended to the confluence of the forks of the Toutle River are included in the subsequent frequency analysis. Based on the stratigraphic evidence, it can be strongly inferred, however, that the two lahars moving long distances in the South Fork originated directly with this catastrophic activity, either as transformations of avalanches or of the pyroclastic surge itself, or both these origins. A long interval of bedrock channel (fig. 6; Scott, 1985a) makes the continuous tracing of individual flow units impossible.

Lahars are interbedded with other types of flows and eruptive products of the Kalama period near the volcano. Lahars of almost certain Kalama age occur in nearly every watershed draining Mount St. Helens. Crandell (written communication, 1983) notes a variety of lahar emplacement temperatures and the extension of flows at least as far as 11 km from the base of the volcano in the South Fork of the Toutle River. A large slope-mantling lahar of Kalama age occurs in the Disappointment Creek section (Appendix).

Goat Rocks eruptive period (180-123 years)

The Goat Rocks dome was formed in the segment of the volcano drained by the North Fork Toutle River. The associated downslope deposits include material emplaced either by pyroclastic flows or lahars carrying both hot and cold debris (Crandell, written commun., 1983). A lahar in this eruptive period, as well as another later flow in A.D. 1855, occurred in the upper South Fork of the Toutle River (Yamaguchi and Hoblitt, in press). No lahars large enough to inundate flood plains a significant distance from the volcano were recognized from this youngest of the pre-1980 eruptive periods.

MAGNITUDE OF LAHARS

FLOW DEPTHS BASED ON THICKNESS OF FLOOD PLAIN FACIES

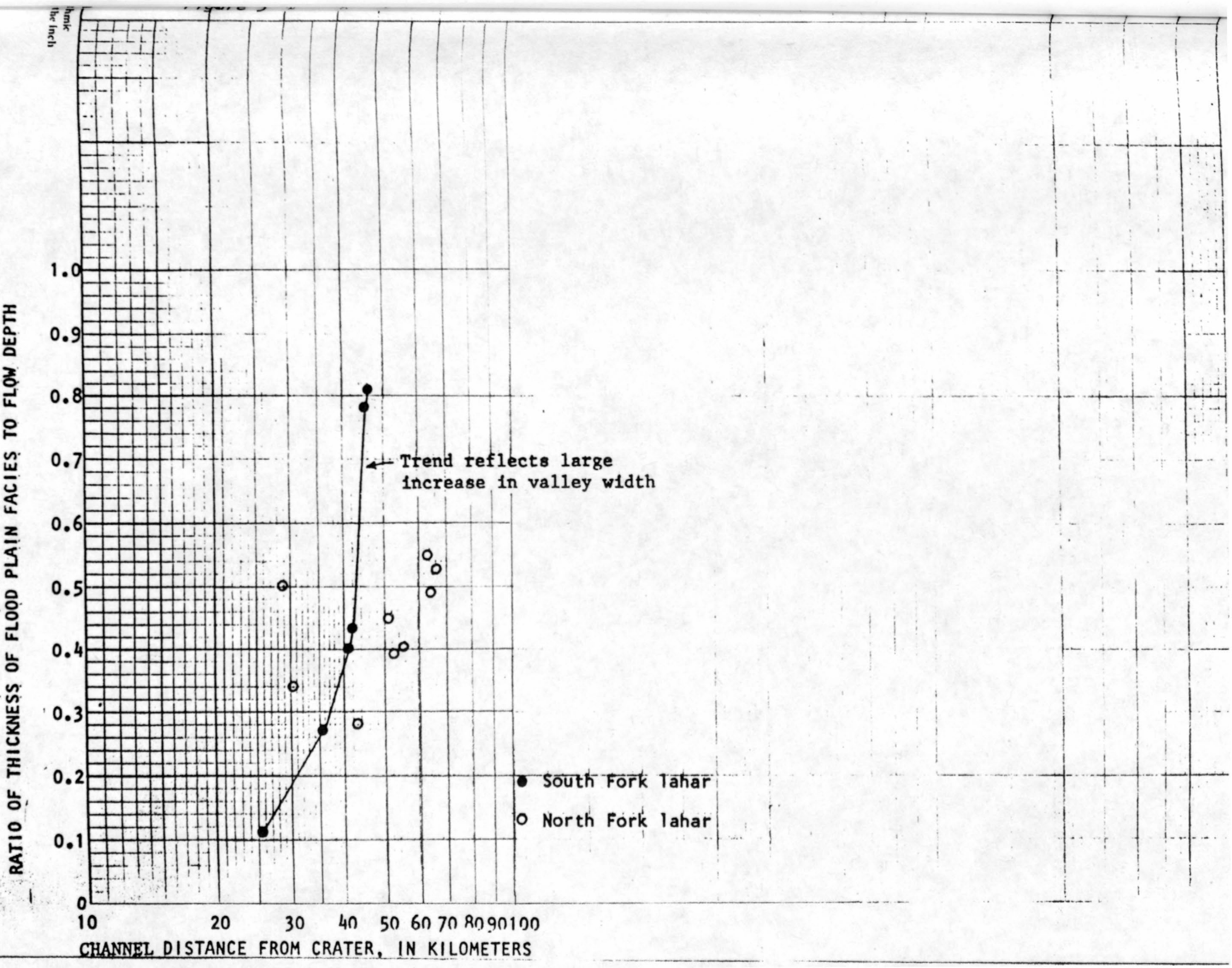
Empirically, the thicknesses of lahar deposits that remain as the flood plain facies are proportional to the sizes of the flows of the modern eruptive period. This should also be true for the ancient lahars. With similar reasoning, Kochel and Baker (1982) found that paleoflood discharge and slack-water flood sediment thickness appeared to be directly related at a given depositional site. Given the general similarity in texture of most of the lahars in the watershed, the thicknesses of the flood plain facies at a downstream location like the confluence of the forks of the Toutle River can indicate the relative sizes of the flows.

3 here

Figure 3 is a plot of the ratio of the thickness of the flood plain facies to flow depth for the two largest 1980 flows in the system. The plot indicates that, downstream and with increasing channel width, the deposits fill a greater proportion of the flow cross sections in the case of both the relatively high-clay North Fork lahar and the more typical granular and noncohesive South Fork lahar before the transformation to a lahar-runout flow began. That is, rates of deposition increased as slope decreased and valley width increased.

A clearly definable and constant relation between deposit thickness and flow depth is not to be expected, particularly because of the close time relation between some older flows. Overbank deposition of a sheet of lahar deposits must cause a period of channel readjustment to the increased flood plain levels during which the relation between deposit thickness and flow depth for a subsequent flow will be changed temporarily. Nevertheless, for older flows that are textural analogs of

Figure 3.--Plot of ratio of thickness of flood plain facies to flow depth, vs. distance from 1980 crater, for the two largest 1980 lahars described in Scott (1985a).



RATIO OF THICKNESS OF FLOOD PLAIN FACIES TO FLOW DEPTH
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
10
20
30
40
50
60
70
80
90
100
CHANNEL DISTANCE FROM CRATER, IN KILOMETERS
Trend reflects large increase in valley width
South Fork lahar
North Fork lahar

one of the 1980 flows, the ratio of the thickness of the flood plain facies to flow depth at a similar channel slope and configuration should in most cases yield a useful estimate of the overbank flow depth (Table 3). Such an estimate, however, is a recourse secondary to measurement of the actual flow cross sections of the older flows.

ble
3
here

Table 3.--(1) Thickness of flood plain facies, (2) depth of flow on flood plain, and (3) measured and estimated peak discharges for lahars in the Toutle-Cowlitz River system. Data are from the vicinity of the confluence of the forks of the Toutle River unless otherwise indicated.

Eruptive stage or period	(1) Thickness of flood plain facies (m)	(2) Overbank flow depth (m)	(3) Discharge (m^3/s)
Modern			
March 1982 North Fork lahar	Runout phase not overbank at confluence	0	a960 (Kid Valley)
May 1980 North Fork lahar	1.5-2.0	b1.0-4.0	c6,800
First May 1980 South Fork lahar	0.5	b<1.0	c3,600
Second May 1980 South Fork lahar	Overbank only where dammed by North Fork lahar at confluence	0	500
Kalama (probable)			
Lahar from North Fork	>1.8	d >4.0	
Conformably underlying lahar	Probably not overbank	0	
Lowest conformable lahar at Kid Valley	Probably not overbank	0	
Lahar from South Fork at Camp 12	1.3	d2.0	
Lahar from South Fork at Camp 12	1.0	d1.5	
Castle Rock (probable)			
Lahar at Camp Baker	Confined to channel	0	
Pine Creek			
fourth lahar (PC 4)	0.0-1.5	d≦ 2.5	
third lahar (PC 3)	2.6->4.4	e > 8.0	f48,000 (Kid Valley)
second lahar (PC 2)	0.0-2.2 (mean = 0.8)	d≦ 3.0	

p.2 of 3

Table 3 (cont.)

first lahar (PC 1)	2.4-7.0	e≤14.0	g200,000-300,000 (30-50 km from crater) f85,000 (gorge below Coal Bank Bridge) g50,000 (Highway 99)
Smith Creek			
Lahar at Kid Valley	0.4	d0.8	h<1,200
Unit 16 of Coal Bank Bridge section	3.2	d6.5	h25,000 (confluence of forks) i20,000 (Highway 99)
Unit 15 of Coal Bank Bridge section	1.0	1.5	2,000
Lahar in South Fork	1.4	d3.0	i5,000
Swift Creek			
Unit 14	0.5	d1.0	
Unit 12	1.4	d3.5	
Unit 9	1.2	d3.0	
Unit 8	1.5	d2.3	
(Units 14–8: Coal Bank Bridge section)			
Swift Creek (probable)			
Unit 7	0.4	d1.0	
Unit 6	0.3	d0.8	
Unit 4	0.6	d1.5	
Unit 3	1.2	d3.0	
Unit 2	1.7	d4.2	
Unit 1	j>1.0	d>2.5	
(Units 7–1: Coal Bank Bridge section)			
Cougar			
Lahar in Cowlitz River Valley	>1.3	d>3.2 (Cowlitz River)	
Ape Canyon			
5 lahars	most >1.0	most d>2.0	
Largest lahar	3.0	d~6.0	

Table 3 (cont.) footnotes

a Pierson and Scott (1985).
b Flow depth measured from peak stage marks.
c Fairchild and Wigmosta (1983).
d Flow depth estimated from ratio of thickness of flood plain facies to flow depth of appropriate 1980 lahar at a location with a similar slope and channel configuration.
e Flow depth measured from distribution of peak flow deposits.
f Discharges based on measured cross sections and estimated velocities.
g Discharges based on measured cross sections; velocities based on measurements of runup.
h Discharge based on depth estimated from thickness of flood plain facies; velocity estimated.
i Based on attenuation rate of the texturally similar 1980 North Fork lahar.
j Based on relative thicknesses of channel and flood plain facies of 1980 lahars.

MEASUREMENT OF CROSS SECTIONS OF LAHAR FLOOD WAVES

A significant practical aspect of the study of lahar boundary features (Scott, 1985a) is the identification of specific flows in lateral deposits on slopes. Figure 4 shows how the flow cross sections of lahar PC 1 were measured and how the cross sections of lahar PC 3 were estimated. The lateral equivalents of the "ball-bearing bed" at the base of PC 1 and a sandy sole layer at the base of lahar PC 3 were keys in correlating the respective units. These two lahars are the largest in the history of the post-Mount St. Helens Toutle River.

