Z. Geomorph. N.F.	Suppl.-Bd. 46	103–121	Berlin · Stuttgart	Oktober 1983

Erosion of tephra-covered hillslopes north of Mount St. Helens, Washington: May 1980–May 1981

by

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with 2 photos, 10 figures and 6 tables

Zusammenfassung. Der Ausbruch des Mount St. Helens 1980 brachte weitverbreitet eine Vernichtung der Vegetation und die Ablagerung von $70{,}0 \times 10^6$ m^3 ($93{,}0 \times 10^6$ t) Tephra an Hängen, insgesamt ein Gebiet von 352 km^2 im Einzugsgebiet der North Fork Toutle, South Fork Toutle und des Green River bedeckend. Eine schnelle Abtragung folgte. Lokale Erosionsraten, mit großem Aufgebot von Erosionspflöcken gemessen, schwanken zwischen 0,5 und $75{,}8 \times 10^3$ m^3/km^2-Jahr. Sie werden kontrolliert durch die Oberflächenbedeckung, das Hanggefälle, die Mächtigkeit und Textur der Tephra. Durch Kartierung der Verbreitung dieser kontrollierenden Variablen konnten die Abtragungsraten für die Einzugsgebiete geschätzt werden. Während des ersten Jahres nach der Eruption wurden $8{,}0 \times 10^6$ m^3 ($11{,}1 \times 10^6$ t) Tephra und $1{,}3 \times 10^6$ m^3 ($1{,}0 \times 10^6$ t) Kolluvium aus dem Einzugsgebiet herausgetragen. Diese Werte ergeben Abtragungsraten von $22{,}7 \times 10^3$ m^3/km^2-Jahr ($31{,}5 \times 10^3$ t/km^2-Jahr) and $3{,}6 \times 10^3$ m^3/km^2-Jahr ($2{,}9 \times 10^3$ t/km^2-Jahr) für Tephra und Kolluvium, was zusammen einer Abtragung von 26,3 mm/Jahr (=26,300 Bubnoffs) entspricht. Dreißig Prozent des Materials von den Hängen wurden in Seen aufgefangen, die durch Schuttlawinen abgedämmt wurden, die im North Fork Toutle River Tal am 18. Mai 1980 aufliefen. Von dem verbleibenden $8{,}4 \times 10^6$ t Material, das das Toutle River System erreichte, waren 37% Ton und Schluff, 57% Sand und 6% Kies.

Summary. The 1980 eruptions of Mount St. Helens resulted in the widespread destruction of vegetation and deposition of 70.0×10^6 m^3 (93.0×10^6 t) of tephra on hillslopes covering a 352 km^2 area in the drainage basin of the North Fork Toutle, South Fork Toutle, and Green Rivers. Rapid erosion ensued. Local rates of erosion, measured with large arrays of erosion stakes, ranged between 0.5 and 75.8×10^3 m^3/km^2-yr and were controlled by the surface cover, hillslope gradient, tephra thickness, and tephra texture. By mapping the distribution of these controlling variables, basin-wide erosion rates were estimated. During the first post-eruption year, 8.0×10^6 m^3 (11.1×10^6 t) of tephra and 1.3×10^6 m^3 (1.0×10^6 t) of colluvium were eroded from the basin. These values represent erosion rates of 22.7×10^3 m^3/km^2-yr (31.5×10^3 t/km^2-yr) and 3.6×10^3 m^3/km^2-yr (2.9×10^3 t/km^2-yr) of tephra and colluvium, respectively, equivalent to a denudation of 26.3 mm/yr (=26,300 Bubnoffs). Thirty percent of all sediment eroded from hillslopes was trapped in lakes impounded by the debris avalanche that filled the North Fork Toutle River valley on 18

0044-2798/83/0046-0103 $ 4.75

May 1980. Of the remaining 8.4×10^6 t of sediment that entered streams of the Toutle River system, 37% was clay and silt, 57% was sand, and 6% was gravel.

Résumé. Les éruptions de 1980 du Mont St-Helens ont provoqué la destruction de la végétation sur une vaste région et le dépôt de 70.0×10^6 m^3 (93.0×10^6 t) de téphra sur les versants couvrant une surface de 352 km^2 dans le bassin de la North Fork Toutle, de la South Fork Toutle et de la Green River. Une érosion intense s'ensuivit. Des vitesses locales d'érosion, mesurées à l'aide d'un large dispositif de piquets se situent entre 0,5 et 75.8×10^3 m^3/km^2-an et furent contrôlées par la couverture superficielle, l'intensité de la pente, l'épaisseur des téphra et leur texture. En cartographiant la distribution de ces différents facteurs, l'intensité de l'érosion dans l'ensemble du bassin a été estimée. Pendant la première année qui a suivi l'éruption 8×10^6 m^3 ($11{,}1\times10^6$ t) de tephra et 1.3×10^6 m^3 (1.0×10^6 t) de colluvions ont été emportées du bassin. Ces valeurs représentent des vitesses d'érosion de $22{,}7\times10^3$ m^3/km^2-an ($31{,}5\times10^3$ t/km^2-an) pour les tephra et $3{,}6\times10^3$ m^3/km^2-an ($2{,}9\times10^3$ t/km^2-an) pour les colluvions, ce qui équivaudrait à une dénudation de 26,3 mm/an soit 26.300 Bubnoffs. Trente pourcent de tous les sédiments enlevé des versants ont été piégés dans des lacs formés dans les débris d'avalanches qui colmatèrent la North Fork Toutle River le 18 mai 1980. Des $8{,}4\times10^6$ t de sédiments qui s'engagèrent dans les cours d'eau du bassin des Toutle, 37% étaient de l'argile, 57% du sable et 6% du gravier.

