# *Chapter 11* Lahars

The name lahar is Indonesian for volcanic breccia transported by water (van Bemmelen, 1949, p. 191) but has come to be synonymous in geological literature with volcanic debris flow, a mass of flowing volcanic debris intimately mixed with water. The term lahar refers both to the flowing debris-water mixture, and also to the deposit thus formed. A classic review of the various origins of lahars is that of Anderson (1933). A more recent discussion of lahar deposits by Parsons (1969) is included in a review of volcanic breccias. Crandell (1971) gives an account of the origin and characteristics of post-glacial lahars from the slopes of Mount Rainier volcano (Washington), and Neall (1976) has prepared a bibliography of their global occurrences. The recent eruptive phases of Mount St. Helens (Washington) produced lahars in a variety of ways (Christiansen, 1980; Janda et al., 1980; Janda et al., 1981; Harrison and Fritz, 1982) but investigations of these have not been completed to date.

Many lahars are associated with stratovolcanoes of which they may comprise significant volumes of the volcanoes' bulk. Most stratovolcanoes are of andesitic to dacitic composition, and hence most lahars have been reported from Indonesia, the western U.S. (Cascade volcanic chain), Japan, New Zealand, and Central and South America, but they are also associated with stratovolcanos of other compositions such as Vesuvius (Italy) and Hekla (Iceland). Lahars of much smaller dimensions occur during many phreatomagmatic eruptions of diverse chemical composition.

Most modern, Holocene, or Pleistocene lahars are relatively limited in extent and occur in valleys or on alluvial aprons or lowland areas immediately surrounding volcanoes, but in the geologic record there are extensive areas of laharic accumulations where volcanic edifices no longer exist. These can cover thousands of square kilometers and span several million years in time. For example, in the Absaroka Mountains (Parsons, 1969), extensive early Eocene to early Oligocene laharic breccias associated with lava flows and related volcaniclastic sediments once covered about 10,350 $km^2$. In the central and northern Sierra Nevada, late Miocene and early Pliocene lahars (Curtis, 1954) extended over 31,080 $km^2$, and in the southern Cascade Range, late Pliocene lahars covered 5180 $km^2$ (Anderson, 1933; Lydon, 1969). Although the rocks of these large volcanic tracts are of diverse origin, lahars are dominant. However, there are no comprehensive studies that treat the facies of such large accumulations or their relationships to the evolution and possible periodicity of the growth of a volcano.

## Debris Flows as Fluids

Many lahars are initiated directly by volcanic eruption, whereas others originate in ways similar to nonvolcanic debris flows, but once flow begins their fluid characteristics appear to be similar or identical. Thus, studies of all kinds of debris flows contribute to our understanding of the fluid properties of lahars. Debris flows are non-Newtonian fluids that have a yield strength. They behave like plastic materials similar to wet concrete, have a high bulk density, and exhibit the property of strength which greatly influences the final textures and structures of the deposits. The Newtonian properties of water (i.e. lacking in yield strength) begin to be modified by particle interference when the volume of solids exceeds 9 percent (Bagnold, 1954b, 1955). Estimates vary, but at volume concentrations of about 20 or 30 percent particle interactions almost completely dominate flow behavior (Middleton, 1967).

Beverage and Culbertson (1964) defined hyperconcentrated streams as those with 40 to 80 percent by weight of solids, and mudflows (debris flows) as containing 80 percent by weight or more (about 60 percent by volume) of solids. Debris flows, however, differ from hyperconcentrated streams (streams in flood) in flow behavior and depositional mechanisms, but the concentrations that determine behavior depend also upon the grain sizes and their size distribution. In stream flow, including that of hyperconcentrated streams, large and small particles are carried in the water by turbulence and traction processes; as velocity decreases, progressively smaller fragments settle out of the water. On the other hand, debris flows are fluids in which the water and solids form an intimate mixture that flow with laminar motion. As velocity decreases, the entire flow stops rather abruptly, after which water separates from the granular material by percolation or evaporation. On steep slopes, velocities may be rapid enough (internal shear stress high enough) to keep the entire mass in motion, but as slope decreases, internal shear stresses fall below the critical yield stress, so that the mass will congeal unless it is thick enough to maintain a high shear stress at the base of the flow. If so, the basal part of the flow will continue to move in laminar fashion and carry the rigid plug above it. As the gradient decreases, velocities decrease, and the flow thins, shear stresses increase until the flow congeals to its very base and deposition is complete (Johnson, 1970). Observations by Broscoe and Thomson (1969) on a debris flow in the Yukon showed that the newly deposited debris remained in a quasi-fluid state for many days, and 2 weeks after coming to rest, a thin crust developed over still-fluid material beneath.

If the concentration of solids in a debris flow is taken to be 80 percent or more by weight, then many flows called lahars or mudflows with lower concentrations actually are water floods (hyperconcentrated streams). Lahars described by Waldron (1967), for example, were mostly floods because they varied in concentration from 20 percent to about 80 percent. Maximum concentration values greater than 90 percent for nonvolcanic debris flows have been reported (Curry, 1966); a commonly reported lower limit is 70 percent (Sharp and Nobles, 1953). The distinction between debris flow and hyperconcentrated stream deposits, however, is poorly defined and it is not certain if their deposits can be separated on field criteria.

