CHAPTER 3

Lahar Deposits

L. C. Bliss leans against a surviving Douglas fir on the edge of the Muddy River Lahar. The scour marks are 8 m above the deposit (July 1980).

What is a lahar?

Lahars, from a Javanese (Indonesia) designation, are preferred to the inelegant English term "mudflow" when referring to events on volcanoes. Lahars include any rapidly flowing masses of earth saturated by water flowing under the force of gravity. They can be triggered when natural rubble dams collapses to unleash a pent-up lake trapped behind it. Lahars are mudflows formed in several ways by volcanism. When hot tephra falls onto a cone laden with snow and ice, the rapid melting causes lahars that flow down canyons. Slurries entrain soil, rocks and anything caught in the path, and severely erodes the canyon margins. Similar events can occur by heating from within, as hot magma moves into the cone. As a lahar ebbs, it usually leaves a deposit of sediments sorted by distance from its origin.

A lahar can also form as a debris avalanche hurtles from a volcano entraining everything in its path. As it becomes increasingly liquid, leaving larger materials behind, the debris avalanche becomes a less turbulent and continues to flow as a lahar. While lahars usually stay confined to the river channel, they can overflow their constraints and spread

Fig. 3.1. *Castle Lake was created when Castle Creek was blocked by North Fork Toutle River debris avalanche (July 8, 1980).also prominent (July 30, 1980.*

out. Glaciers and snow fields melt rapidly and small blocking dams (often glacial moraines) collapse to produce massive surges that swallow everything in its path. While sweeping down steep canyons, the lahar scours margins before spreading out and coming to rest on nearly level terrain to form lahar deposits. On its journey, a lahar can surge through lakes, fill deep canyons, block streams (Fig. 3.1) and wreak havoc on villages and fields sitting on flood plains. Lahars often fill former river valleys with loose rubble that is soon eroded to form very steep-sided, unstable channels (Fig. 3.2). Lahar deposits s are more fertile than tephra, pumice or decomposed lava because new deposits come from older, reworked volcanic materials, plus a bit of topsoil, plants and even a little animal remains. Lahar deposits, particularly when bounded by undisturbed vegetation, are recolonized more quickly than large, isolated habitats.

Lahars and debris avalanches in history

Lahars have always threatened populations living in valleys associated with volcanoes. Casualties from lahars are common, but only rarely are they on the massive scale of pyroclastic flows (Chapter 5) or deep tephra deposits (Chapter 1). Occasionally lahars strike from a distance to produce massive casualties. Lahars are usually associated with other volcanic terrors, each threatening a different population. As human populations grow, more people are at risk; as global warming continues, ice masses on mountains shrink to shrink the volume of future lahars.

An infamous documented lahar happens to have descended from another Cascades volcano. About 5,600 years ago, the flanks of Mt. Rainier collapsed producing a cataclysmic event. There was no eruption, but over the millennia, the summit rock of the then much higher cone was repeatedly heated and cooled, becoming “rotten” (or as geologists say, hydrothermally altered). Triggered by an earthquake or possibly by magma movement in the volcano’s throat, the summit buckled to form what today we know as the Osceola Lahar. This lahar formed deposits at least 150 m thick and covered an astonishing 500 km^2 of Puget Sound. Several Washington towns remain at risk to future lahars (e.g., Orting, Buckley, Puyallup, Auburn and Kent). Such lahars cannot be outrun (lowland speeds exceeded 70 km per hr). Current residents of Puget Sound might have from 45 minutes to about 3 hours to reach the safety of high ground.

Lahars continue to inflict immense damage, and have reshaped the modern landscape. Their potential for destruction increases as people increasingly build towns and farms on valleys below active volcanoes and their flanks (del Moral and Walker 2007). In densely populated central Honshu, Japan, the notorious Bandai volcano experienced a huge phreatic eruption in the summer of 1888. Phreatic eruptions occur when magma contacts water within the pressurized confines of the cone. Vaporization explodes the cone. Steam expands, entraining everything in the way. A prodigious coughing fit called a Plinian eruption soon follows. So it was with Bandai. The eruption also generated a debris avalanche to the north, followed by pyroclastic flows. The warm, torrential rain caused by the eruption plume then

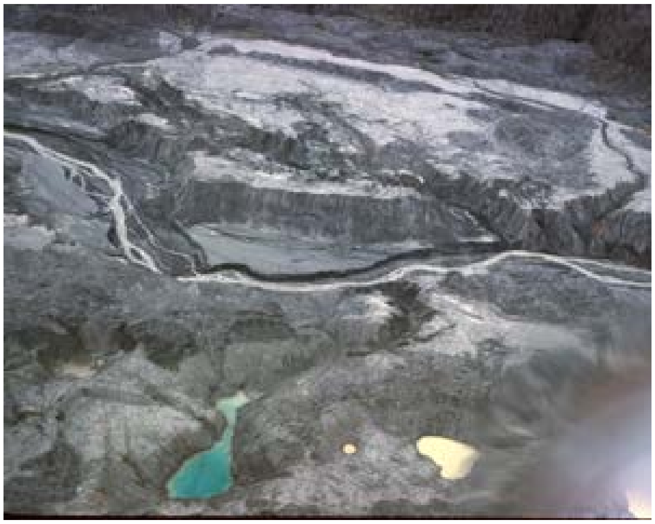

Fig. 3.2. *Toutle River valley showing deeply incised canyons in the debris avalanche deposit produced in one year (June 8, 1981).*

Fig. 3.3. *Volcan Cotopaxi lurks among the clouds above this small canyon that routinely sends lahars down to the valley below (4500 m; February 8, 2012).*

Fig. 3.4. *The force of the directed blast moved several hundred meters up Coldwater Ridge, leaving scours in its wake (July 14, 2003).*

produced thick lahars. Forests and farms were transformed into a wasteland and several villages disappeared under relentless torrential deposition. Rivers were diverted or blocked, others formed and beautiful multicolored lakes developed on the new land. Bandai became famous as the subject of a classic paper in volcanology. Its remnant cone was the subject of the very first photograph published by the *Yomiuri Shimbum* (today the world's largest newspaper). The newly formed Japanese Red Cross moved in to the region, its first disaster mission. The new landscape is now a tourist haven.

