U.S. Geological Survey—Reducing the Risk from Volcano Hazards

Lahar—River of Volcanic Mud and Debris

Lahar, an Indonesian word for volcanic mudflow, is a mixture of water, mud, and volcanic rock flowing swiftly along a channel draining a volcano. Lahars can form during or after eruptions, or even during periods of inactivity. They are among the greatest threats volcanoes pose to people and property. Lahars can occur with little to no warning, and may travel great distances at high speeds, destroying or burying everything in their paths.

Lahars form in many ways. They commonly occur when eruptions melt snow and ice on snow-clad volcanoes; when rains fall on steep slopes covered with fresh volcanic ash; when crater lakes, volcano glaciers or lakes dammed by volcanic debris suddenly release water; and when volcanic landslides evolve into flowing debris. Lahars are especially likely to occur at erupting or recently active volcanoes.

Because lahars are so hazardous, U.S. Geological Survey scientists pay them close attention. They study lahar deposits and limits of inundation, model flow behavior, develop lahar-hazard maps, and work with community leaders and governmental authorities to help them understand and minimize the risks of devastating lahars.

Lahars are among the most destructive and far-reaching ground hazards associated with volcanic eruptions. They can travel many tens of miles down valleys, move tens of miles per hour, and spill far beyond river-channel confines. Unlike floodwaters that recede and generally leave structures standing but coated in relatively thin deposits, lahars are slurries of sediment that can transport abundant rocks and woody debris. As a result, they can demolish buildings and other infrastructure and deposit muddy sand and gravel many feet (sometimes tens of feet) deep. Because of their destructiveness and propensity to deposit thick, rocky sediment, the effects of lahars can be long lasting, making reoccupation of inundated land difficult. Between 1600 and 2010, lahars caused more than 44,000 deaths worldwide, nearly 20 percent of all recorded fatalities associated with volcanic eruptions.

Lahars can occur during or after eruptions. Primary lahars are associated directly with eruptions. Secondary lahars occur after eruptions or during quiet periods between eruptions. Secondary lahars are a result of remobilization of volcanic sediment by heavy rainfalls, landslides, lake breaches, or water releases from glaciers, and they can occur weeks, months, or even centuries after an eruption.

Oblique aerial view of the remains of the town of Armero, Colombia, devastated by a lahar associated with the November 1985 eruption of Nevado del Ruiz. The lahar traveled more than 45 miles before destroying the town and killing more than 20,000 residents. U.S. Geological Survey photograph by R.J. Janda.

Eruptions, Landslides, Floods, and Downpours: Many Processes Generate Lahars

Lahars form in many ways. Major initiation mechanisms include:

- when hot volcanic rocks from explosive eruptions melt snow and glacier ice to form a mixture of water and debris that flows down slope;
- when very wet volcanic landslides liquefy and flow;
- when explosive eruptions eject water from crater lakes to form floods that erode sediment;
- when floods by other processes form at volcanoes and erode sediment from volcano slopes and river channels; and
- when rainfall erodes fresh volcanic ash from steep slopes.

How lahars begin can greatly influence flow volume, composition, behavior, and downstream damage. Lahars formed during explosive eruptions by snow-and-ice melt or ejection of crater lakes, by the failure of vast amounts of wet, weak rock from a volcano, or by sudden release of water from large lakes dammed by volcanic debris are likely to be large, fast, and very destructive far downstream from the volcano. Lahars formed by rainfall erosion of volcanic ash or by release of modest volumes of subglacial water are likely to be smaller and less far-travelled, but they are also more frequent and can overwhelm river channels and significantly affect downstream communities closer to volcanoes.

Video of a small lahar at Curah Lengkong River, Semeru volcano, Indonesia, January 19, 2002. Flow front is 11.5 feet tall, and flow is moving at a speed of about 12 miles per hour. Video courtesy of F. Lavigne, University of Paris, used with permission.