Introduction

The lateral eruption of Mount St. Helens on 18 May 1980 destroyed the forest vegetation and deposited a tephra mantle on hillslopes in the drainage basin of the North Fork Toutle, South Fork Toutle, and Green Rivers. Tephra were deposited on a number of surfaces including: hillslopes covered with killed or living trees; those covered with trees downed by the directed blast; forest land where trees were clearfelled prior to the eruption, and forest land that was stripped of tree cover by the directed blast and debris avalanche on 18 May. Since the eruption, these tephra and the underlying colluvium have been eroded into the streams of the Toutle River system by sheet wash and rill wash. The destruction of vegetation and deposition of easily eroded sediment in a wet, steep region provides a unique opportunity to study sheet and rill erosion and the preservation of tephra layers, matters which are important in the evolution of landforms and the formation of a stratigraphic record.

We have studied the dependence of erosion on the physical properties of the deposits, hillslope gradient and length, and the surface cover. Previous studies of recent tephra erosion (SEGERSTROM 1950, 1960) (WALDRON 1967) (OLLIER & BROWN 1971) include many observations on the controls of surface erosion, but the controls are not systematically evaluated. In this paper we quantify the effects of the dominant variables influencing erosion in the first posteruption year based on measurement of local erosion at sample sites. We then describe how, by mapping the distribution of the dominant controls of erosion in a rapidly-eroding catchment, estimates of basin-wide sediment yield were obtained.

Study area

The lateral eruption on the morning of May 18 (LIPMAN & MULLINEAUX 1981) was initiated by a magnitude 5 earthquake that triggered the detachment of a 2.3 km^3

rockslide from the north slope of Mount St. Helens. As the rockslide-avalanche traveled down the North Fork Toutle River, the explosion of a shallow cryptodome and associated hydrothermal system during failure of a second rock mass produced a pyroclastic surge (HOBLITT et al. 1981) (MOORE & SISSON 1981) or pyroclastic density flow (WAITT 1981) that expanded rapidly throughout an 180° arc north of the volcano. The blast uprooted and removed trees from many south-facing hillslopes within 13 km of the volcano. On slopes sheltered from the blast and at greater distances (up to 28 km) from the volcano, trees were toppled or snapped, but they were not removed. Trees were killed but remained standing within the singed-tree zone, a narrow (0–4 km wide) area at the margin of the blast-affected area. The area in which trees were toppled or removed (herein termed the downed-tree zone) and the singed-tree zone are shown in fig. 1.

Turbulent ash-laden convective clouds from the ground-hugging surge produced a thin air-fall layer that mantled the thicker surge deposits. The deposits of the pyroclastic surge and air-fall are referred to collectively in this paper as tephra. Their stratigraphy can be summarized as follows. At the base is layer A1, a poorly-sorted sandy gravel that ranges in thickness between 0 and 150 cm and is confined to within approximately 12 km of the

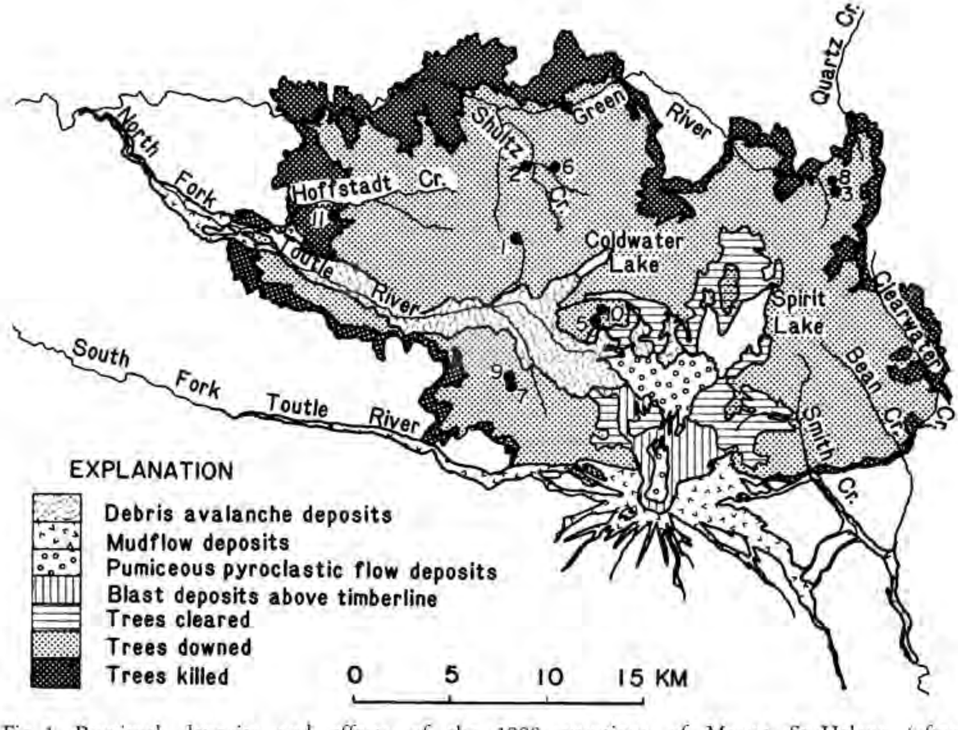

Fig. 1. Proximal deposits and effects of the 1980 eruptions of Mount St. Helens (after LIPMAN & MULLINEAUX 1981, plate 1). The eastern one-fifth of the area affected by the blast, drained by Quartz, Smith, Bean, and Clearwater Creeks, was not included in this study. Numbered locations refer to study sites listed in table 2.

volcano. Layer A2 is a poorly- to moderately-sorted silty sand averaging 10 to 30 cm in thickness in the downed-tree zone and thinning to 2 to 4 cm in the singed-tree zone. Layer A3 is a silty air-fall layer that averages 2 to 6 cm in thickness. In the southwestern part of the blast-affected area, overlying these deposits from the 18 May directed blast is a sandy air-fall from the 25 May eruption (WAITT et al. 1981) (fig. 2). The texture of each tephra layer is summarized in table 1, and the total thickness of tephra is shown in fig. 3.

