reliable models of channel erosion for different types of debris flows as well as different surficial materials, and (ii) to take into account various discontinuities and anomalies that may persist in a given basin, which may prove detrimental to slope stability and make them prone to debris flow initiation.

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1996 TUMALT CREEK DEBRIS FLOWS AND DEBRIS AVALANCHES IN THE COLUMBIA RIVER GORGE EAST OF PORTLAND, OREGON

Sarah E. Johnson[1]

ABSTRACT

Several canyons along the southern side of the Columbia River about 35 miles east of Portland, Oregon produced debris flows on February 7th and 8th, 1996. Two types of flow occurred in the channel of Tumalt Creek. The earlier flow was more rapid and destructive, carrying boulders up to three meters in diameter with very little mud, and while it left boulder levees on the banks of the channels, the channels themselves were left clean. This flow may be appropriately described as a debris avalanche. The later flow was slower and more gentle, behaving more like a typical muddy debris flow, leaving deposits of muddy debris within the channel as well as in boulder levees along its length.

INTRODUCTION

A series of debris flows issuing from several canyons including Tumalt Creek Canyon (Figure 1) swept through Dodson and Warrendale, small communities in the Columbia River Gorge 35 miles east of Portland, Oregon on February 7th and 8th, 1996. Three flows reached interstate 84 and the railroad, closing the interstate for five days and the railroad for three. Residents were evacuated from the area and several homes were damaged or destroyed. During the event, Tumalt Creek changed its course and now enters the Columbia River almost half a kilometer west of its previous location (Powell et al. 1996).

At 3:00 a.m. February 7, Mark Chandler went outside his home by Tumalt Creek and watched as the rushing waters of the creek suddenly stopped. He then heard a rumbling from the forest and initially thought that two freight trains had collided. Shortly after, a mixture of boulders, mud, water and trees rushed out of the woods on its way to the Columbia River (Briggs 1996). Within the hour, residents half a kilometer to the west were awakened by the sound of muddy water rushing towards their homes when Tumalt Creek claimed and overtopped its new channel. Hours later, as they were digging the mud out of their basements, another debris flow deposited boulders and mud in their front yards.

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Debris flows are not rare in this area. According to the U.S. Forest Service, which manages the Columbia River National Scenic Area, there are numerous small debris flows every year. There was a large one within a few miles of Tumalt Creek in 1987, and in 1918 a major debris flow from a nearby canyon covered the old Columbia River Highway with meters of mud and boulders (Powell et al. 1996).

During the first flow event, when the water stopped as reported by Mark Chandler, the old Tumalt Creek channel was blocked by debris and the main water flow was diverted to a channel on the western edge of the fan. As a result, the debris-flow deposits in the original channel were protected from subsequent erosion. I mapped those deposits in detail, at a scale of 1:250, in July and August of 1996. In this paper I will describe and compare the deposits and other features of these flows, and briefly discuss their mechanisms.

Two distinct types of debris were deposited on the Tumalt Creek fan, and the debris flows that produced them seem to have behaved in strikingly different manners, though they both contained boulders up to 3 m in diameter. The early flows were very fast-moving and destructive. They knocked down acres of trees, and debarked and embedded gravel into the lower 2 to 4 meters of others. On the upper fan, the resulting deposits contain very little fine material (Figure 2a), and many of the boulders within the deposits are freshly fractured and abraded. On the

