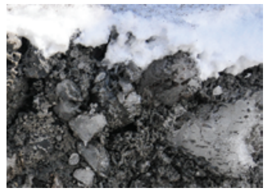
Natural hazards explained



Water, ice and mud: lahars and lahar hazards at ice- and snow-clad volcanoes

Large-volume lahars are significant hazards at ice and snow covered volcanoes. Hot eruptive products produced during explosive eruptions can generate a substantial volume of melt water that quickly evolves into highly mobile flows of ice, sediment and water. At present it is difficult to predict the size of lahars that can form at ice and snow covered volcanoes due to their complex flow character and behaviour. However, advances in experiments and numerical approaches are producing new conceptual models and new methods for hazard assessment. Eruption triggered lahars that are ice-dominated leave behind thin, almost unrecognizable sedimentary deposits, making them likely to be under-represented in the geological record.

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The term lahar is an Indonesian word that means 'volcanic mudflow' and the most common modern usage refers to the process rather than the deposit. A lahar is a flowing mixture of water, rock debris and sediment that originates on a volcano. A lahar can therefore include a variety of subaerial gravity-driven flows that range from debris flow and hyperconcentrated flow, to sediment-laden stream flow. Lahars commonly develop during explosive volcanic activity as a result of an interaction between hot eruptive products, snow and ice. They can result from intense rainfall on the flanks of a volcano, by the catastrophic draining of lakes impounded by volcanic debris, by evolving from large debris avalanches, or from explosive eruptions at ice and snow covered volcanoes. The first three of these types of lahars will not be considered further here, rather, the focus of this article is on lahars that originate during explosive eruptions at ice and snow covered volcanoes because these lahars are typically much larger (and therefore more hazardous) and convey much more sediment than extreme floods (Fig. 1). Lahars are one of the most significant volcanic hazards because they can attain great volumes (up to 10^9 m^3) and travel long distances (tens to hundreds of kilometres) in confined river valleys. The size and reach of a lahar makes them extremely hazardous to people, facilities and infrastructure in the flow path. Historically, a significant loss of life has resulted from the lahar inundation of populated areas. This article reviews the origin, evolution, magnitude and hazards associated with lahars that have arisen from recent eruptions at snow and ice clad volcanoes and highlights a few recent studies documenting the unique characteristics and processes associated with these events.

Modern understanding of lahars and associated sedimentary deposits was largely a result of two volcanic eruptions that produced very voluminous and deadly lahars: the 1980 eruption of Mount St Helens in Washington, USA and the 1985 eruption of Nevado del Ruiz in Colombia. Analysis of the lahar deposits generated during the 1980 Mount St Helens eruption led to an improved sedimentological understanding of how lahars evolve as they move downstream. The accessibility and good exposure of the lahar deposits permitted detailed examination of the various deposited facies and facilitated a process-based interpretation of flow transformations. This made it possible to relate stratigraphic and sedimentological data on older lahar deposits to the flow process, which was an important advancement. The 1985 eruption of the Nevado del Ruiz Volcano tragically highlighted the hazardous nature of voluminous lahars (at least 20 000 people were killed) and prompted major research efforts in

