Hybrid Wet Flows Formed by Hot Pyroclasts Interacting with Snow During the 1992 Eruptions of Crater Peak, Mount Spurr Volcano, Alaska

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CONTENTS

ABSTRACT

During each of the three 1992 eruptions of Crater Peak at Mount Spurr volcano in Alaska, hot pyroclasts interacted with snowpack to form mixed snow-pyroclast flows. Some flows were mostly of snow that melted slightly to be mobile but still cold; others were mostly of pyroclasts whose snow component melted entirely to make the flows more mobile and cooler than ordinary pyroclastic flows. Some pyroclastic flows were large enough to substantially melt and erode glacier ice to generate a lahar that greatly enlarged a moraine breach. The largest wet flows coalesced, swept down and off the volcano flanks, and transformed into lahars. On the volcano flanks were a wide range of hybrid flows between conventional pyroclastic flows and conventional lahars. The hybrid flows of mixed debris from Crater Peak resemble some formed by swift pyroclast-snow interactions at Mount St. Helens, Washington, during explosive events between 1980 and 1991; at Nevado del Ruiz, Colombia, in 1985; at Augustine Volcano, Alaska, in 1976 and 1986; and at Redoubt Volcano, Alaska, in 1989–90. Wet pyroclastic flows are hazardous insofar as their reduced internal friction projects destructive flows down valleys beyond the reach of dry pyroclastic currents. The trajectory of pyroclasts launched over the crater rim by a partly obstructed, inclined vent produced flows on the southeast and east flanks in addition to those along a southward route through the low point of the crater rim.

INTRODUCTION

Crater Peak at Mount Spurr volcano, Alaska (fig. 1), erupted three times in 1992: June 27, August 18, and September 16–17. These eruptions, each lasting 3 to 4 hours, were the first activity since a single eruption on 9 July 1953 (Juhle and Coulter, 1955). During each of the 1992 eruptions, hot pyroclasts turbulently interacted with snowpack to form mixed snow-pyroclast flows.

Pyroclastic flows and surges on the one hand, and lahars on the other, are commonly treated as distinct phenomena. Hybrid flows lie somewhere in between. This report describes the deposits and the erosion of glaciers by hybrid pyroclast-snow flows on the flanks of Crater Peak, gives photographic documentation, qualitatively discusses pyroclast-snow interaction processes, and analyzes flow-initiation mechanisms. Of the 1992 Crater Peak eruptions, chronology and overview are addressed by Eichelberger and others (this volume), pyroclastic flows by Miller and others (this volume), tephra deposits by Neal and others (this volume), and sizable lahars on the lower volcano flanks by Meyer and Trabant (this volume).

The behavior of a hybrid mixed flow depends partly on the proportion of components. Two end members of mixed flows are: (1) mostly snow that only partly melts but including a minor pyroclastic component; and (2) mostly pyroclasts but including a minor proportion of snow that entirely melts. The pyroclast component can vary between lithic and pumiceous end members. A pyroclastic flow that incorporates only a small proportion of snow will behave more or less as a conventional hot and dry pyroclastic flow but be somewhat cooler. A small pyroclastic flow that triggers a huge snow avalanche will behave more or less as a snow avalanche—albeit a wet one because of some melting. Intermediate pyroclast-snow mixtures form a wide variety of fluid flows ranging from wet pyroclastic flows, to slushflows, to debris flows, to floods.