A surface crust that formed on the silty air-fall unit soon after the eruption contributed to a low infiltration capacity. Values measured on hillslopes in the Shultz Creek catchment ranged from 2 to 5 mm/hr (HERKELRATH & LEAVESLEY 1981). Overland flow was able to erode the surface of the air-fall layer before being channeled into rill flow which then eroded the underlying surge deposits. Organic material on and within the pre-eruption soil often inhibited rill incision, but many rills have breached the underlying colluvium. (In this paper, the pre-eruption soil, older tephra layers, and regolith will be referred to collectively as colluvium). The infiltration capacity of the sandy 25 May air-fall layer was not measured, but it was probably greater, and smaller volumes of overland flow would have been produced on hillslopes covered by the sandy tephra layer.

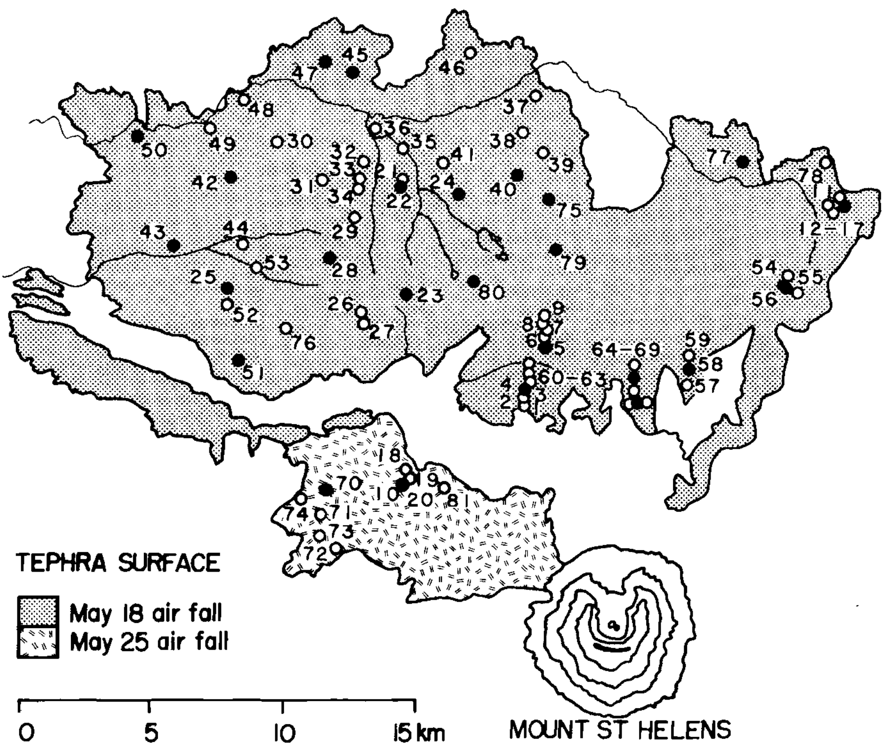

Fig. 2. Surficial tephra units and sites at which tephra mantles were described and sampled.

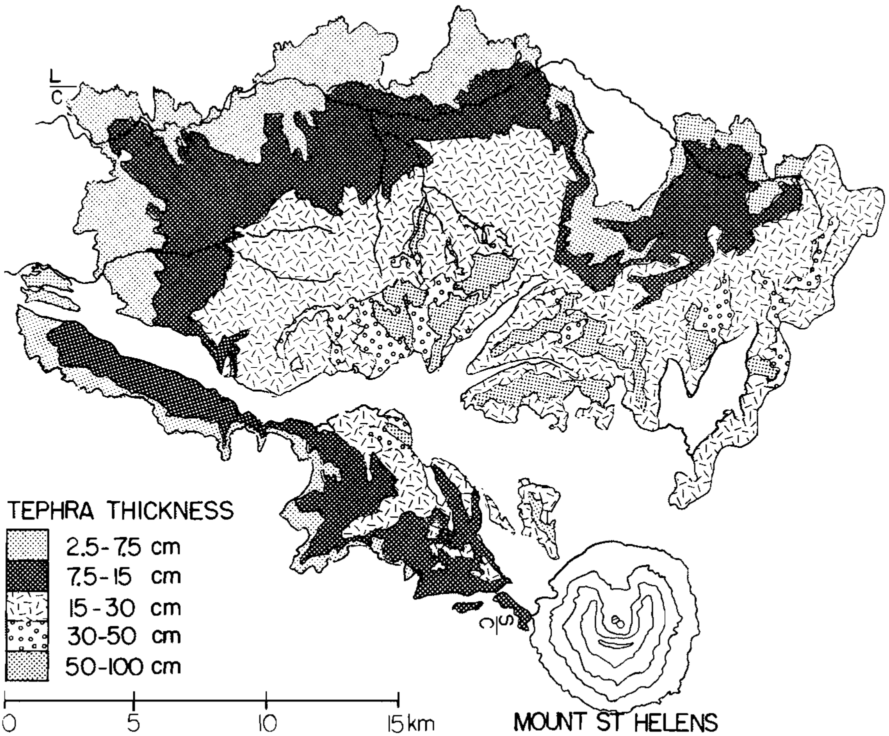

Fig. 3. Generalized map of tephra thickness. Tephra are thicker on ridge crests and valley floors than on steep side slopes. Thick tephra layers intermixed with debris avalanche deposits on the lower flanks of the volcano and on the surface of the debris avalanche deposit were not mapped; these deposits have been eroded by channel development and enlargement. (LEHRE et al. this vol.) Mapping in Cowlitz County is based on preliminary data from the Washington State Dept. of Natural Resources; mapping in Skamania and Lewis County is from aerial photography with limited field checking.

Study sites and techniques

Study sites (table 2) were established during the summer and fall of 1980 in the basins of the upper Green River, the South Fork of Castle Creek, and the South Fork of Coldwater Creek. The sites represent hillslopes with different cover types (Photo 1), the distribution of which is shown in fig. 4. Within each cover type, hillslopes were selected with a range of gradient between 0.16 and 0.66 and a range of length between 200 m and 750 m.