In 1953, a natural dam blocking a lake on the volcano Mount Ruapehu in New Zealand failed. The ensuing lahar swept downstream to weaken a railway bridge. Moments later, the overnight express started to cross the bridge, causing its failure. Over half of the train and 151 people disappeared. This tragic even led to the deployment of a lahar warning system. In 2007, the dam forming a crater lake on this same volcano also failed, but within minutes all road and rail traffic was stopped, no one was hurt and no damage to the infrastructure occurred. Lahars, debris flows and avalanches should become more frequent and potent as climate change leads to storms of increasing intensity while logging destabilizes slopes over wider areas.

Fig. 3.5. *Logs and stumps from the margins of the debris avalanche and lahar ended up near the I-5 corridor (July 8, 1980).*

Lahars can emerge suddenly from beneath a cloud layer, far from the maelstrom of the eruption, often at night, to kill many people. The Colombian stratovolcano Nevado Del Ruiz last erupted in 1985. Like Mount St. Helens, it has built itself by alternatively pumping out tephra and oozing lava. Lately, it has specialized in Plinian eruptions and pyroclastic flows, like most Andean volcanoes. It is a steep, tall (5,300 m) volcano laden with glaciers and snowfields. Pyroclastic flows melted glaciers and the gathering lahars were further fueled by torrential rains. The lahars swept down the valleys unnoticed and provided no warning. Worse, as lahars scoured the slopes, they expanded in volume and rose up the canyon walls to become dense battering rams. This stealthy lahar buried towns over 100 km away, in what known as the Armero tragedy. And although the hazards were known, this lahar still killed over 25,000 people, a record for lahars.

Other Andean volcanoes pose serious threats from lahars. The Ecuadoran Volcan Cotopaxi (the tallest volcano in the world at 5897 m) routinely spews forth lahars and threatens thousands of people in valleys and towns of the Andean highlands (Fig. 3.3). It is overdue for an eruption.

Lahars devastated valleys and colonial towns such as Latacunga in 1744, 1768, 1877 and 1903. Amazingly, the 1977 eruption generated lahars that reached both the Pacific Ocean (over 100 km distant) and descended far down the Amazon River. The Pan American highway, which skirts the western flank of Cotopaxi, is studded with serious lahar warnings. Skeena et al. (2010) studied high elevation succession on lahars of Cotopaxi. On this seasonally wet and perennially cool mountain, they found that succession followed a traditional path: lichens and mosses dominated early succession. Alpine herbs and prostrate shrubs common at higher elevation dominated lahars that several centuries old. Shrubs, including fuchsias, were common on lahars from 1534, the year that also saw the last pitched clash between Spaniards and Incas. Even after 475 years, succession in these paramo habitats was far from complete.

The lahars of Mount St. Helens.

Two distinct mechanisms formed lahars on Mount St. Helens (Foxworthy and Hill 1982). By far the largest and most terrifying was caused by the debris avalanche that announced the start of the May 18 eruption. The trigger was an earthquake that caused a landslide. As the avalanche raced down the slope, it entrained everything in its path, mixing huge amounts of the cone, giant boulders, large trees and huge chunks of ice and much of Spirit Lake. The directed blast followed immediately and overtook the avalanche so all of these components were joined by steam and molten materials from the throat of the cone. This blast resulted because the weight of the cone kept the superheated water in liquid form; when the avalanche released the pressure, water flashed to steam. The force of the blast forced much of the debris avalanche towards the slopes of Coldwater Ridge (Fig. 3.4) and then it flowed west to rampage down the North Fork of the Toutle River. As it roared down the drainage, it impounded creeks to form Castle Lake, Coldwater Lake and Green Lake, among others, and left deep deposits in its wake. It scoured valley walls from 10 to 20 m above the original stream level. The surging debris avalanche exceeded 40 m, and new deposits average about 45 m deep. Channels were quickly cut into this mass to form steep-sided canyon walls. About 20 km from the crater, the massive conglomeration slowed and spread out on more gentle terrain, becoming a lahar that continued far down stream (Fig. 3.5), eventually disrupting navigation when it emptied into the Columbia River (Major et al. 2009).

Small lahars can be formed when glaciers and snowfields melt rapidly under the combined effects of magma heating the cone from within and from pyroclastic flows descending from the crater. Magma rises in the throat of the volcano and when the heat pulse surfaces, a predictable result is that glaciers and snowfields began to melt…slowly at first, then with frightening speed. Episodic pyroclastic flows accelerated this effect to create lahars entrained soil, trees and boulders, removed soil and vegetation along its margins and cut deep canyons. They produced scouring along existing landforms, but then, as the topography flattened, substantial deposits formed. This mechanism spawned lahars on the south and east side of the volcano, including those on the Muddy River, Kalama Creek and the South Fork of the Toutle River (Fig. 3.6).

Far less dramatic, but of considerable interest, were two small lahars that swept the southwest flank of the cone above Butte Camp. One terminated near a gentle bench, burying existing vegetation. The other left a thick deposit on a broad ridge, and then carried on to the Kalama River, washing out trails and roads (Fig. 3.7) as it went. This pair of lahars has allowed me to study the effects of proximity of colonists on vegetation recovery rates and species composition (see del Moral 1998).

Vegetation recovery on lahars at Mount St. Helens

Several groups of ecologists studied aspects of vegetation recovery on lahars at Mount St. Helens. Refreshingly, each group has developed similar insights into the factors that drive succession. However, each location has its own story.

Fig. 3.6. *Lahar, South Fork Toutle River (July 20, 1984). Lahars have volumes that are limited by the size of the drainage from which they are spawned.*

Debris avalanche. Virginia Dale and her collaborators (Dale et al. 2005) studied several sites at lower elevations on the debris avalanche of the North Fork Toutle River. Recall that the debris avalanche that started on the north face of Mount St. Helens turned westward; it became a lahar about

18 km from the volcano, then continued on to the Columbia River. The debris avalanche covers about 60 km^2. As would be expected, there has been a gradual increase in species numbers and overall cover since 1980, but some surprising patterns emerged. Study plots were located near the newly formed Castle Lake and lower on the deposit near Jackson Lake. The debris avalanche deposit initially lacked seeds, but it was not purely a primary succession because some plants survived as rhizomes (e.g., fireweed, Canada thistle and Cascade lupine). Species richness increased slowly at first, then accelerated. The number of species declined from 1994 to 2000, and may have had to do with erosion during the exceptional rains and runoff of 1996-1997. The mean number of species in 2000 was about 19 per 250 m^2 plot. Vegetation cover increased steadily to reach about 66% of the surface, and the increase in some species may have excluded others. By 2000, the mixture of species types