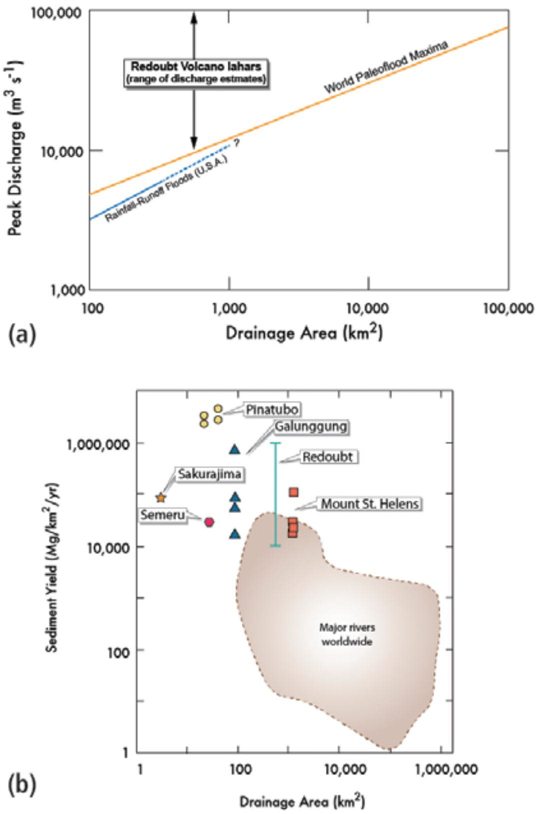

Fig. 1. a. Peak discharge versus drainage area plot for large floods in relation to large lahars such as those that occurred at Redoubt Volcano in 2009. The curves shown are envelope curves based on data for rainfall-runoff floods from and for palaeofloods. Figure modified from Costa (1987) and Baker (2006). **b.** Annual sediment yield versus drainage area for major rivers of the world and lahars associated with eruptive activity at Mount Pinatubo, Galunggung, Mount St Helens, Sakurajima, Semeru, and Redoubt. Sediment yield estimates for Pinatubo, Galunggung, and Redoubt volcanoes are based on estimates of lahar deposit volume and assumed deposit bulk densities of 1.3 g/cm. (Figure modified from Hayes *et al.*, 2002).

numerical modeling and lahar hazard zonation and assessment, which continue to this day.

Eruptions and lahar generation at snow and ice clad volcanoes

Many volcanoes around the world are shrouded in snow and ice as a consequence of their location, high elevation, or both (Fig. 2). The snow and ice cover on a volcano is susceptible to rapid melting during eruptive activity, thus liberating melt water and providing a source fluid for lahars and floods. At most volcanoes world-wide, explosive eruptions commonly produce pyroclastic density currents. These hot, fast-moving, particle-laden, mass flows can thermally and mechanically erode and melt snow and ice and generate significant volumes of melt water. The dynamic interaction of pyroclastic density currents with snow and ice is a primary means of initiating lahars, and thus all snow and ice covered volcanoes that erupt explosively typically produce large lahars. Although other volcanic processes can generate melt water (e.g. lava flows on ice, sub-glacial fumarolic or effusive activity), the highly dynamic nature of the interaction among pyroclastic flows and underlying snow and ice typically generates significantly more melt water.

Snow and ice cover on volcanoes world-wide is generally declining in response to climate change over the past century. The implications of ice loss on the severity of future lahars are uncertain. In some locations, decreased snow and ice cover exposes loose, unconsolidated sediment that could become additional source material for lahars. In other areas, decreased ice cover has reduced the lahar hazard because less ice is available for melting. Nonetheless, due to their location many volcanoes will continue to support substantial snow and ice cover and lahar generation associated with eruptive activity will be an ongoing, long-term hazard.

An important consideration for assessing lahar hazard has to do with the location of the vent with respect to the distribution of ice on the volcano (Fig. 3). At many volcanoes, the glacier area–altitude (hypsometry) relation is such that most of the ice mass is situated near or below the vent. In these cases, the potential for lahar generation during unrest and eruptions is high. In contrast, if the bulk of an ice mass is well above the vent, lahar potential is generally lower. Additionally, timing is important; winter eruptions at snow-covered volcanoes would experience some degree of lahar generation regardless of the distribution of ice on the volcano.

Generally there is a positive relation between total ice volume and degree of lahar hazard. If substantial glacier ice were available for melting, the size of a resulting lahar could be extremely large, but would depend on the efficacy of melt water generation during the eruption. At Redoubt Volcano in Alaska, pyroclastic flows generated by explosive eruptions typically cannot spread laterally because they are confined by topography, and pyroclastic flows are repeatedly funneled over glacier ice. This results in very voluminous lahars in the drainage downstream. Given that most valley glaciers on volcanoes are underfit with respect to the valleys that they occupy, pyroclastic density currents generated by explosive eruptions elsewhere