A useful concept for the theoretical and practical treatment of debris flows is to consider them to be composed of two phases: (1) a continuous phase (matrix or fluid phase) consisting of an intimate mixture of water with particles $<2$ mm; and (2) a dispersed phase consisting of particles $>2$ mm (Fisher, 1971). Thus, even though there may be a continuum of grain sizes from clay to boulders, it is possible to conceptually consider viscosity, density, strength, etc. of high concentration dispersions without regard to the individual properties or behavior of single particles: the continuous phase is the fluid that transports the large fragments. Moreover, treatment of the continuous (matrix) phase separately from the dispersed phase would be useful for standardizing size limits used by various authors to characterize and compare different debris flow deposits.

## Distribution and Thickness

Lahars follow pre-existing valleys and may be interstratified with alluvium, colluvium, pyroclastic rocks of diverse origin and lava flows derived from the same source area. They may leave thin deposits on steep slopes and in the headwaters of valleys, but become thicker in valley bottoms and form fans that coalesce or else form broad individual digitate lobes in lowland areas on very low slopes somewhat similar in distribution to pyroclastic flow deposits (Figs. 11-1, 11-2). The movement of lahars down valleys generally occurs in surges, or peaks of flow. During their course down a valley, lahars tend to leave thin "high water" marks (veneers) where a constriction momentarily causes a large debris flow to pond up to several tens of meters above the valley bottom and then drain away. Also, their momentum may carry them farther up the outer part of a bend in a stream curve. Veneers of over 150 m above present valley floors are reported by Crandell (1971).

Lahar assemblages at Nevado de Toluca volcano, Mexico (Bloomfield and Valastro, 1977) occur as an older series of overlapping and coalescing sheets and fans that give rise to a smoothly-rounded undulating topography. They lie upon a sloping (6°–8°) piedmont area surrounding the volcano. Farther up on the volcano, the rugged, forested slopes are underlain by lava flows. Younger lahars radiate outward from the volcano and occupy valleys cut in the older lahar assemblages and lava flows. It is possible, however, that some of the lithic-rich deposits described as lahars by Bloomfield and Valastro (1977) are pyroclastic flows. As evidence for a lahar origin they cite absence of bread-crust blocks and carbonized wood and small content of pumice and glass (Bloomfield and Valastro, 1977). However, the May 8 and May 20, 1902 nuée ardente deposits from Mt. Pelée (Fisher et al., 1980) fit this description, as do some of the pre-1980 deposits at Mount St. Helens Volcano, Washington (Crandell, personal commun., 1978). Thermoremanent magnetization of some of the lithic-rich Mount St. Helens deposits (Hoblitt and Kellogg, 1979) indicates that they were emplaced above their Curie temperatures, and thereby suggests that water was not the mobilizing agent.

Lahars vary greatly in thickness. They tend to maintain a relatively constant average thickness on relatively low slopes but locally vary depending upon the configuration of underlying topography. Lahars and other debris flows come to rest with steep sloping lobate fronts (Johnson, 1970). Most lahars are probably less than 5 m thick (Mullineaux and Crandell, 1962; Schmincke, 1967b; Crandell,

**Fig. 11-1.** Peripheral laharic fans formed a few days to weeks after the January to April 1976 eruption of dacitic Augustine Volcano (Alaska). Deposits are covered with pumice pebbles and are cut by stream valleys. (Photograph taken August, 1976)

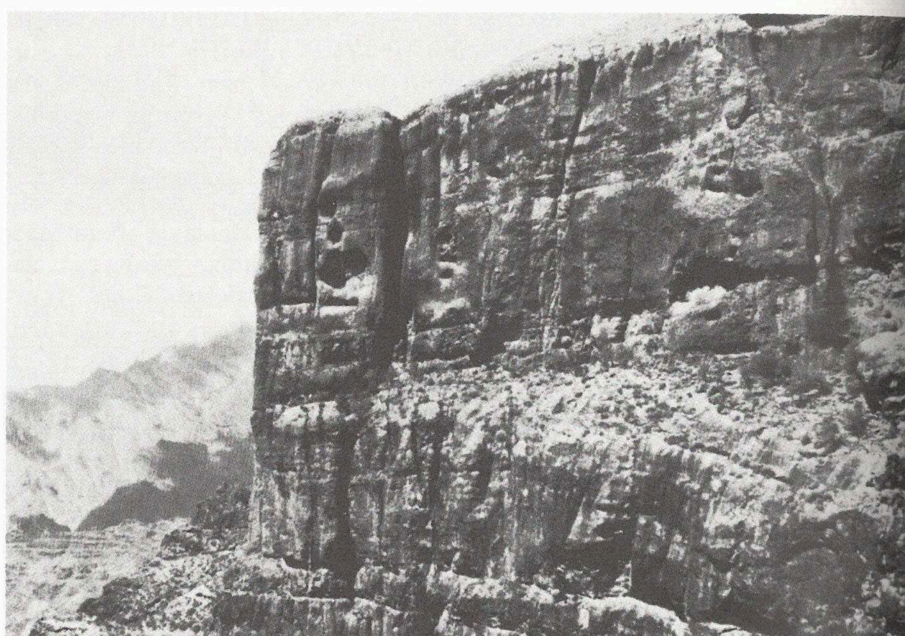
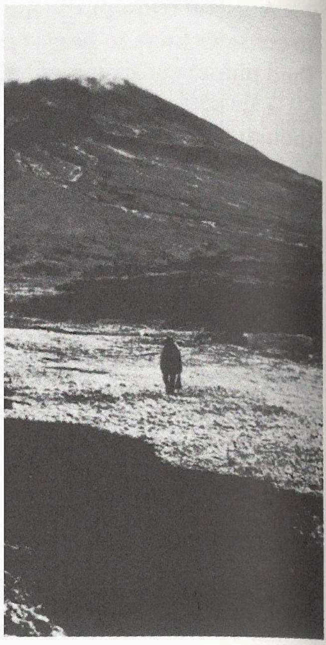