View video online at https://doi.org/10.3133/fs20183024.

Lahar—A Range of Sediment-Water Mixtures

A lahar can look and act very differently depending on its ratio of solids to water. A high-sediment-concentration *debris-flow lahar* has roughly equal proportions of sediment and water and looks very much like a flow of wet concrete. It transports sediment that typically ranges broadly in size, from clay particles to boulders as large as cars. A more dilute *hyperconcentrated-flow lahar* consists of more water than sediment, and has a more liquid appearance commonly described as oily or creamy. It is a type of flow broadly transitional between muddy water and a dense, concrete-like slurry. The sediment carried by this intermediate-type flow is dominantly sand, but it can roll large rocks along the channel bed, and it can be very damaging to channel banks and bridge piers. As a lahar moves downstream, its character and appearance can evolve as it erodes or deposits sediment and mixes with river water.

Oblique downstream views of a water flood (left) and high-sediment-concentration slurry (right) that formed on White Salmon River following the breach of Condit Dam, Washington. The high-concentration slurry is very similar to lahars that form at volcanoes. Note the thick, almost milkshake-like, texture of the slurry compared to the turbulent water flood. Inset images show sediment-concentration samples from the passing flows. Channel is about 100 feet wide. U.S. Geological Survey photographs by J.E. O'Connor.

Eruption-Triggered Melting and Mixing of Snow and Ice

At snow-covered and glaciated volcanoes, hot, dry flows of volcanic rock debris and gas—known as pyroclastic flows or surges (or more generally as pyroclastic currents)—commonly trigger lahars. The hot currents sweep across snow- and ice-covered slopes, intensely scour and mix with snow and glacier ice, and produce watery floods or slurries that flow away from the volcano. As these volcanically triggered flows race downhill, they erode additional sediment from the volcano's flanks and river channels, grow in volume, and become sediment-rich lahars. Notable lahars of this type formed during eruptions of Mount St. Helens, Washington, in 1980, and Nevado del Ruiz, Colombia, in 1985.

At Mount St. Helens, hot debris from a pyroclastic current swept across the snow-covered upper west and east flanks of the volcano. On each flank, the hot debris scoured and mixed with snow and ice and swiftly formed lahars with volumes of about 20 million cubic yards. These lahars traveled many tens of miles downvalley at speeds of tens of miles per hour.

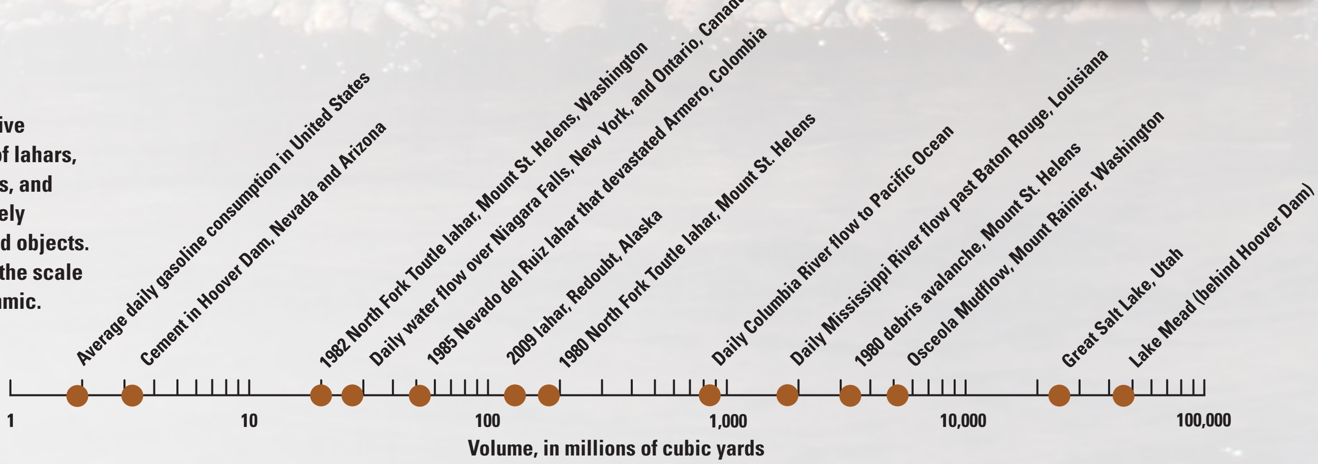
At Nevado del Ruiz, pyroclastic currents from a modest-sized eruption rapidly melted snow and ice on the volcano's summit and produced abundant meltwater. The resulting floods eroded ample sediment from several steep, narrowly confined valleys, and transformed to lahars. Those lahars descended more than 16,000 feet in elevation from the summit and traveled more than 60 miles. One lahar emerged from a confined canyon 45 miles downstream from the summit and destroyed the town of Armero, killing more than 20,000 people.

