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Stream Channel Adjustments After the 1980 Mount St. Helens Eruptions

by

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ABSTRACT

Stream channel response to the 1980 eruption of Mount St. Helens has varied widely. Stream channels that received only airfall deposits have shown no significant sedimentation following the eruption. In drainage basins that received both blast and airfall deposits, localized channel modification has been observed. However, as the blast/airfall deposits are predominately sand-sized, they have been quickly removed from the steep low-order channels surrounding the mountain with little net effect on pre-eruption channel morphology. Some subsequent channel modification has resulted in lowered gradient reaches downstream as sediment eroded from upstream hillslopes and stream channels has been redeposited in these reaches. Long-term effects in blast/airfall-affected streams appear limited to channel subjected to debris torrents resulting from shallow-seated landsliding and breakup of in-channel debris jams.

Channels and floodplains affected by lahars were covered by as much as 1 to 5 meters of material and were initially reduced substantially in size. Subsequent flow has increased channel width, often as much as 100 percent, and caused a complex sequence of scour and fill over a range of several meters in bed elevation. Even in reaches characterized by up to several meters of aggradation, the net volume of sediment stored in valley bottoms has decreased due to large increases in channel width. In the North Fork of the Toutle River, the integration of stream systems on the surface of the 2.5-km^3 debris-avalanche deposit has resulted in the fluvial reworking of large volumes of sediment. Transport of this sediment dominates fluvial processes otherwise influenced by blast, airfall, and lahar deposits, causing ubiquitous channel widening and complex sequences of channel scour and fill.

INTRODUCTION

The 1980 eruptions of Mount St. Helens, Washington, had a major impact on the hydrology and sediment load of all streams in a 600-km^2 area around the mountain (fig. 1). The lateral blast destroyed vegetation and deposited sand, silt, and gravel over a large area north of the mountain. A massive debris avalanche filled the bottom of the North Fork Toutle valley. Lahars (volcanic mud flows) flowed down all major streams that drain the mountain, and fine-grained airfall ash blanketed an area beyond the blast zone.

The effects of these events on fluvial systems depend upon (1) thickness, grain size, and distribution of volcanic deposits, and (2) preeruption topography of valleys and stream channels. On the basis of these characteristics two types of channel are blast area channels and lahar-affected channels. Irregular longitudinal profiles of blast area channels (fig. 2) create local tendencies for either transport or deposition of sediment. The primary sediment source for blast area channels is sandy tephra (the lateral blast deposit, ash, and pumice) that blankets the landscape. Sediment is produced mainly by hillslope erosion. The complex drainage networks that transport the sediment extend nearly to drainage divides. Lahar-affected channels contain thick (1-5 m) deposits that range in size from clay to boulders. Such deposits from the 1980 eruption as well as from previous eruptions have created channels with distinctively smooth concave longitudinal profiles (fig. 2). Important channel changes have resulted from reworking of May 18, 1980 and older lahar deposits.

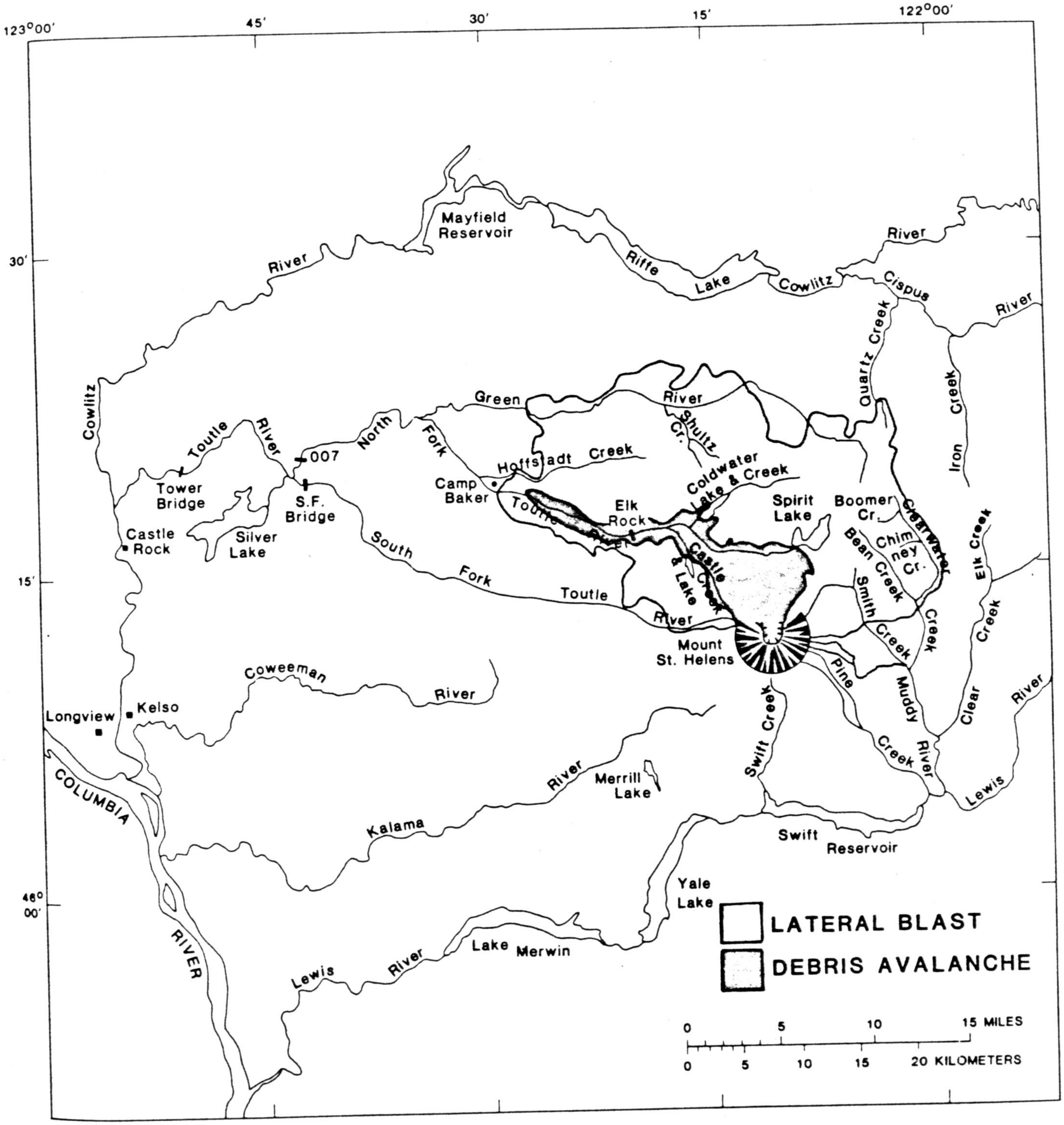

Figure 1. Mount St. Helens area, major drainage systems, lateral blast-affected area, and debris avalanche deposit.