**Fig. 11-2.** Lahars of tephritic composition of Pliocene Roque Nublo Formation interbedded with 5-m-thick lava flow in lower part. Gran Canaria (Canary Islands) (Schmincke, 1976)



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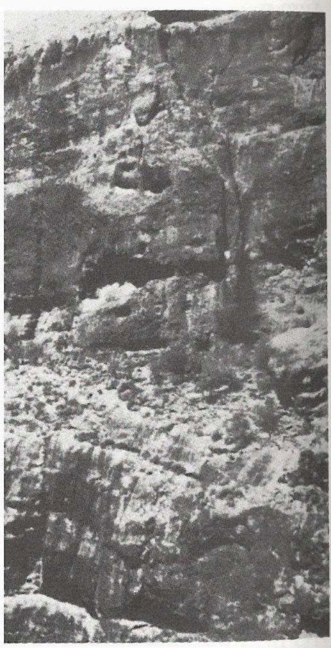

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**Table 11-1.** Dimensions of some lahars

| Name of lahar, volcano or formation | Date of eruption | Distance travelled (km) | Thickness (m) | Area (km²) | Volume (km³) |
|---|---|---|---|---|---|
| Ellensburg Formation, USA (Schmincke, 1967b) | Miocene | 60 | | | |
| Yatsuga-dake, Japan (Mason and Foster, 1956) | Pleistocene | 24 | | | 9.6 |
| Raung, Java (Macdonald, 1972) | Prehistoric | 56 | | | |
| Paradise, Mt. Rainier, USA (Crandell, 1971) | 6000 y. BP | 30 | 4.5 (max.) | 34 | 0.1 |
| Osceola, Mt. Rainier, USA (Crandell, 1971) | 5700 y. BP | 110 | 6 (av.) 60 (max.) | 260 | >2.0 |
| Mount St. Helens, USA (Mullineaux and Crandell, 1962) | 2000 y. BP | 65 | | | |
| Electron, Mt. Rainier, USA (Crandell, 1971) | 600 y. BP | 50 | 4.5 (av.) 8 (max.) | 36 | 0.15 |
| Galungung (Macdonald, 1972) | 1822 | 65 | | | 0.03 |
| Cotopaxi, Ecuador (Anderson, 1933) | 1877 | >240 | | | |
| Mt. Lassen, USA (Macdonald, 1972) | 1915 | 46 | | | |
| Kelut, Java (Anderson, 1933) | 1919 | 40 | 50 (max.) | 130 | |
| Santa Maria, Guatemala (Anderson, 1933) | 1929 | 100 | | 15 | |
| Mount St. Helens, N. Fork Toutle River, Washington, USA (Janda et al., 1981) | May 18, 1980 | >120 | 1–2 | | >0.36 |

1971), but some are more than 200 m thick (Bloomfield and Valastro, 1977) and may be as thin as 0.5–1 m (Curtis, 1954). Despite their importance as common products of stratovolcanoes and as one of the most dangerous of volcanic hazards, there are few detailed sedimentological studies of either fossil or historic lahars (Table 11-1).

## Surface of Lahars

Lahar surfaces tend to be remarkably flat over wide areas but in detail contain local swells and depressions interpreted to be caused by differential compaction over an irregular underlying surface (Crandell and Waldron, 1956). The form, shape, and size of irregularities, however, depend upon the viscous properties of the flows and the number and characteristics of multiple lobes. In the past, deposits interpreted

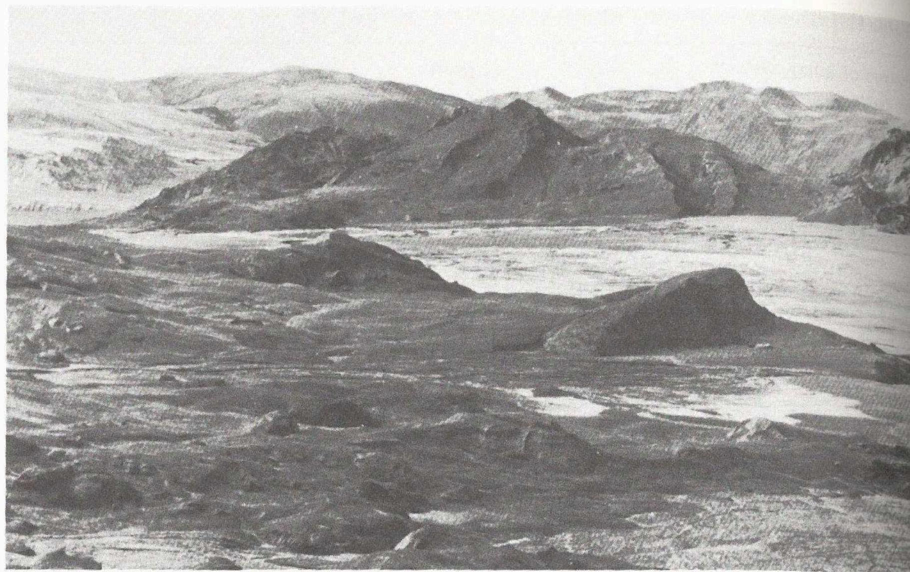

**Fig. 11-3.** Dark, hummocky landslide-debris flow of May 18, 1980 Mount St. Helens eruption, Washington (USA). Hummocks about 30 m high. Light colored area with planar surface is underlain by pumice flow deposits. (Photograph taken September 1980)