Eruptions of ice-clad Redoubt volcano, Alaska, in 1989–90 and 2009 also generated large lahars. Several of these lahars flowed more than 25 miles to Cook Inlet and threatened or partly damaged an important oil storage and transfer facility. In 2017, the terminal owner decided to close the facility to eliminate environmental risk from future lahars.

Lahar flows can be deep. Mud coating on trees (above right) shows the depth of a lahar in Toutle River valley caused by the 1980 eruption of Mount St. Helens. U.S. Geological Survey photograph by L.J. Topinka.

Deposits of ancient (~2,500-year-old) lahars at Mount St. Helens, Washington (immediate right), caused by breaching of a lake dammed by volcanic material. Note the coarse, poorly sorted textures of the deposits that consist of particles ranging in size from microscopic clay to basketball-size boulders. U.S. Geological Survey photograph by J.J. Major.

House and bridge (left) damaged and buried by lahars from the 1980 eruption of Mount St. Helens, Washington. U.S. Geological Survey photographs by L. J. Topinka (above) and R.B. Waitt (below).



Comparative volumes of lahars, river flows, and other widely recognized objects. Note that the scale is logarithmic.

Transformation of Landslides

Collapse of a large segment of a volcanic cone can produce a very large lahar if the landslide is very wet and transforms from a slide to a flow as it hurtles downslope. A classic example of this type of lahar is the Osceola Mudflow from Mount Rainier, Washington, which formed during an eruption 5,600 years ago. High on the volcano's flank, weak, water-saturated rock collapsed. That material slid downslope and transformed to a deep, concrete-like flow within one mile of its source. This lahar, nearly a cubic mile in volume, funneled into and filled mountain valleys 250–500 feet deep, flowed more than 60 miles to Puget Sound—filling in one of its bays—and flowed as far as 10 miles underwater.

Most catastrophic landslides at volcanoes do not transform immediately, if at all, to lahars. For example, the 0.6-cubic-mile landslide that occurred during the 1980 eruption at Mount St. Helens (known as the debris avalanche) slid off the volcano and came to a complete stop. Then, over the next hours, water-saturated parts of the deposit liquefied and began to flow. Many small flows coalesced to produce the 180-million-cubic-yard North Fork Toutle River lahar. The lahar was the largest of the 1980 eruption. It flowed about 60 miles from the volcano to the Columbia River, where it filled the channel and disrupted international commercial shipping for months.

Heavy rainfall and snowmelt can also trigger smaller landslides at volcanoes. Such meteorologically triggered landslides are generally shallow slope failures (a few tens of feet thick). Unlike larger catastrophic landslides, these smaller but still dangerous landslides commonly transform to lahars that range from a few thousands to a few hundreds of thousands of cubic yards in volume. Intense rainfalls in 2009 at the inactive San Vicente volcano, El Salvador, and in 2013 at Izu Oshima volcano, Japan, triggered several shallow landslides that evolved into damaging and deadly lahars.