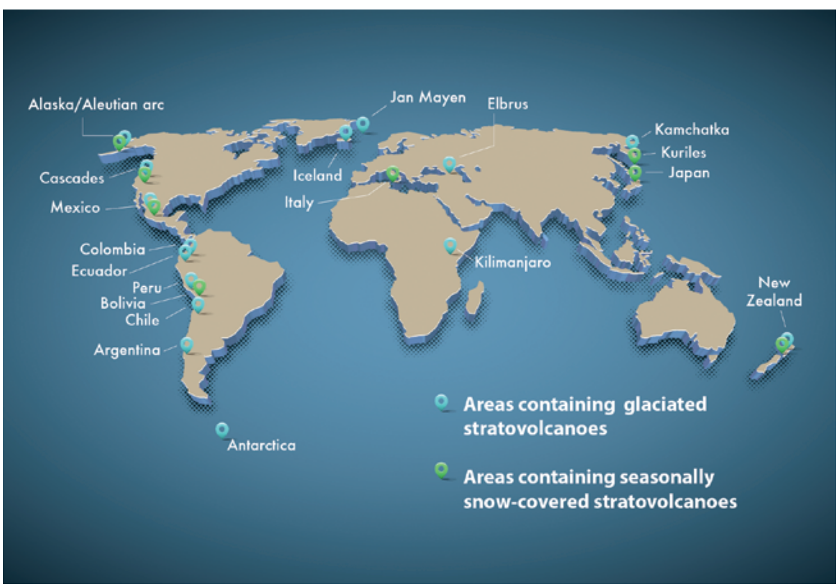

Fig. 2. Distribution of glaciated volcanoes and volcanoes with seasonal snow cover.

Fig. 3. Mount Spurr Volcano, Alaska. This photograph illustrates how the distribution of glacier ice with respect to the vent can influence lahar magnitude. Should a future eruption occur at the Mount Spurr summit vent, hot eruptive products would be distributed over a significant mass of glacier ice (ca. 67 km^3 total ice volume) and result in substantial melt water generation, likely producing large lahars, potentially down multiple drainages. Historical eruptions from the Crater Peak vent have produced pyroclastic flows that swept over seasonal snow and some glacier ice resulting in lahars that were relatively small in volume (< 10^5 m^3).

might be expected to behave similarly, which could lead to larger lahars in areas where the topographic confinement of pyroclastic density currents occurs.

It is difficult to accurately predict the volume of melt water generated by eruptive activity involving the interaction of pyroclastic density currents with snow and ice, and estimates typically span at least an order of magnitude. The information shown in Table 1 gives some idea of the relation among eruption magnitude, volume of ice melted and lahar magnitude. It should be noted that some of the largest lahars documented were associated with relatively modest eruptions. This highlights that it is the efficacy of melt water production that is a key process in the generation of voluminous lahars.

Lahar evolution at volcanoes

Retrospectively, the volume of water produced by the interaction of pyroclastic flows with ice and snow is typically estimated from the volume of lahar deposits. An initial solids volume fraction of the lahar is assumed based on an analysis of lahar deposits, or is determined from estimates of the amount of snow and ice melted during an eruptive event that results in a lahar. Most debris-flow lahars (Fig. 4) have a solids content of about 50–75 percent by volume and hyperconcentrated-flow lahars are about 10–50 percent solids by volume. The volume fraction of solids in a lahar may vary from being initially melt water dominated to then gaining or loosing sediment as they flow down valley. In general, most lahars increase in volume by the addition of solid material in large enough quantities that the solid–fluid ratio of the initial flow is appreciably changed. This process is known as ‘bulking’ and it results in a significant increase in the overall mass of the lahar. The amount of bulking, or bulking factor, can be several times the initial flow volume depending on the availability of loose unconsolidated sediment and the erodibility of valley bed and banks. This is a difficult factor to estimate prior to the onset of a lahar and as a result, most numerical models used to simulate lahar flow or lahar inundation assume a constant flow volume.

In addition to flow bulking, lahars resulting from melt water usually exhibit distinctive types of flow transformations and the sediment–water mixtures that make up typical lahars form a type of sediment continuum; with debris flows and sediment-laden wa-

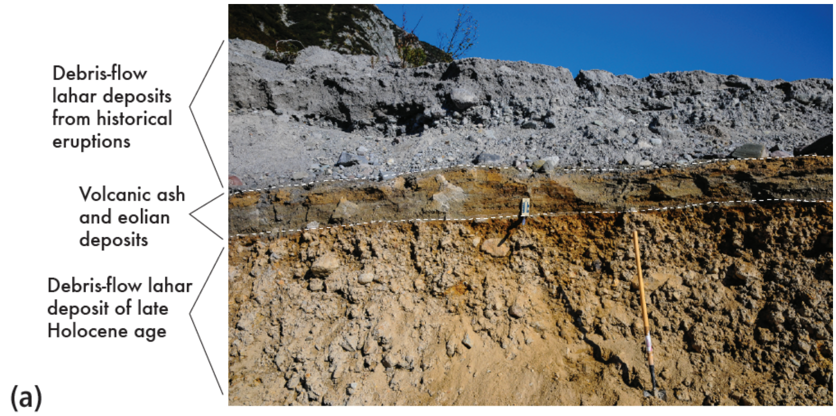

Fig. 4. a. Typical debris-flow lahar deposits produced by eruptions of Redoubt Volcano, Alaska, consisting of massive, poorly sorted, clast-supported gravel, sand and silt. In the Drift River valley at Redoubt Volcano, these deposits grade downstream into better-sorted, sandy hyperconcentrated flow deposits, **b.** that exhibit bedding and water-escape features indicative of rapid deposition. Scale in **b.** about 3 cm.