Fig. 3.7. *Butte Camp lahars from above (September 10, 1980). Lahar 1 is at the extreme left, Lahar 2 is on the right.*

Fig. 3.8. *The upper Muddy River Lahar, looking north, with scoured large trees and remnants of the forest that once clothed this drainage. Note the start of an incision that reached over 12 m within 10 years (July 26, 1980).*

Sidebar 3.1. *Life never really left the mountain*

On July 26, 1980, I found myself slogging up Pine Creek Ridge, a dry, barren ridge that only two months before was an inferno that had suffered a lethal nightmare of hot mud and boulders. My mission was to find plants…any would do. Below, on the Muddy lahar, plants were exceedingly scarce and no large animals had yet to be observed. I thought that perhaps on the ridge, where impacts may have been less severe, something would have survived. Suddenly, my attention was drawn to a solitary ant (*Formica subnuda*) bravely scouting this now alien landscape. I was amazed. Ants normally are predators, of course. It may take some imagination, but perhaps a deeply buried, dormant nest could have survived those awful, recent, events. But, I asked myself, what could it be looking for? I soon found a large group of foragers, focused above what I assumed to be their nest. The ants appeared to have been transformed from predators to carrion feeders. This speculation heralded two major discoveries. Survivors (i.e., legacies) are crucial to the pace and direction of recovery. Novel food chains, in which predators like ants and spiders become cannibals and scavengers, are likely to develop, if only ephemerally. These ants were hastening succession by incorporating nutrients into the subsurface, breaking up the impervious silt surface and creating microsites where seeds might safely germinate. Despite an intensive search, I found no plants, birds or mammals on this ridge until the following year. These less deadly lahars produced intense local effects, each with compelling ecological stories. The Muddy River Lahar was generated by numerous melting ice fields and the Shoestring glacier. The slurry swept across the Plains of Abraham and the upper Muddy River floodplain. The lahar then squeezed through a gorge at Lava Canyon and formed two deltas before reaching the eastern edge of the Swift Reservoir. Along the margins of this lahar, many stately Douglas firs survived even though their bark was removed on one side up to 8 m above the new surface.

Fig. S3.1. *An agitation of ant workers* (Formica subnuda) *searching for any food. The rills had exposed the original surface through about 12 to 15 cm of lahar deposit (July 26, 1980).*

began to resemble that of the surrounding areas not impacted by lahars, yet succession is far from complete. Annuals had declined greatly, and species with belowground regeneration were dominant. Red alder had replaced willows as the dominant species while conifers remained uncommon. Several exotic species (e.g., birds-foot-trefoil, velvet grass and cat's ear) were common because of the proximity to clear-cuts and because aerial seeding in 1980 had introduced several agronomic species in a vain attempt at erosion control. Exotic species and short lived species were in decline by 2000 because tree canopies were increasingly dense. Recovery on the debris avalanche was more rapid than has been observed at higher elevations due to the low elevation of the study area, stabilization of the surface, proximity of sources of colonization, relative fertility of the substrate and nitrogen fixing by alders and lupines. Dale et al. (2005) noted a pronounced landscape effect on seedling establishment. Major colonists tree were wind-dispersed species such as red alder and black cottonwood and the distance from the edge of the deposit strongly influenced both the quantity and the nature of the seed rain (see Chapter 6).

Pioneer species (e.g., fireweed and pearly everlasting) did very well soon after the deposit, but they then declined as other species invaded (see Chapter 7). Nitrogen fixing species did well on these infertile substrates, and continued to expand. Unlike high elevation sites on lahars, exotic species remained common and may have inhibited conifer establishment. Large herbivores such as elk are abundant and can alter succession trajectories by browsing conifers, dispersing seeds and by promoting nonnative species. Late seral species did occur on barren substrates, but their abundance and potential spread appears limited by their ineffective dispersal. Nitrogen fixers improved site fertility and appear to be effective at facilitating subsequent development of late-arriving species.

The Dale study of the debris deposits corroborates conclusions from lahar studies. Early succession is slow due to infertile, dry substrates with few biological legacies. This also provides an open habitat that permits new combinations of species to occur. Even short distances from sources of propagules restrict the kinds of early colonists. Disturbances that occur after succession has begun often reset succession. Herbivory by large animals can slow and deflect succession by favoring consuming potentially dominant species.

Muddy River Lahar deposits. The 1980 lahar was a highly energetic event that started on the eastern flank of the cone. Melting snow and glaciers on the northeast and east portions of the cone formed lahars that scoured the Plains of Abraham. As lahars dropped into the upper Muddy River drainage, they were joined by material from the melting Shoestring Glacier and snow fields. A branch of the lahar found its way into Ape Canyon and scoured the Smith Creek drainage. A wall of mud, boulders and logs more than 1 km wide and over 5 m thick swept the wide upper Muddy River fan. It sheared off trees at the surface. Along the margins of the flow, badly abraded and frayed trees stood firm and many survived for decades (Fig. 3.8). Within the channels of the lahar all soil and any organisms it contained were scoured away. The two lahars joined at the confluence of Smith Creek and the Muddy River and then swept through the Cedar Flats Research Natural Area and ultimately into the Swift Reservoir. When the lahar subsided, a relatively thin (ca. 1 m) deposit of sand and boulders remained. In the years that followed, deep channelization of the Muddy River and newly formed Fire Creek produced deep, steep-sided canyons (Fig. 3.9).

Fig. 3.9. *Deep erosion characterizes this tributary to the Muddy River (July 9, 2009). This creek did not exist prior to the eruption because the water previously flowed into Pine Creek.*

Weber et al. (2006) described the effects of the Muddy River Lahar at Cedar Flats (elevation 365 m) through 1999 using permanent plots. They were concerned with the recovery of tree species. Mortality of the tree layer was dependent on deposit depth. Deposits thicker than 1 m killed nearly all trees by smothering the roots, while deposits less than 40 cm allowed most to survive. Intermediate depths influenced species differentially, and other factors such as natural, small depressions affected survival. This produced a complex pattern of succession. Succession in deep deposit of the primary kind and was relatively predictable. In thin deposits with high survival, changes reflected recovery from burial, rather than succession, and were relatively predictable. Where mortality was moderate and sites were protected by standing trees that had died over several years the succession rate was rapid. Primary succession on deep deposits was dominated by red alder. Intermediate deposit depths invited stochastic establishment by lowland conifers and some surviving trees. Shallow deposits recovered quickly as red alder joined conifers and soon established roots in old surfaces.