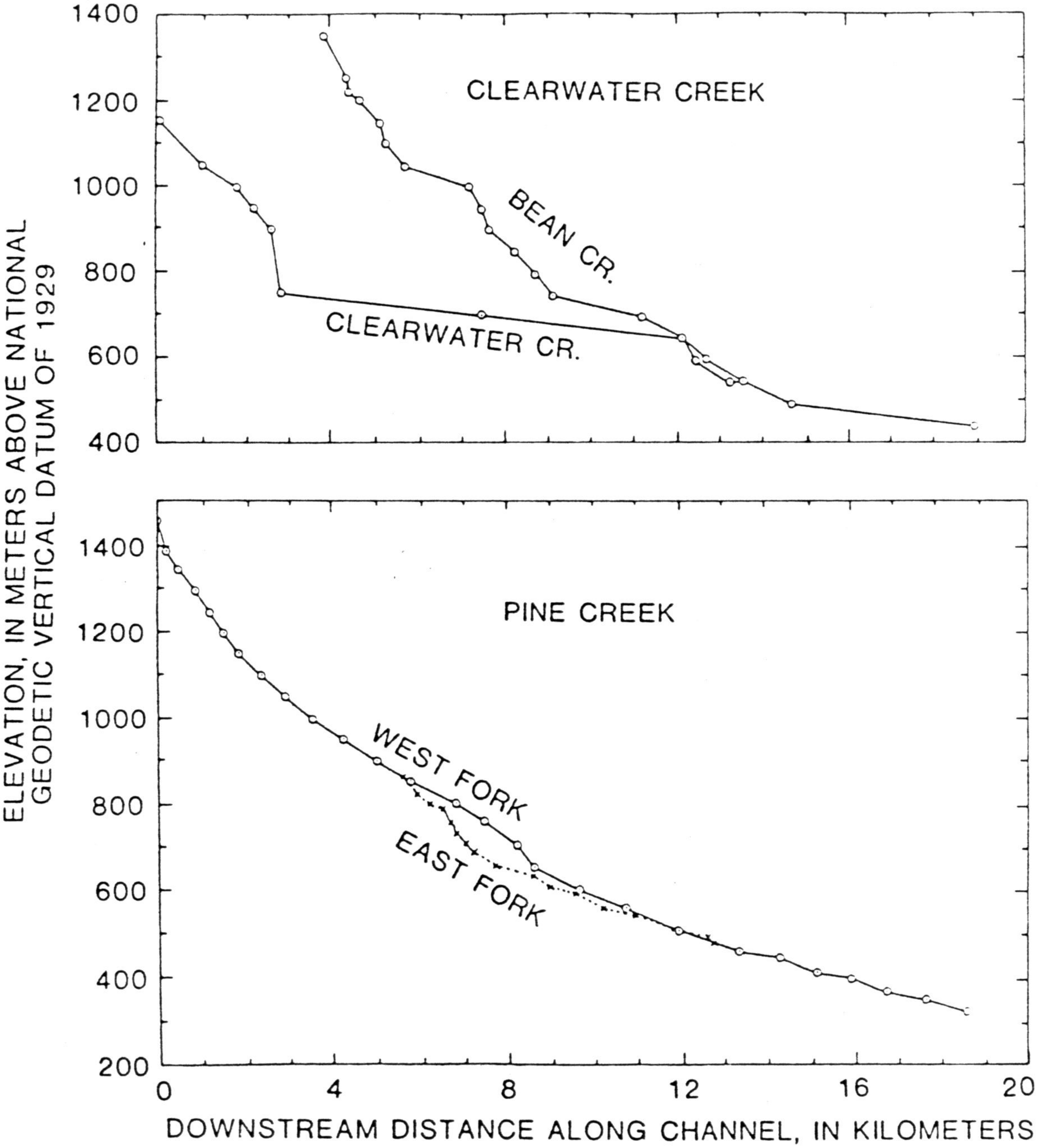

Figure 2. Longitudinal profiles of Clearwater Creek (blast area channel) and Pine Creek (lahar-affected channel), constructed from topographic maps.

This paper reports qualitative and semiquantitative post-eruption changes in drainage basins altered by the blast--to include those of the Green River, Shultz Creek (tributary to the Green River), and Clearwater Creek--and by lahars--to include those of the Toutle River, Muddy River, and Pine Creek (fig. 1). Each basin received different types and amounts of deposits during the 1980 eruptions, and the dominant processes involved in erosion and transport of these deposits in part depend on these differences.

Other investigators report on channel development on the debris avalanche in North Fork Toutle River (see Janda, this volume); problems of the lower Toutle and Cowlitz Rivers (see Stockton, this volume); and erosion on hillslopes (see Swanson and others, this volume).

Study Sites and Methods

Cross sections and longitudinal profiles in all major channels that drain the blast area were established in 1980-1981 to monitor post-eruption changes in the morphology of channels and valley bottoms, net changes in sediment storage, and the amount and rate of bank erosion. Aerial photographs (1:9600, October, 1981) provided an overview of channel change.

Blast-Area Channels

Emplacement of volcanic deposits in blast-area channels and subsequent erosion, transport, and storage of sediment vary with topography and rates of sediment input at points along drainage networks. These processes are discussed below in order of occurrence and distance downstream.

Volcanic Events and Hillslope Deposits of 1980

The lateral blast of May 18, 1980, removed or toppled all vegetation in a 550-square kilometer area north of Mount St. Helens. Especially in the periphery of the blast-affected area, the blast shock wave and hot gases were channeled away from the general blast direction down major valleys that lead west, north, and east (Kieffer, 1981). The blast deposited from 0.025 m to more than 1 m of lithic particles and woody debris on hillslopes throughout the devastated area. In the North Fork Toutle and Green River drainages the blast deposit contains about 15 percent gravel, 63 percent sand, and 21 percent silt and clay, as well as various amounts of woody debris (Collins and others, 1982).

Tephra (airfall) deposited on May 18 and during five subsequent eruptions (May 25, June 12, July 22, August 7, and October 16-18, 1980) ranges in thickness from more than a meter on the volcano's flanks to only a few millimeters 20 km away (Waitt, 1981; Waitt and Dzurisin, 1981; Waitt and others, 1981). Prevailing winds on May 18 carried most of the ash to the north-northeast. Drainage basins adjacent to this side of the volcano were covered with up to 0.33 m of tephra having large proportions of pumiceous gravel. Ash deposits in other directions around the volcano were insignificant. May 18 airfall deposits to the north of the mountain consist largely of silt and very fine sand; to the east along the path of the plume they include pebble- and gravel-sized pumice fragments.

Subsequent eruptions (particularly that of May 25) locally deposited a thin layer of coarse sand (Waitt and others, 1981).

A few examples depict the variation between drainage basins in thickness and size composition of deposits on hillslopes. In Shultz Creek basin (fig. 1), 12-20 km northwest of the volcano, 0.1-0.5 m of sandy blast deposit is topped by 0.02-0.06 m of silty airfall ash; in Boomer Creek basin (fig. 1), 12 km northeast of the mountain, 0.18 m of sandy blast deposit is topped by 0.14 m of gravelly pumice and 0.01 m of silty ash. Basins more than 20 km northeast and east of the summit, such as those of Quartz Creek, Iron Creek, and Clear Creek (fig. 1), were outside of the blast, but received up to 0.15 m of sandy/silty ash. Elk Creek, 20 km northwest of the volcano, was largely unaffected by the blast and received only a few centimeters of silty tephra.

Blast deposits reduced infiltration of subsequent rainfall and increased runoff. These effects varied with both grain size and total thickness of tephra. Pumiceous tephra deposits northeast of the cone are more permeable than silty ash to the west. Infiltration rates of about 13 mm/hr in pumiceous tephra and 8 mm/hr in non-pumiceous tephra were measured in the summer of 1981 (Swanson and others, this volume). Infiltration rates in nonpumiceous tephra in Shultz Creek during the fall of 1980 ranged from 3 to 8 mm/hr (George Leavesley, U.S. Geological Survey, oral communication, 1981). Infiltration rates in unaffected forested watersheds in the Cascades are about 100 to 130 mm/hr (Johnson and Beschta, 1981). In areas where tephra is both fine grained and thin, the deposit may reduce infiltration and (or) act as mulch and reduce evaporation from the soil. Erosion of relatively impermeable silty ash and exposure of more-permeable, sandy blast deposits in Shultz Creek basin have increased infiltration rates (Lehre and others, 1982).

Pre-eruption annual runoff averaged 1500 mm in the Toutle River (U.S. Geological Survey, 1981). Destruction of vegetation reduced water interception and transpiration, and may have increased runoff within the affected area by as much as 50 cm during the summer growing seasons after th eruption (Robert R. Ziemer, U.S.D.A. Forest Service, oral communication, 198

The post-eruption hydrologic record is too short for one to draw conclusions about changes in long-term, basin-wide hydrologic response to the lateral blast, but short-term changes are significant. Data from the Toutle River suggest that total runoff and peak discharges have increased. After the first hydrograph rises in the fall of 1980, peak runoff in the Toutle River was consistently higher and earlier than predicted by a model calibrated to historical precipitation-runoff relations (Orwig and Mathison, 1982). It is probable that reduced infiltration rates in the blas area, as well as on the debris avalanche, are responsible for the increase in peak runoff. A discharge equalled or exceeded 1 percent of the time in the Toutle River in water year (WY) 1981 was about 20 percent higher than that of a pre-eruption year, even though more than 8 percent of the Toutle River basin was not contributing runoff because tributaries were dammed by the debris avalanche. During WY 1982, the discharge of the North Fork Toutle River was significantly greater than that during the previous year due to greater precipitation and to expansion of the contributing area by drainage integration on the debris avalanche deposit, upper North Fork Toutle River (Janda, this volume).

The blast and airfall deposits are readily erodible, because they deposited on steep terrain and are unconsolidated and contain predominantly pebble size or smaller material with little clay. Sheet and rill erosion delivered 100 to 400 m^3/ha of sediment to the streams that drain the affected watersheds in the first year after the May 18 eruption (Swanson and others, this volume). Much of the pre-1980 landscape was mantled by poorly weathered but vegetated deposits that are strikingly similar to those deposited during the 1980 eruptions. This is particularly true along the river valleys draining the cone. Banks of unweathered, pre-1980 deposits are easily undermined and large volumes of readily transportable sediment are continually introduced into streambeds. Rills and gullies forming in the 1980 tephra commonly incise into these pre-1980 deposits in areas where rill erosion had not previously occurred.

Erosion and Sediment Transport

Tephra deposits on slopes with gradients less than 70 percent have been eroded chiefly by sheetwash and rilling, while on steeper slopes (comprising 5.5 percent of the blast-affected area of the North Fork Toutle River basin), shallow slides have almost completely removed the tephra cover (Lehre and others, 1982). Much of the sediment eroded from hillslopes, particularly in clearcuts, is carried without intermediate storage to tributaries.

Low order channels in the blast-affected zone were initially choked with sandy and silty tephra (Waitt and others, 1981) and by sliding and avalanching of surge deposits from adjacent slopes during or immediately after their deposition. Blast deposits along streambanks and in fill terraces along Shultz and Hoffstadt Creeks (fig. 1) and their tributaries, for example, range in thickness from 0.05 m to more than 2 m; thickness averages 0.5 to 1 m. Mean particle size distribution of the blast deposit sampled at seven sites along Hoffstadt Creek indicate the material was 10 percent gravel, 75 percent sand, and 15 percent silt/clay.