as lahars with unusually hummocky surfaces have been reported by Escher (1920), Grange (1931), Mason and Foster (1956), Aramaki (1963), Gorshkov and Dubik (1970) and others. However, the collapse and avalanching of the north side of Mount St. Helens volcano on May 18, 1980 produced a hummocky deposit much like those previously described as lahars and cast doubts upon their interpretation as lahars (Voight et al., 1981). The Mount St. Helens rockslide-avalanche deposit, with a volume of 2.8 $km^3$, has hummocks that are as much as 170 m wide and protrude about 30 m above the mean elevation of the surface of the deposit (Fig. 11-3). The material was emplaced at a temperature that approached boiling water. It was unsaturated by water during emplacement, but its momentum imparted to it an enormous mobility. The hummocks consist of huge brecciated chunks of the mountainside set in a poorly sorted "matrix" ($S_0 = 2.9$ to 13.0; average $= 7.1 : S_0 = Q_{75}/Q_{25}$, where Q is the size measure on a cumulative curve at the indicated percentages 25 and 75 and $S_0$ is a sorting measure; Table 5-6). There is no systematic down-valley change in sorting values of the matrix. The question of how the matrix developed from the original solid rock of the mountainside remains unsolved.

## Basal Contact of Lahars

Although lahars and other debris flows may be very thick and carry large boulders, they commonly do not erode the surfaces on which they flow except on very steep slopes. Curry (1966) reports that talus was incorporated by a bouldery debris flow observed by him moving on slopes of 35° to 41°, but on slopes of 7° to 10°, where velocities were low, the flow did little harm to meadow grass despite the fact that large boulders were abundant. The 1941 Wrightwood, California, debris flow rests in places on a carpet of pine needles covering low slopes (Sharp and Nobles, 1953), and Crandell (1957, 1971) notes that debris flow deposits conformably overlie soft soil profiles, peat deposits and thin layers of sand and volcanic ash on slopes of up to 7.5°. Molds of inclined grass were noted at the base of several Miocene lahars of the Ellensburg Formation, Washington (Schmincke, 1967b). Lahars can pick up loose materials from surfaces on steep slopes or where local turbulence develops within the flow owing to highly irregular channels. Some Pleistocene lahars in the southern part of the Puget Sound lowland, however, have traveled 60 to 80 km from their source without picking up appreciable debris from the surface on which they flowed (Crandell, 1963).

## Components of Lahars

Depending upon their origin, lahars may be monolithologic or heterolithologic. Monolithologic varieties are likely to be derived directly by eruption, whereas collapse of crater walls or avalanching of rain-soaked debris covering steep volcanic slopes are more likely to give rise to heterolithologic types. Pumice-rich lahars are described (Bond and Sparks, 1976; Wright, 1978), which resemble pumice-rich deposits of hot, dry pyroclastic flows (Mullineaux and Crandell, 1962), but are distinguished from hot flows mainly by thermal analysis of the magnetism (Aramaki and Akimoto, 1957).

Lahars characteristically contain dense angular to subangular rock of dominantly andesitic to dacitic composition mixed with ash-sized minerals and lithic particles.

Many lahar deposits contain charred wood (Crandell and Waldron, 1956; Fisher, 1960; Mullineaux and Crandell, 1962; Schmincke, 1967b; Crandell, 1971), indicating that they were initiated as hot pyroclastic flows then cooled down during transport. Analysis of fragments from one lahar containing charcoal showed clustered rather than random orientation of north-seeking poles, suggesting that parts of the deposit were above the Curie point when the deposit came to rest (Mullineaux and Crandell, 1962). Emplacement temperatures of various deposits are discussed by Hoblitt and Kellog (1979).

## Grain-Size Distribution

Particles carried by lahars range from clay- to boulder-size, but the percentages of each size fraction vary enormously from deposit to deposit and also within a single deposit. In general, lahars are coarser-grained and more poorly sorted than pyroclastic flow deposits, although there are many exceptions. The block-and-ash flows from the ill-famed 1902 eruptions of Mt. Pelée, for example, are coarser-grained than many lahars that originate from loose ash on the steep slopes of volcanoes.

Grain-size parameters reported by various authors (Table 11-2) show the obvious fact that lahars and nonvolcanic debris flows have a wide range in grain size and are coarse-grained and poorly sorted, but the data are not strictly comparable

**Table 11-2.** Grain-size parameters of some lahars compared with nonvolcanic debris flows

| Locality | $Md_\phi$ | $\sigma_\phi\ (=\phi_{16}-\phi_{84}/2)$ |
|---|---|---|
| Mt. Rainier, Washington (Crandell, 1971) Lahar Deposits | Range: 3.4 to −3.7<br>Av.: −1.7<br>(30 samples) | Range: 2.78 to 5.79<br>Av.: 4.44<br>(38 samples) |
| Irazu Volcano, Costa Rica (Waldron, 1967) Flowing Lahars | Range: 3.87 to 0.75<br>Av.: 1.88<br>(10 samples) | Range: 2.62 to 4.04<br>Av.: 3.12<br>(10 samples) |
| Tokachi-Dake Volcano, Japan (Murai, 1960) Lahar Deposits | Range: 0.20 to 1.23<br>Av.: 0.58<br>(4 samples) | Range: 3.07 to 5.43<br>Av.: 4.06<br>(4 samples) |
| Non-volcanic debris flows from an alluvial fan (Bull, 1964) | Range: 0.2 to 10.0<br>Av.: 2.9<br>(48 samples) | Range: 4.0 to 6.2<br>Av.: 4.7<br>(27 samples) |

because of different sampling procedures, laboratory techniques, and total number of samples analyzed by individual authors. Also, because lahar deposits tend to contain abundant coarse-grained fragments, fine-grained lahars or the finer-grained matrix of coarse-grained lahars are more apt to be analyzed granulometrically for technical convenience. In outcrop (Fig. 11-4), however, many lahar deposits appear to be coarser-grained than shown by granulometric analysis because the statistically few boulders that might be present are visually more impressive than the smaller particles and thereby give a false impression of true size values. The presence of large boulders, commonly exceeding 1 m in diameter, is one of the most characteristic features of lahars except perhaps, in their terminal zones (Crandell and Waldron, 1956; Crandell, 1971; Curtis, 1954; Schmincke, 1967b).