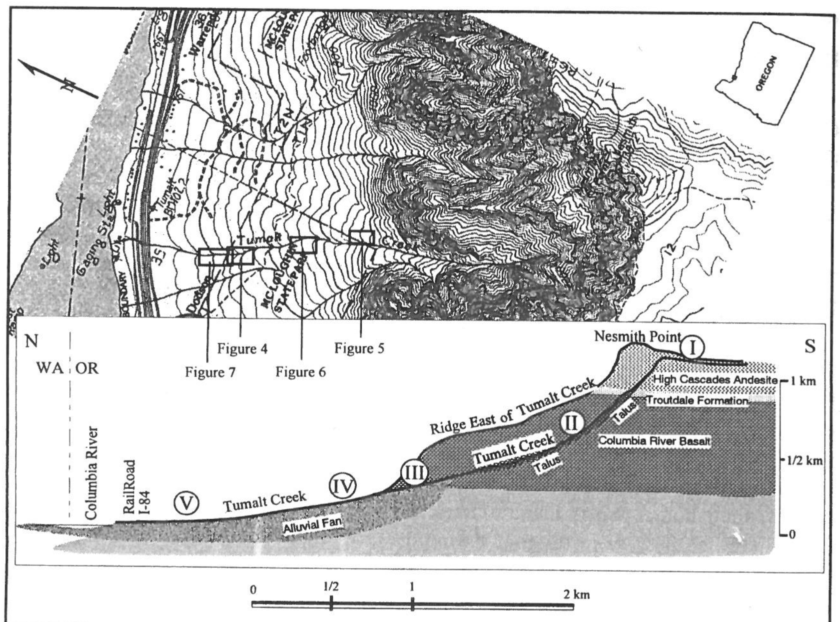


Figure 1: Cross-section along Tumalt Creek. Topography from USGS Multnomah Falls Quadrangle (1986). Geology from Allen (1984). 40ft contour interval, no vertical exaggeration.

lower parts of the fan, the deposits contain more fine material. These early flows may best be described as *debris avalanches:* inertial or Bagnoldian flows in which the flow behavior is dominated by the collisions of clasts. Such deposits are seen throughout the top of the fan, and along all of the five main distributary channels to the lower fan and the road.

The later flows were not so destructive, moving more like wet concrete. In contrast to the debris-avalanche deposits, these deposits contain an abundant matrix of mud, sand and gravel, and any protruding boulders are coated with that mixture (Figure 2b). These flows may be described as *muddy debris flows:* macro-viscous flows in which the behavior of the flow is dominated by the viscosity and strength of the fluid (Johnson 1996). Muddy debris-flow deposits were found only in the westernmost three of the five main distributary channels.

The two flows at Tumalt Creek may be thought of as two members within a continuum between inertial flows and macro-viscous flows (Iverson 1987). That two such different flows were produced during the two-day event was perfect for a comparative study.

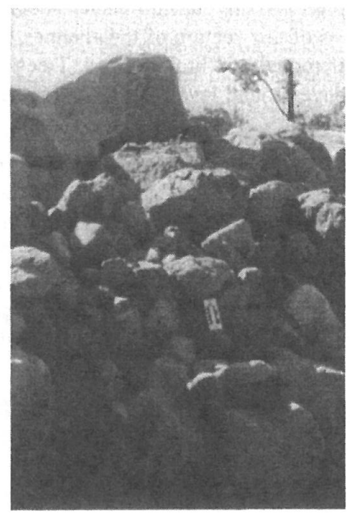


Figure 2a: Debris levee deposited by a debris avalanche, composed of andesite boulders, cobbles, and a thin coating of finer material.

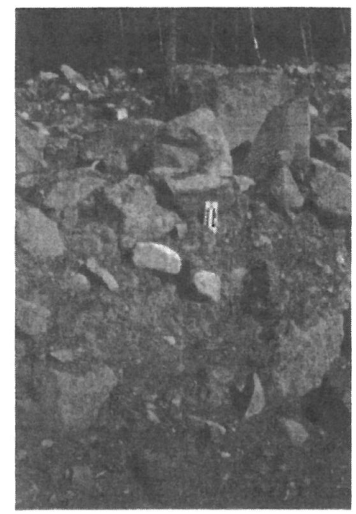


Figure 2b: Debris levee deposited by a muddy debris flow, composed of boulders, cobbles, and abundant finer material.

TRANSITIONS: OBSERVATIONS FROM SOURCE TO TOE

From the lip of the cliff near Nesmith Point overlooking the Columbia River three kilometers to the north and over one kilometer below (point I on the profile in

Figure 1), Tumalt Creek and debris scars are plainly visible in the largely forested landscape. The upper 200 m of the cliffs are composed of the High Cascade Andesite, a light-grey basaltic andesite forming vertically jointed, nearly horizontal layers. Weathering along these joints forms rounded boulders up to 5 m in diameter. Beneath the High Cascade Andesites is the Troutdale Formation, a thin, orange-colored, crumbly layer of sand and gravel deposited by the ancient Columbia River (Allen 1979). The underlying Columbia River Basalt forms cliffs that are highly fractured, producing cobble-sized talus much smaller than the andesite boulders from above.

The many small tributary streams that feed Tumalt Creek rush down 40° slopes, as steep as talus cones (II in Figure 1). Most channels are swept clean, but some are still full of debris. In the channels still full of debris, commonly there are parallel levees of material, an outer levee composed of cobbles of basalt, and an inner levee of large boulders of andesite, reflecting different source areas in either the basalt or the andesite talus above. Dozens of recent slide cavities tens of meters high have enlarged the channels now clear of debris.