Frenzen et al. (2005) also reported on vegetation at Cedar Flats in detail. The lahar was relatively narrow (200 to 350 m wide) and there were refugia in areas with little deposition. Thus, understory vegetation could develop quickly, at least in the shallow deposits. Nurse logs and root mounds provided habitats for key understory species and standing trees assisted in regeneration by providing shade and reducing wind. Trees that survived despite thin deposits promoted recovery of the understory species. On thicker deposits, tree seedling establishment was needed. Shallow deposits are reverting to a conifer canopy with an understory of salal. Thicker deposits are developing conifers with dense red alder in the overstory and trailing blackberry and sword fern in the understory. The several studies of lahar effects at Cedar Flats all emphasized that survivors and nearby seed sources were prime drivers of succession.

The lower Muddy River (360 to 520 m), near its confluence with Smith Creek (550 m) and the upper Muddy River alluvial fan (900 to 1350 m) were also studied by Frenzen et al. (2005). They concentrated on comparisons of site stability. As expected, the number of plant species and their cover increased from 1981 to 1991. Stable surfaces always had more species than unstable sites, some of which received repeated erosion events that restarted succession. Vegetation on stable primary surfaces was sparse at low elevation and became progressively sparser at higher elevations. There was a pronounced reduction of species diversity with elevation. Species that occurred consistently were all wind-dispersed. These species include pearly everlasting, white-flowered hawkweed and cat's ear. Wood groundsel was common at lower elevations, and willows were scattered throughout the study area. These studies provided further evidence for the importance of biological legacies and dispersal limitations in directing succession.

The upper Muddy River Lahar has been the site of several studies. Larson and Bliss (1998) explored conifer invasion patterns across the lahar deposits where they are over 1 km wide. They found that age and size of saplings were not correlated. Instead, development was related to the thickness of the lahar deposit and old seedlings could be small or large. Species composition changed with distance as a function of local pools of colonists and the dispersal ability of the seeds, demonstrating that distance by itself is a significant filter.

In subsequent years, I studied dispersal patterns in this region, with an emphasis on all plant species (del Moral and Ellis 2004) and described patterns of vegetation (Fig. 3.10). Along the creek drainages, little vegetation has developed and the surface remains a jumble of cobbles. In places, recurrent lahars prevent vegetation establishment (Fig. 3.11). However, much of this lahar deposit has experienced dramatic transformations since 1980. As the surface stabilized, dust that had been deposited on the surface during eruptions began to fill in between the cobbles. Eventually rock moss and prairie lupine invaded and A moss-lupine meadow with beardtongue and scattered conifers covered much of the lower lahar deposit. Along its margins, there were more conifers and persistent woody species, particularly bird-dispersed ones. Much of the lower lahar had a varied mix of species in a matrix of prairie lupine and rock moss. Moist sites near the surviving forest included surviving conifers with Cascade lupine and beardtongue and species adapted to shadier conditions. A few plots, dominated by pinemat manzanita, occurred sporadically over the range of elevations and formed a well-vegetated surface. Hiking up this lahar became progressively easier. What once required a tricky balancing act, hopping from rock to rock, became a relatively simply, though sweaty, hike on terrain with only a few challenging segments. Higher on the lahar, vegetation remains relatively scarce

***Fig. 3.10**. The upper Muddy River Lahar, looking south. The surface is dominated by logs and boulders (August 26, 1980).**Fig. 3.10. The upper Muddy River Lahar, looking south. The surface is dominated by logs and boulders (August 26, 1980).*

In 2007, we conducted a survey of the vegetation of the upper Muddy River Lahar (del Moral et al. 2009). We sampled 151 plots on the 1980 surface. This vegetation was classified into nine communities using standard methods. The typical and common species communities are shown in Table 3.1. The values in bold designate characteristic species. Most communities had significant concentrations of prairie lupine and rock moss, but there were different amounts of conifers and of persistent forbs.

The presence of these mats reduced local diversity and demonstrate how priority effects (competition from an early colonizer) can arrest succession (see Chapter 9). In some places, tall shrubs and black cottonwood were set among various herbs, but this vegetation appeared to establish in a capricious way. Upper lahar sites had low dominance and heterogeneous composition. The vegetation of this lahar deposit remains in early succession, still demonstrating the effects of random dispersal. Species composition remains poorly predicted by environmental factors.

Together these studies of the Muddy River Lahar deposit revealed several general principles of recovery. Recovery will be accelerated if there is any biological legacy and if surfaces are stable. Trees that were smothered, but remained upright provided some shade and their leaves dropped to provide an enhanced seed bed. Thin deposits permitted species to emerge to start the recovery process rapidly. Intermediate sediment deposits kill selectively. When with surface heterogeneity, nurse logs and root wads combine heterogeneous vegetation results. The width of a lahar affects species composition and succession rates simply through distance effects.

Lahars at Butte Camp. Vegetation on the small lahars at Butte Camp has been followed since 1982. Lahar 1 terminated north of the Butte (an old lava dome) on a gentle slope. It is next to a young intact forest dominated by subalpine fir and lodgepole pine (Fig. 3.12). The deposit thickness was at least 1 m except for the tongue of the lahar. This lahar smothered conifers along the margin, but it took several years for these stress-tolerant trees to die (Fig. 3.13).

