LAHARS

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Glossary

bulking The erosion and incorporation of secondary, exotic debris by lahars as they move downstream.

debris avalanche A flowing mixture of debris, rock, and moisture that moves downslope under the influence of gravity. Debris avalanches differ from debris flows in that they are not water saturated and in that the load is entirely supported by particle–particle interactions.

debris flow A water-saturated mixture of debris and water having large sediment concentration that moves downslope under the influence of gravity. Forces related to both solid and fluid phases act together to drive debris flows and determine their distinctive behavior. A fairly uniform mixture of solid and liquid phases in vertical profiles characterizes debris flows and distinguishes them from more water-rich hyperconcentrated flows. The literature suggests a gradational boundary of 50% to as much as 60% sediment by volume separating debris flows and hyperconcentrated flows. Sediment concentration is not definitive because behavior also depends on factors such as sediment-size distribution and degree of agitation.

debulking A process in which the lahar selectively deposits certain particles, owing to their size or density, as it moves downstream. Debulking differs from the general deposition of bulk sediment in preferentially removing particles, usually large or dense ones, from the flow.

granular temperature A measure of degree of particle agitation, usually defined as the ensemble average of the square of the fluctuating components v_s' of instantaneous grain velocities, v_s: $T = \langle v_s'^2 \rangle = \langle (v_s - \bar{v}_s)^2 \rangle$, where $\bar{v}_s$ is the mean velocity component. Granular temperature may be interpreted as twice the fluctuation kinetic energy per unit mass of granular solids.

hyperconcentrated flow A gravitationally driven, nonuniform mixture of debris and water having water content larger than that of debris flow but less than that of muddy streamflow. Some variation with depth of solids fraction characterizes hyperconcentrated flows and distinguishes their behavior from that of debris flows. The literature reports depth-integrated solids concentrations of between 20 and 50–60% for hyperconcentrated flows. Hyperconcentrated flows possess fluvial characteristics, yet carry very high sediment loads.

lahar An Indonesian term that most commonly means debris flow, transitional flow, or hyperconcentrated flow originating at a volcano. Though some floods and muddy streamflows are genetically related to lahar events, most are not, and the term lahar is not generally extended to include such flows. Although many workers use lahar for both the process and the deposits that result from it, it is better to restrict the term to the process.

muddy streamflow A flow that essentially transports sediment as normal streams do, with fine-grained sediment in suspension and coarse-grained sediment moving piecemeal along the bed as bedload. Muddy streamflows and floods have smaller sediment concentrations than do hyperconcentrated flows.

phase (of flow) The flow type in a lahar wave at some time and place. Phases associated with lahars include debris flows, hyperconcentrated flows, and muddy streamflows.

stage (of flow) The height above the channel bottom of the flowing lahar. Examples of lahar stages include the initial rising or waxing stage, the peak-inundation stage, and the final long-duration falling or waning stage.

turbulence Chaotic fluid movement [normal to direction of flow], or deviation of flow from laminar. Turbulent flow characterizes streamflows but not debris flows or sediment-rich hyperconcentrated flows.

LAHARS OCCUR DURING volcanic eruptions or, less predictably, through other processes common to steep volcanic terrain when large masses of sediment, and water, sweep down and off volcano slopes incorporating additional sediment. Because lahars are water saturated, both liquid and solid interactions determine their unique behavior and distinguish them from other related phenomena common to volcanoes such as debris avalanches and floods. The rock fragments carried by lahars make them especially destructive; abundant liquid contained in them allows them to flow over gentle gradients and inundate areas far away from their sources. People in such distal areas commonly neither expect the danger nor anticipate the destructive power of lahars.

I. Definition and Significance of Lahars

A. Historic and Prehistoric Examples of Lahars

Lahars at volcanoes inundate surrounding areas and damage or destroy nearby communities. Torrential rains mobilized loose debris and generated hundreds of lahars after Mount Pinatubo in the Philippines erupted cataclysmically in 1991. Although each of the Pinatubo lahars was relatively small, within 3 years, they cumulatively remobilized nearly 3 of the 10 km^3 of juvenile pyroclastic debris emplaced during the eruption. Filling of downstream channels and overbank flow onto surrounding fields and villages inundated more than 400 km^2 and displaced more than 50,000 people. In contrast, the 1985 pyroclastic eruption of Nevado del Ruiz in Columbia was relatively small (0.01 km^3) but generated much larger lahars (total volume of $\sim$0.1 km^3). The interaction of hot pyroclastic flows or surges and glacial ice and snow at the summit of the volcano caused these lahars. The lahars flowed up to 100 km down four of five drainages that head at the volcano. These were the deadliest lahars worldwide to have occurred during historic time. They destroyed more than 5000 homes and killed more than 23,000 people. In the town of Armero, 73 km downstream of the volcano, virtually all structures in the path of a lahar were obliterated and three-quarters of the inhabitants killed.

Studies of prehistoric lahar deposits indicate the potential for even greater disasters. About 5600 years B.P., the enormous (3.8 km^3) prehistoric Osceola Mudflow from Mount Rainier in Washington state began with a debris avalanche that transformed to a lahar as it deformed [and dilated] because of the enormous volume of water contained in pore spaces and in the volcano's hydrothermal system. It filled valleys from depths of 85 m to as much as 200 m, flowed more than 120 km down valleys, and continued for up to 20 km under the water of Puget Sound while retaining sufficient coherence to transport large gravel and wood fragments. It inundated an area in excess of 350 km^2, which is now populated by hundreds of thousands of people. A large pyroclastic flow that mixed with more than 1 km^3 of glacial ice and snow generated a prehistoric lahar at Cotopaxi in Ecuador that was as voluminous as the Osceola Mudflow. The lahar filled valleys to depths of 80–200 m, flowed more than 300 km to the Pacific Ocean, and covered at least 440 km^2.

B. Purpose

Because the timing of lahar events is unpredictable and working with active flows can be hazardous, much of our present knowledge of flow behavior is inferred from study of lahar deposits. Nonetheless, a few key observational and experimental studies have improved understanding of debris-flow processes. The chief purpose of this article is to summarize what is known about the nature and behavior of lahars on the basis of observations, experiments, and careful examination of deposits and further to describe carefully the nature of deposits derived from such events.

C. Terminology

Lahar is an Indonesian term that most commonly means debris flow, transitional flow, or hyperconcentrated flow originating at a volcano. Muddy streamflows and floods have lower sediment concentrations than do hyperconcentrated flows and essentially transport sediment as normal streams do, with fine-grained sediment in suspension and coarse-grained sediment moving along the bed. Although some floods and muddy streamflows are genetically related to lahar events, most are not, and the term lahar is not generally extended to include such flows. Although many workers use lahar for both the process and the deposits that result from it, it is better to restrict the term to the process.

II. GENESIS OF LAHARS

Lahars may be primary (syneruptive) or secondary (posteruptive or unrelated to eruptions). Lahar genesis requires (1) an adequate water source; (2) abundant unconsolidated debris that typically includes pyroclastic-flow and -fall deposits, glacial drift, colluvium, soil, etc.; (3) steep slopes and substantial relief at the source; and (4) a triggering mechanism. Water sources include pore or hydrothermal water, rapidly melted snow and ice, subglacially trapped water, crater or other lake water, and rainfall runoff.