Low-gradient reaches of low order channels in the blast-affected area, particularly above channel constrictions such as culverts, bridges, and blow-down timber, locally contain relatively thick (0.6 to 5 m) deposits of reworked coarse sandy ash with a total volume of 10^5 m^3 or less. These deposits show poorly to moderately well-defined stratification and commonly contain layers of logs or branches, particularly at the top or bottom of the deposit. The top of the deposit is generally flat to gently undulating and fairly smooth. A particularly thick deposit along West Fork Shultz Creek contains logs at its base and a convex downstream shaped log-jam embedded in its surface.

Large volumes of fresh sandy volcanic material introduced to small channels were transported up to a few kilometers by three types of flow and deposited in low gradient storage sites. In the Mount St. Helens area, muddy flows are relatively shallow Newtonian flows that contain high concentrations of sandy material and locally caused rapid aggradation. Debris flows are nonerosive slurries of sandy material with greater sediment concentrations than muddy flows. Debris torrents are also sediment-rich slurries, but they also contain coarse channel and hillslope material and organic debris often eroded by the break-up of dams formed by blast-downed trees. Presumably, organic debris were overridden and buried or borne along in highest concentration at the top of the torrent fronts.

The processes responsible for generating these sediment-laden flows are not clear. Before the May 18 eruption, snowmelt was already contributing moderate runoff, and thick snowbanks probably persisted along steep streambanks of small, high elevation streams. Although evidence of overland runoff generated by rapid melting of snow on hillslopes is lacking (Fred Swanson, U.S.D.A. Forest Service, oral communication, 1982), the blast concentrated in valleys may have rapidly melted streamside snowbanks. Failure of unstable matrices of blown down timber that temporarily stored water and sediment apparently triggered compounding debris torrents in Shultz Creek, for example. In other cases, sediment transported by muddy flows and debris flows passed through log matrices without appreciably disturbing them.

Blast deposits were scoured from channel banks and bed in higher-gradient reaches and deposited in lower-gradient reaches where flows or torrents could spread out or pond. These deposits, first evident on the June 19, 1980, airphotos, were most likely emplaced during or shortly after the May 18 eruption. Although muddy flows and debris flows and torrents were not inventoried, it is likely that they were relatively common in steep, low-order channels in the blast zone immediately after the May 18 eruption. Muddy flows and debris torrents have been more common than debris flows during the following high runoff seasons, but less frequent than shortly after the May 18 eruption. In view of the changing nature of deposits, sediment loads have generally declined in low order channels, except where hillslope and channel failures have released debris torrents.

Chimney Creek, a third order tributary which flows over an alluvial fan before entering Clearwater Creek, exemplifies sediment transport and deposition in low order tributaties during the first 2 years after the eruption. On May 18 a muddy flood of predominantly sand-sized volcanic material moved down Chimney Creek as far as the midpoint of the alluvial fan. Near the flow terminus, sediment was deposited as far as 30 m from the channel over the fan surface (fig. 3). Subsequently incision down to a series of steps formed over organic debris in the summer of 1980 left fill terraces as high as 3 m (fig. 4) and added more sediment to the flow terminus but negligible amounts of sediment reached the mouth of Chimney Creek. Another muddy flow traversed the entire length of Chimney Creek during the winter of 1980-1981, depositing as much as 0.5 m of sediment over the fan as far as 100 m from the channel (fig. 3). High flow levels were less than 0.3 above the highest terrace, as indicated by preservation of airborne ash on logs above the channel. This suggests that rapid aggradation caused a relatively shallow flow to overtop the banks and to deposit a large volume of sediment over the alluvial fan. Subsequent flows re-incised the channel down to organic steps or to a preexisting armor layer and exposed preexisting streambanks, as most of the unconsolidated sediment recently stored in the channel was removed (fig. 4).

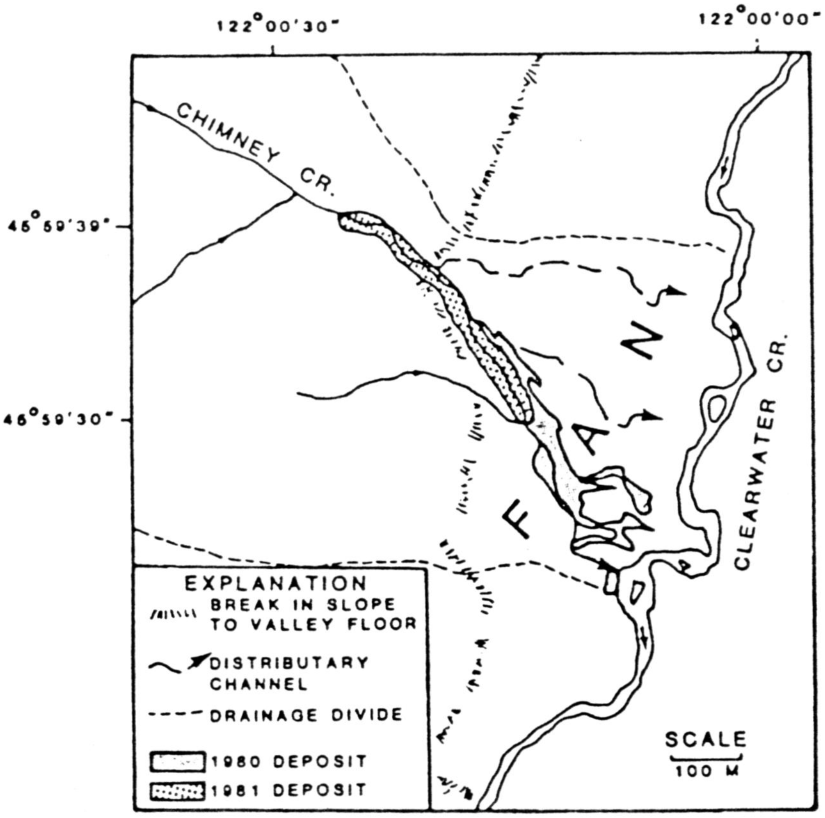

Figure 3. Deposits of 1980 and 1981 in lower Chimney Creek. Deposits are thickest near the main channel. The terminus of the 1980 muddy flow corresponds to a decrease in slope.

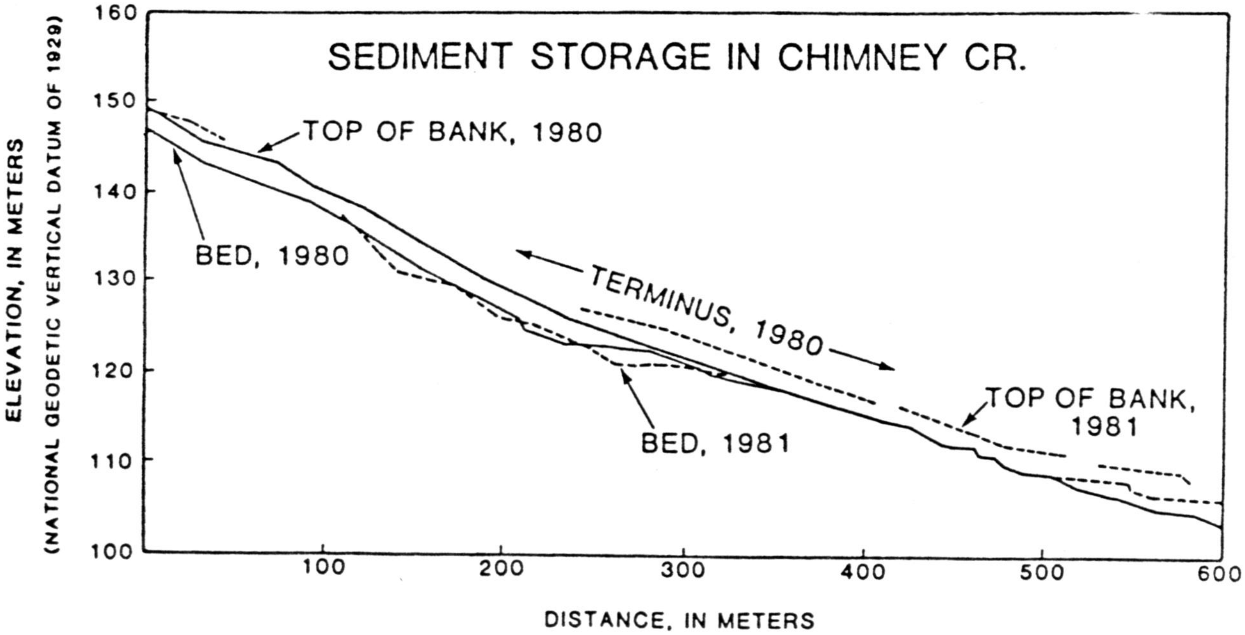

Figure 4. Longitudinal profile of Chimney Creek from the head of the alluvial fan to the mouth. Profiled banks are fill terraces composed of recent volcanic alluvium; gap in bank profile (for example, from 40 to 240 m, 1981) indicates absence or erosion of fill terraces.