Lahar 2 was larger and continued down the slope wreaking destruction to forest roads and campsites many kilometers from the cone. It spread over a broad ridge and was isolated from forests by several hundred meters (Fig. 3.14). These lahars shared an initiation date and were of similar materials, yet the rate of plant community development differed significantly and species composition diverged over time. Unfortunately, torrents from vicious storms in the winter of 2006 cut so deeply into the canyon separating the

Fig. 3.11. *Secondary erosion; the small lahar barely suggests the power of full scale events (July 26, 1981).*

Fig. 3.12. *Lahar 1 viewed from above and to the west (July 9, 2008). Adjacent forest vegetation strongly influenced the development of this vegetation.*

Table 3.1. *Mean percent cover of species common in the nine communities described on the Muddy River Lahar. Order of species reflects dominance across an elevation gradient. The communities are arranged by their average elevation. Species may not decline regularly with elevation because factors such as distance from the margins can influence their distribution. Bold values are species characteristic in the community. "Non-random" indicates the degree of certainty that the pattern is not random. Superscripts divide species into statistical groups; the strength of the relationship is shown in the final column.*

	Communities (N plots in type)									
Species	**A (17)**	**B (11)**	**C (20)**	**D**	**E (21)**	**F (5)**	**G (14)**	**H (11)**	**I (28)**	**Non-random**
Prairie lupine	**21.70^{c}**	1.56^{a}	2.70^{ab}	8.42^{bc}	6.91^{b}	1.20^{a}	**20.32^{c}**	0.96^{a}	1.77^{a}	Very high
Cat's ear	0.98^{a}	0.06^{b}	0.06^{b}	0.20^{b}	0.14^{b}	0.00^{b}	0.07^{b}	0.02^{b}	0.04^{b}	Very high
Douglas fir	4.28^{a}	**9.88^{b}**	2.94^{a}	2.35^{a}	2.34^{a}	0.22^{a}	0.57^{a}	0.49^{a}	0.54^{a}	Very high
Juniper haircap moss	5.87^{bc}	3.52^{ab}	1.37^{a}	1.95^{a}	1.83^{a}	**9.72^{c}**	2.16^{a}	3.46^{ab}	1.24^{a}	Very high
Noble fir	0.87	0.37	0.53	**2.81**	**2.92**	0.02	2.54	2.56	1.59	High
Roadside rock moss	**39.94^{d}**	**29.26^{c}**	**53.19^{e}**	**32.00^{c}**	**18.46^{b}**	**9.96^{ab}**	3.78^{a}	4.15^{a}	4.32^{a}	Very high
Cardwell's beardtongue	3.46^{a}	**14.06^{b}**	4.13^{a}	4.03^{a}	3.31^{a}	4.20^{a}	1.09^{a}	3.36^{a}	1.11^{a}	Very high
Subalpine fir	0.00^{a}	0.08^{ab}	0.01^{a}	0.04^{a}	0.10^{a}	0.02^{ab}	0.24^{ab}	**3.21^{b}**	0.06^{a}	High
Pine mat manzanita	1.31^{b}	5.15^{b}	5.59^{b}	0.65^{b}	1.09^{b}	**49.3^{a}**	1.34^{b}	3.32^{b}	1.91^{b}	Very high
Lodgepole pine	0.12^{a}	1.70^{b}	0.24^{a}	0.44^{a}	0.66^{ab}	0.04^{a}	0.26^{ab}	**3.66^{b}**	0.19^{ab}	Weak
Parry's rush	0.34^{a}	0.24^{a}	0.55^{a}	1.09^{bc}	0.66^{ab}	0.24^{a}	**1.67^{bc}**	0.75^{ab}	1.24^{ab}	Very high
Lodgepole pine	0.45	2.54	2.17	0.63	0.67	0.04	0.06	**3.32**	0.34	Moderate
Dune bentgrass	0.11	0.27	0.20	0.11	0.28	1.16	0.71	**3.97**	1.44	High
Partridge food	0.04^{b}	0.06^{b}	0.13^{b}	0.15^{b}	0.17^{b}	0.22^{b}	1.18^{b}	**2.86^{a}**	1.13^{b}	Very high
Cascade lupine	0.12^{ab}	1.55^{bc}	0.62^{ab}	0.19^{a}	0.89^{ab}	1.52^{ab}	0.29^{ab}	**3.91^{c}**	0.49^{a}	Very high

Fig. 3.13. *Large subalpine fir survived burial by the lahar, but its roots were denied oxygen and the tree slowly perished (August 22, 1982).*

Fig. 3.14. *Lahar 2 viewed from above and to the east (July 9, 2008). All portions of this lahar were equally isolated from sources of colonists.*

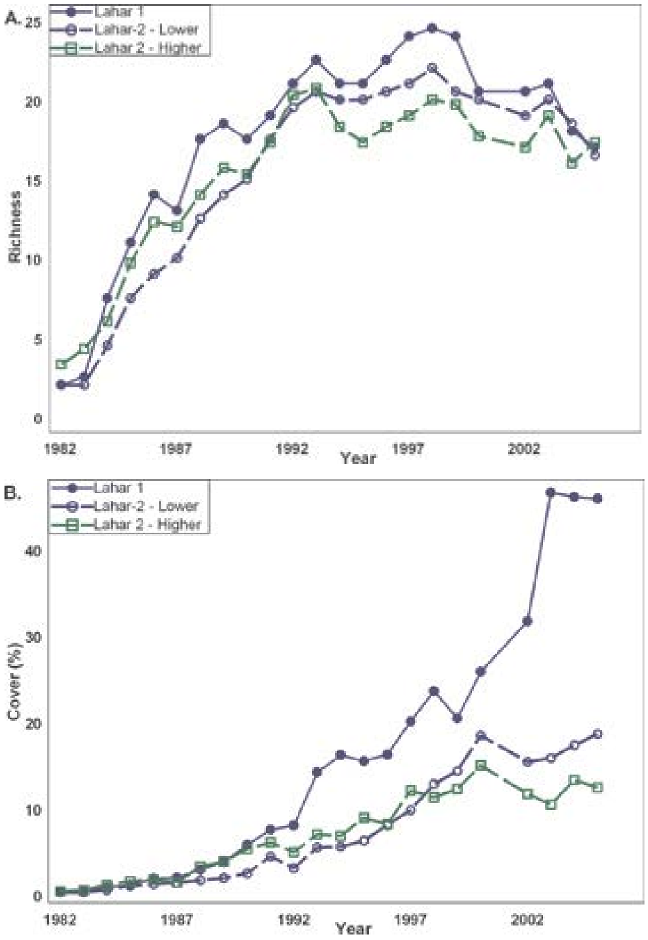

Fig. 3.15. *Vegetation structure on permanent plots established on lahars near Butte Camp: A. richness; B. percent cover.*

lahars that access was interdicted, so comparisons monitoring data ceased in 2005.