Sediment Erosion During Floods

Though many lahars start with large volumes of solids—newly erupted rock fragments or landslide debris—others start as abrupt water floods that subsequently erode and ingest enough sediment to grow in volume and become thick slurries. These floods form by sudden release of water, such as from a summit crater lake, by breaching of a valley-margin lake dammed by volcanic sediment, by eruption-triggered meltwater floods, or by sudden release of water from a volcano glacier.

Lahar at Mount St. Helens generated by melting of crater snow during a small explosion in March 1982. U.S. Geological Survey photograph by T. Casadevall.

The largest known lahar at Mount St. Helens occurred about 2,500 years ago when a large lake dammed by volcanic debris breached its blockage. Sudden release of lake water produced a series of flood surges that entrained channel sediment over a miles-long valley reach. The largest of this series of flows had a volume of about 1 billion cubic yards.

In 1980, the debris avalanche from the eruption of Mount St. Helens also dammed the outlet of a large lake at the foot of the volcano, which caused lake water to rise. To prevent the lake from breaching this new blockage and forming an enormous lahar similar to those 2,500 years ago, the U.S. Army Corps of Engineers built a drainage tunnel to provide a safe outlet and stabilize the lake level.

The largest lahar at Mount St. Helens since the 1980 eruption happened when a temporary meltwater lake formed and spilled from the crater. In 1982, an explosion from the lava dome growing in the volcano's crater sprayed hot rock across the crater walls, which melted thick snowpack. The snowmelt formed the temporary lake when the rate of melt exceeded the rate that water flowed from the crater. Released lake water produced a flood that eroded sediment and transformed into a 20-million-cubic-yard lahar that flowed at least 50 miles downstream. It damaged a small sediment-retention dam, but otherwise caused no significant harm.

Release of water from existing crater lakes can occur during an eruption. Kelut volcano in Indonesia is notorious for blasting water out of its crater lake during eruptions and generating large, hot, acidic floods that scour sediment from the volcano's flanks and form deadly lahars. In 1919, an explosive eruption of Kelut through its crater lake caused lahars that killed more than 5,000 people. An eruption in 1966 again blew water out of the lake, causing lahars that killed another 211 people. Drainage tunnels now limit the volume of the crater lake, reducing the amount of lake water available to form lahars.

Crater lakes can also release water during periods of inactivity. Several times, the summit crater lake at Ruapehu volcano, New Zealand, has breached its volcanic sediment dam (formed during eruptions by heavy ash fall) during lulls between eruptions and produced notable lahars. The most tragic of these happened in 1953, when the sediment dam failed and released much of the lake water. The resulting lahar poured downvalley and destroyed a railroad bridge only minutes before arrival of a passenger train, which plunged into the valley, causing 151 deaths. A monitoring system implemented after this disaster now triggers automated warnings of impending flows so that trains can stop.

The sudden release of water stored within or beneath glaciers can also produce flood surges that spawn lahars. These glacier-outburst floods can occur during eruptions when heat or volcanic events (such as subglacial lava flows or pyroclastic eruptions) melt glacier ice, or during spells of hot weather or heavy rainfall. In Iceland, for example, lahars sometimes form from very large glacial outburst floods, which are common when eruptions occur beneath massive glacial ice caps that overlie many volcanoes there. But destructive lahars caused by glacial outburst floods also occur on a much smaller scale. In the Cascade Range of the Pacific Northwest, relatively small, but nonetheless damaging, lahars formed by outburst floods are common. Outburst-flood lahars occur frequently at Mount Rainier, but most are relatively small volume (typically tens of thousands of cubic yards) and they generally travel only a few miles.