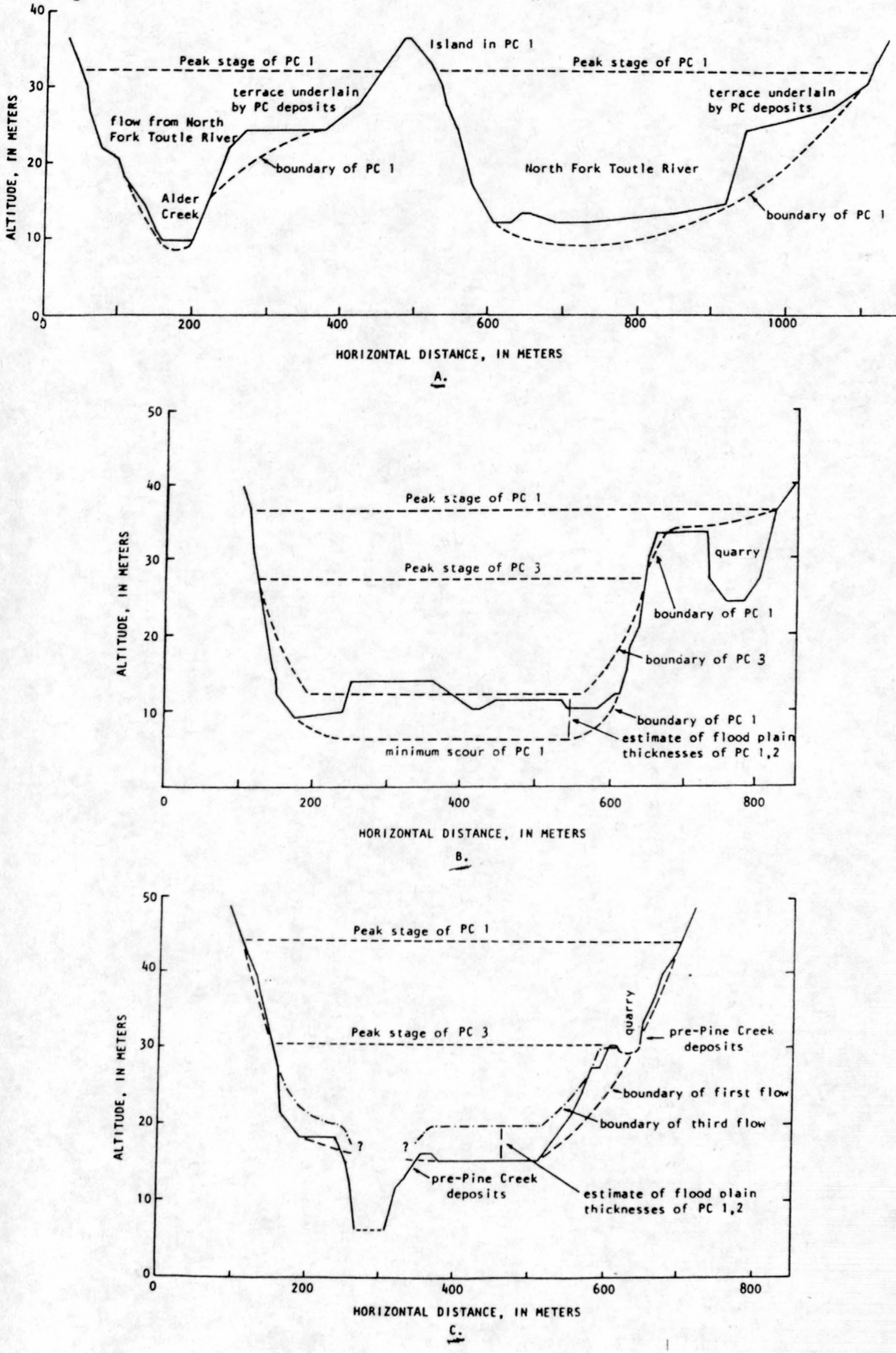
The altitude of the channel thalweg in the North Fork Toutle River at the start of lahar deposition in the Pine Creek eruptive period was close to its modern altitude. The base of the channel facies of lahar PC 1 is nearly coincident with the present channel at such widely separated locations as Pullen Creek and the Green Mountain Mill on the North Fork, and Tower on the main Toutle River. Once the peak flow level was identified, the cross-sectional area of the flow could be determined by adding the appropriate cross-sectional areas of Pine Creek deposits and modern alluvium to the existing cross-sectional area. This approach yields highly accurate flow sections in predominantly bedrock reaches, where erosion of valley side slopes has been minimal since Pine Creek time.

MEASUREMENTS AND ESTIMATES OF VELOCITY AND DISCHARGE

Velocities of the large older flows are difficult to determine from superelevations on steep slopes because of the thinness and sporadic distribution of the depositional coating. The deposits were removed by erosion at most such locations, which is not surprising considering that by 1985 the peak flow deposits of the 1980 lahars had been eroded at many

Figure 4.--Selected measured cross sections of flow for lahars PC 1 and PC 3 of Pine Creek age. A, near downstream end of flow island near Alder Creek; B, near Pullen Creek; and C, near Kid Valley.

Figure 4


Peak stage of PC 1
Island in PC 1
Peak stage of PC 1
terrace underlain by PC deposits
flow from North Fork Toutle River
boundary of PC 1
Alder Creek
North Fork Toutle River
terrace underlain by PC deposits
boundary of PC 1
ALTITUDE, IN METERS
HORIZONTAL DISTANCE, IN METERS
A.
Peak stage of PC 1
Peak stage of PC 3
quarry
boundary of PC 1
boundary of PC 3
boundary of PC 1
estimate of flood plain thicknesses of PC 1,2
minimum scour of PC 1
ALTITUDE, IN METERS
HORIZONTAL DISTANCE, IN METERS
B.
Peak stage of PC 1
Peak stage of PC 3
quarry
pre-Pine Creek deposits
boundary of first flow
boundary of third flow
pre-Pine Creek deposits
estimate of flood plain thicknesses of PC 1,2
ALTITUDE, IN METERS
HORIZONTAL DISTANCE, IN METERS
C.

analogous locations. Peak flow deposits of lahars PC 1 and 3 are easily identified on moderate slopes where runup was locally significant, however, because of their characteristic boundary features.

An example of a locality where peak mean velocity of lahar PC 1 could be determined was the island near the center of the flow upstream from the community of St. Helens. At several locations on the upstream flank of the island the levels of the highest clasts of Mount St. Helens rock types were compared with the same peak flow level on the downstream side, with adjustment for channel slope. The levels were also compared with upstream peak flow levels and the probable ratio of deposit thickness to flow depth. A distinction must be made between velocities determined this way, applying to the time of peak stage, and velocities applying to the time of peak discharge. In much smaller flows, log jams or boulder fronts may act as moving dams and form peak stages (mudlines) hydraulically inconsistent with the subsequent peak discharges. Peak stage and discharge for most significant lahars, and particularly for those the size of PC 1 and PC 3, were almost certainly coincident.

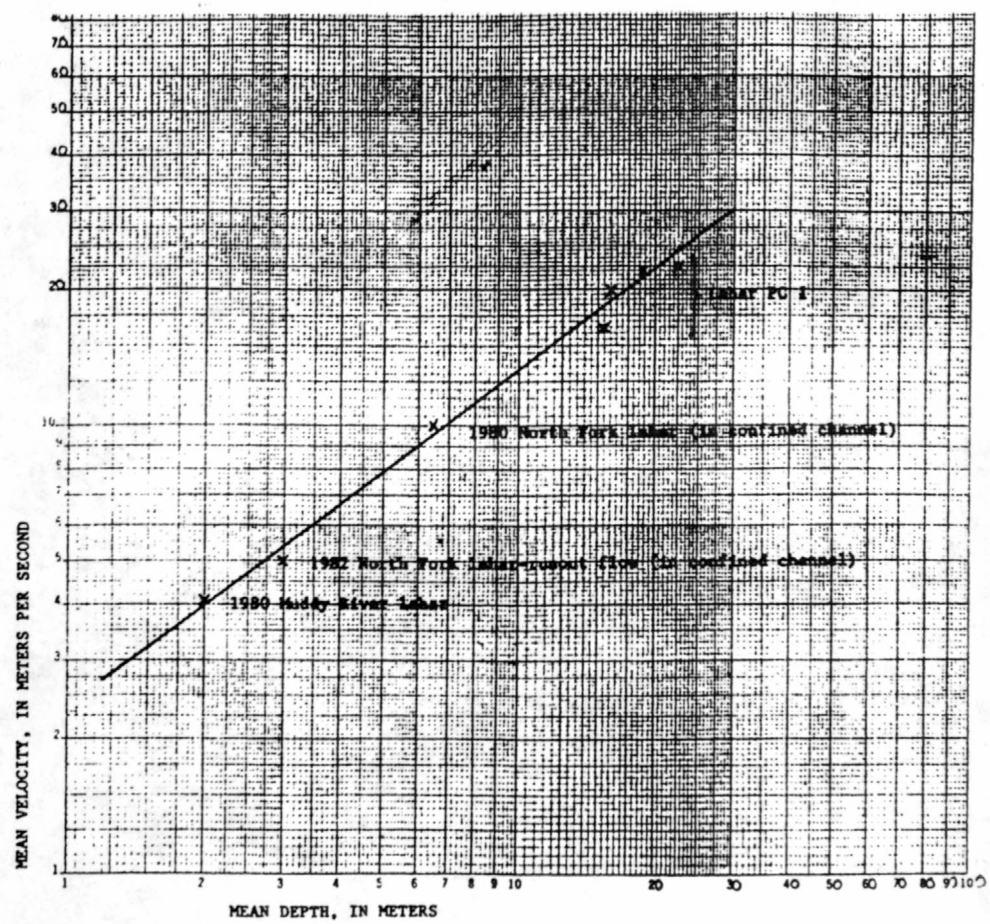
The peak mean velocity of lahar PC 1 was in the range of 15-22 m/s (meters per second) in the North Fork Toutle River between 30 and 50 km from the crater. This range encompasses the measured velocity of 15-18 m/s in the broad valley containing the flow island near St. Helens, and other measurements of runup and superelevation in bends in downstream reaches where flow was deeper and more constricted. Velocity certainly increased between the flow island and the narrower reaches; the amount of increase is also indicated by (1) an increase in velocity from 7.8 to 9.5-12.0 m/s for the 1980 North Fork flow over the same channel interval (Fairchild and Wigmosta, 1983), and (2) a reduction in lahar cross-sectional area that is expectable from configuration of the reach rather than from attenuation of the peak discharge. For example, the cross-sectional area of lahar PC 1 near Kid Valley was 13,500 m^2 (square meters); upstream at the flow island, the flow cross section was a minimum of 15,600 m^2. Assumption of hydraulic continuity, minimal deposition, and the certainly of no flow transformation between those points yields an increase from 15-18 m/s at the flow island to 17-21 m/s at Kid Valley. This extrapolation corresponds with measurements of the velocity of lahar PC 1 near Kid Valley, which were, however, less exact than those at the flow island.

For streams, although mean water velocity at a cross-section increases markedly with increasing discharge, the downstream velocity increase seen in flows of equivalent frequency is commonly small (Leopold and Maddock, 1953). In an attenuating lahar, a downstream decrease in velocity may be pronounced because of the effects of decreasing depth and slope on losses through deposition and also because of the triggering of the transformation of a granular distal debris flow to hyperconcentrated streamflow. Both processes are effects of the debulking of the lahar.

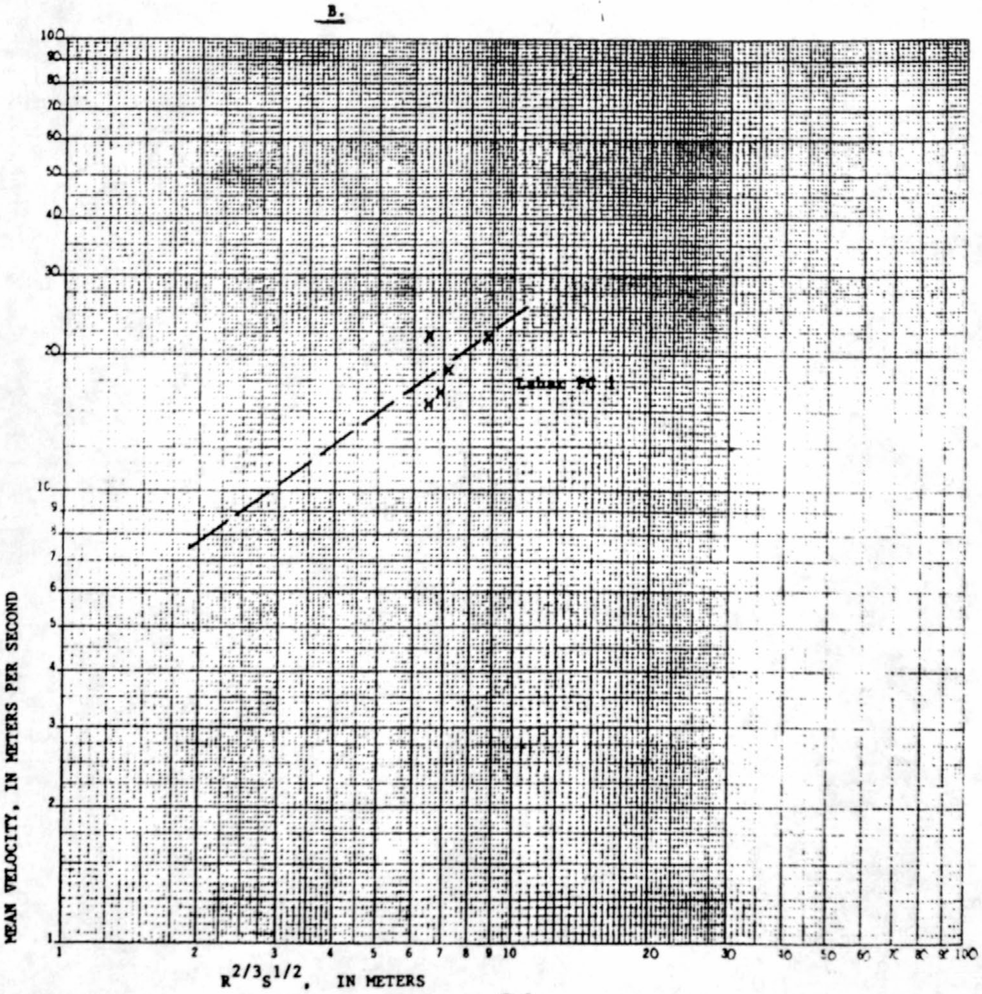
The flow velocities of the huge lahars can also be determined from general relations (fig. 5) of velocity to depth, or to the product of slope (S) and hydraulic radius (R) in the Manning equation. Hydraulic radius is the channel area divided by twice the depth plus the width (the wetted perimeter). Both relations are plotted in figure 5, where the velocity-depth relation appears with little scatter. The plot of velocity and the product of R and S is based only on measurements of lahar PC 1. Figure 5 is a basis for estimating velocities at downstream locations where the flow cross sections, but not velocity, can be

Figure 5.--Plots of lahar flow velocity vs. flow and channel properties: A, velocity in relation to $R^{2/3}S^{1/2}$, and B, velocity in relation to mean depth. Position of regression line in A is based on lahar PC 1; slope is that shown by Pierson (1985) for the same relation and is also nearly the same as in B.