A. Lahars Induced by Sudden Melting of Snow and Ice, Voluminous Floods, or Torrential Rains

Floods of water moving across the easily erodible loose clastic sediments common on the flanks and aprons of volcanoes easily incorporate that debris and may quickly bulk up to form lahars (Figs. 1A and 1B). Bulking is critical to all lahars that begin with sudden water releases. Lahar formation depends on the right mix of readily available sediment and water discharge. If peak-water discharge is huge, the amount of sediment available for bulking may be inadequate and a flood results instead of a lahar. Similarly, when high-discharge flow continues for many hours or even days to weeks, as it can during lake-breakout floods, there is not enough sediment available along the drainage system to form lahars. Lastly, in catchments where there is little or no easily erodible clastic debris or soil material, bulking is retarded, and lahars do not occur.

At volcanoes, lahars induced by sudden water release can occur by four principal means. (1) Pyroclastic flows and surges mix with and rapidly melt glacial ice and firn. Generally, such pyroclastic flows come to rest or nearly do, forming meltwater that then runs off, coalesces, and erodes the pyroclastic debris to form water-rich lahars. The lahars continue to bulk up with volcaniclastic debris, glacial drift, alluvium, and colluvium as they flow downstream so that within a few kilometers to several tens of kilometers they become debris flows. Lahars of this type are considered primary. (2) Eruptions can displace large volumes of crater-lake water that form lahars downstream. Crater lakes, caldera lakes, and volcanically debris dammed lakes can also break out months to years after eruptions. Such delayed breakouts occur when water levels gradually rise and then overtop and rapidly incise fragile debris dams. (3) Subglacial eruptions can form subglacial lakes that eventually break out when a section of the ice cap becomes buoyant and releases the trapped water. Small-scale outburst floods occur as normal glacial processes during periods of ablation. Although huge eruption-driven outbursts cause sediment-rich, water floods called jökulhlaups, small secondary ones commonly bulk up to form lahars. (4) Lahars owing to intense rainfall often occur after pyroclastic eruptions deposit abundant loose debris in the form of pyroclastic-flow or -fall deposits surrounding vents of volcanoes. Lahars of this type are commonly small but frequent in occurrence during rainy periods. Size and frequency of rain-induced lahars may increase in the months or years following the primary pyroclastic eruption and then slowly decrease as drainage networks and vegetation reestablish themselves (e.g., Mount Pinatubo after its 1991 pyroclastic eruption).

Because clay-rich sediment is both uncommon on the flanks or aprons of active volcanoes and resistant to erosion, lahars induced by sudden water release generally appear to be clay-poor (less than about 5% clay/(sand + silt + clay).

B. Edifice- or Flank-Collapse-Induced Lahars

Although most edifice collapses behave as debris avalanches, those with sufficient, widely dispersed, pore and

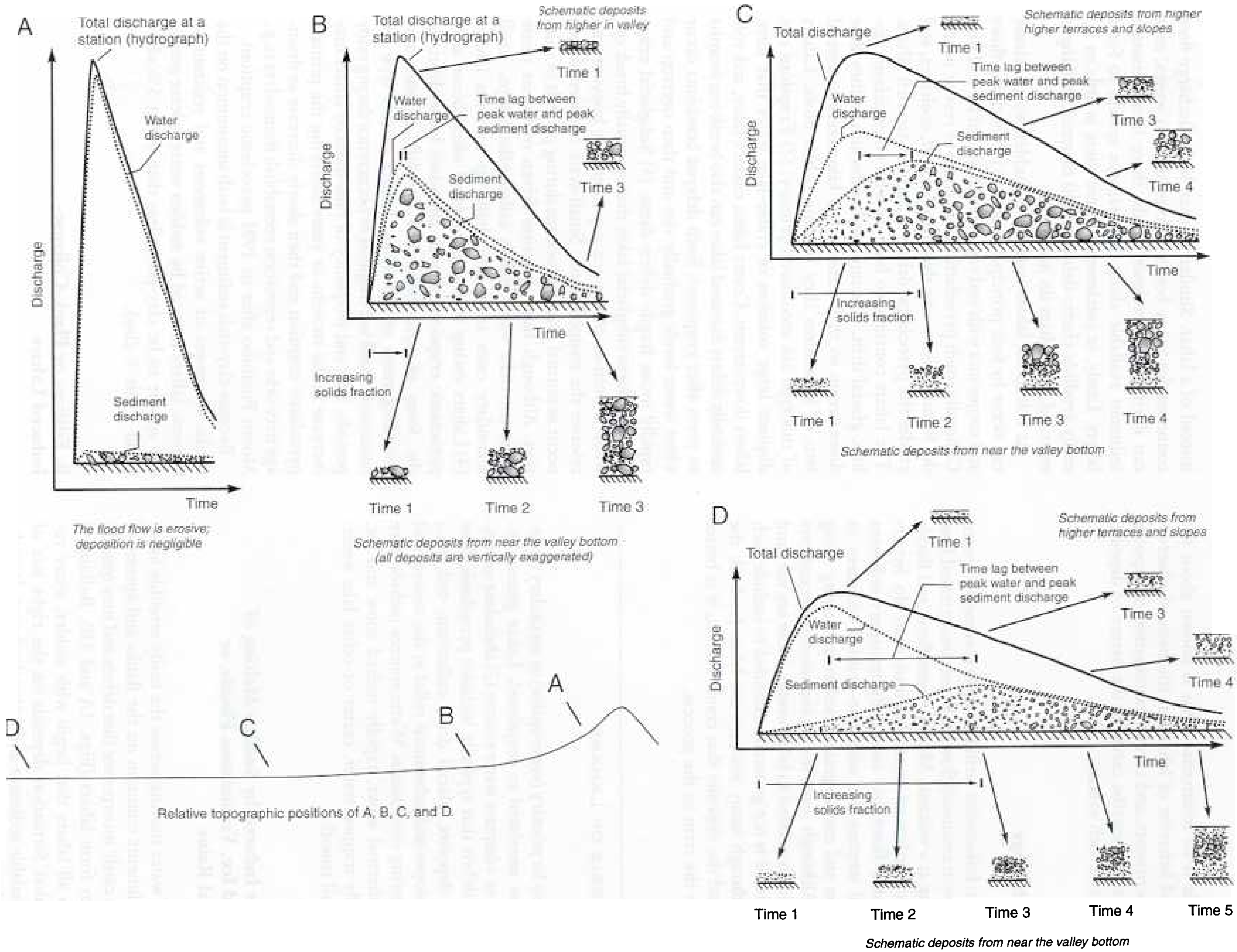

FIGURE 1 Schematic hydrographs showing how lahars beginning with water floods are initiated and behave when they undergo downstream dilution. Flood phase is shown in A, debris-flow phase is shown in B; and transitional phases are shown in C and D. The diagram also illustrates the progressive-aggradation model of inverse grading in C and D.

hydrothermal water in the precollapse rock liquefy as the material deforms during collapse. The shallow intrusion of magma within an edifice is the likeliest cause of collapse-induced lahars larger than about 0.2 km^3. Smaller collapse-induced lahars may have various triggers, including magmatic or phreatic volcanism and volcanic or tectonic earthquakes.

The process of hydrothermal alteration, especially at glaciated volcanoes, increases the probability of edifice-collapse lahars. Acid-sulfate leaching in hydrothermal systems removes mobile elements, adds sulfate, and breaks down framework silicates to form silica phases, such as cristobalite and opal, and clay minerals, such as kaolinite and smectite. This process weakens the rock so that it more readily disintegrates during deformation after collapse. Thus, huge blocks typical of debris avalanches are less common in lahars of this type even though their origin is the same. Abundant alteration minerals, especially clay minerals, increase porosity and decrease permeability of the rock and thus, in combination with the hydrothermal system, trap a widely dispersed reservoir of water within the precollapse mass. Because of its water content and its tendency to disintegrate, hydrothermally altered rock, unlike fresh rock, easily liquefies as it deforms. Collapse-induced lahars are typically clay-rich, and most are observed to have greater than 5% clay/(sand + silt + clay).