Rainfall-Runoff Erosion of Volcanic Ash and Other Pyroclastic Sediment

Blankets of fine volcanic ash can greatly reduce the ability of the landscape to absorb rainfall, increasing runoff during storms. Surface runoff can erode large amounts of ash as well as underlying loose debris. When runoff incorporates enough ash and other volcanic sediment, lahars can form. As these lahars move downstream, they can erode river channels and augment their sediment load. These sediment-entrainment processes are particularly efficient at generating lahars in volcanic regions subject to heavy rainfall. Such lahars can occur frequently and persist for many years after an eruption. Though individual lahars of such origin are not particularly large, they can happen frequently and can have significant cumulative effects downstream. Lahar deposits can overwhelm channels and cause rivers to change course unpredictably.

Notable examples of rainfall-runoff lahars have occurred at Mount Pinatubo (Philippines), Irazú volcano (Costa Rica), and Chaitén volcano (Chile). Following the massive 1991 eruption of Mount Pinatubo, lahars generated by rainfall runoff persisted for many years, destroyed several villages, and harmed many local economies. In the 1960s, repeated ash eruptions of Irazú volcano perpetuated scores of rainfall-runoff lahars over several years. At Chaitén volcano, in a region that receives abundant annual rainfall, a very modest daily rainfall of less than one inch after days of fine ash fall triggered a lahar (followed closely by a water flood) that filled a river channel with 16 feet of sediment within 24 hours. That fill, and additional fill over the next 24 hours, forced the river to leave its original channel and cut a new channel through the middle of a town 6 miles downstream from the volcano.

Sedimentation along the Bamban River at Mount Pinatubo (Philippines). A single rainfall-runoff lahar in August 1991 deposited nearly 30 feet of sediment. Photographs courtesy of R.S. Punongbayan, Philippine Institute of Volcanology and Seismology.

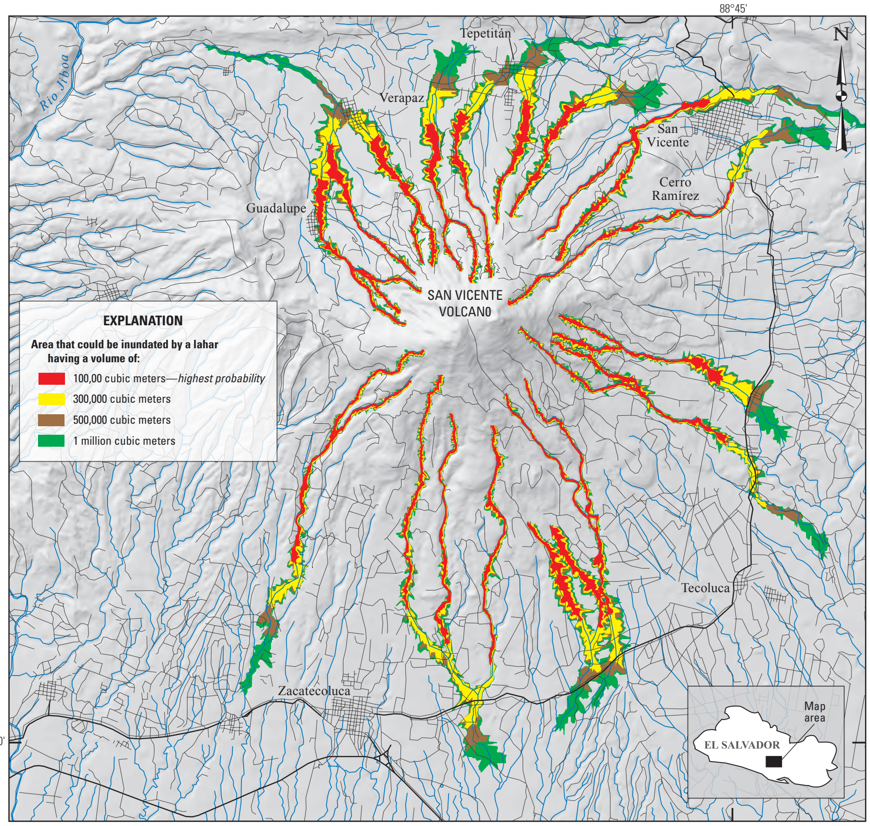
Oblique aerial view of the town of Chaitén, Chile. A lahar (and nearly coincident water flood) caused by rainfall runoff eroded freshly deposited ash and filled the main river channel with more than 20 feet of sediment, causing the river to cut a new channel through town. Photograph courtesy of P. Duhart, Servicio Nacional de Geología y Minería, Chile.