Figure 5


Lahar PC 1
1980 North Fork lahar (in confined channel)
1982 North Fork lahar-runout flow (in confined channel)
1980 Muddy River Lahar
MEAN VELOCITY, IN METERS PER SECOND
MEAN DEPTH, IN METERS

B.


Lahar PC 1
MEAN VELOCITY, IN METERS PER SECOND
$R^{2/3}S^{1/2}$, IN METERS

A.

measured. It is used in estimating the discharges of the larger flows at such locations, along with considerations of slope and flow texture, and the probability that downstream velocities would have gradually approached the upper limits of the ranges for the smaller 1980 flows.

The discharges calculated for lahars PC 1 and 3 (table 3), and based on measured cross sections and measured and estimated velocities, are good indicators of the truly catastrophic sizes of those flows. The instantaneous peak discharge of lahar PC 1 is equal to the discharge of the mid-course Amazon River at flood stage (Oltman and others, 1964), or to more than three times the largest recorded flood peak of the Mississippi River. Although attaining an estimated discharge of "only" 50,000 m^3/s (cubic meters per second) near Kid Valley, the inundation level of lahar PC 3 locally approached and may have locally exceeded that of PC 1 in downstream reaches, so great was the aggradation caused by the larger flow. However, the inundation levels mapped by Scott and Janda (1982), as shown in figure 1, predominantly reflect the levels attained by lahar PC 1.

The largest discharge determined for any flow at Mount St. Helens is over 1 million m^3/s for the proximal phase of the 1980 lahar in the South Fork Toutle River (Scott, 1985a). That discharge, however, applies to the dispersed phase of that flow, which is best described as a lithic pyroclastic surge. It is, therefore, not directly comparable to the discharges discussed here.

FLOW MAGNITUDES FOR PLANNING PURPOSES

The magnitude of a lahar with a recurrence interval of near, but less than 100 years (see section on frequency) would be sufficient to inundate nearly all flood plains throughout the Toutle River system to a probable depth of at least 2 m (mean flow depth of overbank lahars in table 3, excluding lahar PC 1, is 2.7 m). This depth corresponds to a peak discharge of at least 10,000 m^3 on the broad flood plain near the confluence of the forks of the Toutle River. This figure is somewhat larger than estimates of design discharges for lahars based only on hypothetical interactions of pyroclastic flows with snowpack, as described in the section on origin of the lahar series of Pine Creek age. The variety of lahar origins in both forks of the river (Scott, 1985a) shows that large lahars can form in other ways.

The true signicance of lahar hazards in the river system is apparent from a comparison with flood flows of similar recurrence interval. For example, the Corps of Engineers (1982, Table B-1)) determined that a flood with a recurrence interval of 100 years would have a peak discharge of 1,810 m^3/s at Highway 99, near the mouth of the Toutle River, and a peak discharge of 2,880 m^3/s at Castle Rock in the Cowlitz River below the confluence with the Toutle River. At upstream stations in the Toutle River, flood discharges of the same recurrence interval would be less. Both flood discharges reflect post-eruption changes in the rainfall-runoff regime.

The emphasis in this report is on lahar magnitudes at the forks of the Toutle River, over 50 km downstream from the 1980 crater. Of the lahars and lahar-runout flows listed in tables 1 and 3, at least 35 inundated flood plain surfaces in that vicinity. At least six of the flows reached the Columbia River as lahars or lahar-runout flows large enough to cause serious inundation there, over 100 km downstream.

In hydrologic analysis, the use of the term "worst-case" is not good practice because it is always possible to have a flow that is worse than those recorded. In this example, however, the spectrum of flow magnitudes and origins is known throughout the entire history of the volcano, as are the worst-possible lahar-forming conditions. Consequently, the term is used in the following discussion with a connotation more valid than usual. Two extreme or worst-case lahars are described: (1) a lake-breakout lahar with a probability that will increase over the long term, and (2) a smaller lahar, derived from a slope failure, that is relatively more probable over the shorter term because of remedial engineering works that have lowered lake levels or stabilized their outlets.

Lahar PC 1 of Pine Creek age is clearly the worst to be considered for design purposes, because it very probably originated as a flood surge released by breaching of a naturally dammed ancestral Spirit Lake (see Scott, in press). Spirit Lake is the largest source of water available, or potentially available, to form a lahar. A natural dam consisting of deposits of the 1980 debris avalanche has blocked the natural outlet of the lake since May 18, 1980. In 1985 a drainage tunnel lowered and stabilized the level of the lake, and thereby eliminated the immediate risk of an analog of lahar PC 1 being caused by overtopping of the dam by precipitation runoff. With time, however, the potential for future volcanic activity will increase the possibility of a PC 1 analog. A large flow of volcanic origin could displace sufficient water to overtop the dam or cause a piping failure of the avalanche deposit. Extrapolations of catastrophic phenomena based on rate of dome growth or the behavior of other volcanoes are made by Glicken (1986). Given the history of the volcano and the lengths of past eruptive periods, the probability of renewed explosive activity within a 100-yr time span is significant.

If the risk of lake-breakout lahars is reduced by the present engineering works, however, the magnitude of the extreme or worst-case lahar is also reduced. In the last 4,500 years, the largest lahar with a relatively low lahar-bulking factor (LBF) and relatively high clay content is the widely distributed lahar of Smith Creek age (unit 17 of Coal Bank Bridge section). That lahar probably originated as a slope failure and was texturally similar to the 1980 North Fork lahar (Scott, 1985a). The flow of Smith Creek age had a peak discharge estimated at 25,000 m^3/s (table 3). Although much smaller than lahar PC 1, it was approximately 4 times the size of the 1980 North Fork flow and would inundate flood plains throughout the Toutle-Cowlitz River system. The inundation would occur regardless of normal channel capacity in the Cowlitz River.

A lahar having the size and texture of the Smith Creek flow would behave much like the 1980 North Fork lahar, which had a smaller rate of attenuation than the more typical flows with a lower clay content. Peak discharge of the 1980 North Fork lahar only declined from 7,000 to 8,500 m^3/s near Camp Baker to values of 6,000-6,500 m^3/s on the lower Toutle River (Fairchild and Wigmosta, 1983). The older flow, like its 1980 textural analog, underwent no transformation to a lahar-runout flow. Even the huge lahar PC 1 began to transform in the lower Toutle River; it was granular and formed mainly of stream alluvium bulked into a flood surge.

With time, however, the extreme or worst-case lahar will again become a PC 1 analog. A lahar the size of PC 1 would overtop the terrace of the lahar-emplaced fill of Pine Creek age; this fill locally occupies much of the valley. The terrace surface is well populated throughout the river system; on it are built significant parts of the communities of Toutle, Silver Lake, Tower, and Castle Rock. Lahars equivalent to the smaller Smith Creek flow would only locally inundate the terrace, by an amount dependent on the amount of Pine Creek-age fill locally remaining. The terrace was overtopped in some places by the 1980 North Fork lahar downstream from Camp Baker and, downstream from the Green Mountain Mill, the terrace surface was in places within 2.5 m of the peak stage of that flow.

Two unknowns presently influence a risk analysis of lahars in the river system. (1) The stability of the blockage of Castle Lake (fig. 1), one of the avalanche-impounded lakes, is not a certainty (Meyer and others, 1985). A combination of elevated ground-water levels and an earthquake with a seismic coefficient one-half that of the maximum credible earthquake could cause substantial deformation of the blockage. Failure cannot be assumed, even under those circumstances. Whether debris flow or hyperconcentrated streamflow would result from blockage failure depends on the degree of saturation of the downstream debris avalanche and the modeling assumptions of downstream bulking as well as debulking. The size of the flood wave is also strongly influenced by assumptions of breach width and time of development. Preliminary modeling of a flood wave that could result from a failure indicates a rapidly attenuating hyperconcentrated flow that would inundate flood plains throughout at least the Toutle River system (A. Laenen, oral commun., 1986). (2) A second unknown is whether, depending on fiscal constraints, a large sediment-retention structure will be constructed at a site near Pullen Creek on the North Fork Toutle River. The structure also would function to impound lahars and lahar-runout flows. Reservoir capacity will not, however, be maintained, and the reservoir will fill progressively. No impoundment structure is planned for the South Fork Toutle River, a prolific source of ancient lahars as well as two lahars in 1980.

THE NATURE OF LAHAR HAZARDS

The essential conclusions regarding lahar magnitude are that (1) a lahar of 100-yr frequency would inundate modern flood plains and low terraces throughout at least the Toutle River system, and (2) that either extreme or worst-case lahar described above would inundate all flood plains and most terraces throughout the Toutle-Cowlitz River system. The high-frequency lahar, as well as the larger worst-case flow, would evolve distally into a lahar-runout flow. The smaller worst-case lahar, probably derived from a slope failure like the lahar of Smith Creek age and the 1980 North Fork lahar, would not.

Extensive observations of damage from the 1980 lahars indicate that most of the damage from a lahar occurs upon initial inundation of the flood plain surface. Further increase in depth does not necessarily increase damage proportionally. Where the 1980 North Fork lahar inundated flood plains, trees were killed (but later salvaged), structures were destroyed, and most agricultural uses of the flood plain were lost at least temporarily. Most houses inundated by the lahar, even if not damaged structurally (like the mobile homes that were floated in place to the surface of the deposits by passive flow on the flood plain) were salvaged for materials.

Timber floating in the lahar caused extensive structural damage, and the lahar deposits permeated all parts of inundated structures, including interior walls. The main source of the timber in the flow was growth on flood plains adjacent to active channels, where trees were removed by the higher-velocity channel flow (see fig. 32, Scott, 1985a). Felled trees stored at Camp Baker were also incorporated.

Even if the possibility of lake-breakout lahars was completely eliminated by the stabilization of the avalanche-impounded lakes, there would not be a reduction in damage proportional to the difference in size of the two worst-case lahars discussed above. The smaller of the two would still inundate flood plains and parts of the main terrace surface.

The risk of lahars is only partly reduced by engineering stabilization of the modern avalanche-impounded lakes. The debris avalanche remains as a source of sediment potentially additive to any meltwater surge from the volcano. The LBF's of the lake-breakout lahars show that stream alluvium can bulk a flood surge to a lahar, probably without other sediment sources. Rocks underlying the steep channels of the volcano that debouch into the South Fork Toutle River provide source material for catastrophic mobilization that could be triggered by explosive activity less violent than the eruption of May 1980.

RECURRENCE INTERVALS OF LAHARS AND LAHAR-RUNOUT FLOWS

As shown in the preceding section, lahars large enough to inundate flood plains are of critical magnitude and are recorded by a significant thickness of deposits of the lahar flood plain facies. Such lahars are thus the objective of frequency analysis (tables 1 and 3). Of the two levels of probability, one is based on the total distribution of flows and the other on flows within eruptive periods. The latter thus is conditional on an active eruptive state, like the present. A conditionality based on only the total distribution of flows would obviously underestimate the existing potential, but would be appropriate for the volcano in a quiescent state.

Evidence presented below indicates that, after one lahar has occurred, the probability of others is significantly increased. The occurrence of lahars is thus less random than the occurrence of precipitation-induced floods. In a normal flood frequency study, the recurrence of one major flood does not necessarily increase the probability of a second large flood beyond the relatively small statistical effect of adding a large flow to the total time series.

The number of flows inferred from the stratigraphic record provides a minimal estimate of the actual number. For example, flows of Castle Creek age are less likely to be recorded because of the dominantly erosional regime that followed emplacement of the Pine Creek-age deposits. Although the succession of flows away from the volcano mainly coincided with the eruptive chronology as determined by Mullineaux and Crandell (1981), the durations of the episodes cannot be considered exact.

The recurrence interval of an overbank lahar or lahar-runout flow will vary with the length of the record that is analyzed. The recurrence interval of a lahar or lahar-runout flow that will extend overbank at the confluence of the forks of the Toutle River, for the eruptive episodes of the last 13,700 years (tables 1 and 3), is 247 years. For the eruptive periods of the last 4,500 years, the comparable recurrence interval is 128 years. In the eruptive periods of the last 4,500 years, logically excluding the Castle Creek period for the reason previously mentioned, the recurrence interval is 94 years.