A study by Sharp and Nobles (1953) of the 1941 Wrightwood debris flow showed lateral changes in grain size of boulders. The large fragments progressively decreased in number and size away from the source, although the finer constituents (matrix) did not show corresponding changes. Erratic fluctuations in median diameter were attributed to the longitudinal inhomogeneity of the flow caused by deposition from individual debris tongues that differed in grain size. The flow occurred as a succession of many debris flow surges per day over a period of 10 days; the longest of the surges travelled a maximum distance of 26 km. The total deposit is a sequence of overlapping tongues of variable length. One study of a lahar in Japan (Murai, 1960) showed that median diameters did not vary systematically over a distance of 3 km, but only four samples were analyzed.

Because boulders cannot be included in standard size analyses and therefore lahars cannot be completely characterized granulometrically, we compare (Fig. 11-5) matrix phases (sand/silt/clay recalculated to 100%) of different debris flows and also the May 18, 1980 Mount St. Helens rockslide avalanche and blast deposit (Voight et al., 1981). As shown, lahars tend to contain less clay-size material than nonvolcanic debris flows. A possible reason is that fragments in volcanic deposits on the whole may be diagenetically less mature than nonvolcanic debris which is derived by weathering rather than explosive or other volcanic processes. The abunı nonvolcanic debris flows

| $\sigma_\phi\ (=\phi_{16}-\phi_{84}/2)$ | $S_0=\sqrt{Q_{75}/Q_{25}}$ | Comments |
|---|---|---|
| Range: 2.78 to 5.79<br>Av.: 4.44<br>(38 samples) | Range: 3.41 to 17.0<br>Av.: 10.37<br>(39 samples) | $Md_\phi$ figures converted from mm units using graph |
| Range: 2.62 to 4.04<br>Av.: 3.12<br>(10 samples) | Range: 2.58 to 7.01<br>Av.: 4.61<br>(10 samples) | $Md_\phi=0.75$ converted from mm units given by Waldron. Published figure is wrongly given as $Md_\phi=3.35$ |
| Range: 3.07 to 5.43<br>Av.: 4.06<br>(4 samples) | Range: 1.81 to 3.72<br>Av.: 2.70<br>(4 samples) | The 4 samples reported are from the lahar of May 24, 1926 |
| Range: 4.0 to 6.2<br>Av.: 4.7<br>(27 samples) | Range: 5.1 to 25<br>Av.: 9.7<br>(46 samples) | |

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dance of clay that occurs in the matrix of a few lahars has been a matter of some debate, but Crandell (1971) convincingly shows that the clay in Mount Rainier lahars is derived from a source area where marked hydrothermal alteration had occurred. This kind of plot does not distinguish the Mount St. Helens rockslide avalanche matrix from lahars.

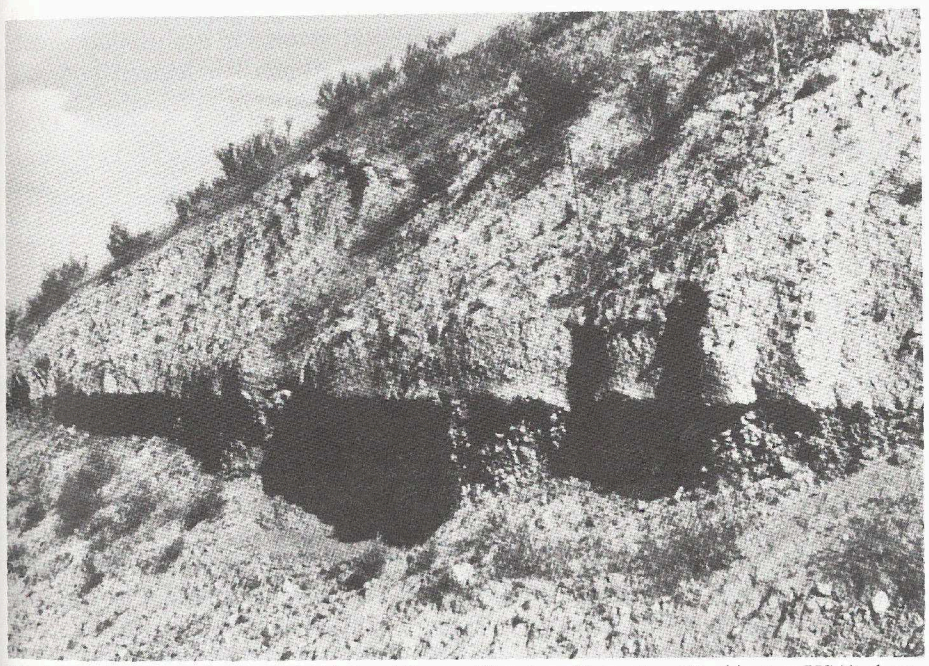


**Fig. 11-4.** Dacitic lahar (~4 m thick) in late Miocene Ellensburg Formation (Washington, USA), showing 10-cm-thick fine-grained base and concentration of larger boulders in lower third (Schmincke, 1974a)