Permanent plots were established in 1982 (del Moral 2010). Two were established on Lahar 1 and five on Lahar 2. The number of species increased relatively quickly (Fig. 3.15A), but plots on Lahar 1 had more species than did those on Lahar 2. A subsequent decline occurred in all plots when the developing dominant species excluded rare ones. On Lahar 1, subalpine fir and lodge pole pine became dominant. On Lahar 2, lupines and grasses achieved dominance. Due to the proximity of dense vegetation, cover percentage on Lahar 1 increased rapidly as conifer seedlings began to develop. By 2009, plots on Lahar 1 were dense and difficult to walk through, while those on Lahar 2 remained easily traversed (Fig. 3.15B). These changes are documented by photographs taken from the same point in representative plots over the years (Fig. 3.16A-D).

Changes in species composition are reflected in time-course vectors. They indicate moderate changes (Fig. 3.17) compared to other habitats; each arrow represents vegetation dynamics determined from DCA and thus directly compare degree of change in time. The two plots on Lahar 1 move away from the others, a result of the conifer invasion. By the end of the study, plots on Lahar 1 were similar to each other, and those on Lahar 2 were also relatively similar to each other. However, floristic differences between lahars were four times greater than those among Lahar 2

Fig. 3.16. *Lahars at Butte Camp: A. Lahar 1, 1982; B. Lahar 1, 2005; C. Lahar 2, 1982; D. Lahar 2, 2005.*

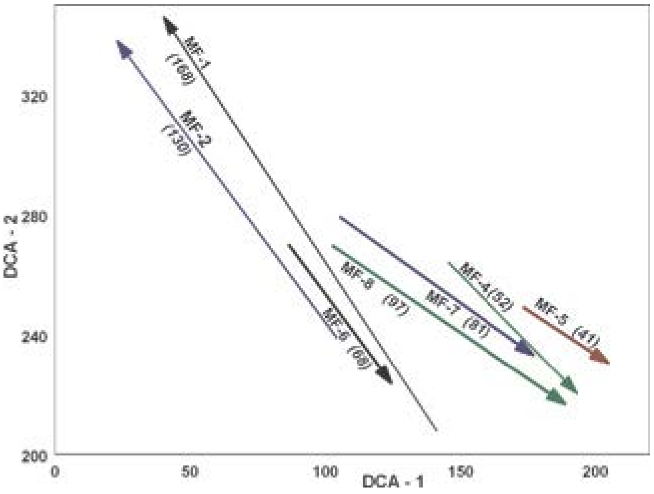

Fig. 3.17. *Trajectories of seven permanent plots on lahars at Butte Camp (1982-2005). Numbers in parentheses indicate Euclidean distance traveled by plots in floristic space determined using DCA.*

plots. Thus, proximity to the intact forest made a huge difference how vegetation developed on these lahars. course vectors. They indicate moderate changes (Fig. 3.17) compared to other habitats; each arrow represents vegetation dynamics determined from DCA and thus directly compare degree of change in time. The two plots on Lahar 1 move away from the others, a result of the conifer invasion. By the end of the study, plots on Lahar 1 were similar to each other, and those on Lahar 2 were also relatively similar to each other. However, floristic differences between lahars were four times greater than those among Lahar 2 plots. Thus, proximity to the intact forest made a huge difference how vegetation developed on these lahars.

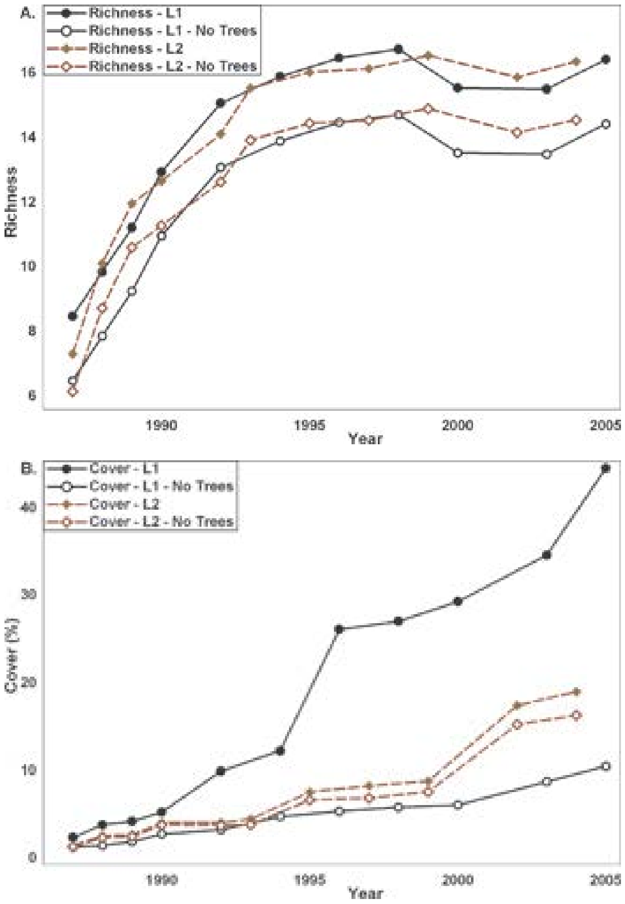

Fig. 3.18. *Vegetation structure comparisons on grids on Butte Camp lahars: A. Richness, with and without tree species; B. Cover percent, with and without tree species.*

Both lahars were also sampled using a grid system starting in 1987 in order to develop a detailed idea of recovery. The grids used contiguous square 100m^2 plots. Each species was recorded in each plot using an index of cover, from which the number of species (richness) and cover percentage were determined (see del Moral and Wood 2012 for details). Both increased during the study (Fig. 3.18A, B). Vegetation on both lahars was initially sparse. By the end of monitoring, plots on Lahar 1 were dominated by subalpine fir and lodge pole pine. Richness on the two lahars was similar throughout the study. The ground layer of Lahar 1 became sparser as conifers matured. In contrast, Lahar 2 supported a diverse ground layer assemblage that included pussypaws, alpine buckwheat, prairie lupine, Cardwell's beardtongue, Davis' fleeceflower, hawkweed and red heather. Total cover was lower due to the limited conifer cover. When trees were excluded, the cover of species on Lahar 2 was twice that of that on Lahar 1, suggesting that conifers reduce understory cover. The species were grouped into six growth form classes used for purposes of comparison between the lahars as follows: conifers, shrubs (e.g., huckleberry), sub-shrubs (e.g., Davis' fleeceflower), persistent herbs (e.g., bentgrass), pioneer species (e.g., fireweed) and mosses (e.g., rock moss). Mean values of the cover percentages were calculated for all plots in each grid. The most obvious difference between the lahars was the abundance of conifers in Lahar 1 (Fig. 3.19A). Shrubs were relatively uncommon on both lahars, while sub-shrubs were significantly more abundant on Lahar 2. In contrast, persistent species were five times more abundant on Lahar 2 than on Lahar 1. Mosses began to be common on Lahar 1 in response to the development of shade (Fig. 3.19B).