Thus the most reasonable recurrence interval of an overbank flow at the confluence of the forks of the Toutle River is about 100 years (an exceedence probability of about 1 percent). However, the occurrence of lahars not preserved or exposed, combined with the evidence of grouping of lahars discussed in the following section, suggests that the present probability of a lahar or lahar-runout flow is higher. The shortening of the recurrence interval, as only recent eruptive periods are considered, is more likely due to a lack of exposure of older flows than to an increasing frequency of flows. It is also due to a less-precise definition of the older eruptive episodes.

Because of the change in composition of the eruptive products of Mount St. Helens at the close of Pine Creek time, the frequency or type of lahars may also have changed. Factors that support a uniformitarian extrapolation of past events to the future are (1) the essential comparability of each 1980 flow to one or more pre-modern-cone lahars and (2) the similarity of the sequence of lake-breakout lahars of Pine Creek age with the potential for an analogous sequence now. Crandell and Mullineaux (1978) presented a map of volcanic deposits of the last 4,500 years—the period for which design recurrence intervals were calculated above--as a guide to hazard potential; they selected this time period partly because they believed it likely to represent future volcanic activity.

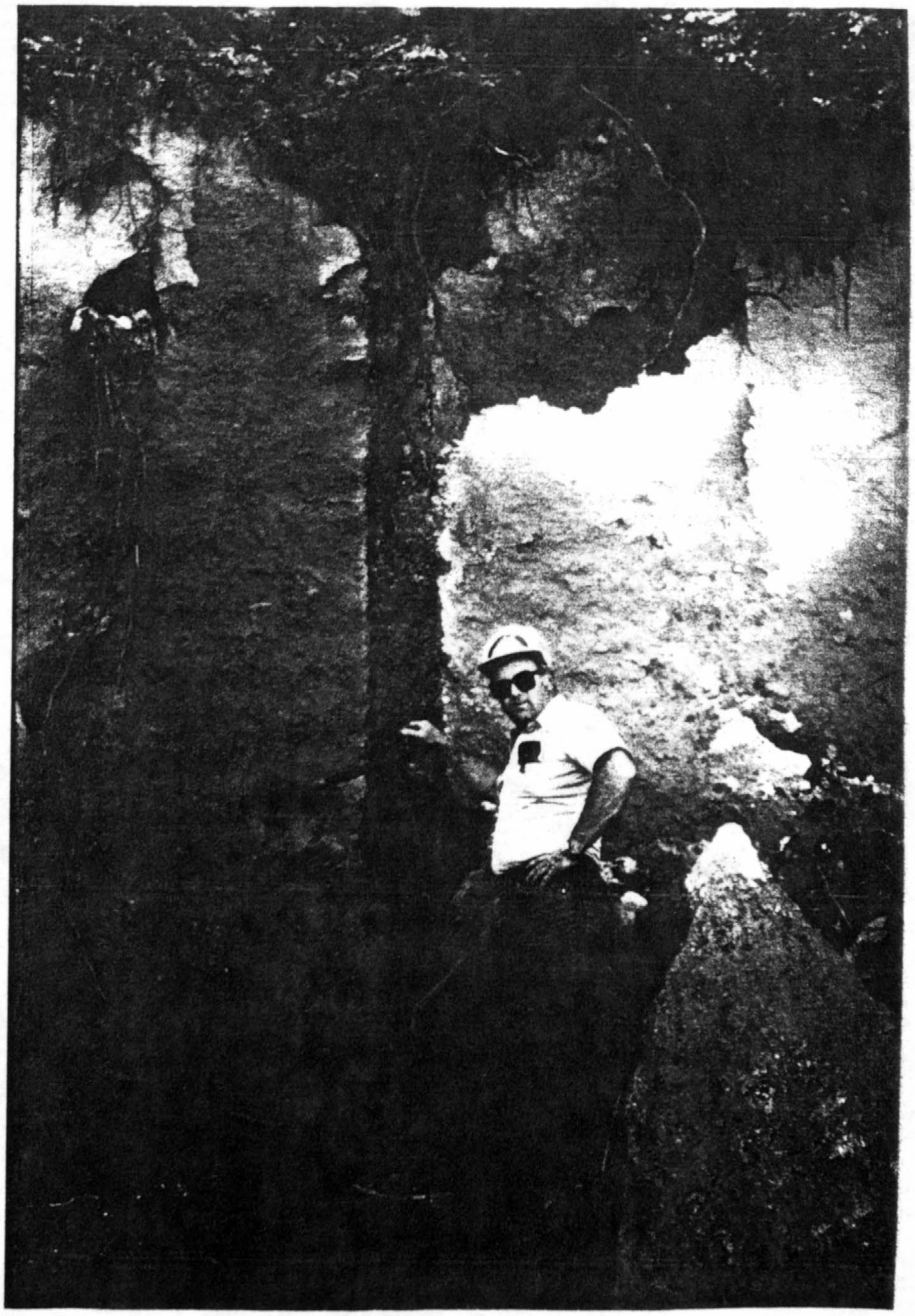
Long-term planning (tens of years) can employ a 100-year lahar recurrence interval in the same way that a design-flood recurrence interval is used for the purposes of zoning on flood plains or for benefit-cost appraisals of engineering works. Similarly, decisions for the terrace surface underlain by the Pine Creek-age sequence can reflect the magnitudes of the worst-case lahars discussed above. As in most analyses of extreme events, a meaningful recurrence interval cannot be assigned to the worst-case flows. Decisions related to levels other than those of the flood plain or Pine Creek terrace surfaces would obviously depend on the nature of the problem; new bridge and highway construction, for example, optionally could reflect an extreme or worst-case lahar on major evacuation routes.

EVIDENCE OF TIME-GROUPING OF LAHARS

A more conservative approach to lahar hazards is indicated by evidence of nonrandom grouping of the lahars within parts of the established eruptive periods. The occurrence of one lahar increases the odds of a recurrence above those based on the overall recurrence intervals in eruptive periods. This change in probability cannot be calculated because the time intervals involved are too short for accurate definition by radiometric dating.

One line of evidence, based on tree molds, shows that a runout flow and the lahars of Pine Creek age occurred within a period measured in 10's of years or less, rather than having been distributed throughout the 500-year span of the eruptive period. Tree molds (fig. 6) penetrated all four lahars, and occur as vertical cylindrical shafts open at the

Figure 6. Photograph of tree mold penetrating flood plain facies of lahars PC 1 and PC 3, of Pine Creek age, near the Green Mountain Mill section. Shovel is inserted at the contact between those lahars. Lahar PC 2 is missing at this point.



surface. They are known locally as tree "wells." They are especially common in the triangle formed by the forks of the Toutle and a north-south line transecting the Green Mountain Mill. Depths reportedly exceed 25 m, but I measured none in excess of 10 m, a depth close to the probable maximum total thickness of the flood plain facies of the Pine Creek lahar series. Wood within the lahar sequence is totally removed by weathering, but wood is preserved as underlying stumps surrounded by the basal runout deposit and reworked runout sands.

The interior surfaces of some freshly exposed tree molds have a pattern indicating that bark remained intact throughout emplacement of the Pine Creek lahar series. Based on the normal decompositional evolution of a standing old-growth Douglas fir (Franklin and others, 1981, fig. 16), this indicates that the entire sequence was emplaced in less than 20 years.

A second line of evidence indicates an even shorter time interval for emplacement of the Pine Creek lahars. The stratigraphic contacts are sharp and nearly planar where there was no primary relief. They may be separated by thin intercalations of sand, deposited by dewatering of the flow or by the first runoff after emplacement. Vegetation regrowth did not occur. By 1985, however, the flood plain facies of the 1980 lahars were covered with a nearly impenetrable growth of alders. This evidence suggests that the entire sequence of Pine Creek age was emplaced within several years or less.

This second type of evidence applies to the lahars of Swift Creek and Kalama age as well, but generally in lesser degree. The sequence of Swift Creek units in the Coal Bank Bridge section contains lahars with sharp contacts indicating a very close time association, although the channeled base of unit 8 is a possible exception. The original exposures at that locality revealed contacts over distances of 100 to 200 m. Part of the evidence in this case could be ascribed to the overlapping of approximately synchronous flows from each fork of the Toutle River. The original exposures of the Kalama sequence at Kid Valley in the North Fork Toutle River were not as extensive as those of the Swift Creek sequence, but they showed the same stratigraphic relations.

CHARACTER OF THE ERUPTIVE EPISODES

Cumulatively considered, the foregoing evidence indicates that significant lahar-generating events were grouped in relatively small parts of the eruptive periods and stages. This in turn strongly suggests that the significant eruptive events were likewise concentrated, and that the actual eruptive periods could be more numerous but shorter than the periods and their durations (table 1) used to calculate the lahar recurrence intervals. An implication of this possibility is that the probability of a lahar within an eruptive episode like the modern period is higher (the recurrence interval is lower) than that calculated on the basis of the durations of the periods and stages as shown in Table 1. That is, once a lahar has occurred, more are likely to follow.

Apparent concentrations of eruptive activity were one reason leading Crandell (written commun., 1983) to designate the three oldest eruptive periods--Ape Canyon, Cougar, and Swift Creek--as eruptive stages, and to group the younger periods in a single eruptive stage, the Spirit Lake stage. The evidence from the lahar sequences supports this approach, and the terminology consequently is used here. Implicit in this terminology is the probability that the three older eruptive stages incorporate eruptive periods yet to be recognized.

The lengths of the eruptive stages and periods (table 1) are in part a function of the largely unavoidable spread in radiocarbon ages (as illustrated by table 2) due to sample and sampling variations, as well as to variations from changes in atmospheric radiocarbon. The latter variations are particularly pronounced during the Pine Creek and Kalama eruptive periods. Another factor is the removal by weathering of wood from virtually all lahars of pre-Kalama age beyond the base of Mount St. Helens; radiocarbon dating, by necessity, is accomplished from wood taken from underlying or overlying strata (albeit closely related in time). The results consequently make the dating of the lahars less precise.

LAKE-BREAKOUT LAHARS OF THE PINE CREEK ERUPTIVE PERIOD

A factor acting to reduce the calculated recurrence probability of lahars in the river system is the origin of the Pine Creek lahars by lake-breakout (Scott, in press). The engineering works that stabilize the natural dams created by the 1980 debris avalanche thus reduce the chances of an analogous modern sequence of flows. Although failure as a result of precipitation inflow to the lakes has been eliminated, overtopping and failure of the natural dam blocking the natural outlet of Spirit Lake could occur as a result of a large volcanic flow entering the lake. If the risk of lake-breakout lahars were eliminated completely, the four lahars of Pine Creek age, including the two largest lahars in the history of the watershed, could be removed from the time series from which the recurrence intervals were calculated. This would, in effect, increase the recurrence interval (thereby decreasing the probability) of a lahar or lahar-runout flow large enough to inundate flood plains 50 km away during the last 4,500 years from about 100 years, to approximately 130 years. This decrease in probability, however, may not compensate for the increase related to the close time association of lahars.

EVIDENCE OF LAKE-BREAKOUT ORIGIN

Evidence that the sequence of Pine Creek lahars was derived from lake-breakout flood surges includes (1) the great magnitude of the initial lahar relative the lesser magnitudes attributable to other origins; (2) a high content of alluvium introduced into the flood surge beyond the base of the volcano; (3) abundant megaclasts derived from a debris avalanche that may have blocked the drainage of the North Fork Toutle River; and (4) occurrence in a time-clustered sequence.

Comparison of Magnitudes of Lahar PC 1 and Lahars of Other Origins

A common cause of volcanically induced flood surges is the interaction of a pyroclastic flow with a thick snowpack and the commonly associated effects of hot, explosively distributed eruptive products on snow and ice. Also commonly associated are the melting effects of tephra on snow or ice. The high pumice content of the flows of Ape Canyon age indicates that this was probably a common mode of origin during that time. Subsequently, lithic pyroclastic flows and their associated effects have probably accounted for many flows of intermediate and small size in the river system (Scott, 1985a).

As part of a preliminary analysis of hazards in the river system, Dunne and Leopold (1981) calculated the potential size and rate of attenuation of mudflows resulting from various sizes of pyroclastic flows over snow. The most extreme conditions of snow accumulation and width of pyroclastic flow yielded a peak discharge of 3,900 m^3/s at Kid Valley. The calculation reflected the present topography of the volcano, representing optimal conditions for discharge into the North Fork Toutle River. Peak discharge of the 1982 lahar, which resulted from eruption-induced snowpack melting in the crater, was 960 m^3/s (Pierson and Scott, 1985) at the same location.