Slopes decrease to about 20° as the tributaries coalesce into Tumalt Creek. The nearly vertical edges of the channel are 10 m high and are cut into ancient debris-flow deposits. Small springs issue from the walls of this section of the channel. On the channel banks are levees of boulders and uprooted and broken trees. Trees on the edge of the channel are scarred 3 to 4 m above ground level, possibly from the impact of moving trees or airborne boulders.

Where the Tumalt channel exits the cliffs (III in Figure 1), the slope decreases to about 15°. Here the top of the alluvial fan is deforested where debris overtopped the banks of the main channel, destroying the new-growth forest and finding other channels to follow. All that is left are stumps, most about 20 cm in diameter. The few older, larger trees that survived have bark stripped off to a height of 2 to 4 m and are embedded with gravel; pools of sap lie at their bases. Stumps and bare roots line the channel walls, but remarkably, ferns and flowers and pockets of soil have been left intact in many places, indicating minimal erosion.

Several channels with slopes of 10 to 15° lead into the older forest of McLaughlin State Park (IV in Figure 1). The old Tumalt channel is bordered by boulder levees and lined with mud and cobbles. In places the debris overtopped the channel and either claimed a new channel or deposited a lobe of debris.

As the old Tumalt channel exits the park, its slope decreases to about 5° and enters an open space where numerous small trees are bent over almost parallel to the ground (V in Figure 1). Here the main channel divides into many small channels that continue into a young and still upright forest of maples. The deposits in this forest are mainly flat-topped muddy lobes which persist all the way to the old Columbia River Highway, becoming progressively more sheetlike.

TUMALT MUDDY DEBRIS FLOWS

A schematic for a moving debris wave at Tumalt Creek is shown in Figure 3. It has a steep front consisting of the coarsest material available, and is nearly devoid of finer material. The body of the debris flow contains poorly sorted material ranging in size from mud to boulders and exhibits a crude fining of large clasts towards the rear of the wave (Johnson 1965). A transverse profile of the surface of the wave is flat or slightly convex. A longitudinal profile shows the wave is thickest at the front and thins towards the rear. Judging from the deposits at Tumalt, the muddy debris wave fronts were up to 4 m high and consisted of andesite boulders up to 3 m in diameter.

Due to the interaction of the flow with the edges of the channel, the debris travels more slowly at the margins than in the center of the channel (Johnson 1965). This velocity distribution is reflected in the rounded plan shape of the wave front. As the wave travels, boulders in the wave front are pushed aside and may be deposited along the edges of the channel or in overbank deposits, forming *debris levees.* At Tumalt Creek, the muddy debris levees range up to 2 m in height and contain boulders up to 2 m in diameter, cobbles, and muddy material. (Figure 2b).

Medial deposits are deposited along the axis of the channel through which the flow passes. The deposits consist of the fine material from within the body of the flow and are much finer than the adjacent levee deposits left by the same flow. The medial deposits of the muddy debris flow are about 10 cm thick and are comprised of muddy material, cobbles and occasional small boulders (Figure 4b).

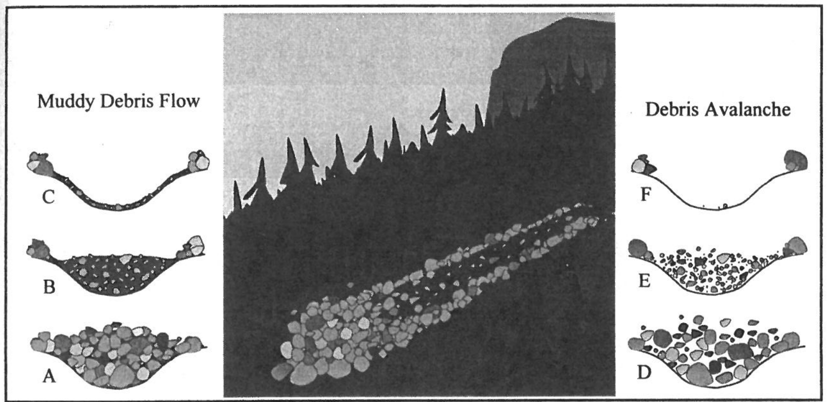
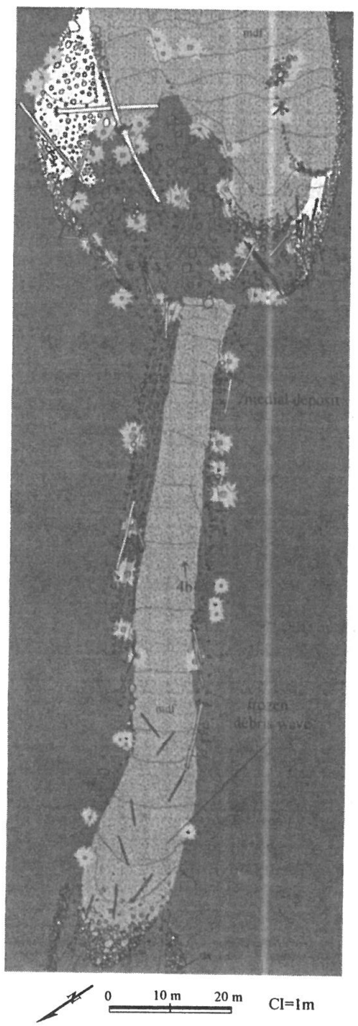