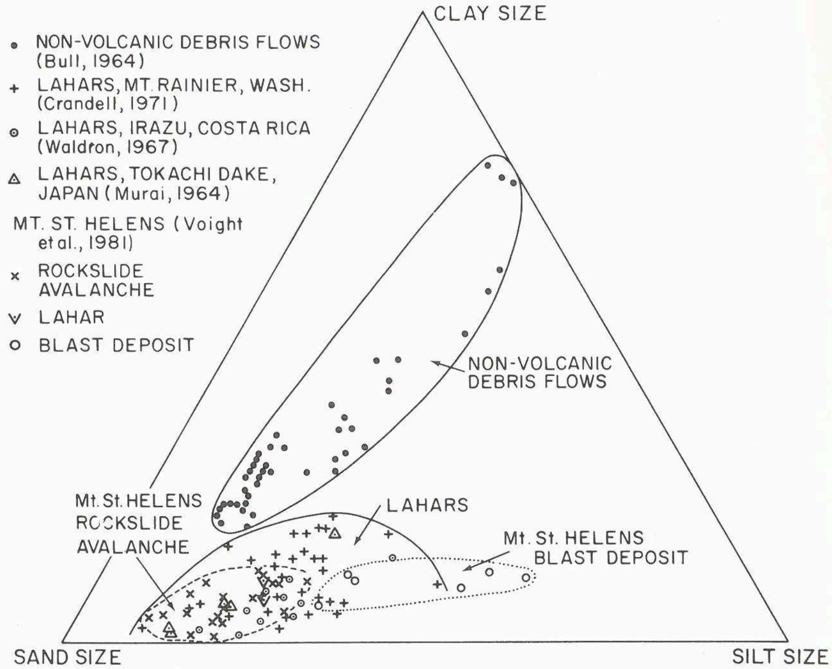
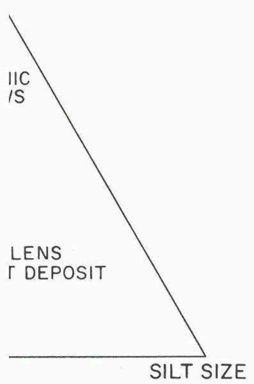



**Fig. 11-5.** Grain size of matrix of volcanic and nonvolcanic debris flows, and Mount St. Helens rockslide avalanche deposit (Washington, USA)

## Vesicles

Air spaces that we call vesicles occur in lahars (Crandell and Waldron, 1956; Crandell, 1971), base surges and other hydroclastic deposits (Chap. 9). Vesicles also have been reported by Sharp and Nobles (1953) and Bull (1964) in nonvolcanic debris flows. In fine-grained deposits air spaces tend to be spherical whereas in coarse-grained deposits air spaces are irregular in shape and therefore may be overlooked. Vesicle diameters range from nearly a millimeter up to a centimeter or more and may by scattered or concentrated adjacent to large particles or impermeable clastic horizons.

Vesicles in lahars have been explained as trapped air bubbles (Crandell and Waldron, 1956; Crandell, 1971) rather than by the draining away of free water after the lahar came to rest. The best evidence of air bubble origin is the occurrence of spherical cavities. Steam cavities also may form in some hot lahars, similar to those in tuffs formed by phreatomagmatic eruptions. We observed that small cavities are common in debris flow deposits at Wrightwood, California and elsewhere, but nearly all such cavities are irregular in shape; only rarely can spherical cavities be found, and these are confined to muddy parts of the deposit.




flows, and Mount St. Helens rockslide

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## Grading

Many lahar deposits show a subtle grading of the coarse-grained (>2 mm) dispersed phase, but it may not be evident in the matrix phase (see Crandell, 1971, Table 2). Single depositional units generally have an irregular but slightly more concentrated arrangement of large fragments a short distance above the base of the lahar (Schmincke, 1967b); such layers are reversely graded (Fig. 11-4). The large fragments in a lahar rarely rest directly upon the depositional surface. However, reverse grading with the coarse fraction becoming progressively larger to the top of a deposit is very rare unless low density pumice is abundant. Photographs in Crandell (1971, Figs. 10, 21, 27, 29, 33), Macdonald (1972, Plate 8-7), Parsons (1969, Plate 3) and examples of many other lahars, e.g. in the Canary Islands and Eifel, Germany, observed by us also show reverse-to-normal grading within the same bed (i.e., large boulders tend to be more common in the lower central zones). A relatively fine-grained basal layer from a few to several centimeters thick is indeed a common feature of lahars as well as pyroclastic flows (Sparks, 1976; Fisher et al., 1980) and also of nonvolcanic debris flows (Fisher, 1971).

Understanding how grading (or its absence) is developed is aided by observations of moving debris flows and by laboratory experiments. Reports of boulders bobbing along on the surface of flowing debris are common (Blackwelder, 1928), but whether the large fragments are actually floating at the top of a flow, tumbling within it, or saltate in slow fashion and bob to the surface occasionally, depends upon the settling velocity of the large fragments relative to the density and the plastic strength of the fluid. Some workers have suggested that large boulders are suspended by turbulence. Johnson (1970), however, convincingly shows that debris flows move in laminar fashion; therefore, large boulders are suspended by a combination of high density (buoyancy) and high strength of the matrix. His conclusion is based in part upon laboratory experiments with kaolin-water slurries that tended to move in laminar fashion when the clay content was greater than 10 percent by weight, and in part by observation of moving debris flows in the field. Field observations showed an essentially smooth-flowing surface indicative of laminar flow rather than a choppy surface characteristic of turbulent flow. Evidence from deposits that indicates gentle handling of debris, hence the absence of turbulence, includes unmodified fragile fragments such as tin cans, large blocks of brittle shale and wood fragments, but most convincing is the presence of unweathered fractured boulders that are still coherent or else so slightly scattered that the fragments can be fitted together like jig-saw puzzles. Johnson (1970, p. 513) attributes the gentle handling to plug flow (see section on fabric).