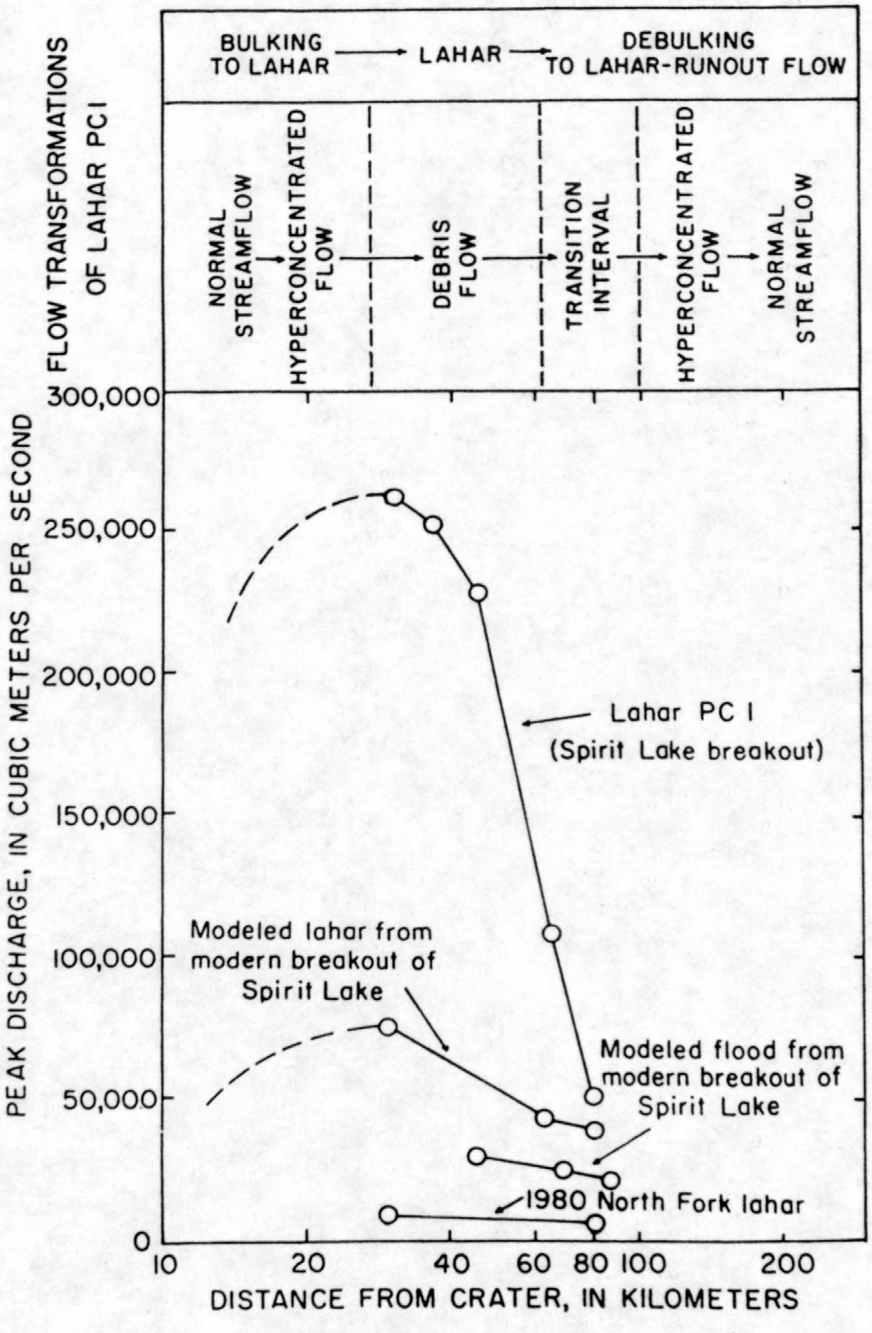
The Corps of Engineers (written commun., 1984) used as a design criterion an "operating basis mudflow" with a "most likely" peak discharge of 7,100 m^3/s upstream from Camp Baker. The likelihood of the event was considered "very small." The calculation assumed a pyroclastic flow affecting an area of 13 km^2 and melting of the entire underlying snowpack within "minutes." Also considered was the idea of a "maximum mudflow," defined as the "most severe mudflow believed to be possible...in the foreseeable future on the basis of geologic and volcanic evidence." This flow had a peak discharge upstream from Camp Baker of 42,500 to 113,000 m^3/s, and also would have attenuated downstream. It assummed a pyroclastic flow that would melt all the snow over an area of 45 km^2 and occur at the time of maximum snow accumulation.

The above hypothetical flows are small compared to the peak discharge of lahar PC 1 (table 3 and fig. 7). Catastrophic ejection could have formed a large lahar (Scott, 1985a), but the flow would have a low LBF, unlike lahar PC 1. The most likely, if not the only, possible source of the flood surge that transformed to that lahar was ancestral Spirit Lake, with the natural dam at or downstream of the pre-1980 outlet. The most probable circumstance involves a natural dam, but lake water could have been displaced by a volcanic flow into the lake. The existence of a summit crater lake in Pine Creek time cannot be entirely ruled out, but such lakes are rare at modern Cascade Range stratovolcanoes. Craters now filled or partly filled with significant amounts of glacial ice are present at Mount Rainier and South Sister.

Implications of Lahar Bulking Factors

The two largest lahars in the Pine Creek sequence, PC 1 and PC 3, have high LBF's (Scott, 1985a). The two smaller flows also have high LBF's, although this conclusion is based on field comparisons of clast roundness with that of the larger flows. Thus the sequence was formed by transformation of flood surges to lahars beyond the base of the volcano. In the case of lahar PC 1, the deposits record this transformation only after almost 20 km of flow from the north side of the volcano. Comparable LBF's are rare in the entire record of lahars in the Toutle-Cowlitz River system, indicating the uniqueness of the Pine Creek lahars in this respect.

Figure 7.--Peak discharges of lahar PC 1, a modeled lahar from a modern breakout of Spirit Lake, and a modeled flood flow from a modern breakout of Spirit Lake. Peak discharge of the relatively high-clay North Fork lahar (3-5 percent) is shown for comparison.


BULKING TO LAHAR → LAHAR → DEBULKING TO LAHAR-RUNOUT FLOW
FLOW TRANSFORMATIONS OF LAHAR PC1
NORMAL STREAMFLOW → HYPERCONCENTRATED FLOW → DEBRIS FLOW → TRANSITION INTERVAL → HYPERCONCENTRATED FLOW → NORMAL STREAMFLOW
PEAK DISCHARGE, IN CUBIC METERS PER SECOND
300,000
250,000
200,000
150,000
100,000
50,000
0
Lahar PC1 (Spirit Lake breakout)
Modeled lahar from modern breakout of Spirit Lake
Modeled flood from modern breakout of Spirit Lake
1980 North Fork lahar
10
20
40
60
80
100
200
DISTANCE FROM CRATER, IN KILOMETERS

Megaclasts

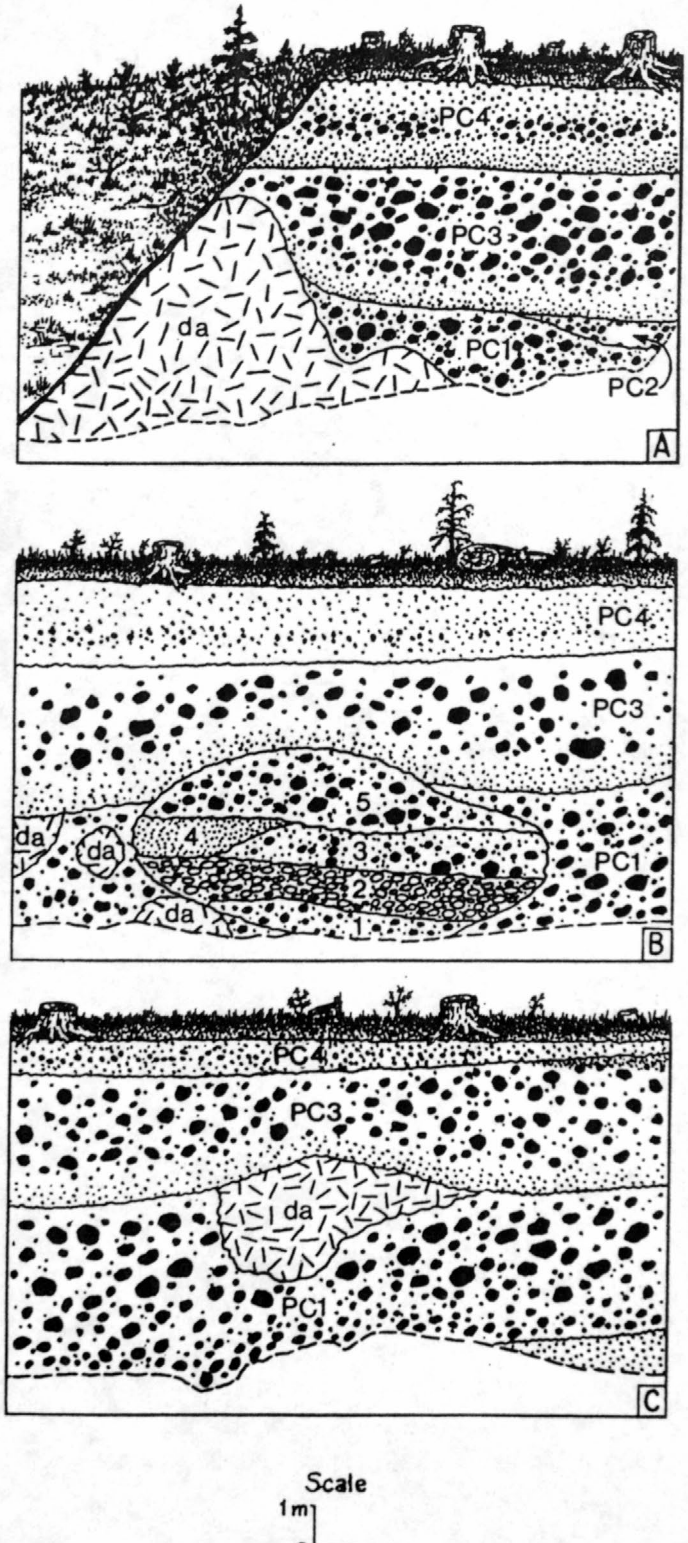
Masses of hydrothermally altered dacite breccia (fig. 8, A and C) are common in lahar PC 1, and locally are sufficiently abundant that they form a diamicton with the laharic diamicton acting as the matrix. They are, with the exception of the brecciation, like the rocks of pre-Castle Creek age exposed in the core of the modern crater. Dacite megaclasts are as much as 8 m in exposed intermediate diameter, and originated as blocks from an ancient debris avalanche. The convincing evidence for this conclusion is described in Scott (in press). The abundance of the dacite megaclasts suggests that the natural dam, from which the flood wave transforming to lahar PC 1 was released, had that origin.

The only flow of pre-Pine Creek age in the river system with any similar megaclasts is the rubbly lahar of Swift Creek age (unit 8 of the Coal Bank Bridge section), in which two megaclasts of hydrothermally altered, brecciated dacite were observed. This flow is notable for clast angularity so cannot be demonstrated to have begun as a flood surge.

A second, much-rarer variety of megaclast consists wholly or partly of alluvium (fig. 8, B). The megaclast of figure 8 was more than 5 by approximately 12 m in original exposure and contains 5 stratigraphic units:

Figure 8.--Megaclasts (da) in lahar PC 1 as exposed near the confluence of the North Fork Toutle River and Pullen Creek. A, downstream-most exposed dacite megaclast, resting on channel surface and extending above the surface of lahar PC 1; B, megaclast containing pre-lahar stratigraphic section of flood plain stratigraphy (see text for explanation of numerals); and C, dacite megaclast that may have floated on the surface of lahar PC 1, although the most recent exposures suggest that it may have grounded on a clast-supported diamicton of dacite megaclasts.

fig. 8


PC4
PC3
da
PC1
PC2
A
PC4
PC3
5
4
3
2
1
da
da
da
PC1
B
PC4
PC3
da
PC1
C
Scale
1m
0
0
1m

3"

5. Lahar; cobble mode with high degree of roundness; identical in both roundness and texture to the incorporating lahar..>1.8 m
4. Alluvium; sandy, stratified, fills channel cut mainly in unit 3...1.1 m
3. Lahar; pebble mode, but contains cobbles and boulders........1.1 m
2. Alluvium; cobble mode, size distribution and roundness shown in Scott (1985a).....................................>1.2 m
1. Lahar; similar in texture and clast angularity to the largest lahar of Smith Creek age............................>0.8 m

Units 1 through 4 represent a section of flood plain stratigraphy in the broad valley upstream from the community of St. Helens before lahar PC 1 occurred. The flood plain surface, represented by the upper surfaces of units 3 and 4, was inundated by lahar PC 1, the deposits of which form unit 5 in the megaclast. As lahar depth increased, the block was detached, probably by lateral erosion of a channel cutbank. As indicated by their textural identity, unit 5 is probably an early deposit of lahar PC 1. The alluvium-bearing megaclast "grounded" on numerous dacite megaclasts in the flow, tilting the delicate mass upstream at an angle of 7 degrees. The rafted deposits of the enveloping flow, which form unit 5, may have been deposited before detachment, or later as the mass was riding in the lahar. They clearly were part of the megaclast as seen in original exposures, and deposition before detachment is considered more likely.