On each hillslope, contour transects 80 m to 200 m long were established at 10, 20, 40, 60, and 80 percent of the distance from ridge crest to valley bottom. At either 2-m or 5-m intervals along these transects, 75-cm long metal stakes were driven vertically through the tephra and into the underlying colluvium. Two transects were also set out parallel to the general gradient along the entire length of the hillslope. Fifty erosion stakes were

Table 1. Average grain-size parameters of tephra.

Tephra unit		$\bar{D}_{84}$ ± S.E. (mm)	$\bar{D}_{50}$ ± S.E. (mm)	$\bar{D}_{16}$ ± S.E. (mm)
I. Surge deposits[1]	Within limit of unit A1:			
	A1 (n=7)	18 ±5	2.3 ±0.6	0.24±0.05
	A2 (n=7)[2]	1.9±0.6	0.19±0.03	p.n.d.
	Outside limit of unit A1:			
	A2a (n=6)	1.8 ±0.2	0.40±0.02	0.11±0.01
	A2b (n=6)	0.65±0.08	0.20±0.02	p.n.d.
II. Air-fall deposits	A3 (n=2)[3]	0.18	0.027	0.0056
	25 May (n=4)[4]	1.0±0.1	0.55±0.06	0.33±0.04

[1] Data from sample sites with a solid symbol in fig. 2.
[2] Subunits of layer A2 were not differentiated within the area covered by layer A1. Outside this limit, subunits A2a and A2b were described individually. Stratigraphic nomenclature follows WAITT (1981).
[3] From locations 3 and 45 in fig. 2.
[4] From locations 10, 18, 70, and 73 in fig. 2.
p.n.d.: parameter not determined.

Table 2. Cover type and gradient of study sites.

Study site	Cover type	Gradient
(1) Maratta Creek	clearcut	0.16
(2) Shultz Creek I	clearcut	0.25
(3) Green River II	clearcut	0.25
(5) S. Coldwater Creek I	clearcut	0.36
(6) Shultz Creek II	clearcut	0.56
(7) S. Castle Creek I	clearcut	0.66
(8) Green River I	downed trees	0.25
(9) S. Castle Creek II	downed trees	0.45
(10) S. Coldwater Creek II	downed trees	0.54
(11) Hoffstadt Creek II	singed trees	0.45

spaced along each of these transects. The distance between the top of each stake and the tephra surface was measured at the time of installation and at intervals during the following year to allow computation of net erosion or deposition at each stake. The magnitude of sheetwash erosion was taken as the mean change of elevation in inter-rill areas. Erosion by sheetwash prior to the installation of erosion stakes in September 1980 was estimated by extrapolating from plots of erosion per unit rainfall vs. time (COLLINS,

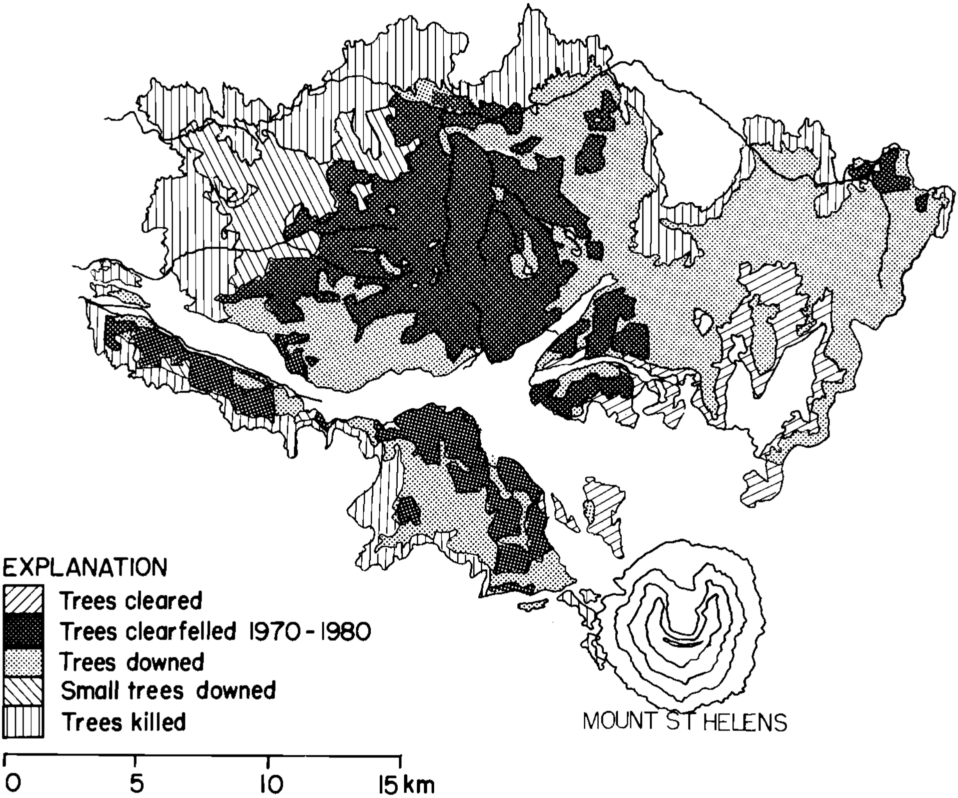

Fig. 4. Distribution of hillslope cover types, based on interpretation of 1:24,000-scale aerial photography taken 19 June 1980.

in prep.). At the time of each measurement, undisturbed tephra were sampled and analyzed for possible change in bulk density which would interfere with the measurement of sheet erosion. There was no measureable change in the bulk density of the deposits during the first year of measurement, so that the changes in surface elevation recorded by erosion stakes reflected lowering by sheet erosion.

The cross-sectional area of each rill intersected by the transects and the depth to which it penetrated the underlying colluvium were measured and used for a computation of the volumes of recent tephra and older colluvium removed by rilling. The magnitude of rill erosion was taken as the change in the cross-sectional area of all rills corrected for lowering in inter-rill areas (fig. 5). Study sites were remeasured in December 1980, March 1981, and May 1981.