Debris torrents produced by post-eruption winter storms have deposited organic debris and coarse sediment scoured from channels and adjacent hillslopes in downstream reaches. Shallow-seated debris avalanches, which often flow into channels and create debris torrents, have increased in number since the 1980 eruptions, as large storms have occurred and soil strength has declined due to rotting of roots in the area of blown-down trees (Swanson and others, this volume). For example, storms of November 1980 produced the first major runoff events after the eruption; sections of Main Fork Shultz Creek (fig. 5A) filled as a result of a debris torrent. The sandy-gravelly post-eruption bed was replaced by coarse gravel, cobbles, and small boulders. Large logs up to 1.3 m in diameter were moved. In tributaries of Shultz Creek, post-eruption debris torrents have left trim lines as high as 6 m above the channel bottom. Torrents in this case were probably generated when dams of logs and branches in narrow channel reaches suddenly broke and released a flood wave capable of transporting logs, cobbles, and boulders. Scour during subsequent storms has gradually removed some of these torrent/flood deposits (fig. 5B).

Land managers have been concerned that flow diversion by unstable organic debris may cause extensive bank erosion and channel wandering across valley flats. However, such channel instability has not been observed in the blast area. Although fine-grained volcanic sediment has been readily removed from bank storage, in most cases the pre-existing streambanks have eroded little. They are apparently cohesive, largely due to shear strength provided by roots of herbaceous plants and shrubs,

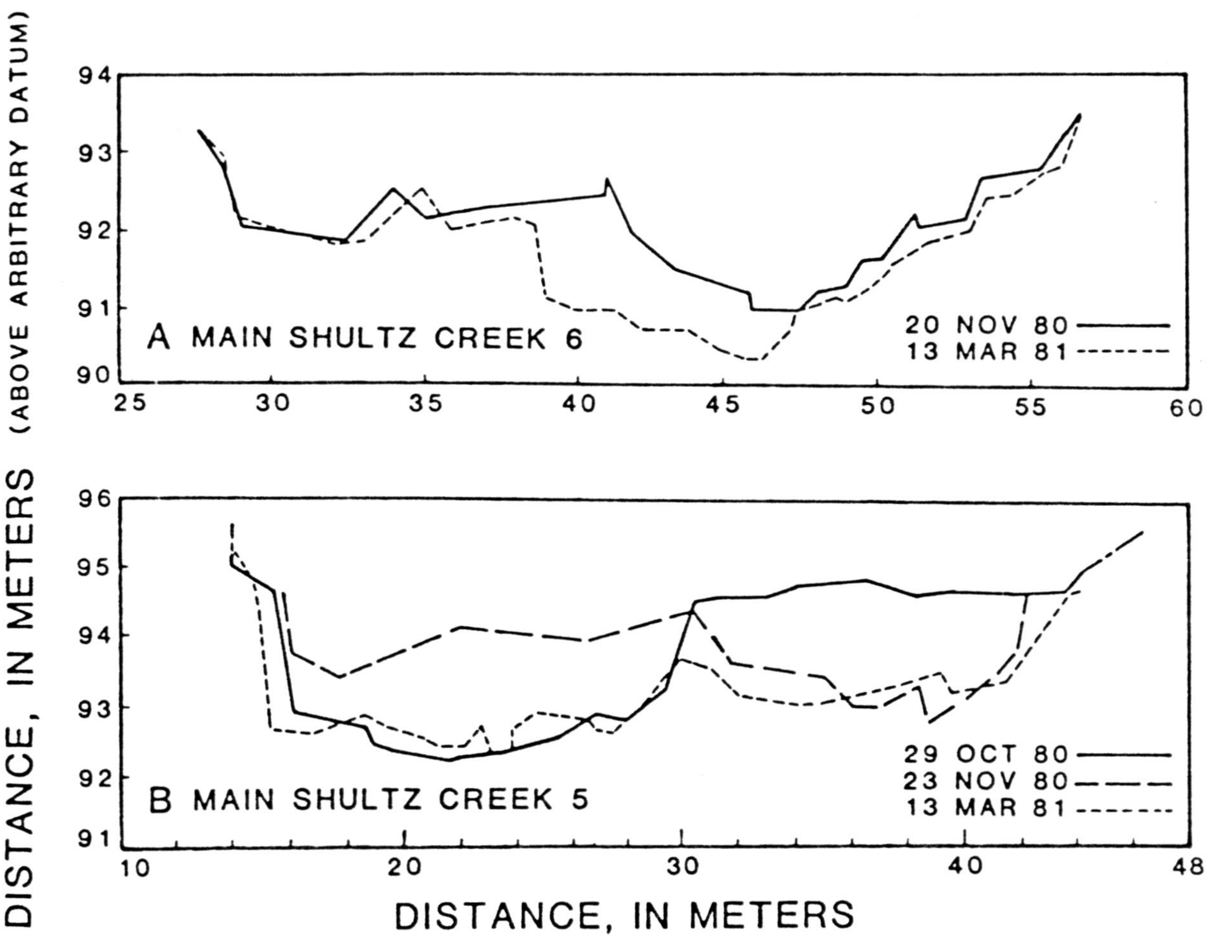

Figure 5. Posteruption changes in sediment stored in the channel of Main Fork Shultz Creek: A. Main Shultz Creek, cross section 6. Post-eruption debris torrents filled channel with coarse gravelly deposits in October and November 1980; winter flows have progressively removed these and reduced channel gradient. Channel bed is now near its preeruption position.
B. Main Shultz Creek, cross section 5. Between October 29 and November 23, 1980, high flows removed tephra deposits 1.5 m-thick on right bank; during same period debris torrent filled left half of channel with 1 m of coarse gravelly debris. Winter high flows have since degraded channel to nearly its original (preeruption) depth.

which have resprouted and grow vigorously because shade was eliminated and volcanic material was quickly removed from steep streambanks exposed to channel flow. Trees blown down from old-growth riparian areas were large (commonly 1 m in diameter and 40 m or more in height), their stems remain attached to root wads, and thus they are relatively stable. Blown down trees that move are usually anchored on one bank by their root wads or long stems. They tend to rotate about their root wads and form acute angles with the streambank, thus diverting the flow away from the streambank. Submerged logs extending across the channel can direct flow into the opposite bank, but more often only part of a log diverts the flow. Logs often broke over the channel so that two pieces were rotated by the flow and formed acute angles on either bank.

In drainage basins affected by the lateral blast, scour has generally progressed downstream to third or fourth order channels. In most low order channels the bed has scoured down to an armored layer or to bedrock, except where sediment is retained by debris; most sediment stored along the preeruption streambanks was removed by the summer of 1981. For example, at about half of the monitored cross sections in Hoffstadt Creek, Shultz Creek, and upper Green River, the channel had eroded down to bedrock or to large bed material by the summer of 1981. Subsequent erosion in these reaches has removed unconsolidated volcanic material from streambanks. Most of the remaining stored sediment resides in fill terraces and over adjacent valley flats and alluvial fans. In some places a storage reach has been depleted while an adjacent downstream site has filled. For example, during the winter of 1981, a large amount of sediment stored behind an open framework of large organic debris in the upper Green River (cross sections 60.05-60.25, table 1) was removed and redeposited in a downstream reach (cross sections 60.40-60.50). Without further large sediment contributions, sand- and silt-sized material comprising the bulk of volcanic sediments that were in contact with winter flow have been removed. Scour to stable levels by channels that have not been affected by lahars is generally followed by bank erosion of unconsolidated volcanic material deposited during and after May 18. For example, the reach of the upper Green River that filled in 1981 has scoured downward, but had not yet widened by summer 1982.

Table 1. Changes in cross-sectional area of Green River channel, summer 1980 to summer 1982. Total change in cross-sectional area was divided by bankfull width to facilitate comparing the magnitude of changes observed.

Cross section No.	Distance from mouth of Green River (km)	Area change 1/ (m^2/m)
60.05	47.75	+0.52
60.10	47.70	+0.22
60.15	47.66	+0.39
60.20	47.61	+0.49
60.25	47.57	+0.51
60.40	46.00	-0.38
60.50	45.95	-0.33

1/ Negative value, channel aggradation; positive value, channel scour

Although large volumes of sand remain in storage above the high water levels for the winters of 1980 and 1981, much of the material eroded from hillslopes has probably been carried out to major rivers (Lehre and others, 1982). This hypothesis is supported by time-sequential photographs of stream reaches taken from monumented points. The photographs show progressive coarsening of the bed, removal of tephra deposits on banks, and no systematic buildup of sediment around logs and stumps on footslopes. Fine sediment, which makes up the bulk of the material in storage sites, is rapidly transported through the drainage systems into high order channels. Sediment concentrated in storage reaches may be expected to disperse as it moves downstream.

Sediment Storage

Sediment storage in blast-area channels depends on (1) rate of sediment delivery to potential storage sites (sediment delivery is apparently most rapid where thick tephra deposits initially covered steep channels and hillslopes); (2) storage potential (length and width of valley flats, amount of large organic debris, and channel gradient); and, (3) coarseness of deposits.