The sequence of events recorded by the megaclast illustrates how the large volume of valley-fill alluvium was incorporated into the Pine Creek flows. That the mass probably was not transported far is shown by the fragile nature of the alluvium (it crumbles to the touch). Most masses of eroded alluvium probably disintegrated immediately, with their components dispersed into the flow. That the alluvium was preserved intact in the megaclast was due to its stratigraphic sandwiching between the two lahars (units 1 and 3). Estimates of the volume of the flood wave and the erosion depth necessary to form lahar PC 1 are discussed by Scott (1985a and in press).

NATURAL DAMS AT VOLCANOES

Considered together, the above evidence indicates that the flood surges transforming to the lahars of Pine Creek age were formed by breaches in a natural dam or dams. The results are remarkably similar to the sequence of events that would have followed emplacement of the 1980 debris avalanche. The abundance of dacite megaclasts in lahar PC 1 suggests that at least the initial natural dam may have also been a debris avalanche. The geometry of the northward growth of the apron of volcanic and volcaniclastic deposits, and its abutment against Harry's Ridge, is one conducive to the creation of natural dams. Spirit Lake had formed behind this apron of deposits by Smith Creek time (Crandell, written commun. 1983). On May 18, 1980, the outlet of Spirit Lake was blocked by as much as 170 m of debris avalanche deposits, and the level of the lake was catastrophically raised by 63 m (Youd and others, 1981; Meyer and others, in press).

Debris avalanches are especially likely to create large and deep lakes impounded by unstable dams because of avalanche size (commonly more than 1 km^3; Siebert, 1984), mobility (median H/L = 0.11; Siebert, 1984), and thick, hummocky deposits. Debris flows may be formed at volcanoes by breakouts through other types of natural dams, including those formed by landslides, large pyroclastic flows (especially lithic types), lahars, rubbly lava flows, glaciers, moraines, and rock, ice or snow avalanches. Some types of blocking deposits may be rapidly eroded, and leave little evidence of their presence except as megaclasts in downstream debris flows.

A thick fill of pyroclastic flows and lahars of Pine Creek age occurs in Castle Creek and it extended into the valley of the North Fork Toutle

River, where individual flows could have dammed the main drainage, releasing flow that formed lahars downstream (Crandell, written communication, 1983). The width of the valley near Castle Creek, the restablishment of drainage between flows, and the fluid nature of both pyroclastic flow and lahar deposits all suggest that this fill could have been a source of multiple lahars, but none so large as the gigantic flows many km downstream in the Pine Creek sequence. Flood surge release through pumiceous pyroclastic flow deposits would have yielded lahars with a characteristic pumice content not seen in large lahars later than Ape Canyon in age (much pumice was incorporated in the small lahars formed by pumiceous pyroclastic flows during eruptions in 1980-81). Mobile lithic pyroclastic flows would have behaved much like lahars in their ability to block stream channels. As discussed in the next section, the surge release from a lahar blockage is likely to be of much lesser magnitude than the downstream continuation of the primary flow. Relatively fluid flows like lahars flow into lateral backwater areas, leaving broad, shallow deposits with gentle lateral slopes.

LAHAR-MARGIN LAKES--MODERN AND ANCIENT

A feature that verified the mapping of inundation area of lahar PC 1 (Scott and Janda, 1982) was the presence of small, slightly infilled lakes on, or adjacent to, the lateral surface of the peak flow deposits. These lakes, now mainly existing as marshy areas or ponds surrounded by marshes, were originally very shallow features analogous to the small lakes that existed temporarily in positions marginal to the 1980 North Fork and South Fork lahars. Most of the modern lakes did not exceed 1 m in depth and were at least partly drained as runoff from the lateral tributaries filled the depressions and breaching occurred. None yielded a discharge of any consequence.

The behavior of the 1980 lahars suggests that they were not capable of creating a significant blockage and lake impoundment. Behavior varied greatly according to size of the tributary. The brief impoundment of the Cowlitz River by the 1980 North Fork lahar is described in Scott (1985a). Similar brief blockages occurred at the confluence of the Green and North Fork Toutle Rivers, as well as at the confluence of the forks of the Toutle River.

Silver Lake, formed as the result of blockage by the Pine Creek lahars, is the exception to the generally small size of lahar-margin lakes. The lake has a surface and lateral marsh area of more than 15 km^2 (square kilometers). However, with a maximum measured depth of little more than 3 m, the feature is an analog of the small lahar-margin lakes. It is doubtful if any downcutting of the broad natural dam has occurred rapidly enough to yield a significant surge. In fact, before construction of a weir and drainage channel in 1971, a serious problem for lakeshore residents was the inability of the lake to drain rapidly through its weed-choked natural outlet after storm inflow. Wind-generated waves in combination with the sustained high water level periodically caused damage. A modern lake-breakout lahar from Spirit Lake possibly could raise the level of the water in Silver Lake, thereby adding to the hazard.

COMPARISON OF LAHAR PC 1 WITH MODELED FLOWS

The measurement of the peak discharges of lahar PC 1 (fig. 7), which resulted from an ancient breakout of Spirit Lake, provides the opportunity for comparison with modeling efforts focused on hypothetical modern breakout flood surges from the lake. The supposition can be made that a model synthesis of a modern Spirit Lake breakout should simulate the actual lahar. The comparison indicates that the behavior of the ancient lahar PC 1 is a much more accurate guide to the behavior of a modern flow than any of three models to date.

Between 30 to 50 km from the volcano, the depths and inundation levels of lahar PC 1 (Scott and Janda, 1982) and of a hypothetical modern lahar from a breakout of Spirit Lake (Swift and Kresh, 1983) are nearly the same. Both levels are plotted by the Cowlitz County Department of Community Development (1983). Flow dynamics and the subsequent downstream attenuation are very different, however. Mean velocities of the modeled lahar were much less than for lahar PC 1, and the rate of attenuation was lower. Velocities of the modeled flow were locally similar to or even less than those of the 1980 North Fork lahar (6 to 12 m/s; Fairchild and Wigmosta, 1983). The latter lahar was exceptional in its origin and relatively high clay content (Scott, 1985a). The differences in behavior between lahar PC 1 and the modeled analog partly reflect assumptions of internal flow resistance for the model, which were too high, in part because of the clay content of the 1980 flow used for comparison (see Scott, in press). The behavior of the ancient lahars in the river system indicates that a modern lahar derived from a Spirit Lake breakout would be granular in character and contain less than 3 percent clay (Scott, in press). That clay content is the approximate transformation-limiting clay content of lahars in the river system. Consequently, an actual flood wave would have undergone the same series of transformations shown in figure 7. It would not behave like the uniform, relatively unchanging mudflow represented by the model.

A second model of a modern Spirit Lake breakout flood surge did not generate sediment concentrations above 15 percent by volume (Bissell and

Hutcheon, 1983). This concentration is below the hyperconcentrated range. The largest of several modeled flood waves was relatively small (fig. 7). There is no similarity with the real-life event represented by lahar PC 1.

The third model assumed formation of hyperconcentrated flow from a modern Spirit Lake breakout (Sikonia, 1985). This assumption was based on the mistaken idea that the only sediment available to the flood surge would be from nearly saturated deposits of the debris avalanche. The high LBF of lahar PC 1 shows the assumption to be unrealistic, even in a case where transformation of the modern flood surge to a debris flow was not completed on the debris avalanche. The LBF's of the Pine Creek lahars clearly indicate that bulking to a lahar would continue below the modern avalanche terminus.

A large lahar like PC 1 also behaved differently from many of the small-scale mudflows described in the literature. Large lahars will commonly be less viscous, their sediment less cohesive, and their progressive mixing with perennial streamflow may be pronounced, leading to the distal flow transformations. Such transformations probably occur in debris flows of alpine and semiarid environments but have not been reported. The transferability of data on these flows to the behavior and deposit characteristics of lahars is generally slight.

CONCLUSIONS

A lahar or lahar-runout flow originating at Mount St. Helens is the chief hydrologic hazard to be considered in land-use planning for the Toutle and lower Cowlitz Rivers, their flood plains, and their higher, lahar-emplaced terraces.

It is highly probable that a major lahar will inundate flood plains and, locally, terraces throughout the Toutle River system within the next 100 years, a typical time frame on which engineering and land-use decisions are based. The most extreme lahar will be larger than the "maximum possible mudflow" calculated by the Corps of Engineers, in part because the risk of gigantic lake-breakout lahars like those occurring in the Pine Creek eruptive period, although now reduced by engineering works, will increase over the long term.

Apart from breakouts of avalanche-impounded lakes, all previous attempts to model a hypothetical lahar or volcanically induced flood surge have invoked a single origin—meltwater from a pyroclastic flow. However, the other formative mechanisms for lahars documented by Scott (1985a) must not be ignored in the modeling and planning processes. The importance of estimating probable future lahar types, hazards, and probabilities on the past behavior and record of flows at a volcano cannot be overemphasized.

The largest lahars in the river system have originated in the North Fork Toutle River. The 1980 crater debouches into that drainage and will probably be the source of numerous lahars of snowmelt origin in the modern eruptive period. The South Fork, however, has been the source of many lahars throughout the history of Mount St. Helens. When explosive activity analogous to that of 1980 reoccurs, the steep volcano flank in the headwaters of that drainage may induce the large (though uncommon) lahars formed by catastrophic ejection or slope failure,

The most probable lahar will be of the granular, noncohesive variety and will undergo the transformations shown in figure 7. It will attenuate more rapidly than debris flow waves such as the 1980 North Fork lahar and the modeled lahar resulting from a modern Spirit Lake breakout. As a result, flood waves consisting of hyperconcentrated lahar-runout flow will probably constitute the chief hazard in the lower Cowlitz River. Models that simulate this behavior, in the distal part of a lahar flood wave, can yield the magnitudes most appropriate for design purposes along the lower Cowlitz River. The most typical lahar flood wave in the system was a flood surge in both its proximal and distal portions.

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APPENDIX

SELECTED MEASURED STRATIGRAPHIC SECTIONS

Green Mountain Mill Section (Channel Facies)

(Location--cut bank on south side of North Fork Toutle River, 1.2 km downstream from mill; in SW 1/4 sec. 16 T. 10 N., R. 1 E.)

Thickness (m)

Deposits of Pine Creek age:

7. Lahar (PC 4): medium pebble mode, gray-silty sand matrix; mainly matrix supported; basal 25 percent of unit is inversely graded, upper 60 percent is normally graded; occurs in shallow channels on surface of lahar PC 3. Exposures at this locality were removed by erosion in late 1981.---------0.0-1.5
6. Lahar (PC 3): cobble mode, mainly similar to underlying units, with 15 to 25 cm gray sandy sole layer at base; limb and trunk molds common; the basal 10 percent of the unit is inversely graded, the upper 40 percent is normally graded. The vertical tree mold present at the margin of the channel facies penetrated all four lahars. Load and flame structures are evidence of post-depositional mobility------------------1.4-4.0
5. Lahar (PC 2): pebble or cobble mode, mainly similar to underlying unit but thins laterally to a locally pumice-rich phase that lenses out laterally between PC 1 and PC 3, where it locally is replaced with a 1-cm ash-rich

layer; the basal 10 to 20 percent of the unit is inversely graded, the upper 30 percent is normally graded.------------0.0-2.0

4b. Lahar (PC 1): cobble or locally boulder mode with silty sand matrix that is light gray to tan; extensive areas of framework support in the coarser part of the unit; basal 20 percent of unit is inversely graded, upper 40 percent of unit is normally graded; contains megaclasts of hydrothermally altered breccia. Subhorizontal limb and trunk molds are common in upper half of unit. By early 1983 a vertical tree mold was exposed as erosion moved the cutbank exposure toward the flood plain facies of the unit.------------------4.5-8.2

4a. "Ball-bearing bed" of lahar PC 1: concentration of marble-size pebbles in framework-supported sole layer; overall slight inverse grading; contact with overlying lahar was observed to be transitional only at this locality.------0.0-1.1

3. Lahar-runout deposit: light gray, medium-grained sand without the iron stain typical of the underlying units, otherwise similar to unit 1; unit surrounds stumps of trees knocked down by lahar PC 1.---------------------------------0.0-0.4

Deposits of Smith Creek or Pine Creek age:

2. Fluvial sand: brownish tan to reddish-brown sand with local coarsening to granule or pebble gravel; stratified and with well-developed cross-bedding; probably represents reworked runout sand.---1.0-2.3

1. Lahar-runout deposit: brownish-tan coarse sand; massive, ungraded except for upper 0.1 m with slight normal grading.-0.0-0.7

Green Mountain Mill Section (Flood Plain Facies)

(Location--southeastward extension of cut bank containing the section describing the channel facies)

Thickness (m)

Deposits of probable Kalama age:

6. Lahar-runout deposit: dark gray medium sand with pumice stringers.---0.0->1.8
5. Lahar, close to transition to lahar-runout flow: granule mode, dark gray (reflecting andesite and basalt content) silty sand matrix; massive; graded.--------------------------0.0->1.9

Deposits of Pine Creek age:

4. Lahar (PC 3): generally similar to unit 2; fine pebble mode, slightly darker gray matrix than unit 2; entirely matrix-supported; poor inverse grading at base; upper 50 percent is normally graded to sand without dispersed coarser clasts; widely dispersed cobbles or boulders in basal half. Tree molds observed at this locality in 1981 penetrated units 2, 3, and 4, with evidence of bark attached where surrounded by unit 4.---2.0-2.8
3. Ash-rich layer: pinkish tan clay-rich unit, grading laterally to pumice-rich lahar (PC 2).-----------------------0.01-0.6
2. Lahar (PC 1): pebble mode, light gray silty sand matrix; unit is entirely matrix supported; locally sandy at base but "ball-bearing bed" or other variety of sole layer is absent; lower 30 percent has poor inverse grading, upper 50

percent has locally well-developed normal grading; contains pumice cobbles in upper 0.5 m.------------------------------2.0-2.5

Deposits of Pine Creek or Smith Creek age:

1. Fluvial sand: identical to unit 2 of the channel facies section. The level from which the trees forming the tree molds grew could not be determined.------------------------- >1.4

Harry Gardner Park Section

(Location—cutbanks on northeast side of South Fork Toutle River 150-200 m downstream from main bridge above confluence of the forks of the Toutle River; in NE 1/4 sec. 29 T. 10 N., R. 1 E.)