Photo 1a

Photo 1b

Photo 1 c

Photo 1. Hillslope cover types: a) densely-rilled hillslope, clearcut-logged prior to 1980, located 14 km NNW of Mount St. Helens (photo taken October 1981); b) trees downed by the directed blast, 18 km NE of Mount St. Helens (photo taken November 1980); c) trees killed by the directed blast, 17 km NNE of Mount St. Helens (photo taken June 1982).

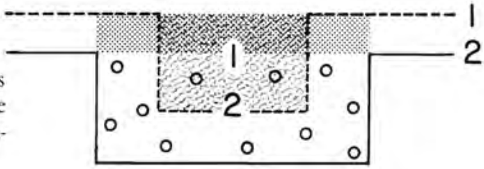

Fig. 5. Rill erosion between time 1 and time 2 is the difference between area 1 and area 2 plus the shaded area, a correction for interrill erosion measured with erosion stakes.

Analysis of local erosion rates

In order to extrapolate basin-wide erosion rates from measurements of erosion on individual hillslopes, our study sites were first grouped by cover type. Hillslope gradient was then related to measured erosion by regression analysis for each group of hillslopes. A linear model was used because it fits the data adequately for the present purpose.

Erosion from hillslopes clearcut prior to the eruption

Figure 6 shows how erosion rates increase with gradient on hillslopes clearcut logged within the past decade. All of the stations are located where the tephra layer is between 15 and 30 cm thick and has a silty surface (layer A3). On gradients of about 0.15, rills account for 70% of total erosion but do not excavate colluvium, whereas on a gradient of 0.55 rill erosion amounts to about 77% of the total, and one-third of this total is derived from the underlying colluvium. All points from the South Coldwater Creek site, at a gradient of 0.36, plot low because the volume of colluvium eroded was less than from other sites and the other points represent sums that include this value; the reason for this is not known. At other sites in the blast zone, field observation and measurement indicate that colluvium erosion is more important than on our sites. For example, in parts of the upper Green River valley, the colluvium is composed of up to 4 m of easily eroded older pumice layers. Rills excavated five times more colluvium from a hillslope near Ryan Lake with pumiceous colluvium than from a hillslope in the Shultz Creek catchment that has more typical colluvium and the same (0.25) gradient (photo 2).

However, over most of the area affected by the directed blast, the recent tephra layer is more erodible than the underlying colluvium, and so rill erosion at sites represented in fig. 6 must have been limited by the shallowness of the tephra. Although colluvium is not excavated at points on fig. 6 with a gradient less than 0.15, the thickness of the tephra layer still limits rill erosion because the colluvium can limit rill incision without being breached. Therefore, on all gradients, the rills represented in fig. 6 would have been deeper and possibly wider if tephra thickness had exceeded 30 cm.

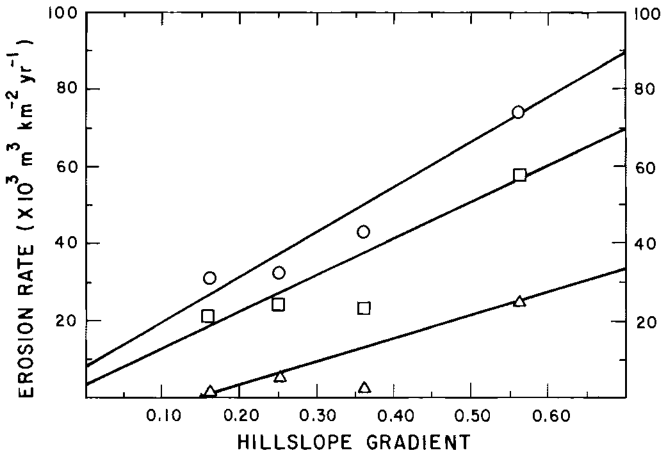

Fig. 6. Erosion of 1980 tephra and underlying colluvium on hillslopes clearcut-logged within 10 years prior to 1980 plotted against hillslope gradient, disregarding the effects of differing hillslope length and annual precipitation. The density of vegetation on all sites was less than 2%. Regression lines relate gradient to total erosion (circles), rilling of tephra and colluvium (squares), and rilling of colluvium only (triangles). Points from the South Coldwater Creek site at a gradient of 0.36 plot below the lines drawn through points from sites in the Shultz and upper Maratta Creek catchments.

Photo 2 a

Photo 2 b

Photo 2. a. Gully cut through thick, easily-eroded colluvium of interlayered ash and pumice layers from earlier eruptions of Mount St. Helens. May 1980 deposits form a thin (25 cm) surficial layer. Deep gullies in pumiceous colluvium were confined to slopes clearcut-logged prior to the eruption in the NE of the Toutle River basin and comprised less than 2% of the study area. b. More typically, rill incision is limited by the presence of organic debris on the pre-eruption surface and by the resistant colluvium. Rounded rill edges in photo (taken October 1982) contrast with the straight-sided rills observed during the first post-eruption year.

In order to test this hypothesis, a separate measurement of rill cross-sections was made in July 1981 along four 40-m transects on each of four hillslopes with a tephra thickness exceeding 30 cm. All of these sites had gradients less than 0.20. Because the surface was covered with the silty air-fall deposit, the magnitudes of sheetwash erosion were estimated from fig. 6 and used for correcting the volumes of rills. Figure 7 shows that the volumes of rills on these thick tephra were greater than those on the thinner deposits used in fig. 6.

Because the sandy air-fall deposit should have a greater infiltration capacity than the silty layer, rill erosion should be less from hillslopes covered with the sandy layer that have the same tephra thickness as hillslopes represented in fig. 6 with a silty surface layer. This expectation was borne out by the measurement of rills on five hillslopes covered by the sandy air-fall layer. Figure 8 shows that rill erosion was less on these hillslopes than rill erosion on hillslopes represented in fig. 6, and that rill erosion increased with hillslope gradient.