Clay-rich, collapse-induced lahars appear to be more common at ice-clad volcanoes than at volcanoes that are free of ice. Glacial erosion tends to expose deeper, potentially more altered, portions of volcanoes by more effectively incising into an edifice. Further, incised slopes in altered rock are more susceptible to failure not only because the rock is weak but also because it is oversteepened. Lastly, melting glacial ice provides a slow-release source of water that is important to the efficient operation of the acid-sulfate leaching process.

At and near some volcanoes, especially tropical ones, tectonic earthquakes cause multiple slope failures that ultimately coalesce and form collapse-induced lahars. Such lahars are unrelated to volcanism but, owing to characteristics of their deposits (commonly clay-rich, hummocky, and voluminous), can be mistaken for lahars generated by major edifice collapse of hydrothermally altered sectors of volcanoes.

III. Behavior of Lahars: Downstream Processes

Lahars can change character downstream. Some floods incorporate enough sediment proximally to become hyperconcentrated flows or debris flows. In medial or distal reaches, debris flows can also transform back to water-rich hyperconcentrated flows or, ultimately, floods. Further, debris avalanches proximal to volcanoes can transform totally to debris flows as they move downstream.

A. Erosion and Bulking

Lahars cause erosion by undercutting steep slopes and terrace scarps and by scouring their beds. Erosion is strongest along steep reaches underlain by loose clastic sediment and weakest either along reaches underlain by highly resistant bedrock or along reaches with very gentle gradients. Along any particular reach, water-rich, hyperconcentrated phases are typically more erosive than sediment-rich debris-flow phases (Fig. 2), but local erosion can occur during any flow phase. The waxing stage of a lahar is likely to coincide with the most widespead and voluminous erosion and bulking. The final waning stages of a lahar are also commonly erosive and ultimately result in the incision of channels in fresh lahar deposits.

Erosion at the base of a lahar occurs by piecemeal dislodgment of particles, by undercutting at upstream migrating knickpoints, and by rip up of sediment owing to root heave of falling trees. The presence of undisturbed, delicate, deposits such as tephra layers at the base of debris-flow deposits suggests that piecemeal erosion of particles occurs chiefly during more water-rich hyperconcentrated phases. Piecemeal erosion is probably not an important process outside of active channels. If channel beds comprise erodible sediment, sequences of upstream migrating knickpoints are common during hyperconcentrated-flow phases. Typically knickpoint steps are a few tens of centimeters to a meter or so high and spaced on the order of tens to hundreds of meters apart. During more sediment-rich flows, knickpoints become higher and more widely spaced. Knickpoints may disappear during debris-flow phases, which, in fact, commonly aggrade rather than erode their beds. Lahars voluminous enough to escape channels knock trees down and incorporate them. Root balls of falling trees drag considerable sediment into the active flow and loosen even more sediment that is then available for erosion. Voluminous lahars that inundate large areas of forested terrain can incorporate considerable quantities of sediment and huge amounts of wood in this way.

Undercutting of steep slopes, fluvial terrace scarps, and active stream banks is probably the most important way in which lahars erode and incorporate sediment.

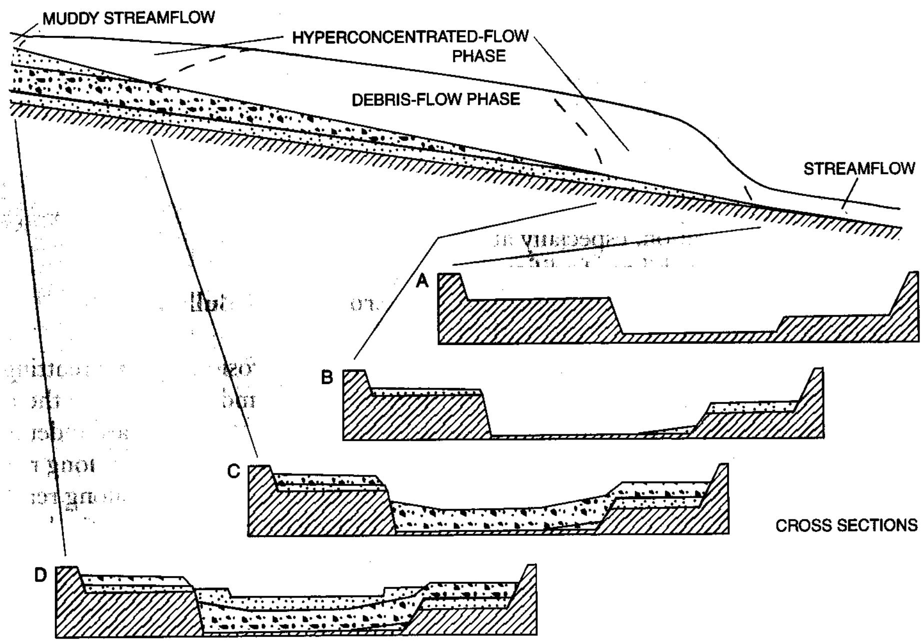

FIGURE 2 Schematic model of a lahar moving down a river undergoing downstream dilution from debris-flow phase to hyperconcentrated-flow phase and deposit facies derived from it [adapted from Fig. 3.31 in Pierson and Scott (1999), "Surficial Hydrological Hazards at Volcanoes," U.S. Geological Survey Open-file Report]. The model shows the expected sequences of hyperconcentrated- and debris-flow deposits in cross section (A–D).

Undercutting is active during both debris-flow and hyperconcentrated-flow phases. Large lahars are capable of incorporating megablocks (>10 m in dimension) of unconsolidated sediment, and sometimes even of bedrock, in this way. Clastic megaclasts may move tens of kilometers downstream before they deform and ultimately break up into individual fragements.

Progressive downstream bulking imposes downstream changes of character on lahars. Bulking transforms flood flows and hyperconcentrated flows to more sediment-rich phases (Fig. 1). If the process continues, both waxing and waning stages of flow ultimately become debris flows. With continued transportation, debris flows become richer in exotic sediment, such as alluvium, colluvium, and glacial drift. Typically, the waxing flow front and following peak stages of the flow are the most erosive and thus most readily incorporate exotic sediment. The sediment-rich falling flow that follows peak flow is less erosive and commonly actively deposits sediment rather than erodes it. The final waning-stage flow is typically more watery, and more erosive, but less voluminous in discharge than the preceding stage. Final waning stages of lahars commonly incise previously deposited laharic sediment.

B. Particle-Size and -Density Segregation Processes

Particles in lahars can effectively segregate by density or size, but the most important segregation processes are mediated by solids fraction, proportion of coarse particles, and fluid density, the latter being determined by the proportion of fine-grained particles in suspension. More dilute flow favors particle settling or buoyant rise because there are fewer particles to hinder these processes. Greater solids fractions hinder these processes and may favor percolation, a process that counteracts preferential settling of large particles. Percolation is a process in which particles, under the influence of gravitational body forces, move downward into gaps that open beneath them. The process occurs chiefly when individual particles influenced by body forces such as gravity rub or collide in vibrating or shearing mixtures.