Green River and Clearwater Creek, the two major basins affected mainly by the blast, have been sculpted not so much by recent volcanism as by fluvial erosion, mass wasting, and glaciation. These processes, operating on materials of varying resistance, have produced breaks in slope in stream channels (for example, Clearwater Creek, fig. 2) and of adjacent hillslopes. Low gradient stream reaches, alluvial fans, and valley flats downstream from steep reaches and at the base of steep hillslopes are common storage sites for fluvially worked volcanic sediment.

Although most sand-sized volcanic sediment has been removed from the channel of Chimney Creek, sediment deposited over the alluvial fan may be expected to remain in storage for centuries because overbank flows are very infrequent. The channel of Chimney Creek presently bounded by high fill terraces appears large enough to carry the highest flows except for perhaps a debris torrent. Important volumes of sediment thus appear to be in long-term storage on alluvial fans and floodplains of low-order tributaries. In Boomer Creek, a tributary to Clearwater Creek and similar in size, morphology, and aspect to Chimney Creek, 34 percent (12,500 m^3) of the storage of recent volcanic sediment is in two alluvial fans. The long residence of sediment on tributary fans is further evidenced by their construction in glaciated valleys since the last major ice advance (about 12,000 yr before present) and their support of a mature forest before the May 18 eruption.

In Boomer Creek, northeast of the crater, much sediment (0.21 m^3/m sampled channel) remains in storage on the beds of low order tributaries (table 2). Relatively low rates of runoff over coarse pumice airfall and many down trees are most likely responsible for greater amounts of sediment remaining in storage in Boomer Creek than in streams to the west, such as Shultz Creek.

Coarse clasts deposited by outburst floods or debris torrents from behind debris dams appear to be the most persistent deposits. For example, alluvial fan deposits dominated by cobbles and boulders at the

Table 2. Sediment in storage components of Boomer Creek. For each storage component, values for sediment volume per unit length of sampled channel are listed above values for the percentage that volume represents of the total stored sediment in each stream order. The volume of sediment per unit length of sampled channel is determined by dividing the volume of sediment in the sampled reach, in cubic meters, by the length of sampled reach, in meters A fourth order channel in this analysis is classified as a third order channel in table 3.

Stream order	Sampled Channel Length (m)	Storage components: Alluvial fans (m^3/m) (%)	High flow terraces (m^3/m) (%)	Debris related (m^3/m) (%)	Bed (m^3/m) (%)	Other (m^3/m) (%)	Total[1] (m^3/m) (%)	Total Channel Length[2] (m)	Total Volume Sediment in Storage[3], [4] (m^3)
1	379	0.004 1	0.053 15	0.118 32	0.152 42	0.036 10	0.363	15,460	5,610
2	464	.237 26	.104 11	.162 18	.401 44	.005 1	.909	6,600	6,000
3	384	0 0	.500 19	1.39 53	.114 4	.604 23	2.61	2,340	6,110
4[4]	1190	1.35 37	.553 15	1.59 43	.129 4	.043 1	12.90	2,240	8,200
All channels[5]		.175 18	.147 15	.364 37	.209 21	.079 8	.974	26,640	

	Storage components: Alluvial fans	High flow terraces	Debris related	Bed	Other	Total Volume Sediment in Storage (m^3)
Total volume of stored sediment (m^3)[5]	4,670	3,920	9,700	5,560	2,100	25,900

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[1] Percentages may not sum to 100% exactly because of rounding errors.

[2] Sampled length plus unsampled length of channel.

[3] Volume of sediment per unit length of sampled channel multiplied by total storage length for all storage components.

[4] A large alluvial fan deposited over the broad central valley of Clearwater Creek is not included in this analysis. This fan contains an additional 11,000 m^3 of stored sediment.

[5] Values calculated by extrapolation of sampled channel data over total channel lengths for all stream orders in the basin.

mouth of Shultz Creek were only moderately modified by flows during the winter of 1981. This stands in marked contrast to the rapid removal of sandy deposits from the active channels of most upstream reaches.

Trees blown into channels by the lateral blast, as well as preexisting large organic debris in streams, cause significant sediment storage in channels as large as fourth order streams (order determined for blue line streams on 7.5 minute topographic quadrangles). Large organic debris (more than 0.1 m in diameter) cause sediment deposition by locally raising the streambed base level, by creating protected eddies in complex matrices that trap sediment, and by increasing the frequency of sediment-laden overbank flows. As observed in other areas (Keller and Swanson, 1979), debris-stored sediment is proportionately greatest in low order channels.

Unless a debris torrent occurs, large organic debris in small channels are not readily moved until they rot away. Sand-sized volcanic sediment may be transported through a framework of large organic debris, but debris on channel bottoms and sealed log jams may cause upstream deposits several meters thick. In Boomer Creek basin, debris accounts for 53 percent of all storage in third order channels and 37 percent of all storage in the entire drainage network, disregarding the alluvial fan at the mouth of Boomer Creek (table 2).

In fourth order channels, debris may be redistributed by high flows and concentrated into debris jams. This may increase the storage effectiveness of organic debris, as in upper Clearwater Creek where a series of debris jams created sediment storage sites that resemble a string of pearls (Fred Swanson, U.S.D.A. Forest Service, oral communication, 1982). In Bean Creek (fig. 1), a tributary of Clearwater Creek, large jams which have formed behind bedrock constrictions at the downstream end of low gradient reaches have ponded large volumes of sediment.

Large organic debris commonly occupy as much as 30 percent of the bankfull cross-sectional area of Clearwater Creek. By thus reducing channel capacity while increasing flow resistance, the debris increases the frequency of overbank flows. A reach with little organic debris in the channel nearly reached bankfull stage during WY 1981. In adjacent reaches with much debris, flows overtopped the banks and deposited sediment over the flood plain in some areas and eroded airfall and blast deposits in others.

Lahars, or the debris avalanche, in the North Fork Toutle River blocked the mouths of tributaries and created 12 large storage sites for sediment eroded from blast-affected drainage basins. Dammed tributary mouths form the largest storage sites in channels that did not carry lahars. For example, 9.2×10^5 m^3 of sediment was stored within 1.3 km of the mouth of Clearwater Creek, which was dammed by a lahar in the Muddy River. This volume, which is probably less than that contained in similar storage sites along the North Fork Toutle River, is greater than that in any other storage reach unaffected by lahar damming. Flow at the mouth of the Green River was impounded behind the North Fork Toutle River lahar, causing deposition of up to 2 m of fine-grained, thixotrophic sediment.

Channel gradient appears to be a determining factor in the storage of sediment since the May 18 eruption. Channel reaches storing significant amounts of sediment in Clearwater Creek, the mainstem Green River, and Shultz Creek were mapped from aerial photos taken in the fall of 1981. In a plot of cartographic slope versus drainage area for channel reaches (fig. 6), a function derived from discriminant analysis separates fields of points that correspond to storage and nonstorage reaches. As expected, the tendency for sediment storage increases with decreasing gradient and increasing drainage area.

Relatively low gradient reaches where sediment has been stored are still steeper than most stable sand-bed streams. Rough estimates of maximum stream gradients of coarse sand-bed channels with zero transport, on the basis of Shield's criteria and estimated flow depths at low flow, range from 0.001 to 0.0003 m/m well below the minimum slope (0.005 m/m) of the reaches represented in figure 6. Before the May 18 eruption, most channels were armored with gravel; these streams will probably become armored again as erosion rates decrease and fine-grained sediment passes out of the drainage systems.

The total length of storage reaches (mapped from aerial photographs) is proportionately greatest in third and fourth order channels (table 3). In lower order channels, storage is less because channel slopes are steeper, valley flats are less prevalent, and upstream channel storage has been depleted. Fifth order channels store sediment along proportionately less of their length, presumably for the following reasons: 1) sediment pulses from upstream reaches have been depleted by deposition and dispersed as they moved downstream, 2) maximum loads may not yet have reached some mainstem channels, and 3) fifth order channels are too large for large organic debris to store sediment.