Table 1. Examples of eruptions at ice and snow clad stratovolcanoes where large lahars resulted

Volcano and period of eruptive activity when lahars were generated	Volcano Explosivity Index	Ice volume lost during eruption (m^3)	Volume of largest lahars (m^3)	Comments	References
Redoubt, Mar–Apr 2009	3	10^8	10^7–10^8	Explosive destruction of ice and pyroclastic flows resulting primarily from lava dome collapse and were funneled down a narrow glacial valley where they melted snow and ice	Waythomas *et al.*, 2013
Redoubt, Dec 1989–Apr 1990	3	10^8	10^7–10^8	Explosive destruction of ice and pyroclastic flows resulting from lava dome collapse and were funneled down a narrow glacial valley where they melted snow and ice	Dorava & Meyer, 1994
Nevado del Ruiz, 13 Nov 1985	3	6×10^7	9×10^7	Pyroclastic flows and surges melted ice in the summit area and removed up to 15% of the ice and snow on the edifice	Pierson *et al.*, 1990; Thouret, 1990
Nevado del Huila, 19 Feb & 18 Apr 2007; 20 Nov 2008	3	Unknown	$3–4 \times 10^8$	Eruptive activity in 2007 and 2008 resulted in >1 km^2 of glacier ice lost. Some of the water released was from hydrothermal sources and some from melting of ice and snow associated with eruptive activity	Worni *et al.*, 2012; Pulgarin *et al.*, 2011
Shiveluch, 12 Nov 1964	4	Unknown	10^5–10^6	Pyroclastic flows were erupted over snow on the flanks of the volcano leading to melt water production and lahars	Gorskov & Dubik, 1970
Cotopaxi, 26 June 1877	4	Unknown	10^7	Lahar initiated by scoriaceous pyroclastic flow interaction with snow and ice on the edifice	Aguilera *et al.*, 2004; Mothes *et al.*, 1998; Barberi *et al.*, 1995
Volcan Hudson, 12 Aug and 11 Oct 1991	5	Unknown but could be up to 10^8–10^9	10^7–10^8	Several explosive eruption induced lahars were generated mainly in August 1991. Lahar volume estimated from values given in Naranjo, 1991, and Best, 1992. During an eruption in 1971, an estimated 50–80% of the 2.5 km^3 of ice in the ice-filled summit caldera was melted	Naranjo, 1991; Best, 1992

ter floods being end members. A typical downstream progression of flow types is: debris flow to hyperconcentrated flow to sediment-laden water flood. However, some flows may de-water, only to bulk up again as they encounter steeper valley floors or areas with easily erodible bed sediment. Recognition of the different types of resultant sedimentary deposits within a single flow unit (indicative of flow transformation) is highly suggestive of a melt water origin for the lahar that produced the deposits.

Ice-rich lahars

Significant ice content is a characteristic of some lahars that form at glaciated volcanoes. Two examples are the lahars associated with the 1991 eruption of Volcan Hudson in Chile and the 2009 eruption of Redoubt Volcano in Alaska. Lahars that formed on 23 March 2009 at Redoubt Volcano consisted primarily of ice derived from erosion of summit crater ice, a valley glacier downstream from the vent (Drift glacier) and seasonal snow cover and river ice in the Drift River valley, the main valley inundated by the lahars.

At Mount Redoubt, the 2009 eruption commenced with eight explosions over seven hours on 23 March that produced three lahars in the upper Drift River valley, at least one of which flowed to Cook Inlet a distance of about 40 km. The first two lahars of the eruption occurred at night and were not observed, but were detected seismically. The durations (50–110 minutes) and seismic amplitudes of these initial lahars indicate that large, energetic mass flows were generated. Empirical travel time curves for lahars indicate that average travel times to points 40 km from source for very large lahars are in the range of about 0.5 to 1.5 hours. This suggests that the average flow-front velocity of these ice-rich lahars was probably about 8–12 m/s. This was corroborated by eyewitness reports of the approximate arrival time of lahars in the lower Drift River valley.