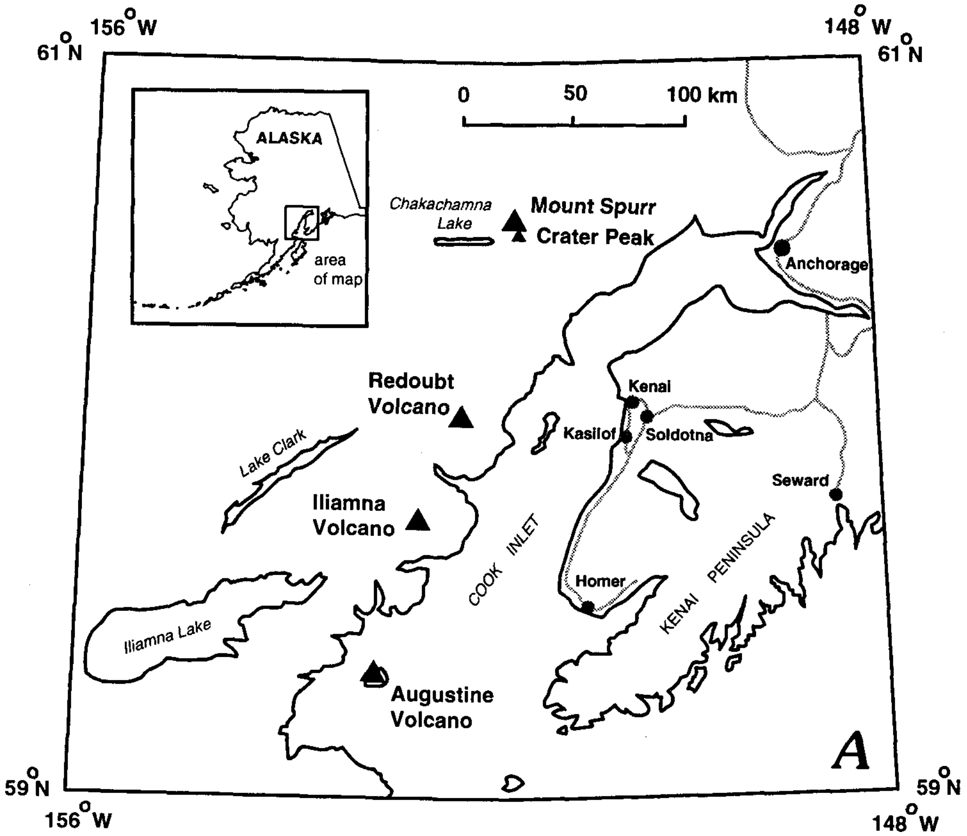
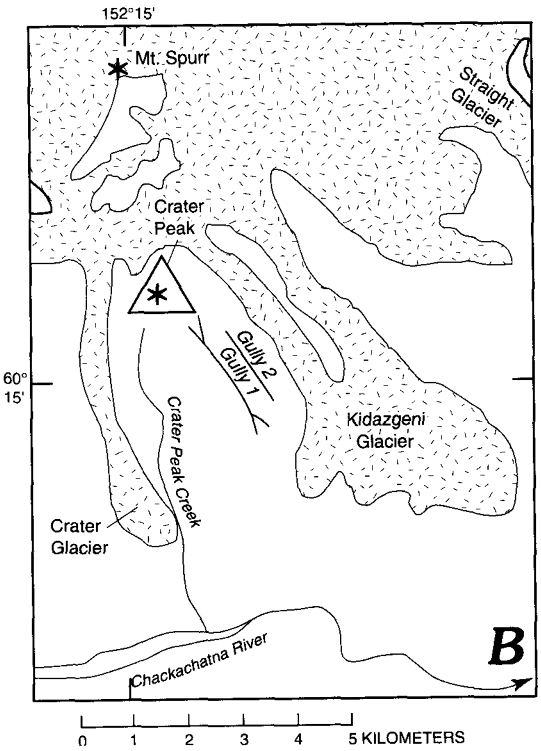


Figure 1. Index maps of (A, above) Cook Inlet area and (B, below left) Mount Spurr and Crater Peak area, Alaska (stipple pattern, glacier).



JUNE ERUPTION

Before the June 27 eruption, snowpack discontinuously clad Crater Peak from the crater rim (2,135–1,950 m) down to 1,370 m, thickest in gullies. Hot pyroclastic debris mixed with this snow during the June eruption to form mixed snow, ice, and rock avalanches that flowed south down creeks between Kidazgeni and Crater Peak Glaciers. These flows entered the Chakachatna River 6 km from the crater in two places. Most of the debris flowed down Crater Peak Creek drainage, the course followed by a lahar that briefly dammed the river during the 1953 eruption.