The rate of sheet erosion from a hillslope in the South Castle Creek catchment covered by the 25 May air-fall layer and with a gradient of 0.66 was 70% less than the rate of sheet erosion predicted by Figure 6 for a hillslope with a gradient of 0.66 and a silty surface. Rates of sheet erosion and correction factors for rates of rill erosion were extrapolated for other gradients by extending a line from this point through the origin (fig. 8).

Erosion from hillslopes covered with large downed trees

Erosion stakes were located on only three hillslopes covered with downed trees. Rates of erosion from these hillslopes are listed in table 3. To compare rill erosion on hillslopes

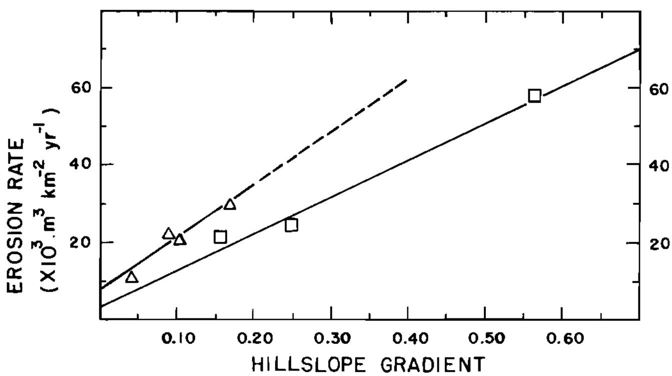

Fig. 7. Effects of tephra thickness on rill erosion from hillslopes clearcut-logged within 10 yrs prior to 1980. Rill erosion on hillslopes with tephra greater than 30 cm thick (triangles) is compared with rill erosion where tephra is between 15 and 30 cm thick (squares). While rill erosion of thick tephra mantles has been extrapolated to a gradient of 0.40, and all data points represent gradients less than 0.20, hillslopes with tephra thickness greater than 30 cm on hillslopes between 0.20 and 0.40 represent less than 2% of the study area.

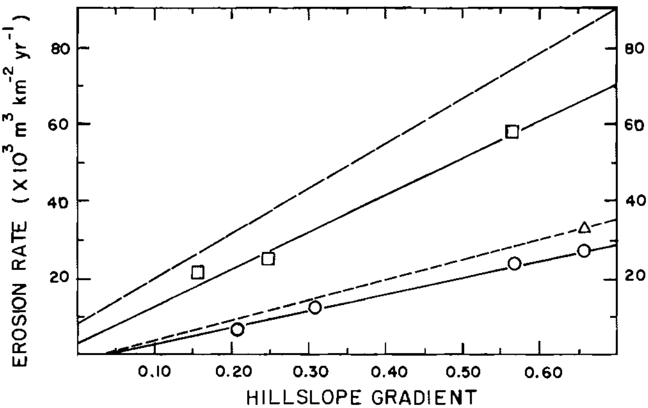

Fig. 8. Effects of tephra surface texture on rill and sheet erosion from recently clearcut hillslopes. Rill erosion on the sandy 25 May air-fall layer (circles) and the silty 18 May air-fall (squares) are compared. The triangle at a gradient of 0.66 represents sheetwash erosion from a site in the S. Castle Creek catchment. Total erosion (short-dashed line) was extrapolated from this point. Total erosion from Fig. 6 (long-dashed line) is shown for comparison. Tephra thickness lies between 15 and 30 cm.

covered with downed trees with rill erosion where trees had been clearfelled prior to the eruption, rills were measured in July 1981 on four hillslopes with a tephra thickness between 15 and 30 cm and a silty surface layer. Rill volumes were corrected to rill erosion by adding a correction factor estimated from the rates of sheet erosion in table 3. Figure 9 shows that rill erosion on all hillslopes with the downed tree cover was less than rill erosion on hillslopes clearcut prior to the eruption. The relation between hillslope gradient and rill erosion shown in fig. 9 is unclear because of a point at a gradient of 0.25 that plots high. This may be because the tephra thickness on this hillslope (27 cm) is greater than the thickness on the other four hillslopes which lie in the lower half of the 15–30 cm range of thicknesses. The dashed lines showing an increase of rill erosion with gradient enclose an estimated range in values. Further analysis should clarify the relation of hillslope gradient to rill erosion; for the present purpose, because the range of rates of

Table 3. Erosion rates ($\times 10^3$ m^3/km^2-yr) on hillslopes covered with large downed trees.

Study site	Gradient	Surface tephra unit	Tephra thickness (cm)	Tephra		Colluvium rill
				rill	sheet	
Green River I	0.25	A3	27	16.1	7.5	1.4
S. Castle Creek II	0.45	25 May	25	7.8	3.3	0.8
S. Coldwater Creek II	0.54	A3	50	39.1	11.3	5.6

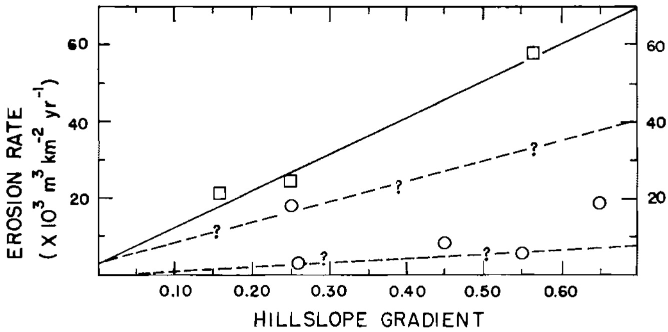

Fig. 9. Rill erosion from hillslopes covered with large downed trees (circles) plotted against hillslope gradient and compared with rill erosion on hillslopes where trees were clearcut-logged prior to the eruption (squares). The silty 18 May air-fall is the surface layer and the tephra mantle is between 15 and 30 cm thick.