Thickness (m)

Deposits of Pine Creek age:

4. Lahar (PC 3): pebble and cobble mode, gray silty sand matrix matrix supported; lower 40 percent of the unit is inversely graded, upper 50 percent is normally graded.----------------1.6-2.0
3. Fluvial sand and gravel: gray stratified and cross-bedded coarse sand and pebble gravel, locally with few pumice clasts mineralogically similar to the P set.-----------------------0.1-0.6
2. Lahar (PC 1): cobble mode with local boulders and light gray or tan silty sand matrix; extensive areas of framework support in basal 60 percent of unit; basal 15 percent with slight degree of inverse grading, normal grading in upper 50 percent; contains megaclasts of hydrothermally altered dacite breccias mainly less than 3 m in maximum exposed dimension; a megaclast of that material, with a vertical dimension equal to the thickness of the lahar, was exposed at the north end of the exposure in 1981. Mean size at this locality is -3.5ϕ (11.2 mm), sorting is 3.5ϕ, and skewness is +0.57.----------------------6.5
1. "Ball-bearing bed" of lahar PC 1: concentrated marble-size pebbles in framework-supported sole layer; not graded at this locality (continuously exposed in 1980-81); sharp upper contact; limb mold 10 cm in diameter in upper half of unit;

roundness and size distribution are very similar to those of the same unit (4a) in the channel facies of the Green Mountain Mill. Underlain by blue clay, possibly of Ape Canyon age, at this locality. Exposures of this unit were covered by bank slumping in 1981.---1.1

Coal Bank Bridge Section

(Location—valley side slopes above left bank Toutle River 0-200 m upstream from Coal Bank Bridge; in SE 1/4 sec. 19 T. 10 N., R. 1 E.; lowest units in section were described from excavations for bridge reconstruction in 1982.)

Thickness (m)

Deposits of Pine Creek age:

21. Lahar (PC 3): cobble mode with sandy matrix that is light gray--similar in color to unit 16 but lighter than that unit and with more of a bluish cast; locally clast-supported in lower part; basal 0.9 m inversely graded, normal grading above; slight relief (5 to 10 cm) on mainly planar lower contact; mean roundness of coarse mode estimated (on cliff face) at 0.50. Pumice from the basal part of the unit contains hypersthene and hornblende and is mineralogically similar to set P. Soil developed on surface is consistent with a Pine Creek age.-----2.0
20. Fluvial sand: gray medium-grained sand, indistinctly stratified, graded; formed during the inter-lahar episode of flood plain sedimentation represented by unit 18 and interrupted by deposition of the ash-rich unit 19.-----0.0-0.2
19. Ash-rich clayey silt: probably mainly fluvial but is so consistent at this stratigraphic level in sections of the lahar flood plain facies (unit 3 of Green Mountain Mill section) that it may locally be an airfall deposit that is not reworked; distinctive pink color, massive to indistinctly laminated; at this locality contains

fine-pebble-size pumice clasts that contain cummingtonite and hornblende and are derived from tephra set Y, but include hypersthene-hornblende pumice like that of set P (identifications by D. R. Mullineaux).----------------------0.0-0.12

18. Fluvial sand: gray medium-grained sand, massive to poorly stratified; similar to unit 20 and probably part of the same sedimentation episode; contains locally abundant pebble-size pumice clasts that are mainly derived from set Y (identification by D. R. Mullineaux).----------------0.05-0.15

17. Lahar (probably locally thin equivalent of PC 1): cobble mode with light gray sandy matrix, distinctly lighter and less bluish than unit 16, but difficult to determine effect of moisture content on color; mainly matrix supported but with local framework support; inverse grading only in lowest 0.1 m, upper 1.7 m is normally graded; mainly planar lower contact; mean roundness of coarse mode estimated (on cliff face) at 0.55.-----------------------------2.8

Deposits of Smith Creek age:

16. Lahar: cobble mode with muddy sand matrix (unit has a higher clay content than any other lahar in section) and is medium gray with a bluish cast when moist; coarser parts with areas of framework support; poor inverse grading in basal 0.3 m, normal grading in upper 1.1 m; mean roundness of modal class is 0.36 0.049. Unit appears more weathered and/or iron stained than the younger lahars in this section.--------------3.2

15. Deposit either of a lahar-runout flow or a dilute lahar (clearly laharic in origin): brownish-gray coarse sand and

granule gravel with no distinct coarse mode; inverse grading in basal 0.2 m, normal grading in upper 0.3 m; slight irregularities in basal contact, relief less than 5 to 10 cm, but mainly planar; roundness of granule class estimated at 0.10-0.15. Upper 0.0 to 0.1 m is locally rich in pumice clasts mineralogically similar to the Y set.------------------1.0

Deposits of Swift Creek age:

14. Lahar with soil development: few subangular pebbles and cobbles in earthy brown silty sand matrix; basal contact locally shows slight channeling with relief less than 15 cm; mean roundness of 4-8 mm class is 0.15 ±0.022, that of the 8-16 mm class is 0.20 ±0.031—locally, roundness of pebble fractions appears greater than these measured values, suggesting possible interbedded fluvial sediment. Finely comminuted, carbonized wood fragments are concentrated in uppermost part of unit and yield a radiocarbon date of 3,760 ±180 years B.P. Many live roots penetrate this unit because of the degree of weathering.----------------------------------0.5

13c. Fluvial sand: brownish gray (moist) to tan (dry) fine-to-medium sand with few pebbles, stratified in beds 0.25 to 8 cm thick.--0.6

13b. Lahar-runout deposit: granule and fine pebble gravel with medium and coarse sand, grayer in color than overlying and underlying sand; crudely stratified but generally massive.---0.6

13a. Fluvial sand: brownish gray (moist) to tan (dry) medium sand with significant granule component; well stratified in beds 0.2 to 8 cm thick. Exposed thickness of unit thins to northwest.-----------------------------------0.1-0.7

12. Lahar: lacks well developed coarse mode and may be transitional to a runout deposit; brownish gray (moist to light gray (dry) coarse sand and granule gravel; generally massive, inverse grading in basal 0.3 m, normal grading in upper 0.7 m; lower contact sharp and nearly planar. Top 0 to 3 cm locally consists of reworked lahar sediment; top 0 to 5 cm locally with concentration of iron stain, clay, and carbonate of phreatic origin, related to ground-water movement and permeability variations, rather than surface weathering. Upper 0.5 m of unit contains widely scattered clasts of pumice that are either Swift Creek or basal Smith Creek in age (identification by D. R. Mullineaux).-------------------------1.4

11. Silty clay: pink to tan, contains ash but is at least partly of alluvial origin. Unit contains molds of small wood fragments.--0.0025-0.015

10. Sand: medium-to-coarse gray sand mainly of colluvial origin, believed to be reworked lahar sediment derived from unit 9; locally impregnated with clay and carbonate of phreatic origin and locally some ash. Other lahars in this section have analogous, less-well-developed units at upper contacts.---0.0-0.06

9. Lahar: medium pebble mode with brownish gray (moist) to light grayish brown (dry) sand matrix; mainly matrix supported; basal 15 to 20 cm locally is relatively uniform sand and is analogous to a sole layer but lacks cohesiveness, slight inverse

grading in upper 0.3 m; lower contact sharp and planar; mean roundness of coarse mode is 0.35 ± 0.063.---------------------1.2

8. Lahar: rubbly appearing with coarse pebble or fine cobble mode and silty sand matrix that is, like units 2 and 4, distinctively brownish gray with a slight pink cast; locally contains megaclasts of hydrothermally altered dacite breccia up to 1.9 m in maximum exposed dimension and showing internal deformation of lithologic contacts. Unit contains a high proportion (like unit 4) of pre-Mount St. Helens lithologies composing the coarse mode; matrix supported, central 60 percent of unit is not graded--inverse grading below this central core, normal grading above (unit is symmetrically graded); basal contact sharp and planar in flood plain facies; a distinctive degree of angularity is present in all clast sizes relative to the lahars of Pine Creek age; mean roundness of clasts <u>in</u> older dacite breccia is 0.17 ± 0.037; roundness of large clasts themselves is estimated as 0.60-0.80. Basal 0.25 to 1.00 cm is silty sand and silty clay containing small carbonized wood fragments. Unit thickens in exposures upstream and fills a paleochannel over 6.0 m deep in exposed section, then thins abruptly on the south side of the paleochannel to its characteristic flood plain thickness of 1.0 m before thinning to a wedge edge against the paleovalley side slope cut in deposits mainly of Ape Canyon age.--1.0->6.0

Deposits of probable Swift Creek age:

7. Lahar: fine pebble mode with medium gray (moist) fine sand matrix, upper 8 cm distinctly browner; mainly matrix supported,

local clast support at center of unit; well developed symmetrical grading; basal contact sharp and planar; mean roundness of coarse mode is 0.21 ± 0.029. This unit is a twin of the underlying lahar.--0.3-0.5

6. Lahar: medium pebble mode with medium gray (moist) fine-to-medium sand matrix; mainly matrix supported, local clast support in center of unit; well developed symmetrical grading; basal contact sharp and slightly undulating--relief of 5 cm on minor scour channels in surface of underlying lahar; mean roundness of coarse mode is 0.39 ± 0.052. This unit is a twin of the overlying lahar.-------------------------0.3

5. Sand: medium-grained gray sand developed as colluvium on and derived from the underlying lahar.---------------------------0.0-0.05

4. Lahar: medium-coarse pebble mode with fine-to-medium sand matrix, distinctively brownish gray (moist) or tan (dry) with slight pinkish cast; similar in color to units 2 and 8 and, in the relatively high proportion of pre-Mount St. Helens rocks in the coarse mode, to unit 8; clasts widely dispersed, unit entirely matrix supported; good symmetrical grading, 3 to 4 mm silty sand at base; slightly undulating lower contact; mean roundness of coarse mode is 0.41 ± 0.062. The weathered surface of this unit is distinctive--the dispersed coarse clasts fall out, resulting in a pock-marked appearance.------------------------0.6

3. Lahar: granule and fine pebble mode with gray silty sand matrix; mainly matrix supported but with some clast support in coarsest part; inverse grading in basal 15 percent of unit, normal grading in upper 60 percent; sharp, planar basal contact.

Uppermost part of unit contains local concentrations of pumice mineralogically similar to the J set of Swift Creek age (identification by D. R. Mullineaux).------------------------0.0-1.2

2. Lahar: medium pebble mode with silty sand matrix that is brownish gray with a slight pinkish cast like units 4 and 8; mainly matrix supported but locally with clast support in coarsest part; inverse grading in basal 0.3 m, irregular normal grading above, upper 15 cm is distinctly sandier and with more dispersed clasts; sharp, nearly planar basal contact; mean roundness of coarse mode is 0.36 ± 0.047.-------------------0.9-2.5

1. Bar facies of lahar: boulder gravel with brownish-gray silty sand matrix; lower coarser part of unit has clast support transitional to matrix support as unit fines upward; marked overall normal grading, upper 12 cm is mainly sand-like matrix of rest of unit; basal contact not seen; mean roundness of boulder-size clasts estimated as 0.55-0.65.------------------ 3.5

Deposits of Ape Canyon age:

Approximately 10 m of incompletely exposed deposits are present upstream from and stratigraphically beneath the above section. The basal unit is a probable lahar-runout deposit over 1.0 m in thickness. That unit is overlain by 1.5 to 2.0 m of well stratified pumiceous alluvium with characteristic cross-bedding in some strata. The alluvium is overlain by a probable pumiceous lahar over 1.5 m in thickness. The pumice in both the alluvium and the probable lahar is mineralogically similar to the C set.

Outlet Creek Section

(Location—valley side slopes above left bank of Outlet Creek near the quarry formerly containing exposures of the Silver Lake lahar assemblage described by Mullineaux and Crandell (1962); in NE 1/4 sec. 30 T. 10 N., R. 1 E.)