Particles such as pumice that are less dense than water rise buoyantly. In addition, particles slightly more dense than water rise to the surface of lahars whose fluid phases suspend sufficient fines (generally clay and silt but in some cases fine-grained sand) to increase the effective fluid density. Consequently, low-density particles commonly collect at the surface of lahars and may ultimately form rafts of material that appear to move en masse. Friction at the bed retards lahars and causes vertical profiles in which velocities are smallest at the base and gradually increase upward. Low-density particles will migrate upward toward the surface where velocities are greater than average and will then migrate forward toward flow margins.

Particles that are more dense than the fluid will settle if the solids fraction is not great. In a viscous liquid, large dense particles will have higher terminal velocities and will settle faster than small particles of the same density. Through this process, the largest particles collect in the lowest horizon of the moving flow and progressively smaller particles will collect in horizons above that; thus a normally graded flow develops. If particle concentrations are great enough, particles collide with and rub one another as they settle. Such particle interactions inhibit the settling process.

In shearing or vibrating flows with particles denser than the fluid and with particle concentrations greater than about 40%, percolation predominates rather than settling. In such flows voids periodically open beneath the particles. If the size of a particle is comparable to or smaller than the size of a void, the particle falls down into the void. In a flow with a mixture of grain sizes, the probability is greater that voids of sufficient size will open beneath small particles than will open beneath larger ones. Percolation operates only downward; so in order to preserve vertical mass balance, there must be a process by which particles migrate upward. Force imbalances or particle rotations can push particles from one layer into another. This process, termed squeeze expulsion, can operate either up or down and need not be size preferential. The combination of percolation and squeeze-expulsion processes in shearing or vibrating particle flows is known as kinetic sieving. The net result of kinetic sieving is that small particles migrate downward and displace large ones, and large ones gradually migrate upward. (Readers should note that in granular flows such as lahars, increased dispersive stress corresponds with increased granular temperature or energy dissipation owing to grain collisions and inhibits size segregation rather than promotes it as suggested by Bagnold.) The large particles then migrate forward toward the margins of the flow because velocities are greatest near the surface. The kinetic-sieve process thus not only can cause the inverse vertical grading that is common in moving debris flows but can also cause the accretion of large particles at flow perimeters (Fig. 3).

Waxing flow fronts are commonly the most erosive part of lahars, especially on steep slopes. The debris available to be eroded and incorporated is commonly coarser grained and better sorted (like alluvium, colluvium, or bedrock) than debris in the main body of the lahar and will be preferentially incorporated at the flow front (Fig. 4). This process can enhance or independently form the coarse-grained, better sorted perimeters that are commonly observed in moving debris flows and their deposits.

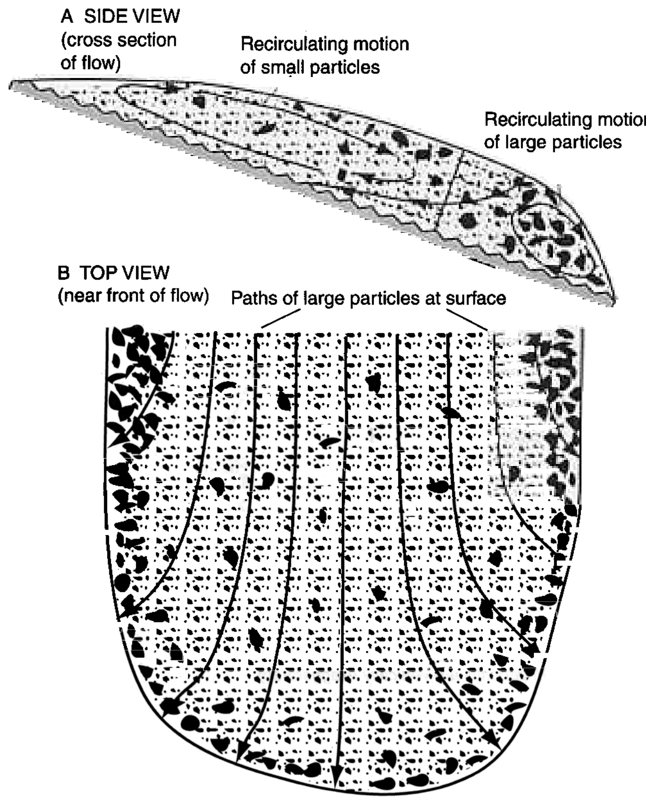

FIGURE 3 Schematic diagram illustrating how inverse particle-size segregation results in (A) longitudinally and (B) laterally graded flows.

C. Downstream Dilution and Transformation

The gradual incorporation of water at the front of a lahar flowing down an active stream channel causes progressive loss of carrying capacity and an eventual change in the nature of the flow with distance downstream (Fig. 1). This process is important only in lahars that follow active rivers or other bodies of water. Though dilution of large lahars can occur, the process has little effect on the behavior of lahars so huge that their volumes are