The mechanisms by which reverse grading develops are not well understood. According to Bagnold (1954b, 1955) dispersive forces act normally to flow boundaries during movement of concentrated dispersions. The transfer of momentum from grain to grain or from close grain encounters during flow supports individual grains throughout the flowing bed. Bagnold's equations show that the dispersive force acting upon a particle is proportional to the rate of shear, suggesting that when particles are sheared together, the larger particles will drift toward the zone with the least rate of shear (Johnson, 1970, p. 462). Sanders (1965, p. 202), Schmincke (1967b) and others have used this concept to explain reverse grading. Middleton (1970), however, suggests that reverse grading develops by smaller clasts falling downward between the larger clasts during movement, thereby preventing the larger ones from moving downward; hence the larger fragments would progressively work themselves relatively upward. The difference between these two ideas, however, appears to be one of *how* the process occurs rather than of different causes. Fisher and Mattison (1968) and Mattinson and Fisher (1970) attempt to explain reverse grading in terms of lift forces supplied to individual large particles resulting from lower pressures at the top than at the bottom of large particles due to different velocity gradients within the flow. Experiments by Southard (1970), however, suggest that such lift forces are very small although the sediments used by him were fine-grained.

Differences in grading, whether it be absent, weakly or strongly developed, normal or reverse, appear to be related to the relative concentration of solids and fluid; the lower the concentration of solids, the more likely it is that normal grading can develop because viscosity, density, and strength of the fluid are less able to support large dense particles as velocity decreases. Where concentration values and therefore viscosity, density, and strength are high, reverse grading is more likely to develop especially if the density of fragments is relatively low. Inasmuch as there may be a wide range in concentration values in different flows, from hyperconcentrated streams to debris flows of Beverage and Culbertson (1964), it is expected that all gradations between different kinds of grading will occur.

## Fabric

The fabric of lahars, and indeed most debris flows, is commonly regarded as isotropic, but in some lahars disc-shaped pebbles and uncharred twigs and tree trunks concentrated low in the central parts of the deposit are oriented subparallel to the base (Schmincke, 1967b).

The development, or lack thereof, of clast fabric in debris flows depends upon the mechanism of movement and deposition, and is a matter of some debate. Convincing arguments by Johnson (1970) and Hampton (1972), however, suggest that matrix strength in debris flows may produce a rigid plug where shear stress is below the yield threshold throughout (Johnson, 1970), and this plug rides on a zone of laminar flow within which the shear stress is greater than the yield threshold. Flow stops when the plug expands to the base of the flow at the expense of the zone of laminar flow, thus fabrics in the shearing region adjacent to the base become frozen in place during the last stages of flow and preserve the clast orientations, textures and structures of the debris flow.

In modern debris flow deposits, preferred orientations of platy or elongate fragments are reported as strongly aligned approximately parallel to flow surfaces (Fisher, 1971, Fig. 1), or random, parallel, and nearly perpendicular to channel axes within a single debris flow deposit (Johnson, 1965, p. 24, 31). Random orientation may be expected within the rigid plug if shearing does not occur, but within the basal zone of flow, movement is probably laminar and should leave its imprint with fragments either parallel to flow, inclined to flow, or imbricated (Enos, 1977). Fabric in debris flow is discussed by Lindsay (1966, 1968) and Enos (1977) and in other kinds of mass flow deposits (subaqueous) by Davies and Walker (1974), Hubert et al., (1975), Hendry (1976) and others.

## Comparison of Lahars with Other Kinds of Coarse-Grained Deposits

Other coarse-grained deposits that have characteristics similar to lahars and may be difficult to distinguish from them if the source rock is largely volcanic include till and tillite, fluvial gravels (flood deposits) and pyroclastic flow deposits. These deposits have no single unique feature that separates them, but several features taken together may help to discriminate between them (Table 11-3).

Lahars may be distinguished from volcaniclastic fluvial deposits by a greater abundance of clay-size particles and presence of extremely large boulders, that is, their extremely poor sorting, general absence of internal layering and channeling, greater thickness, distribution as flat-topped lobate deposits outside valleys, non-erosive basal contacts and presence of charred wood. Poor sorting and large boulders are also characteristic of till, but till lacks charred wood and commonly rests on striated bedrock.

The presence of striated fragments within coarse-grained deposits is regarded as evidence of a glacial origin, but as has been stated many times in the past, they also occur in lahars (Anderson, 1933; Cotton, 1944, p. 239–247; Crandell and Waldron, 1956; Curtis, 1954; Mason and Foster, 1956; and others). Grooves on underlying surfaces generally occur beneath glacial deposits but this also may occur on the surface beneath some lahars (Bloomfield and Valastro, 1977) and pyroclastic flow deposits (Brey and Schmincke, 1980).