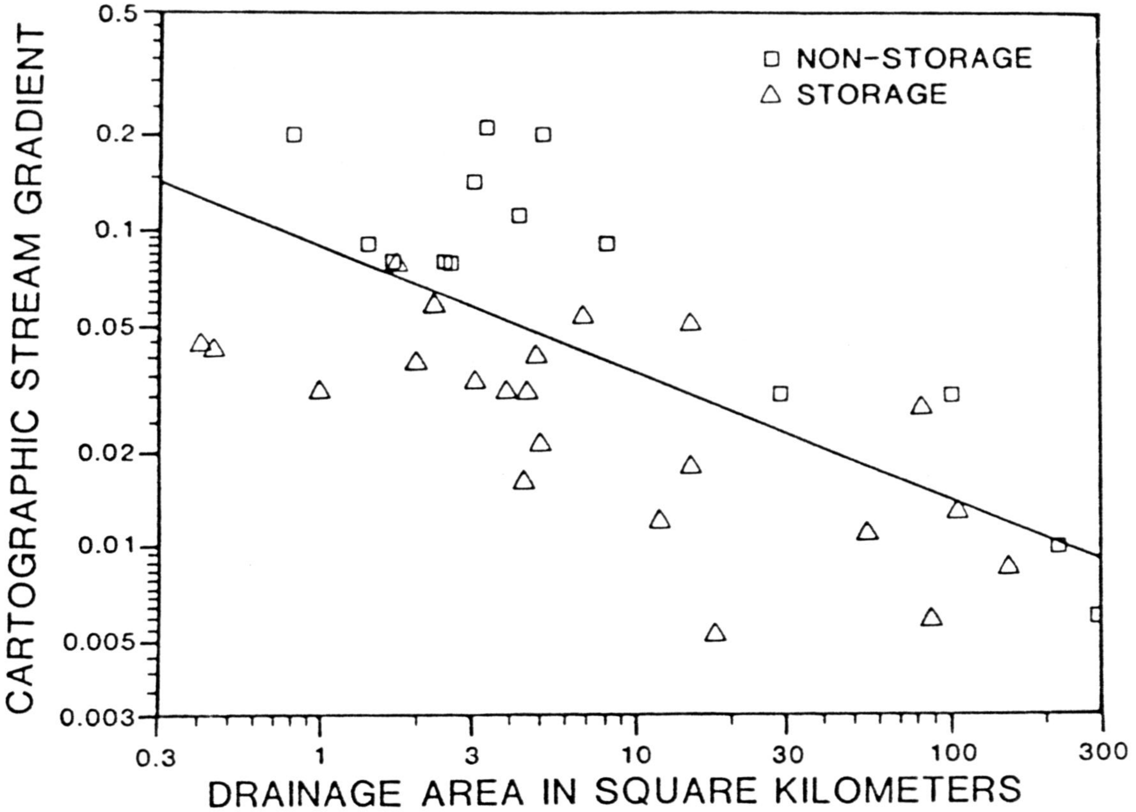

Figure 6. Cartographic slope *versus* drainage area of reaches of Shultz Creek, Clearwater Creek, the mainstem of Green River showing sediment storage in banks and valley flats in October 1981, and of reaches showing no storage. A discriminant function separates storage and nonstorage reaches.

Lahar-Affected Channels

Volcanic Events and Deposits

On May 18 lahars flowed down upstream reaches of all streams flanking Mount St. Helens. Major lahars flowed the entire length of the Toutle River and entered the Cowlitz River, while others flowed down Smith Creek, Muddy River, Pine Creek, and Swift Creek, eventually entering

Table 3. Distribution of sediment storage reaches by stream order in Clearwater Creek, mainstem of Green River, and Shultz Creek. (Mapped from aerial photographs, U.S. Geological Survey series 24327, October 20, 1981.)

Stream order[1]	Percent length of channels[2]			Total channel length (km)
	No storage	Storage limited to one channel width from banks	Storage extending beyond one channel width from banks	
2	65.4	32.0	2.7	20.6
3	29.9	61.4	8.6	19.8
4	14.8	47.4	37.9	19.9
5	62.7	20.8	16.5	25.8

[1] From blue line streams on 7.5 minute quadrangles.

[2] Each reach of channel classified as only one of the three storage categories.

Swift Reservoir (fig. 1). Grain size, composition, and thickness of lahar deposits are highly variable, both down-valley and cross-valley (Janda and others, 1981). Lahar deposits on major streams range from one to several meters thick near the channel and generally thin to zero as they spread across the floodplain or terraces. Where lahars ponded, as on the lower North Fork Toutle River, overbank deposits may locally be thicker than near-channel deposits (Janda and others, 1981). Lahar deposits are poorly sorted and commonly appear similar in grain size and composition to older lahars exposed in stream banks. Mean particle size distributions ranged from 21 percent gravel, 59 percent sand, and 20 percent silt/clay to 74 percent gravel/boulders, 19 percent sand, and 7 percent silt/clay for lahar deposits on the North Fork Toutle River (Lehre and others, 1982).

Lahar deposits are limited primarily to the valley bottoms of the major streams that flank the volcano and thus directly affect main-channel processes. The relative importance of lahars to posteruption channel adjustments depends on the presence of other volcanic deposits in the basins. Basins of Smith Creek and North Fork Toutle River lie mostly in the blast area; basins of Pine Creek and South Fork Toutle River are mostly outside the areas of the blast and the high airfall (fig. 1). In the North Fork Toutle River, fluvial reworking of the debris avalanche deposit has dominated fluvial processes that are otherwise influenced by effects of the blast, airfall, and lahars (Janda, this volume).

The poorly sorted lahar and debris avalanche deposits tend to be nearly impermeable and thus, similar to blast and airfall deposits, tend to increase storm runoff. Although lahars affected a much smaller percentage of the total devastated area than did the lateral blast, runoff from lahars is contributed directly to mainstem channels. The anticipated increase in peak runoff in rivers, however, has not been well documented.

Although lahar deposits are coarser than blast and airfall deposits, they also have low cohesion and are easily eroded by lateral channel migration. They directly contribute a large volume to the sediment load of the major rivers that drain Mount St. Helens.

Sediment Transport and Channel Changes

May 18 lahars in North and South Fork Toutle Rivers, Smith Creek, Muddy River, and Pine Creek apparently transported more sediment than subsequent individual hydrologic events. Because lahars completely or partly buried pre-existing channels, subsequent low flows were contained in reduced channels or incised into the surface of the lahar deposit. Channel roughness was reduced by loss of sinuosity, by disruption or burial of the pre-existing cobble-boulder bed, and by obliteration of bar-pool topography. Winter floods have extensively reshaped lahar-affected channels. High flows have incorporated large sediment loads by enlarging channels formed during recession of lahars and by migrating laterally against highly erodible banks. Channels have simultaneously widened and either aggraded or degraded. In alluvial reaches, volumes of sediment produced by channel widening exceed volumetric changes in storage caused by bed aggradation or degradation. Channel widening thus strongly influences net sediment storage.

Sediment transport and channel adjustment in the mainstem and North Fork Toutle River occur chiefly during high discharge events. This timing is attributed to an increase in peak runoff and to accelerated erosion of the debris avalanche in the North Fork Toutle River during storm runoff. During Water Year (WY) 1981, suspended sediment load of the Toutle River was about 26.8 x 10^6 megagrams (Mg). About 46 percent of this was discharged in four days in two storm-induced floods (fig. 7).

In reaches bounded by banks or terraces of erodible alluvium or lahar deposits, channels were surveyed only between flood events. Frequent surveys at the South Fork County Bridge, North Fork Toutle River at 007, and Elk Rock (within the debris avalanche) from February 1981 to January 1982 showed little change during this period of low peak discharge (fig. 8). At North Fork Toutle River at 007 and Elk Rock, flood-related deposition and erosion after January 1982 were 5 to 10 times greater than during the preceding period of lower flows. The section near Camp Baker showed substantial erosion from May 1981 to January 1982 but also showed pronounced erosion and deposition during the storm period beginning in January 1982.

Channel integration, incision, and widening in the debris avalanche deposit was a major source of sediment during WY 1981 (Janda, this volume). Most eroded material downstream of the debris avalanche consists of older lahar and alluvial deposits. For example, at Camp Baker (fig. 9) material eroded from the right bank consisted of more than