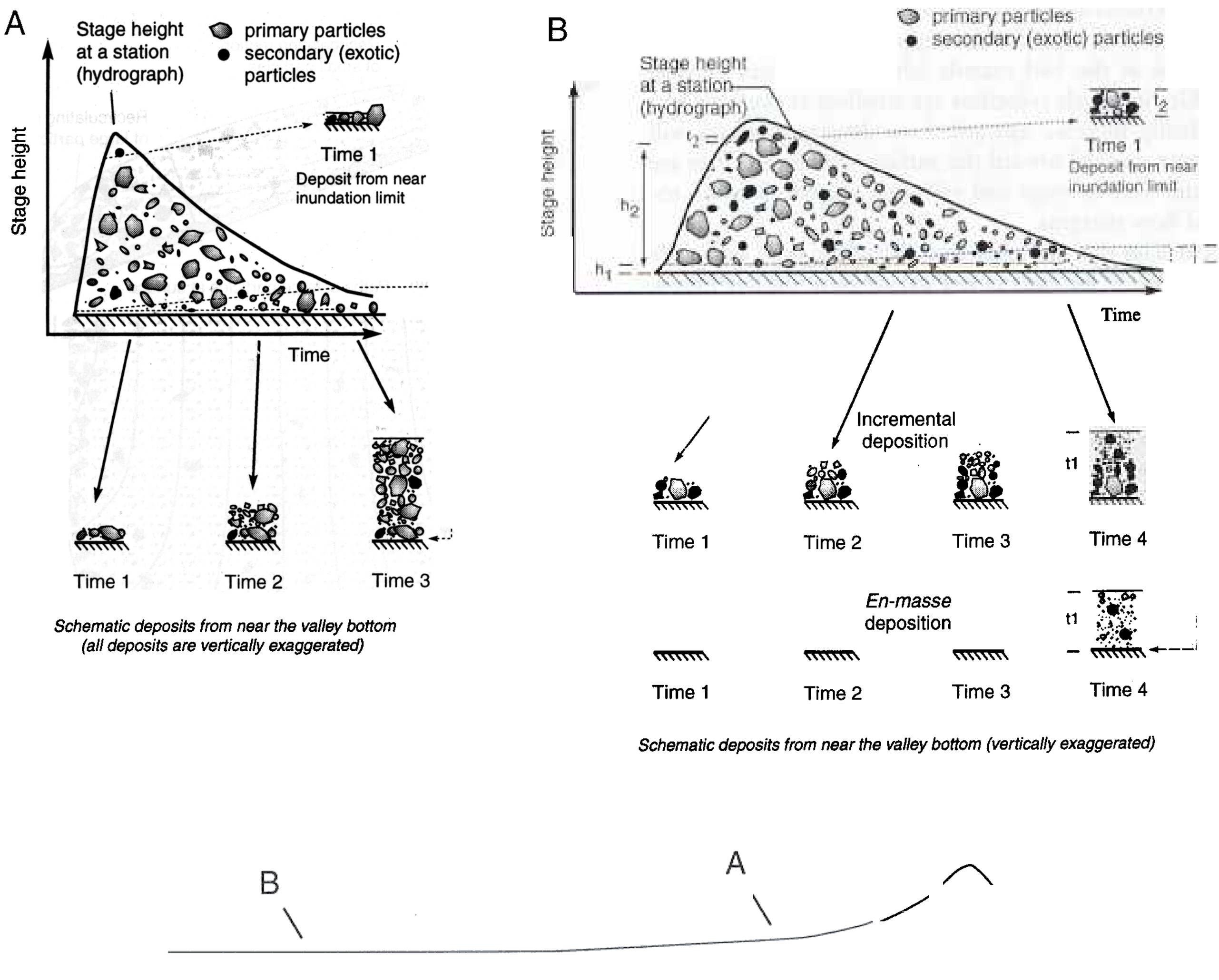

FIGURE 4 Schematic hydrographs showing the behavior and downstream changes of lahars that begin as avalanches of water-saturated debris. Note that with distance downstream (A to B), the lahar incorporates secondary exotic particles, especially near its flow front. The diagram (B) also illustrates how an inverse longitudinally graded flow can accrete incrementally to form a normally graded deposit [adapted from Vallance and Scott (1997)]. Exotic particles are most common at the base of normally graded deposits and at inundation limits (B).

significantly greater than that of the water in the river being overrun. The process of downstream dilution occurs more readily in clay-poor lahars than in clay-rich lahars because (i) clay-poor lahars mix more readily with water and (ii) clay-rich lahars are typically much larger.

Once off the flanks of the volcano and confined in river channels, lahars, which typically move faster than normal stream flow, push river water ahead of them and gradually, with distance downstream, begin to mix with that water. As the flow front becomes progressively more watery, it loses its capacity to carry larger gravel particles, and these progressively lag behind the flow front. With time and distance downstream, a dilution front progresses from the front of the lahar to its middle, and eventually the entire lahar becomes more dilute. In lahars that occurred at Mount St. Helens in 1980 and 1982, downstream dilution occurred over the course of tens of kilometers and caused a complete transformation from debris flow to hyperconcentrated flow (Fig. 1D). In medial reaches, the hyperconcentrated-flow phase preceded the debris flow of the lahar because the dilution process began at the flow front and then gradually worked backward toward the tail as the flow migrated downstream (Fig. 1C).

D. Depositional Processes

Emplacement of lahar deposits can occur en masse, by steady incremental accretion, or, most likely, by some intermediate process in which accretion begins and then accelerates, wanes, or does both alternately. Debris-flow deposits are poorly sorted, generally massive, and unstratified. It is common to infer that such massive deposits are emplaced en masse and that they represent a frozen portion of the debris flow itself. In contrast, hyperconcentrated-flow deposits are better sorted, commonly show faint stratification, and hence are assumed to accrete during significant time intervals.

An increasing body of evidence suggests that deposits of both hyperconcentrated flows and debris flows accrete incrementally. Such evidence includes (1) strong alignment of elongate clasts parallel to flow directions or imbrication of such clasts in upstream directions, (2) strong changes in composition of particles with vertical position in outcrops, especially those that are graded, (3) inundation-limit deposits with clast compositions similar to those at the base of thick valley-bottom deposits, (4) marks of peak-flow levels in upland valleys that indicate flow depths 5–10 times greater than deposit thicknesses, (5) abundant evidence of cataclasis (breakage of clasts owing to collisions), and (6) stratification in deposits of transitional or hyperconcentrated flows.

Although rapid deposition of a vertically size-segregated flow can generate normally and inversely graded deposits, incremental accretion of longitudinally size-segregated flow can also be responsible. Because lateral and longitudinal variations in both sizes and compositions of particles commonly occur in moving lahars, accretion from such laterally graded systems during significant time intervals can cause vertically graded deposits. Figure 4B (Times 1 to 5) illustrates schematically how accretion from a debris-flow wave with a concentration of large particles at its front can generate a normally graded deposit. Note that accretion occurs for a short time only near inundation limits where grading does not occur (Time 1–2). The front of a lahar wave that flows down a river becomes progressively more dilute and less capable of carrying larger particles, which lag behind (Figs. 1C and 1D). Therefore, accretion from a dilute debris flow that coarsens from head to tail produces inversely graded deposits (Fig. 1C). Farther downstream, the entire lahar, and especially its flow front, becomes hyperconcentrated so that accretion produces finer grained beds that may be inversely graded or both inversely graded and normally graded (Fig. 1D). Note that deposits in positions higher in the valley may also be graded, but often less obviously so.

Debris flows that do not undergo downstream dilution commonly form cobble–boulder-rich perimeters owing to the size segregation process described above (Fig. 3). The surface of the flow with its concentration of large particles moves faster than the rest of the flow so that cobbles and boulders migrate to the flow front. Once the flow peak has passed at any particular cross section, boulders begin to accrete at flow margins to form coarse levees. Flow fronts, with concentrations of large angular particles, that move onto gentle slopes become progressively drier because water can more easily escape from more permeable coarse-grained flow perimeters than from fines-rich flow interiors. The net result is a dry, frictional, resistant flow perimeter that surrounds a liquefied interior. When flows of this type reach sufficiently gentle slopes, the frictional perimeter slows to a stop and leaves behind a steep-fronted fines-poor margin and a partly liquefied fines-rich interior. Because resistance to flow is greater at the margin than the interior of the flow, bifurcation of the flow into fingers can result as the more mobile fines-rich interior diverts around the more static perimeter.

Avulsion can occur in lowland areas with gentle slopes where sediment-rich portions of lahars accrete and fill the active channel so that its cross-sectional capacity is diminished. When channel capacity is sufficiently diminished, the flow overtops this channel and cuts a new one. In the strict sense, the term applies only to the breaking away and establishment of the new channel, although a precondition for avulsion is accretion during debris-flow phases of lahars.

E. Two Spectra of Downstream Behavior

Edifice-collapse-induced lahars are debris flows that transform directly from avalanching debris that contain enough water to become water saturated upon deformation. Such lahars commonly contain large megaclasts composed of relatively fresh volcanic rock from the edifice. As they migrate downstream, they incorporate exotic debris, especially at their flow fronts (Fig. 4). Because of their size, avalanche-induced lahars [generally] rarely undergo complete transformation to hyperconcentrated flow as they migrate downstream.

Lahars that begin with water floods can bulk up rapidly to form debris flows or hyperconcentrated flows (Figs. 1A and 1B). If they continue down active river channels, they will gradually incorporate water, become progressively dilute, and undergo transformations to hyperconcentrated flow and muddy streamflow (Figs.

1C and 1D). The flow transformation begins at the flow front and migrates back through the lahar wave as it travels downstream. If lahars of this type occur in arid regions without perennial streamflow, they will bulk up to become debris flows, not undergo significant downstream transformation, and remain debris flows to their termini. Such debris flows will typically develop relatively dry bouldery flow fronts that surround more liquefied interiors.