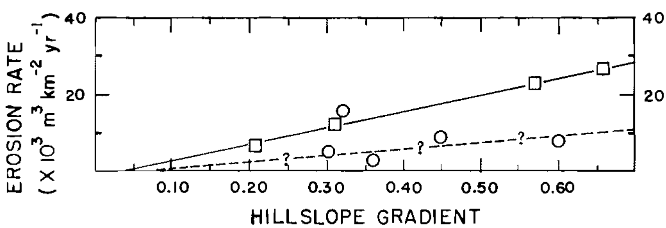

Fig. 10. Rill erosion from hillslopes covered with large downed trees (circles) and from hillslopes clearcut before the eruption (squares) with the sandy 25 May airfall mantling the surface. Tephra thickness is between 15 and 30 cm.

rill erosion in the downed tree cover is not great, an average value was assigned to all hillslopes irrespective of gradient.

Rills were also measured on five hillslopes covered with downed trees with the same tephra thickness as the hillslopes represented in fig. 9 but with the sandy air-fall layer. Figure 10 compares these rates of rill erosion with rill erosion measured on recently clearcut-logged hillslopes with the same tephra thickness and surface texture. The dashed line in fig. 10 was drawn after excluding a point at a gradient of 0.32. The range in values represented by the points in fig. 10 is not great, so an average rate of rill erosion for all hillslopes regardless of gradient is an acceptable approximation for the present purpose. Comparison of fig. 9 and 10 shows that the texture of the surface layer influences rates of rill erosion on hillslopes covered with downed trees less than it influences rill erosion on hillslopes where trees were clearfelled prior to the eruption.

Rates of sheetwash erosion under the downed-tree cover are shown in table 3. Each value is less than the equivalent value predicted by analysis of sheet erosion on clearcut hillslopes: the tabulated values are 34%, 8%, and 33% less, respectively, than the values predicted by fig. 6 and 8 for hillslopes clearcut-logged prior to the eruption.

Erosion from hillslopes covered with standing singed or small downed trees

Less erosion occurred on hillslopes where standing singed trees provided cover than on hillslopes with other cover types. On a hillslope in the lower Hoffstadt Creek catchment with a gradient of 0.45, rills eroded 0.2×10^3 m^3/km^2 of tephra between 18 May 1980 and 22 February 1981. Because no more than 15% of total annual erosion occurred between February and May 1981 at any other site, this value has been taken as an approximate annual rate. Erosion stakes on this hillslope recorded a mean lowering of 0.2 mm in inter-rill areas between 16 December 1980 and 22 February 1981, an amount that is less than the tolerance of the measurement technique and is therefore indistinguishable from no erosion. Tephra layers were generally thin in the singed-tree zone (fig. 3) and the topography of the underlying forest floor frequently disrupted the tephra surface. However, the dominant factor reducing erosion was probably the several cm-thick mat of killed conifer needles that protected the surface from erosion.

In other parts of the singed-tree zone and on hillslopes covered with small downed trees (fig. 4), rills were infrequent. Trees in this latter area were less affected by the directed blast than were the trees nearer to the volcano; as a result, branches and needles remained to provide effective cover. On the basis of a visual comparison (of cover conditions and extent of erosion) with the Hoffstadt Creek site, a total erosion rate of 0.5×10^3 m^3/km^2-yr was assigned to both areas; this rate is one to two orders of magnitude less than rates measured on hillslopes nearer to the volcano that were clearcut-logged prior to the eruption or covered with large downed trees.

Equations relating erosion rate to hillslope gradient on hillslopes with different cover, tephra thickness, and tephra texture are listed in table 4.

Basin-wide erosion rates

We mapped the total amount of each tephra layer erupted onto hillslopes; the bulk density of each tephra layer was then used to convert the total volume of 70.0×10^6 m^3 to 93.0×10^6 t (exclusive of thick tephra layers interlayered with debris avalanche deposits on the lower flanks of the volcano, deposited in lakes, or on the surface of the North Fork Toutle debris avalanche). This amount was then broken down by grain size using the data in table 1: 21% was silt and clay, 63% was sand, and 15% was gravel.

Amounts of sediment eroded were then calculated by first sampling the distribution of hillslope gradient, cover type, tephra thickness, and tephra texture by placing a grid of points over preliminary 1:24,000-scale post-eruption topographic maps and overlays of the mapped parameters. Data from 498 sample points (summarized in table 5) were first grouped by gradient in 0.10 intervals. Sample points in each interval were assigned to one of the seven classes listed in table 4. Erosion rates for the midpoints of each 0.10 interval were calculated using the equations in table 4; these rates were multiplied by the area in each class, giving total amounts of sediment eroded (table 5). To break down total amounts according to their constituent grain size, the simplifying assumption was made that sheetwash eroded only the surficial air-fall layer and that rills eroded through the entire tephra stratigraphy. These calculations indicate that by May 1981, 8.0×10^6 m^3 or 11% of the tephra erupted onto hillslopes in 1980 had been removed by water erosion.

Table 4. Equations relating erosion to gradient where $30 < t < 7.5$ (i) (iii), $t > 30$ (ii), and $2.5 < t < 15$ (iv) (tephra thickness = t cm). Tephra surface is silty 18 May air-fall tephra (i) (ii) or sandy 25 May (iii); equation (iv) applies to either surface texture.