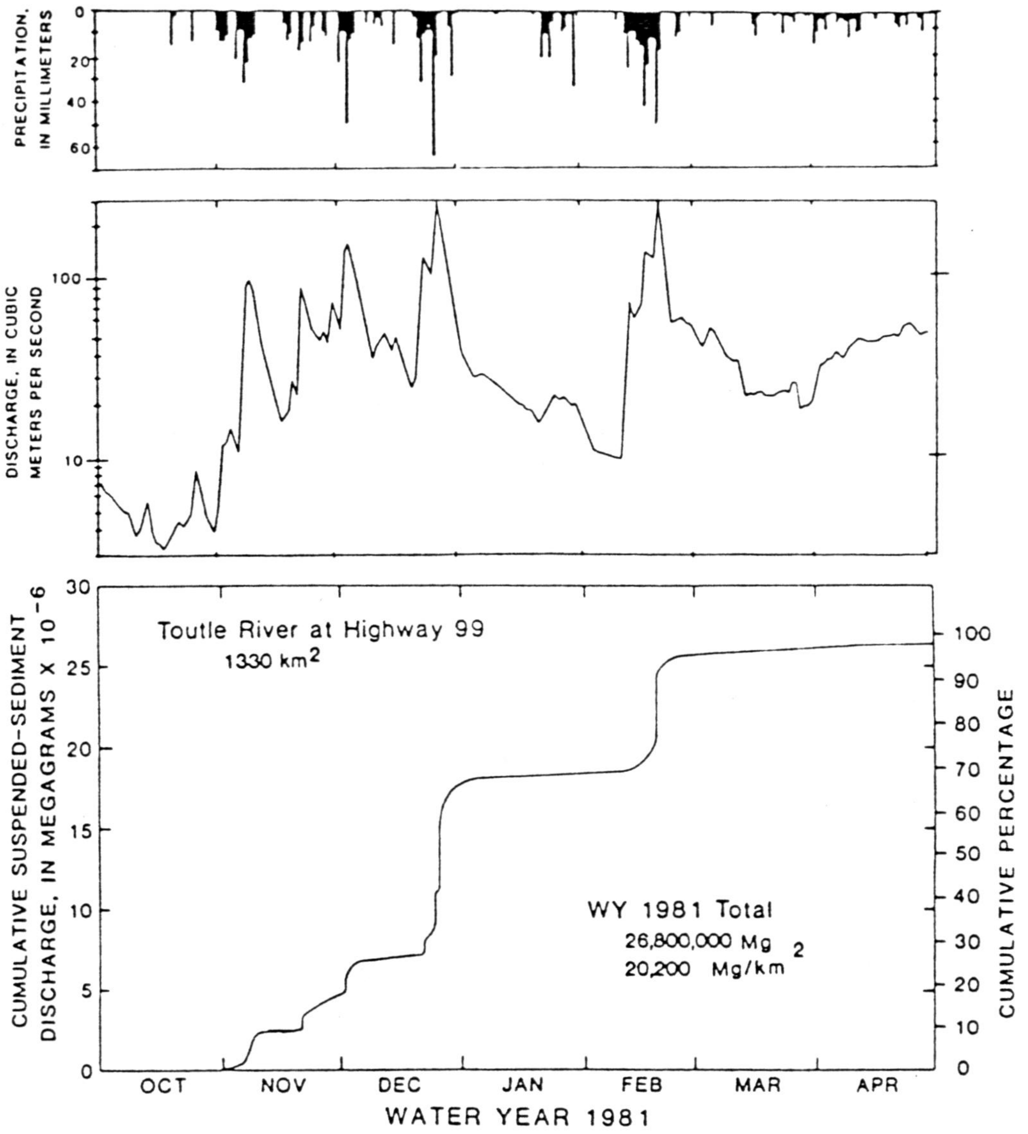

Figure 7. Daily precipitation and daily mean discharge of the North Fork Toutle River near Kid Valley, and cumulative suspended sediment discharge of the Toutle River at Highway 99, WY 1981.

7 m of older lahars and alluvium, mantled by less than 0.5 m of May 18 lahar deposits. Although much of the total load of the Toutle River was derived from the debris avalanche deposit, the portion of the load contributed in the downstream reaches greatly exceeded that deposited by the 1980 lahars (Meyer and others, 1981; Martinson and others, 1981).

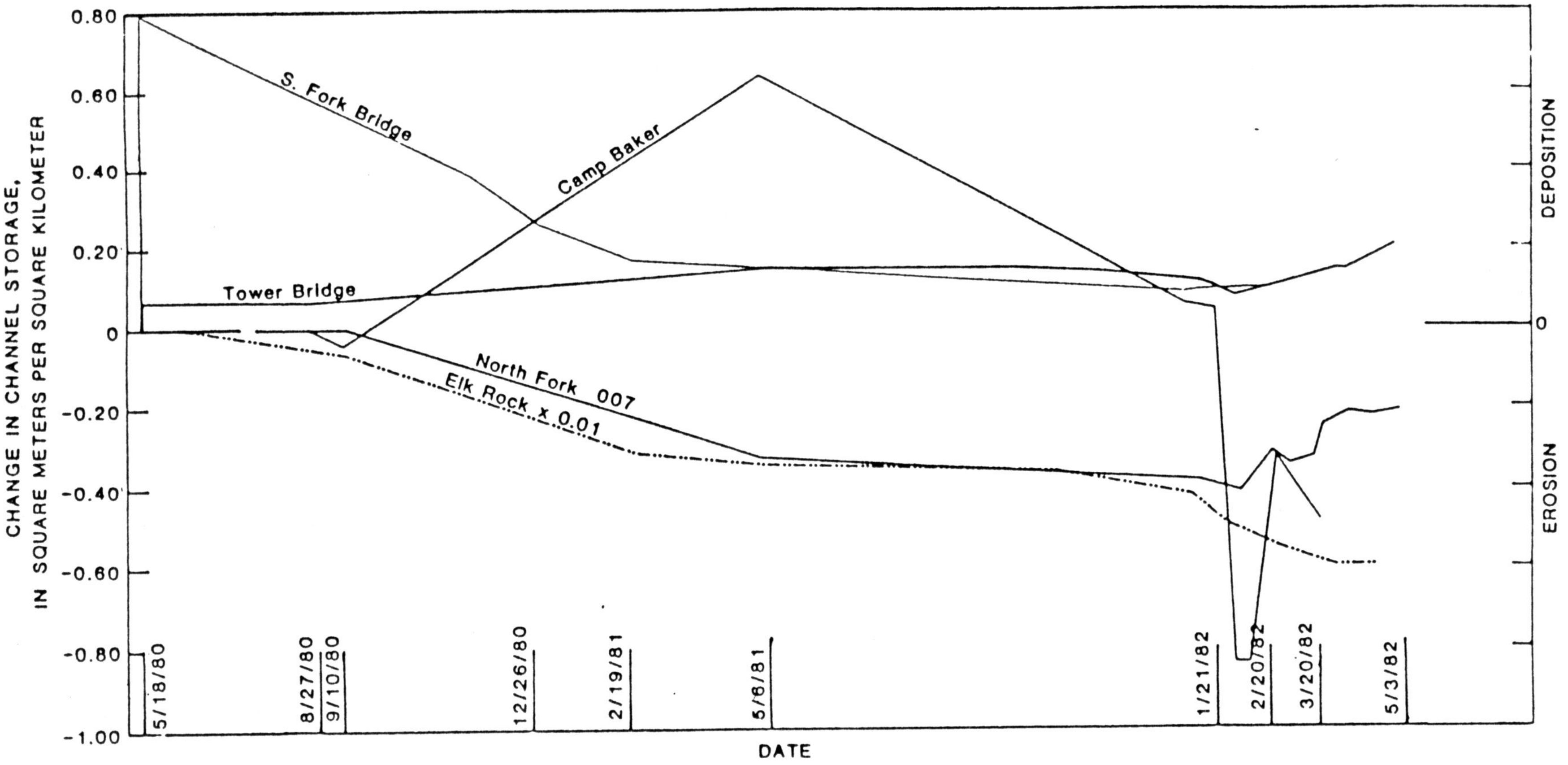

Figure 8. Changes in channel storage, normalized by dividing cross-sectional area by drainage area, at sites on the Toutle River (Tower Bridge), North Fork Toutle River (Camp Baker, 007, and Elk Rock), and South Fork Toutle River (S. Fork Bridge).

As observed with other volcanoes (Davies and others, 1978; Japan International Cooperation Agency, 1980) bed particle size decreases downstream in the Toutle River, presumably due to selective transport of small particles and the disintegration of large ones. The largest boulders in a given reach are generally a lag deposit derived from lahars or eroded banks of older lahars and alluvium, and thus maximum bed material size does not necessarily reflect local competence. Therefore, somewhat finer grains were examined in active bars for an indication of local competence. On the North Fork Toutle River, the size of D_{85} (the grain size of which 85 percent of the sediment in a given sample is finer) decreases downstream. Downstream of the toe of the debris avalanche near Camp Baker, the size of D_{85} is about 100 mm, whereas at the Kid Valley gaging station, 16 km downstream, it is only about 50 mm. En echelon bars, where grain size was measured, are commonly covered by medium- to fine-grained sand deposited during low flows. Below Tower Bridge in the lower Toutle River, channel deposits rarely contain particles larger than coarse sand, and although the channel braids, en echelon bars do not form.

Large volumes of sediment produced during storms have apparently been mainly responsible for channel adjustments downstream. Post-eruption channels were overwhelmed by greatly increased sediment loads. In the Toutle River, channel width commonly increased 150 to 200 percent during the winters of WY 1981 and WY 1982 (fig. 9, for example), and the channel became braided wherever it was unrestricted by bedrock or man-made constrictions. Braiding and aggradation occurred as en echelon bars spread and accreted. Although most braided channels aggraded, net