Observations during daylight on 23 March indicated extensive lahar inundation throughout the Drift River valley, particularly in the area south of the Drift River Marine Terminal, an oil storage and transfer facility located near the coast at the mouth of the Drift River. The oil terminal had been surrounded and partly inundated by the lahar, and the runway at the facility was completely covered with ice, woody debris, sediment and standing water. Along the middle and upper parts of the Drift River, trunks of mature trees were stripped of bark (probably by ice blocks entrained in the flow) to a height of several metres above the top of the lahar deposit and prominent mud and debris lines were evident along the channel. In many areas along the valley margin, depos-

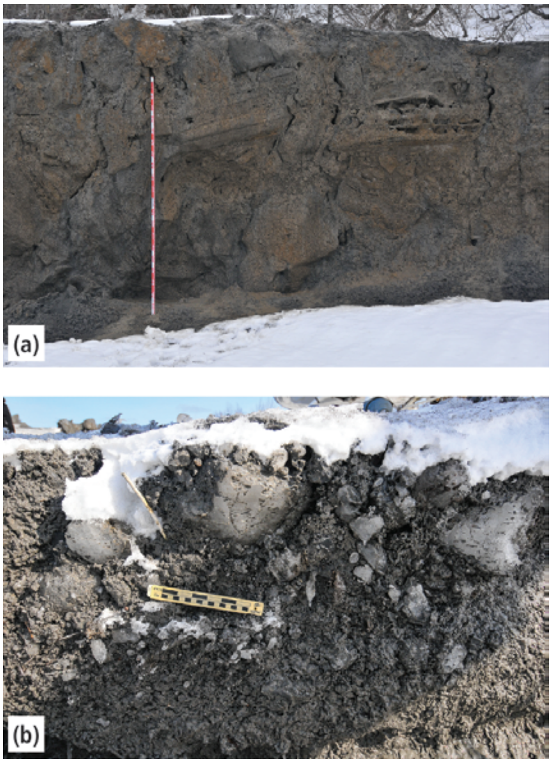

Fig. 5. Ice-rich lahar deposits formed during the 2009 eruption of Redoubt Volcano, Alaska. **a.** Ice-rich lahar deposit consisting of interlocking assemblage of tabular to subrounded river ice clasts emplaced on 23 March 2009. Scale is 2 m in length. **b.** Ice-rich lahar deposit about 40 km downstream from source. This deposit consists of rounded pebble to cobble size clasts of ice in a matrix of fine granular ice and firn. Scale in photograph is 15 cm in length.

its consisting of interlocking tabular ice blocks and subangular to rounded ice cobbles were emplaced and then frozen, preserving the ice-rich deposit fabric (Fig. 5). Deposits consisting of cobble- to boulder-size clasts of ice supported by a granular ice and firn matrix (Fig. 5) were also preserved in various locations throughout the valley. Unlike many of the lahar deposits emplaced during the previous eruption in 1989–90, no steaming clasts or boulders of juvenile rock were observed on the surface of the 23 March deposit and nearly all of the deposits from this lahar were 90–95 percent ice.

Two of the three lahars that formed on 23 March at Redoubt Volcano were among the largest lahars of the 2009 eruption (estimated volume about 10^7–10^8 m^3) and the melt water surge produced by pyroclastic flows and explosive activity invaded a frozen, snow covered valley floor. As a result, the lahar rapidly bulked up with ice and snow and the primary solid material in the flow was ice. Such flows probably behave as giant icy slurries, possibly analogous to the ice-rich flows that develop during ice-jam floods associated with break up of river ice.

Fate of an ice-rich lahar

Lahars that contain appreciable amounts of ice eventually melt and leave behind a deposit that may be difficult to recognize as being the product of a voluminous ice-rich lahar. Repeat visits to the Drift River valley at Redoubt Volcano in 2010, 2011 and 2012 revealed that complete melting of the 23 March 2009 ice-rich lahar deposit produced a 1–3 cm thick bed of silt to fine sand (Fig. 6) that exhibited no obvious textures or characteristics indicative of a very large lahar. Thus, the melt-out deposits of ice-rich lahars could easily go unrecognized in the geological record because they are very thin in comparison to the deposits produced by more typical lahars with high sediment concentrations, whose deposits are rather unmistakable.

At Redoubt Volcano, studies of eruption frequency based on lake core records of volcanic ash deposits indicate that as many as 100 discrete ash layers were erupted during the past 10 000 years. Each ash layer is associated with an explosive eruption. However, fewer than ten documented lahar deposits of Holocene age are known in the major valleys that drain the volcano. Although it is possible that not all of the ash-producing eruptions had associated lahars, it is plausible that many of them were ice-rich and did not produce obvious or preservable deposits.