The presence of abundant pumice may distinguish unwelded pyroclastic flow deposits from lahars, but where lahars have originated from hot pyroclastic flows that enter streams and become mixed with water, they may be difficult to identify. However, a coarse-grained poorly sorted deposit with individual rock fragments that have random directions of remanent magnetism is probably a lahar, and a deposit containing large groups of fragments having a preferred orientation is inferred to have been formed as a hot pyroclastic flow (Aramaki and Akimoto, 1957; Crandell, 1971; Crandell and Mullineaux, 1973; Hoblitt and Kellogg, 1979). Hot pyroclastic flow deposits may be oxidized by hot gases to pale red in their upper few meters. Some lahars derived from hot pyroclastic flows that become mixed with water and carry hot debris may confound all attempts to determine origin until detailed field mapping is done.

## Origin

Macdonald (1972) lists 12 different ways that lahars can originate, and these can be grouped into three major categories (Crandell, 1971):

1. Those that are the direct and immediate result of eruptions: eruptions through lakes, snow or ice; heavy rains falling during or immediately after an eruption; flowage of pyroclastic flows into rivers, or onto snow or ice.
2. Those that are indirectly related to an eruption or occur shortly after an eruption: triggering of lahars by earthquake or expansion of a volcano causing the rapid drainage of lakes or the avalanching of loose debris or altered rock.

**Table 11-3.** Comparison of coarse-grained deposits with lahars

| | Lahars | Till (excluding water-laid till) | Unwelded ignimbrite | Fluvial deposits |
|---|---|---|---|---|
| Large fragments (>2 mm) | May have boulders weighing many tons | May have boulders weighing many tons | Extremely large boulders absent | Extremely large boulders rare |
| Sorting | Poor. May contain abundant clay-size material | Poor. May contain abundant clay-size material | Poor. Clay-size material rare or absent | Poor to good. Clay-size material sparse |
| Grading | Commonly reverse. May be normal or absent | Commonly absent | Commonly absent, but may be normal or reverse | Commonly normal |
| Bedding and thickness | Commonly very thick with vague internal bedding | Very thick. Bedding poor or absent | Commonly very thick with vague internal layering | Thin with channels and cross beds. Shingled gravels |
| Composition | Commonly 100% volcanic. May be pyroclastic or mixed with epiclastic materials. May contain bread crust bombs | Commonly heterolithologic with admixtures from many sources. Plutonic, metamorphic and sedimentary clasts commonly more abundant than pyroclasts | Pyroclastic. May contain abundant bread crust bombs | Material usually 100% epiclastic except in areas of active volcanism |
| Rounding of large fragments | Commonly angular to subangular | Commonly faceted subangular to subrounded. May be faceted with striations and chatter marks | Commonly subangular | Commonly subrounded to rounded |
| Carbonaceous matter | Uncharred to charred | Uncharred | Charred | Uncharred if present |
| Pumice | Common in some lahars | Not present except on active volcanoes | Common | Not present except in areas of active volcanism |
| Distribution | In valleys spreading onto flat piedmont surfaces | Plains and valleys. May mantle all surfaces. Moraines with steep fronts | Lower parts of valleys and flat piedmont surfaces | Confined to valleys |
| Lower surfaces | Commonly not erosional | Erosional. Commonly rests on striated bedrock | Commonly not erosional | Erosional |

[a] Except close to caldera walls and in very proximal facies

| ded rite | Fluvial deposits |
|---|---|
| ely large ders absent | Extremely large boulders rare |
| Clay-size rial rare or nt | Poor to good. Clay-size material sparse |
| only absent, nay be normal verse | Commonly normal |
| only very thick vague internal ring | Thin with channels and cross beds. Shingled gravels |
| astic. May ain abundant d crust bombs | Material usually 100% epiclastic except in areas of active volcanism |
| only sub- ılar | Commonly sub- rounded to rounded |
| ed | Uncharred if present |
| ion | Not present except in areas of active volcanism |
| parts of eys and flat lmont surfaces | Confined to valleys |
| nonly not sional | Erosional |

3. Those that are not related in any way to contemporaneous volcanic activity: mobilization of loose tephra by heavy rain or meltwater; collapse of unstable slopes (in particular of diagenetically or hydrothermally altered clay-rich and water-soaked rocks); bursting of dams due to overloading; lahars that originate on the steep slopes of volcanoes of other volcanic terrane undergoing active weathering and erosion; sudden collapse of frozen ground during the spring thaw.

Perhaps the most common type of lahar forms during the waning stages of an eruption when large amounts of loose pyroclastic fall or flow deposits on the slopes become soaked by heavy rains that commonly occur during this stage of an eruption. Several workers have presented maps showing that with increasing distance from the center of an eruption, nuée ardente deposits are succeeded laterally by lahars on lower slopes of volcanoes (Wolf, 1878; Zen and Hadikusumo, 1965; Moore and Melson, 1969; Lipman and Mullineaux, 1981).

The water for some lahars may be from stores of snow and ice within the crater or locked up inside the porous superstructure of a volcano and driven out by an advancing heat wave (Roobol and Smith, 1975, p. 14) but much is meteoric water vapor drawn into the eruption plume and condensed upon contact with the cold atmosphere aloft. In other cases, the rain may be completely unrelated to an eruption. Other sources of water are melted snow or ice on the slopes of a volcano, rivers invaded by hot avalanches or pyroclastic flows, or crater lakes or dammed-up slope basins whose dams are broken by lava flows or other extruded products. Earthquakes may also trigger lahars, either during an eruption, or later.

Great floods formed at the beginning of many subglacial volcanic eruptions may be associated with lahars. They are especially common in Iceland where they are known as "jökulhaups" (Kjartansson, 1951).