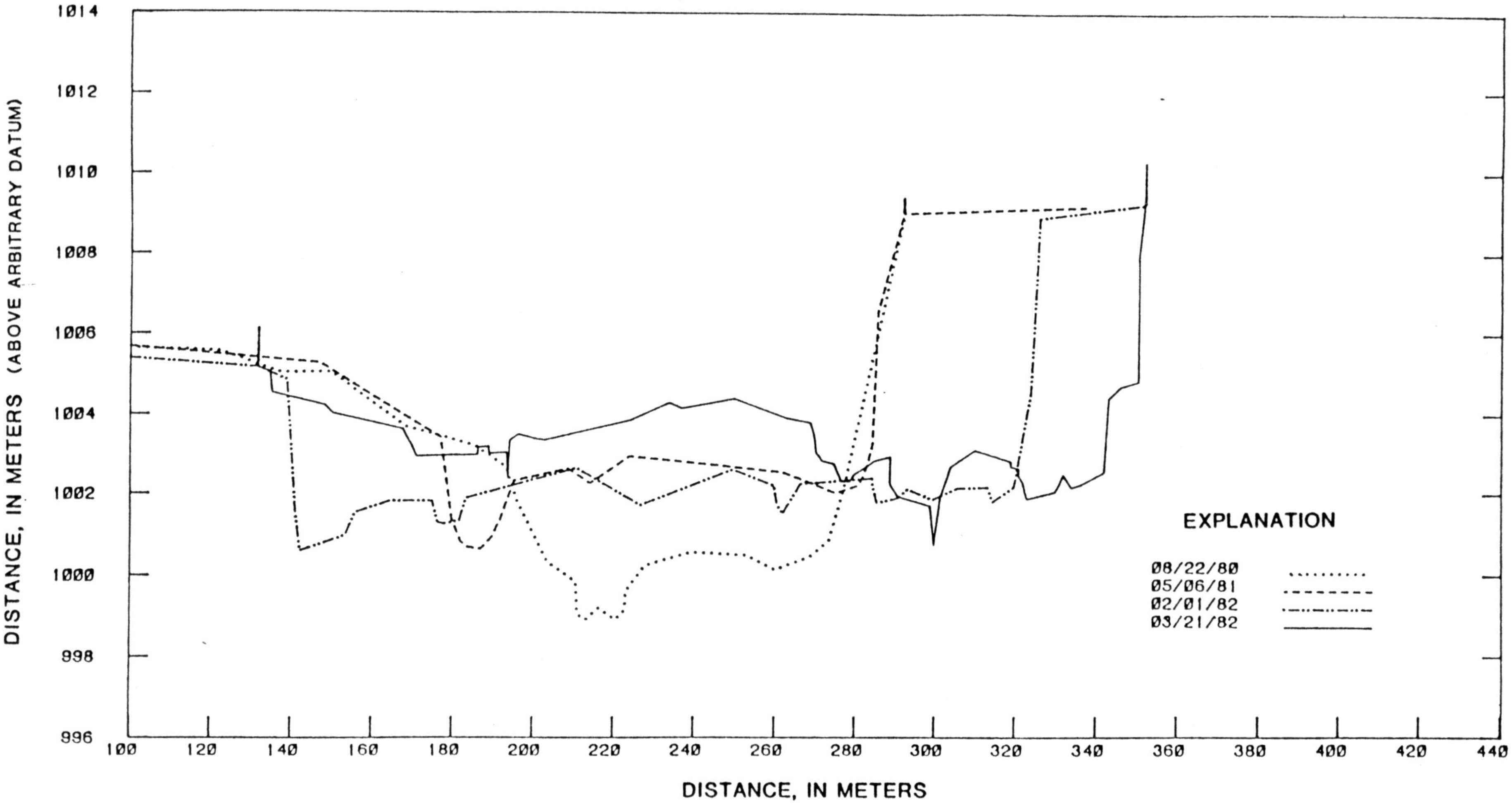

Figure 9. Cross section of the North Fork Toutle River near Camp Baker. Lahars deposited as much as 1 m of sediment on the flood plain. Channel changes during the following low flow season were negligible. During the winter of water year 1981, sediment-laden floods aggraded the channel about 2 m, and the channel pattern shifted from straight to braided. Although the channel widened by about 50 percent, net sediment storage increased. The channel aggraded similar amounts during water year 1982, but massive bank erosion occurred. The decrease in sediment storage caused by bank erosion exceeded the increase in storage by channel aggradation.

sediment storage decreased as larger volumes of material were removed from banks than were deposited in the widening channel. Note, for example, the decrease in sediment storage in cross sections on alluvial reaches at North Fork Toutle River at Camp Baker (fig. 8 and 9) and at North Fork Toutle River 007 (fig. 8).

As in the North Fork and mainstem, changes in the South Fork Toutle River have generally resulted from lateral channel migration with little change in average bed elevation (table 4). Cross sections along the South Fork Toutle River were surveyed less frequently than at many sites on the North Fork and mainstem, but a series of cross sections were surveyed during the summers of 1981 and 1982. Average changes at 20 cross sections were as follows: channel width +12.5 m, bed elevation -0.02 m, sediment storage -35.6 m^2. Changes in average bed elevation in the middle and lower reaches varied randomly, but the upper-most reaches showed consistent incision (less than 0.5 m). All cross sections but two showed significant widening, generally more than 20 percent in the lower 5 km of the channel.

Sediment removal from the South Fork Toutle River channel is similar to that in the North Fork at Camp Baker and 007. Channel widening is nearly ubiquitous. Although changes in average bed elevation are commonly negligible or positive, sediment storage has decreased due to erosion of channel banks composed predominantly of pre-May 18 alluvium and lahar deposits.

In contrast to alluvial reaches, low gradient reaches with narrow valley walls of bedrock (for example, Tower Bridge, fig. 8) have filled discontinuously, resulting in sediment storage. Changes in geometry <u>during</u> floods have been monitored only at nonalluvial reaches where river

Table 4. Changes in channel width, average bed elevation, and sediment storage during Water Year 1982 at selected sites along the South Fork Toutle River.

Cross section No.	Change in channel width (m)	(%)	Change in avg. bed elevation (m)	Change in sediment storage (m^3/m)[1]	Distance upstream from mouth (km)
20-2	9.9	17	-0.31	-40.2	1.3
20-5	1.4	2	-0.29	-25.1	2.2
20-6	25.8	18	-0.45	-182.	2.4
20-7	60.3	91	0.35	-152.	2.6
20-9	42.0	81	0.65	-34.6	3.0
20-13	21.8	41	-0.25	-58.2	4.1
20-15	11.3	29	0.55	11.0	4.5
20-17	38.6	37	0.84	27.2	5.1
20-24	0.9	1	-0.17	-16.9	7.4
20-43	5.3	11	-0.03	-4.91	13.0
20-44	0.8	1	-0.04	-12.8	13.3
20-46	0.6	1	0.14	12.6	13.8
20-47	0	0	0.04	2.23	15.8
20-49	8.7	21	0.27	-0.95	16.4
20-103	4.4	4	0	-9.12	29.5
20-105	10.8	16	-0.56	-61.7	30.6
20-108	3.8	2	-0.23	-46.4	31.8
20-109	1.2	2	-0.44	-60.8	32.1
20-111	0.1	0	-0.26	-12.9	32.6
20-131	2.1	2	-0.26	-47.2	37.8

[1] Positive values, deposition; negative values, erosion.

banks are stable or artificial, such as at gaging stations or bridges. At these sites, channels have scoured during the rise and peak of a flood, then have aggraded during the recession. Some sections along the lower Toutle and Cowlitz Rivers have continued to aggrade for weeks or months after a flood. Downstream transport of fine sediment eroded from the debris avalanche and from upstream bank erosion is probably responsible for persistent aggradation during low flow after floods.

Summary and Conclusion

Post-eruption adjustments of stream channels that drain the area around Mount St. Helens show some significant differences between channels that carried lahars and those that carried only sediment eroded from lateral blast deposits, airfall, and pre-existing soils. The debris avalanche in the North Toutle River and lahars in mainstem channels around Mount St. Helens are ready sources of relatively coarse sediment along major channels. In contrast, blast and airfall deposits are finer (mostly sand-size) and are distributed throughout these drainage basins. Sediment derived from these deposits is transported and stored by sequences of processes operating from hillslopes to tributaries to mainstem channels. The impact of blast and tephra deposition has been manifested primarily in changes in hillslope and low order tributaries, with relatively minor effects on mainstem channels, whereas the debris avalanche and lahars have directly affected channel form and processes on larger streams. Stream channels in basins that received only airfall (no blast) have shown no significant sedimentation.

Changes in blast area channels have generally been shorter term, smaller scale, and more localized than changes in lahar-affected channels. Predominantly sand-sized blast and airfall material introduced into these mostly steep mountain streams has been quickly removed, unless upstream sediment inputs periodically overwhelmed the transport capacity. Large volumes of this material pass through channels without substantially modifying them. Intricate matrices of blown down timber, pre-existing vegetated streambanks, and armor layers appear to be little disturbed during voluminous fill-scour sequences. However, the frequency of erosive debris torrents seems to have increased since the 1980 eruptions, probably due to sudden large impulses of sediment triggered by surficial landslides of volcanic material and by the breakup of debris jams in steep, low order channels. Debris torrents have created long-term changes by scouring channels and depositing coarse debris in low gradient reaches. Deposition at levels high above streambeds by debris torrents and debris flows has placed material in long-term storage over alluvial fans and valley flats. The distribution of sediment storage areas shows a stream gradient threshold decreasing with drainage area. The areal extent and volume of sediment storage increases with stream order, although highest order channels store relatively little sediment due to upstream storage. Blown down trees form many storage sites, particularly in low order channels.

Lahar-affected channels and flood plains were covered by as much as 1 to 5 m of material as large as boulders, and the size of channels was initially reduced. Subsequent high flows have widened alluvial channels and caused complex sequences of scour and fill over a range of several meters in bed elevation. In the South Fork Toutle River, which was affected only by lahars, upstream reaches have been incised, and middle and downstream reaches have changed little in elevation. In the North Fork and mainstem Toutle Rivers, which receive large amounts of sediment from the debris avalanche and blast area, channels have aggraded intermittently.

Ubiquitous channel widening, commonly by over 100 percent, has decreased the volume of sediment stored in lahar-affected channels, in spite of several meters of aggradation. Most of the sediment removed has been derived from pre-1980 lahar and alluvial deposits. Unlike blast area channels, there are no pronounced low gradient reaches in the lahar-affected channels to preferentially store sediment. Sorting and disintegration of sediment in fluvial transport has reduced the size of bed material by one half over a distance of 16 km in the North Fork Toutle River.

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