IV. LAHAR DEPOSITS

A. Characteristics of Deposits

Lahar size, origin, and depositional environment all influence the character of deposits and determine the facies that form. Clay-rich lahar deposits at Mount Rainier reflect deposition solely from debris-flow phases. Such deposits are massive, extremely poorly sorted, and commonly normally graded (Fig. 5). The Osceola Mudflow at Mount Rainier, for example, has proximal and medial hummocky facies that are megaclast rich (Fig. 6). Proximal and medial valley-side facies form thin (0.1–1 m) veneers on steep slopes, and proximal, medial, and distal axial facies form thick (2–20 m) fills with common normal grading in valley bottoms and lowlands. Clay-poor lahar deposits at Mount St. Helens have channel facies, floodplain facies, transition facies, and lahar-runout facies (Figs. 7–10). The last three of these facies reflect downstream dilution of the lahar. Changes in grain size, sorting, and grading are shown schematically in Fig. 7.

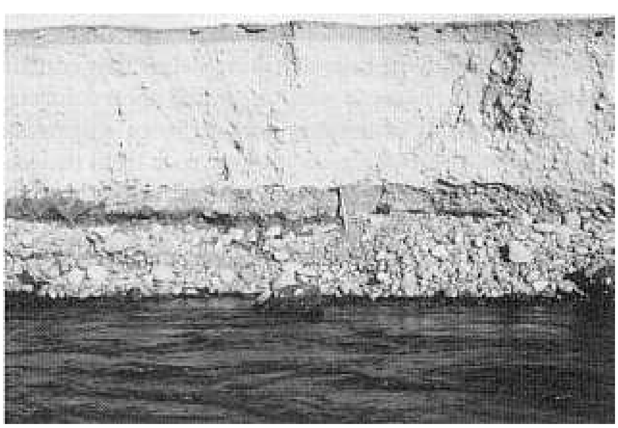

FIGURE 5 Photograph showing normally graded debris-flow deposit. Clay-rich normally graded deposits are common to collapse-induced lahars. A shovel, 60 cm long, is present for scale.

FIGURE 6 Photograph showing hummocks on the surface of an avalanche-induced lahar deposit and, in the upper right, Mount Rainier. Hummocks in foreground are up to 40 m in plan and 10–15 m high. Mount Rainier, 70 km upstream, is the source of the lahar deposit.

In medial reaches, some channel and floodplain facies exhibit unusual basal deposits called sole layers (Fig. 7). Sole-layer deposits are generally fines deficient and contain abundant gravel-size particles that are broken by cataclasis. Unlike other deposits, sole layers apparently accrete during the waxing-flow stages of lahars. Clay-poor lahar deposits not affected by downstream dilution exhibit blunt snouts and prominent lateral levees that contain concentrations of large boulder- and cobble-size clasts (Fig. 11). Deposit interiors are more uniform, massive, poorly sorted, and matrix rich. Deposits left on steep upland slopes typically form thin lags with concentrations of the coarsest, densest particles and a deficiency of matrix.

Generally, lahar deposits may be massive to crudely stratified and graded to ungraded, depending on the proportion of water that the flows contained and the degree of their downstream evolution. Inverse and normal grading, or both in the same outcrop, are common. Sorting is generally extremely poor to poor. Although lahar deposits formed by debris flows, and the hyperconcentrated flows that commonly evolve from them, have some similarities, they have many differences too, and it is necessary to characterize each type of deposit separately.

Debris-flow deposits are massive and very poorly sorted to extremely poorly sorted (greater than 2 Φ units and typically greater than 4 Φ units on the Wentworth scale). Grain-size distributions are commonly bimodal (Fig. 12). They may be normally or inversely graded throughout or, in some cases, can be inversely graded

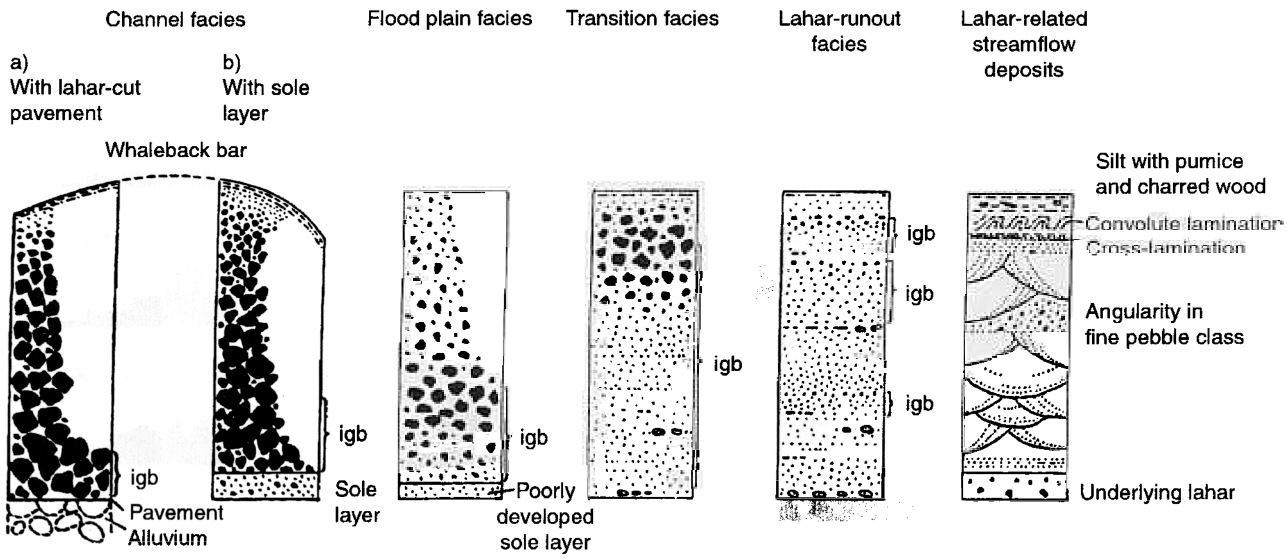

FIGURE 7 Schematic portrayal of facies types in lahars (clay-poor type) that undergo downstream dilution and transformation to hyperconcentrated flow [from Scott (1988)].

near their bases and normally graded near their tops. Fabrics generally are weakly developed. Deposits are extremely compact or, in some cases, indurated so that digging in them is difficult. Particles found within lahar deposits can be monolithologic but are more commonly heterolithologic; they can be rounded to angular, but primary particles are usually subangular to angular. Deposits commonly exhibit vesicles in the matrix, which result from entrapment of air bubbles. Other common constituents include wood fragments, casts of wood fragments, and charcoal. Concentrations of coarse particles, especially low-density particles such as pumice, are common at deposit tops.

Thicknesses of debris-flow deposits can vary from tens of centimeters to tens of meters. Thick fill deposits occur in valley bottoms and on lowlands. Deposits on higher terraces and slopes within valleys are thinner

FIGURE 8 Photograph showing clay-poor debris-flow deposit that is inversely graded at its base and both massive and ungraded at its top (dashed line indicates base of deposit). A shovel, 60 cm long, is present for scale.

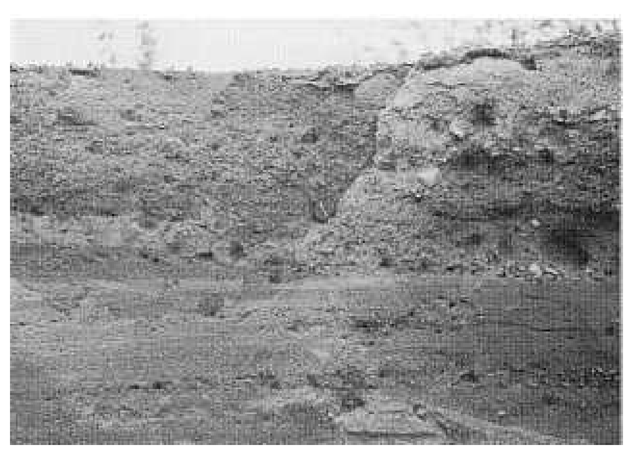

FIGURE 9 Photograph showing faintly stratified hyperconcentrated-flow deposit and overlying transitional debris-flow deposit. A lens cap is present for scale.