Figure 3: Schematic of a moving muddy debris flow showing an oblique view and cross-sections of the flow. Cross-sections show: A, the coarse bouldery front of the wave; B, poorly sorted material behind the front with levees previously deposited by the front of the wave; C, the channel after the debris wave has passed, leaving a finer-grained medial deposit between the coarse debris levees.

Second set of cross-sections illustrating the debris avalanche: D, coarse front of the flow with the particles colliding together; E, poorly sorted material behind the front of the wave between clean, coarse-grained debris levees deposited previously by the wave front; F, channel after the debris wave has passed, leaving only debris levees and no medial deposit.

When the shear stress supplied by gravity drops below the shear strength of the flowing material, the wave can no longer flow and essentially "freezes", preserving the form of the moving wave (Johnson 1965, Shultz 1996). The shear stress may drop when the slope angle decreases, or when the mass of the wave decreases as it produces medial deposits and debris levees. *Frozen debris waves* may be found within a channel or where a wave or part of one overtops the channel. There is a frozen muddy debris wave found in the Tumalt channel as it exits McLaughlin State Park (Figure 4). It is the most distal deposit formed by the muddy debris flow.



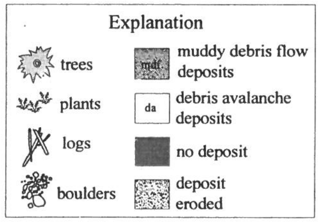


Figure 4a: Map of medial deposit and frozen debris wave deposited by the muddy debris flow. Location of this area is shown on Figure 1. The rear of the frozen debris wave grades into the medial deposit. Final deposit of the muddy debris flow.

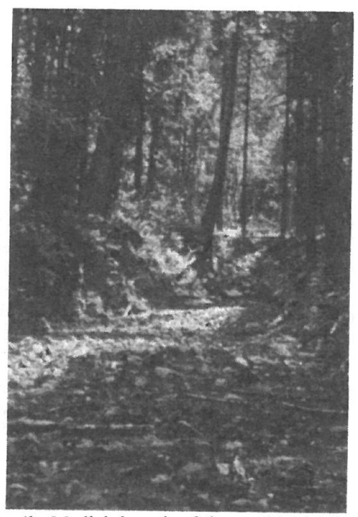


Figure 4b: Medial deposit of the muddy debris flow. The top surface of the cobbles and boulders on the surface are coated with muddy material. The flow descended a 35° slope (right center) without leaving a medial deposit.

TUMALT DEBRIS AVALANCHES

Debris Avalanche vs. Muddy Debris Flow

The key difference between a debris avalanche and a muddy debris flow appears to be controlled by the fluid phase of the flow (Johnson 1996). At Tumalt Creek, the granular phase of the both the debris avalanche and the muddy debris flow contained clasts of cobbles and boulders, and the fluid phase consisted of air, water, clay, silt, sand, and pebble-size clasts. The fluid phase in the debris avalanche apparently had very low strength and viscosity in comparison to that of the muddy debris flow, allowing collisions between clasts in the flow to dominate (Johnson 1996). Collisions of particles cause the flow to be dispersed as explained by Bagnold (1954); the grains are able to move past one another and the flow can maintain a high velocity.

The initiation of a debris avalanche requires a steep gradient. This could certainly have been provided at Tumalt, as the gradient is nearly 3:1 from the source area to the Columbia River, about 2:1 from the source area to the top of the fan, and nearly 1:1 from the source area to the beginning of Tumalt Creek.