Cover type	Regression equation ($E = 10^3\ m^3/km^2$-yr) (r = rilling of tephra; s = sheet erosion; c = rilling of colluvium; t = total erosion)				Percent area
I. Trees clearfelled 10 yrs prior to May 1980	(i)	$E_r = 9.4 + 45.3s$*	$E_s = 6.6 + 18.8s$	$E_c = -10.0 + 61.0s$*	24
	(ii) [1]	$E_r = 6.9 + 132.6s$*	$E_s = 6.6 + 18.8s$	$E_c = -0.6 + 12.1s$*	5
	(iii)	$E_r = 0.7 + 29.1s$**	$E_s = 0.0 + 8.0s$	$E_c = -6.5 + 23.3s$	4
II. Large downed trees	(i)	$E_r = 16.1$	$E_s = 7.5$	$E_c = 1.4$	33
	(ii) [2]	$E_r = 39.1$	$E_s = 11.3$	$E_c = 5.6$	2
	(iii)	$E_r = 8.1$	$E_s = 3.3$	$E_c = 1.4$	5
III. Standing singed or small downed trees	(iv)	$E_t = 0.5$			27

1 $s < 0.40$ for sampled hillslopes.
2 $s < 0.60$ for sampled hillslopes. For other classes, $s < 0.80$. On hillslopes where $s > 0.80$ (1.9% of total area), it was assumed that $E = 0$.
* $2 < n < 5$, $p < 0.05$
** $n = 4$, $p < 0.01$

Table 5. Summary of hillslope characteristics, erosion rates, and sediment yield from catchments of the Toutle River system.

Drainage basin	Hillslope gradient ($\bar{X} \pm$ sd)	Area of cover class (km²) [1]	Erosion rate [2]		Sediment yield and sediment size [3] ($\times 10^6$ t)
			($\times 10^3$ t/km²-yr)	(mm/yr) [4]	
Green River	0.34±0.15	38.4 (cf)	27.4 (t)	19.4 (t)	1.78 (f)
	(n=228)	56.2 (dt)	2.2 (c)	2.8 (c)	2.58 (s)
		60.5 (ssdt)			0.23 (g)
		(155.2)			(4.59)
N. Fork Toutle River	0.42±0.18	76.6 (cf)	36.8 (t)	26.7 (t)	2.53 (f)
	(n=246)	74.3 (dt)	3.6 (c)	4.5 (c)	3.91 (s)
		30.1 (ssdt)			0.89 (g)
		(180.6)			(7.39)
S. Fork Toutle River	0.42±0.14	2.7 (cf)	11.4 (t)	9.5 (t)	0.03 (f)
	(n=24)	9.0 (dt)	1.3 (c)	1.3 (c)	0.14 (s)
		4.1 (ssdt)			0.01 (g)
		(15.8)			(0.18)
Toutle River	0.38±0.17	117.7 (cf)	31.5 (t)	22.7 (t)	4.34 (f)
	(n=498)	139.5 (dt)	2.9 (c)	3.6 (c)	6.63 (s)
		94.7 (ssdt)			1.13 (g)
		(351.6)	(34.4)	(26.3)	(12.10)

1 cf: trees clearfelled prior to the eruption; dt: downed trees; ssdt: standing singed and small downed trees

2 Mass of sediment calculated using bulk densities of 1.23, 1.37, 1.48, ($5 < n < 24$), and 1.07 ($n=2$) for tephra layers A1, A2, A3, 25 May, and an average value of 0.80 for colluvium (from Weyerhaeuser Co. data). c: colluvium; t: tephra

3 Texture of tephra from Table 1; texture of colluvium from data of U.S. Forest Service and Weyerhaeuser Co. f: clay and silt; s: sand; g: gravel

4 For Bubnoffs, multiply by 1,000.

Table 6. Sediment eroded from hillslopes in basins impounded by debris avalanche deposits. Calculations assumed that 100% of sediment was trapped.

Lake and drainage basin	Amount of sediment ($\times 10^6$ t) by grain size			
	< 0.0625 mm	sand	> 2 mm	total
I. Coldwater Creek Lake	0.69	1.06	0.36	2.11
II. South Castle Creek Lake	0.04	0.13	0.06	0.23
III. Spirit Lake	0.40	0.54	0.22	1.16
IV. Jackson Creek Lake	0.03	0.11	0.02	0.16
totals	1.16	1.84	0.66	3.66

The repeated survey of steam channel cross-sections throughout the year following the May 1980 eruption demonstrated that sediment eroded from hillslopes was not stored at the base of hillslopes nor in stream channels (LEHRE et al. this volume). Four major lakes (table 6) impounded by the debris avalanche on 18 May trapped 3.7×10^6 t or 30% of all sediment eroded from hillslopes. The remaining 8.4×10^6 t of sediment thus entered the Toutle River system; 36% of the sediment was clay and silt, 58% was sand, and 6% was gravel.

Erosion rates began to slow in the first rainy season following the eruption, and rates have continued to decline during the second post-eruption year. The forest lands affected by the directed blast were intensively managed for timber production prior to May 1980, and aggressive management of these lands since the 1980 eruption has greatly modified the hydrology of much of the downed-tree and singed-tree zones. Changing spatial and temporal patterns of hillslope erosion resulting from natural processes and human intervention are the subjects of later papers.

Conclusions

The destruction of vegetation and deposition of a cohesionless tephra mantle with an impermeable surface resulted in the rapid erosion of the steep terrain north of Mount St. Helens. Measured erosion rates in the first post-eruption year were most rapid on steep slopes, on thick tephra layers, and where forest trees had been clearfelled prior to the eruption. Large downed trees, where present, reduced erosion an average of 50% below the rates measured where trees had been removed prior to the eruption. The surface texture of tephra is an important control on erosion rate. Rates were slowest where singed trees or small downed trees far from the volcano provided effective cover. Basin-wide erosion rates were estimated by mapping the distribution of the dominant variables controlling erosion. These estimates indicate that 11% of the tephra deposited on hillslopes by the 1980 eruptions was eroded during the first post-eruption year.

Acknowledgements

This study has been supported by the University of Washington Graduate Research Fund, by Cooperative Agreement PNW-80-179 with the U.S. Forest Service, Pacific Northwest Forest and Range Experiment Station, the Washington State Department of Fisheries, and by the Weyerhaeuser Company. We thank F. J. SWANSON, W. E. DIETRICH, and B. HALLET for valuable discussion and comments throughout the study. W. E. DIETRICH, B. HALLET, and L. H. FAIRCHILD offered helpful commentary on this paper, an earlier draft of which appears in the proceedings from a conference held Oct. 7–8, 1981 in Jantzen Beach, Ore., by the State of Washington Water Research Council.

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