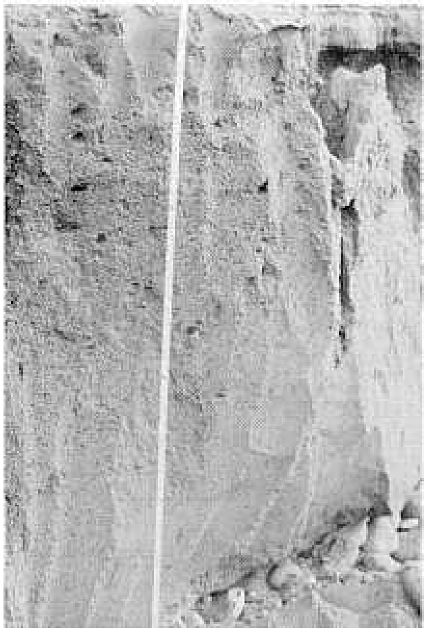

FIGURE 10 Photograph showing hyperconcentrated-flow deposit that is inversely graded in the lowest two-thirds of the outcrop and normally graded in the upper third of the outcrop. Note that the deposit comprises silt, sand, granules, and small pebbles with a single mode of coarse sand and granules. Deposit is about 1 m thick.

than those in valley bottoms, and those on steep slopes will drape underlying topography as thin veneers. Both levees and steep terminal flow fronts are common in the deposits of debris flows relatively unaffected by downstream dilution.

FIGURE 11 Photograph showing coarse-grained lateral levee and terminal snout of an experimental debris-flow deposit. Dimension of grid in foreground is 1 m.

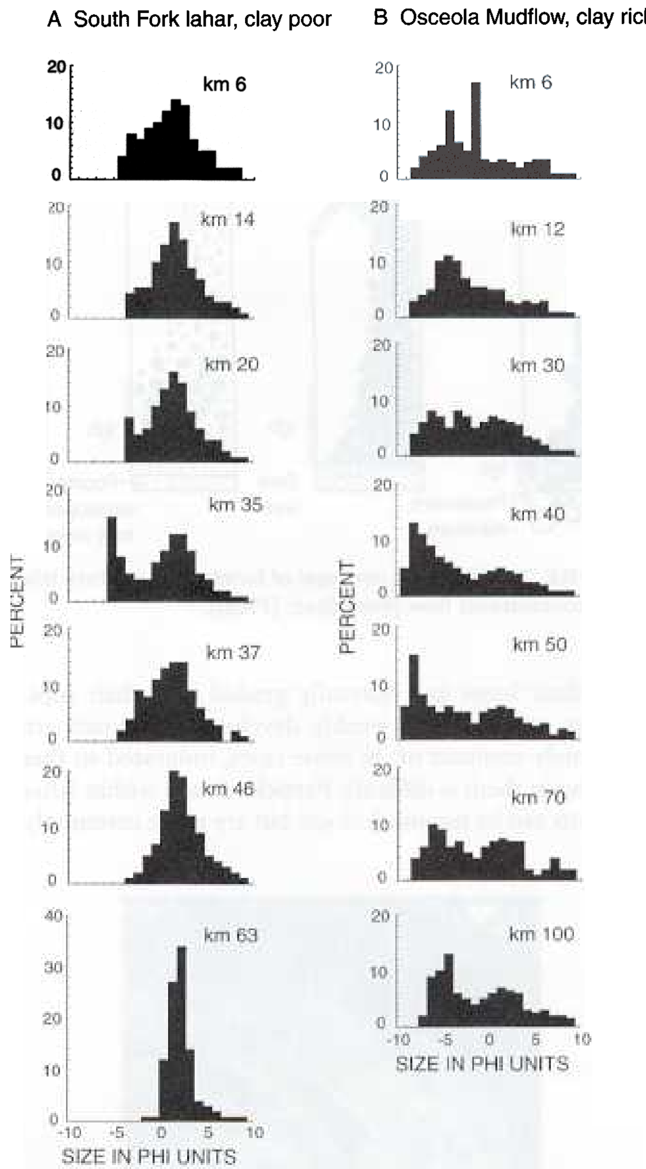

FIGURE 12 Grain-size histograms of (A) clay-poor and (B) clay-rich lahars showing downstream trends [A adapted from Scott (1988); B adapted from Vallance and Scott (1997)].

Hyperconcentrated-flow deposits have characteristics intermediate between debris-flow and alluvial deposits (Figs. 7 and 12). They thus have intermediate sorting coefficients (1–2Φ units) and grain size. They can be massive (Fig. 10) but commonly have weak stratification defined by thin horizontal beds and very low angle cross bed sets composed of fine-grained laminae and thicker coarser grained beds (Fig. 9). Floodplain facies have grain size in the granule, sand, and silt range, with the occasional floating pebble, cobble, or boulder (Fig. 13). If pumice was an important constituent of the flows, zones of nearly 100% pumice are commonly present at the tops of overbank deposits. These pumice concentrations result from pumice rafts stranded during falling-stage hyperconcentrated flow. Channel-facies deposits commonly exhibit strong bimodality and clast support, with huge concentrations of cobbles and boulders surrounding the granule–sand–silt matrix (Fig. 13). Fabrics are moderately strong. Vesicles are sometimes present but less obvious than in debris-flow deposits. Deposits are compact and, except for bouldery channel examples (Fig. 13), have a "chippy" quality when dug with a shovel. Though rare, dewatering features such as dish structures (Fig. 14) and pillar structures are sometimes present.

Hyperconcentrated flow deposits have very flat tops and may vary from a few centimeters to several meters in thickness. Thicker deposits occur in channels or other nearby low areas. Thinner deposits occur on higher ground such as floodplains and valley slopes. Flow tops exhibit scattered pebble and larger particles, especially pumice if present; they also commonly have thin layers of fine sand and silt that form during compaction and dewatering.

FIGURE 13 Photograph showing transitional debris-flow to hyperconcentrated-flow deposits. The basal unit (at the point of the ice axe) contains floating, rounded cobbles and boulders and probably reflects deposition from a hyperconcentrated flow in a channel.

FIGURE 14 Photograph showing dish structure in a hyperconcentrated-flow deposit. The structure evolves during or after deposition owing to dewatering during compaction. Note that the strctures are more strongly inflected toward the top of the unit. Tape measure for scale.