The largest flow exited the south-facing crater breach and followed a sinuous deep gully to Crater Glacier and Crater Peak Creek (fig. 2*A*,*B*) (Meyer and Trabant, this volume). Gully 1, which descends the south-southeast flank of Crater Peak, does not head at the south-facing breach in the crater rim (1,950 m). A snowy debris flow of volume of $1x10^5$ m3 or less descended gully 1, broadly overflowed its sides (fig. 3), and fingered out; the flow in the main channel continued down below altitude 740 m. At a sharp bend

Figure 3. Oblique view northwestward of gully 1 showing distribution of mixed-flow and pyroclastic-flow deposits of 1992 Crater Peak eruptions, Mount Spurr volcano, Alaska. J, broadly distributed June pyroclast-snowflow deposit; A, August pyroclastic flows; S, confined September wet pyroclastic-lahar flows; sr, site of spillover of June and runup of August flows where velocity was measured. Photograph taken September 26, 1992.

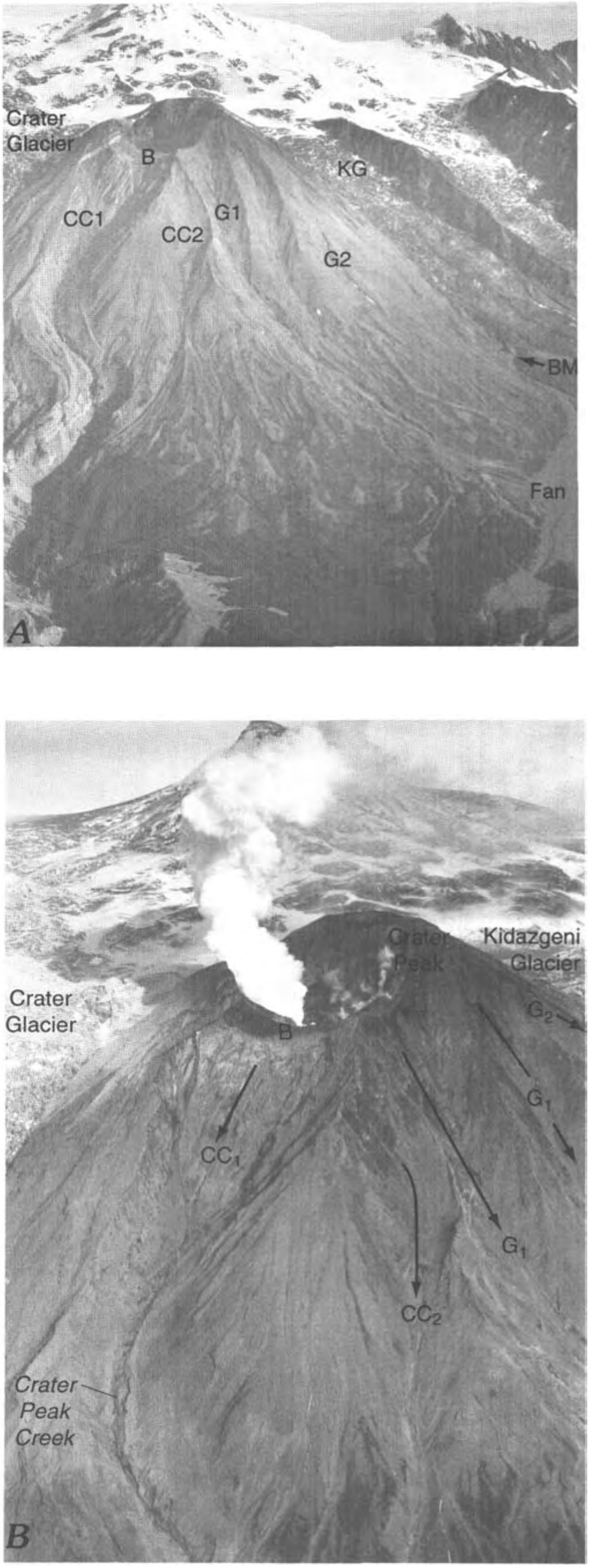


Figure 2. Oblique aerial views north showing Crater Peak, Alaska, on south flank of Mount Spurr volcano, shown at top of both photographs. Between Mount Spurr and Crater Peak is the common head of Crater Glacier and Kidazgeni Glacier. Crater Peak Creek heads at the breach (B) in the crater rim; the southeast crater rim forms a barrier between the crater and the two heads of gully 1 (G1) and especially gully 2 (G2). Arrows show paths of main pyroclast-snow flows of June 27, 1992. CC1 and CC2 show paths of the main and a smaller flow that combined to form main lahar down Crater Peak Creek (see Meyer and Trabant, this volume). BM (photograph *A)* denotes breached moraine where flood of September eruption on Kidazgeni Glacier entrained much debris, deposited on fan below. *A*, Photograph taken July 27, 1993. B, Photograph taken September 26, 1992; steam plume shows position of vent against west crater wall.

in the creek at about altitude 790 m, the flow ran as high as 8 m up a steep wall nearly transverse to flow. The equation $v = (2gh)^{1/2}$ (v, velocity; g, gravitational acceleration; h, runup height) relating kinetic energy converted to potential energy at a runup gives a velocity of 13 m/s or 47 km/hr.