While debris avalanches were much more destructive flows, debris levees and frozen debris waves were produced in a manner similar to those of muddy debris flows (Figure 3). However, there are two striking differences. First, the debris-avalanche deposits are extremely clean. Second, while the muddy debris flows left abundant medial deposits, the debris avalanches left almost none.

Figures 5a and b show an example of a frozen debris wave deposited by a debris avalanche, and may typify the composition of a moving debris avalanche. In contrast to a frozen debris wave deposited by a muddy debris flow (Figure 4), this frozen wave contains only sparse fine-grained material, even in the rear of the deposit. Debris levees deposited by a debris avalanche contain less than 5% of fine material, and the voids between boulders have just a thin coating of muddy material (Figure 2a). In contrast, an adjacent muddy debris-flow levee contains approximately 30% fine material (Figure 2b). The lack of a matrix in these debris avalanche deposits indicates that the fluid phase drained from the deposit after deposition, or that it consisted primarily of water. In any case, it was a fluid of low strength and viscosity.

The phenomenon of a debris avalanche moving through the channels without leaving a medial deposit is shown in Figures 5a and b. While a huge boulder levee has been deposited on the side of the channel by a debris avalanche, the floor of the channel is nearly devoid of debris. This is seen again midway down the fan. Muddy debris-flow levees onlap the debris-avalanche levees along much of the channel. However, in the places where they are separated, the original ground surface is exposed between the levees, showing that the debris avalanche did not leave a medial deposit (Figures 6a and b). This again suggests the fluid phase of the debris avalanche had a low viscosity.

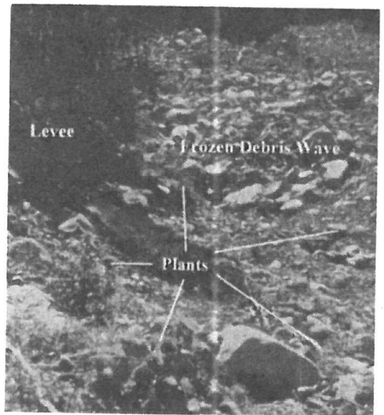


Figure 5a: View upstream near top of fan, showing a debris levee deposited by a debris avalanche under the trees and perennial plants growing throughout channel. Frozen debris wave deposited by a debris avalanche in background. Slope of channel is about 11°.

Figure 6a: Map of debris avalanche and muddy debris flow deposits. At lower right are two frozen debris-waves. Main channel narrows here so debris avalanche may have filled the main channel, overtopped its banks, flowed down the steep bank and formed a crude levee and frozen debris waves.

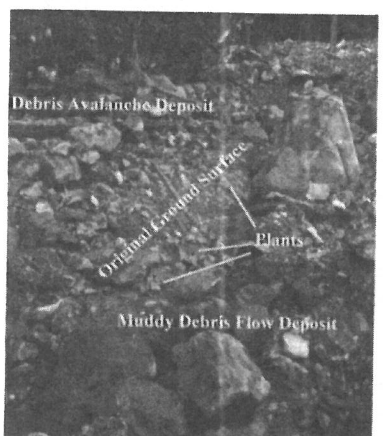


Figure 6b: Sourceward view of two levees with a section of original channel surface exposed between. The debris avalanche did not leave a medial deposit.

Figure 5b: Close-up of frozen debris wave in Figure 5a. Deposit contains only sparse fine material. Largest boulders in front up to two meters in diameter. Channel wall covered by plants in the lower left was left intact by the passage of an earlier debris avalanche.

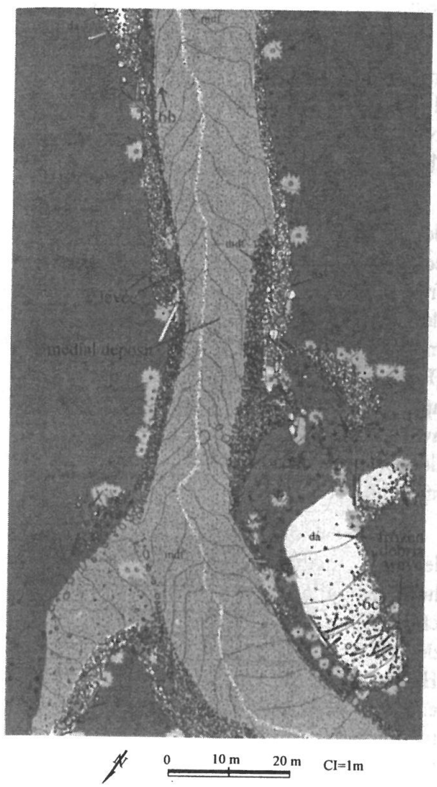


Figure 6c: Boulders up to 1/2 m and logs mark the periphery of the frozen debris wave. The tops of the cobbles and boulders on the surface are clean.