Numerical modelling and hazard assessment

The great size and rheological complexity of lahars that develop during eruptions at ice and snow covered volcanoes presents a substantial challenge to efforts aimed at developing numerical models to evaluate hazards. A few of the numerous difficulties include: reliable estimates of melt water production, the amount of flow bulking relative to the original melt water volume, and hydraulic parameters (such as flow depth and velocity) over the entire length of the flow path. Field studies have helped to further define the range of flows that may arise during eruptions at snow- and ice-clad volcanoes and clearly indicate the high degree of complexity and range of dynamic behaviour exhibited by these types of flows.

Highly unsteady, large volume, transforming, non-Newtonian mass flows are notoriously difficult to model mechanistically. Explanation of the relevant physics of such flows is an area of active research that has benefitted greatly from controlled laboratory-scale flume experiments involving rapid flow of sedi-

Fig. 6. Lahar deposits from recent historical eruptions of Redoubt Volcano exposed in the Drift River valley, August 2011. All that remains of the ca. 2-m thick ice-rich lahar deposit emplaced on 23 March 2009 is a 2–3 cm thick bed of fine silt. Such deposits could be easily overlooked and might not necessarily be interpreted as the products of large volume potentially destructive ice-rich flows.

ment-water mixtures. The role of pore fluid pressure on lahar dynamics and evolution has been a particularly key conceptual development. This is important because high pore fluid pressures lower the strength of a flowing material and can vary with respect to time and location, indicating the non-uniqueness of the relation between stress and strain rate. Several field and experimental studies have shown that lahars exhibit a high degree of variation in pore-fluid pressure, strength, and degree of liquefaction and therefore cannot be characterized accurately with simple rheological formulae. Because a primary purpose of modelling is to make predictions about the extent of lahar inundation and degree of hazard, the application of empirical, statistically-based models generally involve fewer assumptions and less uncertainty and therefore may be better suited for hazard assessment purposes. Hindcast application of numerical hydrologic models can provide insight into the flow properties of large lahars, but typically, the magnitude of such estimates vary by at least an order of magnitude. With regard to the lahars at Redoubt Volcano described here, these flows are so large relative to other types of floods (Fig. 1) that direct measurements and close observations are difficult if not impossible. Furthermore, post-event assessments to determine simple hydrologic properties (such as flow depth) can be problematic because flow-dependent changes in the channel cross-section are almost always unknown.

An empirical model for estimating the lahar inundation of valley floors that has gained widespread usage is based on the physical and statistical relationship between lahar volume and area of inundation (both planimetric and cross-section area), which has been incorporated into a GIS routine, known as LAHARZ. This approach makes use of the proportionality between lahar volume (V) and inundation area (A), such that $A \propto V^{2/3}$. All that is required to estimate the area of lahar inundation is a digital elevation model of the area of interest and some knowledge of reasonable input volumes for plausible lahars, which are typically determined from studies of past events.

The numerical modelling of lahars has been attempted by a number of researchers with varying degrees of success. A full discussion of the different approaches and codes is beyond the scope of this article and thorough reviews of lahar modelling have been published recently. In general, lahars have been evaluated using: (1) theoretical multiphase flow models that employ relevant constitutive laws (conservation of mass and momentum); (2) modified hydrological models where flow resistance terms are adjusted iteratively to achieve goodness of fit among model output and field relations; (3) models that assume a fixed flow rheology; and (4) empirically based relationships between known or estimated flow parameters.

Conclusions

Eruptions at snow- and ice-clad volcanoes often lead to the generation of large volume and far-travelled lahars in the major valleys of the volcano. Lahar size depends on the volume of melt water generated and thus, a key process that warrants additional research is the physical mechanism of melt water production and the dynamic nature of pyroclast–ice–snow interaction. At present, it is difficult to estimate how much melt water will be produced during a given explosive eruptive event. Past flows and lahar deposits offer guidance about the range of lahar size and type that may be possible at a particular volcano, but usually flow volumes can only be estimated to about an order of magnitude. In some cases it may be possible to obtain information on flow velocity using various flow-monitoring devices, provided that they are installed and operational before events occur. The ice-rich character of some lahars presents additional challenges and such flows are envisioned to behave in a manner similar to ice jam floods that occur in many areas during winter break up. Because ice-rich lahars consist mostly of ice, they leave behind rather unremarkable deposits relative to the original flow volume. Such deposits may be difficult to recognize years to millennia after deposition and thus, ice-rich lahars are likely under-represented in the geological record.

Suggestions for further reading

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