At summer's end, the flow deposit was a loose, unsorted diamict with a sandy matrix that carried lithic clasts (no pumice) as large as 0.5 m. The deposit had an intricately rough surface texture in places including small (<20 cm deep) kettles (fig. 4) and an outer margin only 10 to 30 cm high. Scrub willow abraded by the flow was unscorched and uncharred, and by late summer perennials such as fireweed had sprouted up through the deposit where it was thinner than 30 cm—both of which suggest that this flow had not been hot. A high proportion of internal voids formed during summer by melting of a substantial snow component caused the deposit to suddenly deflate when jarred underfoot. The deflatable character and the rough, kettled surface of this deposit was like that of mixed lithic pyroclast-snow flows emplaced during several eruptions at Mount St. Helens between 1981 and 1986 (Waitt and MacLeod, 1987). After a winter season of compaction beneath snow, a spring season of wetting, and a summer season of episodic high winds, the deposit had become fully deflated and its surface smoother. The deposit shows no evidence of having been channeled by free surface water during emplacement, except along the gully axis where a wetter phase carved a broad channel (fig. 5) and transformed into a small debris flow downchannel (Meyer and Trabant, this volume).

Figure 4. View in gully 1 at altitude 770 m of unsorted mixed-flow deposit from June 27, 1992, eruption of Crater Peak, Mount Spurr volcano, Alaska. Mixed-flow deposit in foreground is deflated by melting of its former snow constituent. It is overlapped by August pyroclastic-flow deposit (just behind person). Photograph taken September 26, 1992.

Figure 5. View northwest in gully 1 on Crater Peak, Mount Spurr volcano, Alaska, showing channel (C) cut through snow-flow deposits (J) of June eruption by trailing watery phase of same flow, then partly filled by pumiceous pyroclastic flow of August eruption (A). Photograph taken July 27, 1993.

The trajectory of the Crater Peak eruption debris not only southward through the low point on the crater rim but also broadly over the higher south-southeast rim was influenced by the position of the vent against the northwest crater wall (fig. 2*A*,*B*). This vent position directed explosions southeastward; thus voluminous hot fragmental material lofted over the crater rim and onto the outer flank of the cone where it swiftly and turbulently mixed with snowpack. The ejected debris was mainly lithic, apparently derived from the vent walls and crater wall. Southeastward ejection occurred despite wind that carried the eruption's tephra plume north (Neal and others, this volume).