Primary particles in lahar deposits derive from contemporaneous eruptions or, in the case of avalanche-induced lahar deposits, from the original avalanche mass; secondary particles derive from the erosion and incorporation of downstream volcaniclastic debris, alluvium, colluvium glacial drift, bedrock, etc. It is difficult to recognize the provenance of small particles, though it can be done in some instances. Gravel-sized particles can be readily divided into three groups. Angular volcanic rocks derive from the volcano and are generally taken to be primary. Angular secondary clasts derive from exotic colluvium, drift, bedrock, and any other erodible materials along the lahar path. Secondary rounded clasts derive from exotic alluvium, fluvium, or glaciofluvial deposits. Using these criteria (or sometimes unique compositional or textural features of components of the clast population), one can calculate lahar-bulking factors. The lahar-bulking factor for a size fraction (or any other component) is defined as the proportion of secondary particles to secondary + primary particles in that size class. The total bulking factor, which is the bulking factor for all size classes, can be difficult to determine because of the difficulty of measuring lahar-bulking factors for small particles. If there is a size class or another distinctive component that is relatively uniform in proximal deposits and is not present in bulked material, then apparent bulking factors of small particles and total bulking factors can be estimated. The estimated apparent bulking factor is given by the equation

$$\mathrm{ABF} = 1 - (R_f/R_i)(S_i/S_f),$$

where R is the proportion of the reference component (or size class) not affected by bulking, S is the proportion of any other component (or size class) of interest, i indicates proximal (initial) value, and f indicates downstream values. To calculate an ABF total, note that both S_i and S_f have values of 1 and

$$\mathrm{ABF}_{\mathrm{total}} = 1 - (R_f/R_i).$$

Debulking is the selective deposition of a component—generally large or dense particles. If the bulking factor is negative, debulking may be indicated and a debulking factor can be calculated. The debulking factor is defined as the ratio of a component lost through selective deposition to the initial amount of the component. Assessment of debulking factors of large particles is straightforward. For small fractions, a debulking factor can be calculated,

$$\mathrm{ADF} = 1 - (R_i/R_f)(S_f/S_i),$$

where R is the proportion of the reference component not affected by debulking and S is the proportion of any other component (f and i are as before).

B. Distinguishing Lahar Deposits from Other Common Diamictons

No one characteristic serves to distinguish lahar deposits from those of unwelded pyroclastic flows, glaciers, debris avalanches, and local landslides. Unlike lahar deposits, unwelded pyroclastic-flow deposits do not have matrix vesicles, are not indurated, and contain mainly juvenile particles. Carbonized wood and magnetically oriented clasts help to distinguish them from cold lahar deposits (the vast majority) but not necessarily from hot lahar deposits. Unwelded pyroclastic-flow deposits are usually looser and less compact than lahar deposits. Debris-avalanche deposits generally have more irregular surfaces than lahar deposits. Although lahar deposits, especially clay-rich ones, can have hummocks and lateral levees, these features are more prominent in debris-avalanche deposits. Distal and marginal parts of debris-avalanche deposits can be relatively flat and can contain matrix vesicles, but these features are more typical of lahar deposits. Till can be distinguished from lahar deposits if lateral or terminal moraines can be identified. Unlike lahar deposits, till does not contain matrix vesicles, casts of wood fragments, or the wood fragments themselves. Till is also more heterolithologic than most lahar deposits. Landslide deposits generally have more local distribution and more uniform lithology than lahar deposits do. Mapping will distinguish between landslide and lahar deposits.

V. Physical Modeling

Diverse models have been proposed to explain the behavior of lahars, but there is no convincing evidence that lahars behave according to the assumptions of traditional models. In the absence of evidence to the contrary, it might therefore suffice to model these flows in a unified manner as simple cohesionless grain flows moderated by the influences of diverse grain sizes, sorting processes, varying pore pressure, and varying granular temperature. Any viable model needs to account for significant recent advances in the understanding of granular fluid mixtures. Such advances include recognition that (1) flows of such mixtures are neither steady nor uniform owing to abrupt initiations, flow instabilities, and particle segregation processes; (2) pore pressures in such flows are laterally heterogeneous; (3) the mobility of such flows is often governed by highly fluid interiors with nearly lithostatic pore pressures and resistant coarse-grained perimeters with little or no pore pressure; and (4) there is a gradation from frictional to collisional particle interactions, dictated by the granular temperature.

The Bingham model was developed to describe the behavior of clay slurries and is commonly invoked if a rigid plug is observed or inferred. In its simplest form the model assumes that resistance to flow is the result of viscosity and strength of material:

$$\tau_B = S + \mu \frac{du}{dz},$$

where τ is resisting shear stress, S is the yield strength, μ is viscosity, and u is velocity in the downstream direction. The model assumes a viscous boundary layer and an overriding plug layer but neglects particle interactions such as collisions, frictional rubbing, or segregation. Because cataclasis, rounding, and particle segregation are important in those debris flows with significant gravel fractions (i.e., nearly all debris flows), the Bingham model is incomplete. A simple alternative hypothesis emphasizes particle interactions and explains rigid plugs as the result of particle locking owing to low granular temperature.

A collisional or Bagnold-type model is commonly invoked if inverse grading is observed and if grain collisions are believed important, but Bagnold performed his analysis for a mixture of uniform, neutrally buoyant particles and fluid, and the application of his model to gravity-driven debris flows therefore requires the relaxation of his very restrictive assumptions. Further, high granular temperatures that characterize collisional flow regimes inhibit inverse grading rather than promote it. The resisting stress owing to particle collisions in a shearing granular flow can be simply approximated,

$$\tau_c \sim \nu \rho_s d^2 \left(\frac{du}{dz}\right)^2$$

where ν is the solids fraction, ρ_s is the solids density, d is the characteristic particle diameter, and $d^2(du/dz)^2$ is proportional to the granular temperature, T. Some authors combine Bingham and collisional (Bagnold type) models to derive a "unified" model. However, the mechanics assumed in the two models are incompatible because collisional models (like that of Bagnold) derive ultimately from particle interactions that the Bingham model does not allow.

A few authors have suggested that lahars, or at least their more dilute phases, can be modeled as gravity or turbidity currents. Models of this type presume very low solids fractions and a consequent lack of particle interactions. Since observations of deposits and eyewitness accounts of lahars refute both of these conditions, gravity–current models are wrongly applied to lahars.

A simple model, in which energy dissipation in the flow includes some combination of Coulomb friction and collisional losses at higher granular temperatures, mediated by viscous pore fluid, appears adequate to explain the behavior of many natural grain flows, including lahars. The resisting stress owing to Coulomb friction can be given in simple form as

$$\tau_f \cong \nu(\rho_s g h - P)\tan(\phi),$$

where g is the gravitational constant, h is the depth from the surface, $\tan(\phi)$ is the friction coefficient, and P, the fluid pressure, is hydrostatic such that $P \sim \rho_f g h$. In large-scale debris-flow experiments, however, $\rho_f g h < P < \rho_s g h$ is common and the flow is thus partly liquefied. (Note that if $P \sim \rho_s g h$, pressure is lithostatic and the flow is completely liquefied such that it will move across even the gentlest gradient.) These experiments further show that P varies with position such that the flow perimeter is commonly not liquefied ($P = \rho_f g h$, or hydrostatic) and the flow interior is approximately 80% liquefied ($P = 0.8\ \rho_s g h$, or close to lithostatic) (Iverson gives a more detailed discussion of this subject).

Variation in P results from the segregation and migration of large particles to flow margins. Concentrations of large particles at flow margins diminish permeability there and thus preclude even short-duration pressures greater than hydrostatic. However, interior parts of flows contain abundant fine-grained particles that greatly decrease permeabilities to such small values that pressures much greater than hydrostatic can be maintained for times greater than the duration of debris flows.

Because lahars are unsteady and nonuniform, owing to particle segregation processes, and, in particular, owing to probable variation in P and other parameters with position in each lahar, no simple mechanical model can be successfully applied to these flows. Numerical analysis can approximate lateral and longitudinal variations that are obviously common in most lahars. A two-dimensional, depth-averaged model can include lateral heterogeneities and gives reasonable predictions of flow shape and runout for a wide variety of conditions. Indeed, such a model can qualitatively explain all observed features of large-scale experimental flows described in Iverson. In the future, modelers may be able to extend models of this type to three dimensions without too many restrictive assumptions or too many troublesome analytical problems.

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