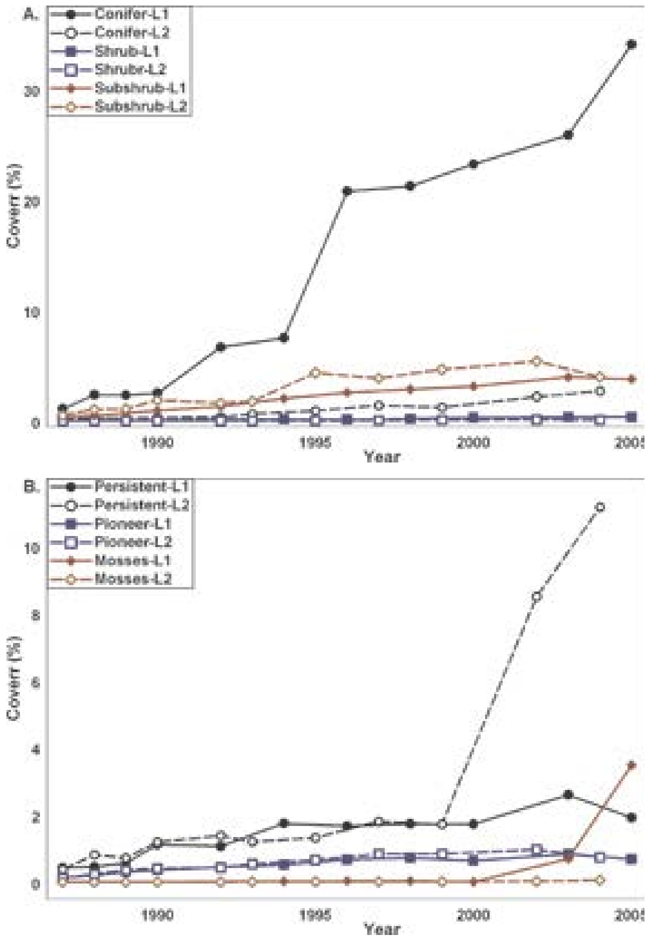

Fig. 3.19*. Cover of species on lahar grids grouped by growth forms: A. Trees, shrubs and sub-shrubs; B. persistent species, pioneers and mosses.*

The floristic and structural differences on the Butte Camp lahars strongly suggested that landscape effects play an integral role in driving primary succession. Isolation, more than the lahar properties, affected the response of vegetation.

Scoured edges. Scouring usually means to cleanse a surface of a durable object (like your sink) by abrasion. River ecologists note that streams scour their banks of vegetation during high water leaving behind only rock and sand. Retreating glaciers reveal thoroughly scoured rocks. On volcanoes, scouring can be caused by lahars. Along the margins of a lahar, erosion removes soil and vegetation, but as the lahar passes, sometimes a thin deposit remains. Lahars may not thoroughly polish the substrate, so an ecotone is created between newly emplaced surfaces and intact vegetation. These are scoured sites. Lahars on Mount St. Helens damaged some plants and removed others; survivors were able to hasten recovery.

Although the presence of surviving species means that recovery is a secondary succession, their scarcity means that the process is closer to primary succession than to recovery in the blown-down zone. Scoured sites have been largely ignored in ecological studies of lahars, probably because they occupy such a tiny area. Scours provide another perspective on vegetation recovery that shows how recovery occurs when only a few plants remain. I investigated scoured sites in Butte Camp and Pine Creek. Lahars removed soil and most vegetation, but some plant life and some soil persisted.

Fig. 3.20*. Scoured slope about Butte Camp, where only a few remnants survived (September 3, 1981). Slope and frequent erosion has limited the recovery of such sites.*

Above Butte Camp, small lahars flowed down canyons in several places. Well above the tephra plots, one lahar removed most vegetation in its path (Fig. 3.20). Because the surrounding vegetation was impacted only by tephra, succession could develop quickly if secondary disturbances permitted. Because soil had been removed and the slope was steep, recovery has been slow. Established plants were frequently removed during years with excessive precipitation. Scoured sites on gentler terrain have recovered substantially, and by 2008 they differed little from surrounding sites that had only received tephra fall (Fig. 3.21). The scour of Pine Creek Ridge showed how disturbance intensity affects community structure. In addition to the blast, which killed the conifers clinging to this slope above 1400 m, rapid melting of the Shoestring Glacier unleashed a torrent that overwhelmed the upper canyon of Pine Creek and swept away most soil and vegetation on the ridges. As this lahar receded, a coating of fine mud clung to the scoured surface. The depth of this infertile material diminished as the elevation dropped because the ridge got wider and Pine Creek canyon got larger. When I first set foot on this ridge on July 26, 1980, it was unbelievable that anything could have survived (Fig. 3.22). The landscape was bleak, dusty, hot and dry. However, as I trudged up slope, I came upon clear evidence that life had indeed survived. A small company of ants was busily attending to its business on a barren surface above 1500 m (Fig. S3.1; see Sidebar 3.1). If ants could survive, perhaps plants had as well.

Fig. 3.21. *This nearby scoured site was nearly barren in 1980, but recovered substantially (August 6, 2008). Dominant species included aster, pussypaws, buckwheat and sedges.*

When I returned to this site on August 20, I found that the meager summer rains and relentless wind had started to erode the mantle of mud (Fig. 3.23). In gullies and in rills, a few plants, mostly bentgrass, struggled to persist (Fig. 3.24). When I returned on September 10 to establish permanent plots, five of nine plots had a few plants, all in sites from which the mud had been removed. Permanent plots established at 1370 m suffered less damage than those at 1525 m. Later, I found that no plants had survived where the mud had persisted to the following year.