Thickness (m)

Deposits of Pine Creek age:

7. Lahar (PC 3): medium-to-coarse pebble mode with a medium gray sandy matrix; matrix supported; basal 0.3 m is inversely graded above a sandy sole layer 15-20 cm in thickness, upper part of the unit is ungraded to slightly graded; lower contact is sharp and slightly undulating in existing exposures—unit appears to unconformably overlie unit 4b elsewhere in quarry; mean roundness of coarse mode is 0.52   0.10; mean roundness of 8-16 mm class is 0.19 ± 0.094; mean roundness of 4-8 mm class is 0.13 ± 0.022. Upper 0.5 to 0.8 m of unit is affected by pedogenesis consistent with a Pine Creek age.--------------2.6->4.4

6. Fluvial sand: tan-gray sand, locally with fine and medium pebbles; stratified with local cross-bedding; few pumice clasts like those in the locally pumice-rich lahar (PC 2) at the Green Mountain Mill sections and which are mineralogically similar to the P set.--0.0-0.3

5b. Lahar (PC 1): medium-to-coarse cobble mode with sandy matrix that is lighter gray and with more of a light brown cast than lahar PC 3 at this locality; less of a bluish cast than lahar described as unit 1 in this section; contains boulders of hydrothermally altered dacite breccia up to 0.9 m in maximum exposed dimension; much of coarsest part of unit has a clast-supported framework; reverse grading in basal 25 percent of unit, good normal grading above, with widely dispersed boulders 1.5 to 2.0 m below top; basal contact with unit 5a is transitional; mean roundness of coarse mode is 0.56 ± 0.12; mean roundness of 8-16 mm class is 0.17 ± 0.029; mean roundness of 4-8 mm class is 0.12 ± 0.016.----------------------------4.2-6.7

5a. "Ball-bearing bed": at base of lahar PC 1: unit interpreted as sole layer of overlying lahar; fine-to-medium pebble mode, striking concentration of clasts in this size range, with brownish-gray sandy matrix like that in overlying unit; framework is mainly clast supported; not graded; upper contact transitional with main body of flow (unit 5b); lower contact is sharp and undulating; mean roundness of 16-32 mm class is 0.27 ± 0.051; mean roundness of 8-16 mm class is 0.21 ± 0.042; mean roundness of 4-8 mm class is 0.15 ± 0.058. The presence of this distinctive unit establishes definite correlation of this unit (5a and 5b) with lahar PC 1 at Harry Gardner Park and the Green Mountain Mill sections. Unit 5a is thinner and less well developed at this location, relative to those sites, because of its position on a valley side slope well above the thalweg of the Toutle River. Observation of this unit at this section requires excavation.------------------------0.05-0.2

Deposits of Smith Creek or Pine Creek age [a radiocarbon date of 2,810 ± 200 years was obtained from wood fragments from sand probably equivalent to unit 3 or 4 (Crandell and others, 1981); pumice probably from unit 3a is most likely from set Y, indicating a Smith Creek age (Crandell and others, 1981) but could be reworked material:

4b. Silt (interpreted as the uppermost fine-grained part of a lahar-runout deposit) with evidence of soil-forming processes: modal class is 5-6 ϕ (0.016-0.031 mm); sample from middle of graded unit contains 16 percent sand and 8 percent clay; mottled light gray and tan in color with abundant carbonized wood fragments in upper part and at upper contact; slight normal grading.--0.03-0.15

4a. Silty sand (interpreted as lower part of a lahar-runout flow deposit): light gray to tan; generally massive but with some poor stratification; local inverse grading in basal 0.1 m; locally rich in pumice like that of unit 3a.--------------------------0.5

3c. Silt (interpreted as the upper graded part of a lahar-runout flow deposit) with possible slight degree of soil formation; closely related to unit 4b; locally rich in carbonized wood fragments; lower contact transitional.----------------------0.1-0.2

3b. Sand (main body of lahar-runout flow deposit): modal class is 1-2 ϕ (0.25-0.50 mm), contains 15 percent silt and 3 percent clay; light gray-brown to brown; uniform and generally massive with slight inverse grading at base, locally crudely stratified with lenses of pumice similar to that of unit 3a.-------------0.3

3a. Pumice gravel (basal deposit of lahar-runout flow): pebble and fine-cobble gravel, locally openwork; commonly with matrix support and interstitial sand like that of unit 3b. Fe-Mg phenocrysts in the pumice are mainly cummingtonite and hornblende. The pumice is probably from set Y (Crandell and others, 1981).--0.0-0.2

Deposits of Smith Creek age:

2. Fluvial sand: coarse, stratified, iron-stained sand with lenses of pebble gravel and pebbly sand; clearly of normal fluvial origin in contrast to the sequence of unit 3; moderately well sorted; roundness of clasts in pebble size range is relatively low (0.20-0.40) because of local origin from the underlying lahar.------------------------------------0.5-0.7

1. Lahar: medium pebble mode with a muddy sand matrix that is medium gray with a characteristic bluish cast; the muddy appearance is also characteristic (a sample 0.3 m from the top of the unit contains 15 percent silt and 3 percent clay); entirely matrix supported; slight overall normal grading in exposed part of unit; upper contact slightly channeled, lower contact not exposed; mean roundness of coarse mode (16-32 mm is 0.24 ± 0.041; mean roundness of 8-16 mm class is 0.15 ± 0.024; mean roundness of 4-8 mm class is 0.12 ± 0.015. Size distribution from the clast-poor upper part of the unit has the following characteristics: mean, 1.22ϕ (0.44 mm); sorting, 3.10ϕ; and skewness, +0.11.-- 1.2

Bear Creek Section (approximately 20 km from 1980 crater; last extensive sequence of exposures in South Fork Toutle River before bedrock gorge) (Location—high cutbank on north side of South Fork Toutle River 0.5 km upstream from confluence with Bear Creek, near center of sec. 29 T. 9 N., R. 3 E.)

Deposits of modern eruptive period:

13. Lahar: pebble mode, wood-rich. Contains andesite and basalt. Unit represents the peak flow deposits of the first lahar in the South Fork Toutle River on May 18, 1980.----------------0.0-0.3

Deposits of Pine Creek age:

12. Lahar: pebble mode, similar to underlying unit. Contains no andesite or basalt. Mantles slopes like underlying unit----0.0-0.5
11. Lahar: coarse pebble mode with a brownish gray sandy matrix; mainly matrix supported; good normal grading throughout most of unit, above local, basal 12-15 cm sole layer. Contains little or no adesite or basalt. Slight soil development in upper 0.3 m consistent with a Pine Creek age. Unit is slope-mantling, inset against the sequence of older deposits exposed in the main cliff face. It cuts section as far as unit 3. In spite of the young date (see unit 10) from soil developed on the underlying erosional surface, the erosion producing the valley side slopes mantled by unit 11 probably occurred during the main part of the dormant interval between Swift Creek and Smith Creek time.--------------------------2.0-4.5

Deposits mainly of post-Swift Creek, pre-Pine Creek time:

10. Soil: well-developed and clay-rich, yellowish orange brown, containing abundant angular rubble of pre-Mount St. Helens

lithologies derived from valley side slopes. Large charcoal fragments near upper surface of soil yield a date of 2630 ± 185 radiocarbon years. The fragments were obtained from below the top of the terrace.----------------------------------1.3-4.0

Deposits of Swift Creek age:

9. Lahar: pebble mode with a few boulders and a brownish gray sandy matrix; entirely matrix supported; pronounced inverse grading contrasts with the well-developed normal grading in the otherwise similar unit 7.--------------------------------------1.5-4.0
8. Soil: sandy, light orange-brown; not as extensively developed as the soils of units 5 and 10.--------------------------------0.1-0.4
7. Lahar: coarse pebble mode with brownish gray silty sand matrix; clast support only in coarsest part; basal 0.7 m is inversely graded, excellent normal grading above that level.-----------4.0-6.5
6. Ash-rich layer: locally present; not associated with pumice; probably of fluvial origin.------------------------------------0.0-0.02

Deposits of Cougar age:

5. Lacustrine silt and sand, with some soil development locally extending into unit 4: clayey, stratified, blue-gray where not oxidized. Abundant plant stems are partially replaced by iron oxide. Wood fragments yield an age of 19,700 ± 550 radiocarbon years.---0.0-0.5
4. Fluvial sand, silt, and fine pebble gravel: well stratified, tan to gray; unit probably related to underlying sequence.---0.2-1.5
3. Alluvium: clast-supported boulders common in brownish gray sandy matrix; rubbly appearance. Coarsest material is in middle of unit, but deposit is not graded comparable to any

lahar. Fine pebbles are markedly rounded, showing that the unit is not the bar facies of a lahar, although in other respects the unit is similar to the 1980 lahar deposits in the adjacent channel. Contains significantly more lithologies from Mount St. Helens than the underlying glacial sequence and therefore is distinctly younger. Unit dissimilar to fluvial deposits of Ape Canyon age, which are common upstream and downstream of this section.-----------------------------------5.5

Deposits of pre-Cougar age (and probably of pre-Ape Canyon age):

2. Sand and gravel, probably of glaciofluvial origin: Interbedded sand and pebble gravel; chocolate brown and weathered to a degree similar to that of the underlying unit; well stratified; clasts are mainly pre-Mount St. Helens metavolcanics. Distinctly different from deposits of known Ape Canyon age.--------------1.2
1. Probable glacial till: cobble mode with some boulders; matrix weathered brown to reddish brown; entirely matrix supported; nongraded and very poorly sorted; clasts are pre-Mount St. Helens metavolcanics; unit rests directly on pre-Mount St. Helens metavolcanics. Unit may correlate with basal unit of sections on opposite side of river; some till-like units in those sections contain a small proportion of Mount St. Helens rock types.--- >~2.0

Disappointment Creek Section

(Location—exposures in high cutbanks on south side of South Fork Toutle River opposite an interval from 0.2 to 0.9 km downstream from Disappointment Creek, in NW 1/4 sec. 3 T. 8 E., R. 4 E., and SE 1/4 sec. 32 T. 9 N., R. 4 E.)

Deposits of modern eruptive period:

11. Lahar: thin coating of peak flow deposits of first lahar of May 18, 1980.--0.0-0.4

Deposits of Kalama age:

10. Lahar: thin coating of a lahar containing andesite and basalt.--0.0-0.3

Deposits of Swift Creek age:

9. Soil: the most prominant soil in the watershed of the upper South Fork Toutle River; marked at most locations by a significant clay content and angular clasts of laterally derived pre-Mount St. Helens rock types. Same as unit 10 of the Bear Creek section.------------------------------------0.3-1.6

8. Lahar: texturally like unit 6, but extensively weathered--underlies the soil of unit 9 (the soil is developed on other units elsewhere). Pumice from this unit is a hypersthene-hornblende type and, given the additional evidence of the depth of soil development, probably can be identified as set J.--0.0-1.2

7. Lahar: texturally like unit 6 but not weathered.------------0.0-1.0

6. Lahar: cobble mode, boulders locally concentrated near center of unit; gray silty sand matrix; good inverse grading in basal 1.0-2.5 m, fair normal grading above. Local sole

layer 0.0-0.3 m in thickness with widely dispersed clasts that weather out, leaving a pock-marked surface like that of unit 4 of the Coal Bank Bridge section. Essentially one unit, but local crude stratification suggests the presence of surges. Upper weathered zone about 1 m thick has locally been removed by erosion of top surface. Clasts are dominated by rock types from ancestral Mount St. Helens, and at least 30-40 percent exhibit shapes indicating direct origin from disintegration of prismatically jointed clasts. Pumice, widely dispersed in the main body of the unit, is mineralogically similar to set S, like that locally concentrated in the uppermost part of the unit.--8.0-25.0

5. Fluvial sand: brownish gray, well stratified, lenticular.---0.0-0.2
4. Fluvial silty sand with ash-rich layers: weathered (prior to succeeding units), orange-brown, massive, with finely comminuted pumice fragments; local 0-3 cm ash-rich layers at top and bottom of unit. The pumice is mineralogically similar to set S, an identification made more probable by the degree of soil formation represented by unit 9.---------0.0-0.4
3. Possible lahar-runout flow deposit: massive to poorly stratified sand.--0.0-1.5

Deposits of probable Cougar age (or pre-Cougar but post-Ape Canyon age):

2. Lahar: rubbly, cobble mode with a few boulders in a gray sandy matrix; clast supported only locally at the coarsest level; bottom 0.3 m is inversely graded; normal grading above that level. Upper 0-20 cm with soil development.-----------0.0-1.8
1. Alluvium: cobble mode with boulders in a gray sandy matrix;

crudely stratified; not obviously bimodal. Sandy subunits show channeling and cross-bedding. The texture and structure of the unit are identical in all obvious respects to those of the modern stream alluvium. Rock types are mainly those of pre-Castle Creek Mount St. Helens. Clasts and matrix are not similar to those of known Ape Canyon deposits, but are similar to those of the Cougar-age alluvium downstream.-------------- >4.5