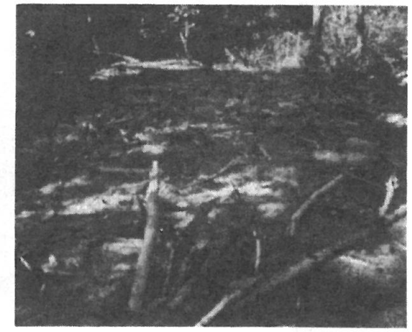


Figure 7a: Frozen debris wave 1/2m thick. Front of the wave in the background composed of small boulders and cobbles.

Evolution of a Debris Avalanche

The distal parts of the fan show an increase in the percentage of fine material in the frozen debris waves deposited by debris avalanches. A possible explanation is that, as the debris waves traveled, they systematically rid themselves of their coarsest material in producing debris levees, thereby increasing the proportion of the finer-grained material in the remaining flow. A finer-grained frozen debris wave deposited by a debris avalanche is seen midway down the fan in Figure 6c. Frozen debris waves are plentiful and even finer-grained on the distal parts of the fan (Figures 7a and b).

The slope of the fan decreases from about 15° to 5° where the old Tumalt channel exits the state park (Figure 1). Debris avalanches were still moving rapidly, as the new growth here has been bent over, debarked and even sharpened to a point by their passage. The debris levees here are smaller in height as well as finer-grained overall, though they still contain 2 to 3 m boulders in places. Interestingly, just short distance beyond where debris avalanches bent over and debarked trees, they began to flow through the trees without damaging them. It is possible that the debris avalanches transformed into muddy debris flows as they reached lower slope gradients in conjunction with having a higher proportion of fine-grained material. A similar transformation from a debris avalanche to a muddy debris flow was reported by Plafker and Erickson (1978). Even in the lower reaches of the fan, however, debris avalanches still produced only very thin medial deposits, through which perennial plants have easily regrown.

ACKNOWLEDGMENTS

I would like to thank the Colorado Scientific Society and the Newby Foundation for funding for this study, and am grateful to Eric Evans, Gwen Moulton, Stephanie Happold and Bill Powell for their assistance in the field.

Figure 7b: Map of distal deposits of the debris avalanche. The debris is deposited in numerous frozen debris waves, each up to one m in thickness.

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EROSION AND SEDIMENTATION IN MOUNT PINATUBO RIVERS, PHILIPPINES

Markus Zimmermann[1] and Dieter Rickenmann[2]

ABSTRACT

The erosion of huge deposits of pyroclastic material in the headwaters of Mt. Pinatubo river systems resulted in very high sediment transfer to the lowlands by lahars, causing enormous devastation. For two river systems, the characteristics with regard to sediment availability, lahar processes and morphological changes are discussed. The evaluation of five rainy seasons revealed an exponential decay of the sediment delivery. The rivers in the lowlands were completely filled by millions of cubicmetres of sediment. The travel distance of the lahars into those low-lying river reaches is mainly controlled by the gradient of the river bed. The debris flow-type lahars stopped at gradients of 3 to 1 %, the more liquid lahars at gradients of 0.3 to 0.2 %. Within 10 to 15 years following the eruption the sediment supply will be close to pre-eruption conditions. However, the secondary sediment transfer will last for one or two more decades.

INTRODUCTION

The June 1991 eruption of Mt. Pinatubo deposited some 7 to 8 km^3 of pyroclastic material on the slopes of the volcano (PHIVOLCS 1994). These pyroclastic deposits form the sediment sources for large-scale and frequent lahars in 7 major river basins draining the volcano. The lahar activity began during the eruption: a typhoon passed the area and torrential rains started to erode the sediments. Since then lahars occur every rainy season, carrying abundant volumes of sediments to the lower reaches of the rivers causing large morphological changes and massive devastation. To the present more than 400,000 people have been displaced and some 350 km^2 of agricultural land are covered with lahar material.

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