Floristic trajectories of scoured plots show moderate change compared to other permanent plots (Fig. 3.25).

Fig. 3.22. *Devastated landscape along Pine Creek Ridge (July 26, 1980).*

Fig. 3.23. *Pine Creek Ridge showing wind erosion and effects of water erosion. Plants in canyons and rills have been seared by eruptions in July and August 1980 (August 20, 1980).*

Fig. 3.24. *Rills due to water erosion developed quickly on Pine Creek Ridge. This allowed rhizomatous plants such as bentgrass and aster to survive (September 9, 1980).*

BCC-1, perched on a gentle slope, changed little and merely increased in cover; it and converged in composition to the nearby BCD-3. BCC-2, in contrast, changed dramatically. It occupies a steeper slope and the new conditions led to its composition becoming distinct from the others. BCD-5 also changed greatly. The Pine Creek scours became increasingly distinct from the Butte Camp ones, generally moving away in composition due to strong bentgrass dominance. The trajectories of plots on gentle terrain moved in parallel, reflecting the development of similar dominant species. PCA-3 and PCB-4 changed little as they represent vegetation on steep slopes that retain snow. Along each transect, plots appear to be converging.

Scour sites show the combined importance of species survival and habitat stability. Consistently unstable sites have not developed, while stable ones have become similar to unscathed plots. Where persistent species survived under stable conditions, there has been little change in species composition, only recovery of the survivors.

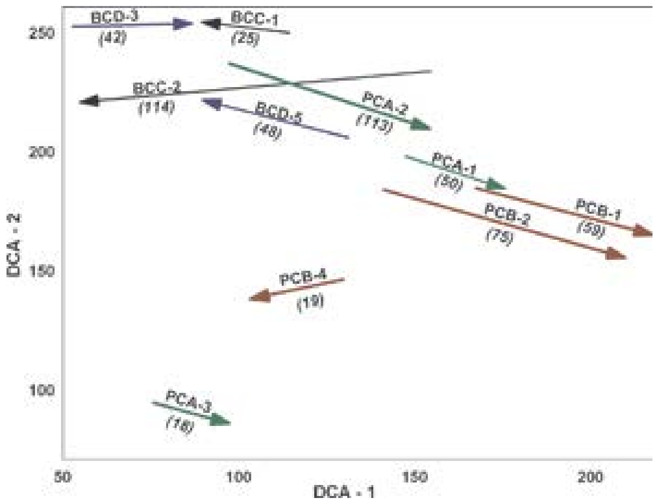

Fig. 3.25 *Trajectories of 10 scoured permanent plots based on DCA scores. Butte Camp trajectories determined from 1980 to 2008; Pine Creek trajectories determined from 1980 to 2009. Numbers in parentheses indicate Euclidean distance traveled by plots in floristic space.*

Impact of lahars on plants

Lahars are devastating. In contrast to lava flows, lahars move swiftly and they often move across a broad front. Few animals can avoid the lahars, so the immediate vicinity becomes devoid of terrestrial animals. Recolonization depends on the nature of disturbances in the surrounding sites. Forests are scooped up to become part of the lahar. Lahars gradually diminish and deposit variable, often coarse and infertile, materials to form the substrate for primary succession. Few plants can survive except on the margins and where the lahar spreads out and slows on gentler terrain. Some trees survive the initial impact of the lahar, only to succumb gradually over several years of by being deprived of oxygen. However, delayed mortality can produce a dense litter of dropped needles and serve to ameliorate conditions on the lahar and hasten the establishment of the first wave in colonists. A few rhizomatous species do occasionally survive if they happen to land near the surface. Lahar deposits, in contrast to pumice, are composed mostly of reworked materials and may include some organic matter. They are more fertile than pumice or other tephra types, and thus recovery is expected to be more rapid than on such substrates. Species that have strong vegetative growth became dominant on lahar deposits and scoured areas.

Importance of lahar deposits

Disturbances associated with lahars demonstrated that once a deposit is deep enough to kill any buried plants, recovery rate is related to distance from sources of propagules. Further, the rate of recovery is a function of the growing season length, so recovery proceeds rapidly at lower elevations (e.g., Cedar Flats) and slowly on high elevation lahars (e.g., Lahar 2). Scours showed that survivors enhance the rate of recovery because they provide an abundance of local seeds and because they help to temper initially stressful conditions.

Where to see lahar and debris avalanche deposits

Lahars on Mount St. Helens provide long vistas and compelling landscapes that enhance the experience of visiting this volcano (Fig. 3.26; see Fig. I.1).

SR-504: North Fork Toutle River debris avalanche can be viewed from several vantages. If you travel east along SR-504, you will have ample chances to see recovering vegetation on the floodplain. These include the Hoffstadt Bluff Visitor Center, the Hoffstadt Bridge, the Forest Learning Center, Elk Rock View Point, the Coldwater Ridge Visitor Center and Johnston Ridge Observatory. You can hike onto the debris avalanche from the Hummocks trailhead, South Coldwater and Johnson Ridge Observatory.

FR-83: The Muddy River lahar may be seen above the Lava Canyon Trail and on your left as you walk up the Ape Canyon Trail #234. If you keep to the left of the lahar, you follow the deeply incised Fire Creek, and up, past the Loowit Trail #216, and further up to Pine Creek Ridge. The views of the lahar are worth the strain of slogging the 6 to 7 km uphill.

Fig. 3.26. *Muddy River lahar (July 27, 2007).*

FR-25: The lower Muddy River and Cedar Flats are crossed by this road.

FR-81: Lahars at Butte Camp can only be reached on foot. The best approach is from FR-81 starting at Red Rock Pass. Butte Camp Trail #238 takes you across an old lava flow, through deep fir forests and into more open pine forests. There is a junction where #238 turns to the northwest; continue uphill on Butte Camp Trail #238A. You will reach a spring and then you will ascend to the open meadow via three long switchbacks. You will encounter the Loowit Trail #216. Turn left (northwest) and you will soon be on the upper edge of a lahar.

Summary

Lahars spawned by the heat of a volcano produce long, slender and barren deposits. Lahars on Mount St. Helens today provide interesting landscapes in which gradients of invasion are prominent. Studies of lahar deposits and scours revealed the importance of landscape factors in determining how vegetation reassembles during succession. Even short distances can affect the species composition of the developing vegetation by altering the composition of colonists.