Mitigating Risk from Lahars Requires Awareness, Planning, and Readiness to Act

Communities, transportation systems, power and communications networks, water supplies, and other infrastructure downstream of volcanoes are potentially at risk from lahars. Large lahars can overwhelm river channels, deposit thick sediment over broad swaths of flood plains, and demolish everything in their paths. Even relatively small lahars are hazardous because they move rapidly, transport large rocks and wood, and can occur without warning. At-risk communities along channels draining volcanoes need to be aware of the hazards posed by lahars and be ready to act to reduce their damaging effects.

The best ways to mitigate lahar risk are to understand which areas are most vulnerable, to understand the conditions likely to generate lahars, to have preparations and plans in place before a lahar occurs, and to learn what to do if a lahar occurs (mainly, get to high ground quickly). Times during and immediately following eruptions require special vigilance. When volcanoes become restless, activation of pre-established emergency response plans can help reduce the harmful effects of lahars.

Lahars can and do kill people and significantly damage property, sometimes far downstream from volcanoes. Yet in many communities along valleys downstream of volcanoes, residents are not fully aware of the risks to life and property from lahars. U.S. Geological Survey (USGS) scientists study lahar deposits, model flow behavior, and have prepared lahar-hazard maps for many volcanoes. The USGS monitors volcanic regions of the United States, including the Pacific Northwest, Alaska, California, Hawaii, and Yellowstone, and works with community leaders and governmental authorities to understand and minimize the risks of devastating lahars. Ongoing volcano monitoring enables the USGS to detect early signs of volcanic unrest and to warn the public of impending eruptions and associated hazards such as lahars.



Base maps from El Salvador 1:50,000 scale series: Puente Cuscatlán quadrangle, 1985 (modified) (2456I); Berlín quadrangle, 1985 (2456II); La Herradura quadrangle, 1983 (2456III); San Vicente quadragle, 1983 (2456IV); from best available source. Digital Base Maps from Titan Averstar, Inc. Universal Transverse Mercator projection, Zone 16, Horizontal Datum North American 1927, Vertical Datum Mean Sea Level, Spheroid Clarke 1866.

Example lahar-hazard zonation map for San Vicente volcano, El Salvador, prepared in 2000. Hazard zones are subdivided into four groups based on hypothetical lahar volumes, which range from 100,000 to 1 million cubic meters (about 130,000 to 1.3 million cubic yards). In 2009, rainfall-triggered landslides at San Vicente produced lahars of about 300,000 cubic meters (nearly 400,000 cubic yards) volume, which flowed into the villages of Guadalupe and Verapaz. The yellow hazard zones depicted here matched well to the distributions of those lahars.

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See also What are Volcano Hazards? USGS Fact Sheet 002-97

Background photo credits: Page 1, lahar deposit on Drift River, Alaska, formed during 2009 eruption of Redoubt volcano. Multiple shallow channels of river are flowing over dark lahar deposit; valley is about 0.6 mile wide. Photograph by R.G. McGimsey, U.S. Geological Survey (USGS) and Alaska Volcano Observatory (AVO). Page 1 banner image by Bobbie Myers, USGS. Pages 2–5, lahar deposit cross section from Trout Lake lowland, Mount Adams, Washington. Photograph by J.W. Vallance, USGS. Page 6, USGS personnel in the field, upper Drift River. Photograph by R.G. McGimsey, USGS/AVO.

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