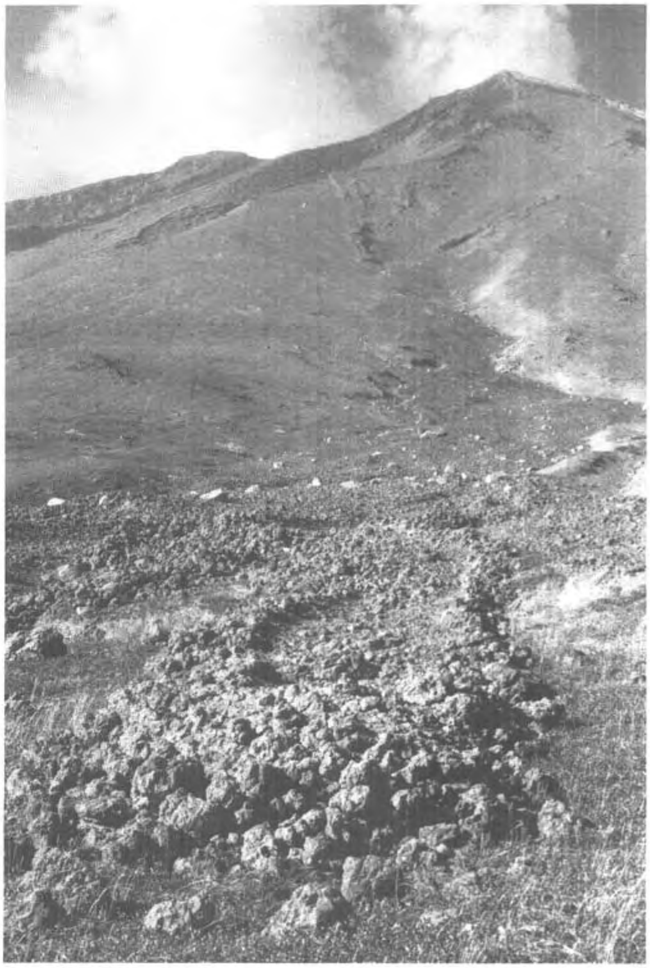


Figure 6. Steep, lobate deposits of hot pyroclastic flows that descended gully 2 during August 1992 eruption of Crater Peak, Mount Spurr volcano, Alaska. Concentrated pumice blocks are at flow margin, beneath which vegetation is charred. Width of lobe in foreground is about 3 m.

AUGUST ERUPTION

The August 18 eruption sent small-volume pyroclastic flows of breadcrusted dark andesite pumice down the east and southeast flanks of Crater Peak (Miller and others, this volume). The deposits at the surface are coarse, clast supported, and fines poor. In gully 1, levees of angular pumice mark the extents of successive flow lobes. They rode up 7 m on a steep nearly transverse side ($v = (2gh)^{1/2} = 12$ m/s or 43 km/hr), and they overflowed the gully sides in a few places but far less than did the June mixed flow (fig. 5). Steep-fronted deposits of the flow terminate in the main channel at about altitude 745 m (fig. 3), well upvalley of the June mixed-flow terminus.

Several pumiceous pyroclastic flows swept the east-southeast flank of Crater Peak, down to 885-m altitude in gully 2, where they left typical steep, fines-poor, lobate margins 1 to 2 m high (fig. 6). The deposits remained hot for days, and blocks at the edges of these flows charred vegetation beneath them.

One of these pyroclastic flows in gully 2 mixed with snow high on the cone to form a flow much more mobile but compositionally identical (pumiceous) to one that descended the west side of the gully down to altitude 780 m (fig. 7). In contrast to typical pyroclastic-flow deposits upslope, this deposit has gently sloping margins only 20 to 50 cm high. The flow did not char vegetation that it had abraded; pumiceous blocks at the flow edge did not scorch underlying tundra plants. Small boulders jammed up behind large ones (fig. 8) much more than in the steep-margined flows—evidence of a crude sorting process that trapped coarse clasts and evidence that flow continued after depositing jams. A water phase must have caused the higher mobility. Traced upgully to altitude 885 m, this mobile-flow deposit merges with a steep-fronted typical pyroclastic-flow lobe on the east side of gully 2. Thus the part of the flow in the deeper part of the gully detached and flowed much farther. This relation is evidence that a single pyroclastic flow divided because part of it mixed with snow in the gully axis, became wet and lost some internal friction, and thus was able to flow farther even on gentle slopes.

These flows descended gully 2 despite that the gully heads on the high southeast segment of the crater rim far from the south-facing crater breach (fig. 2). Downslope from the even higher segment of the crater rim, pyroclastic flows also mixed with snow to form a small watery lahar that flowed down the west side of Kidazgeni Glacier, through a moraine breach, and to Chakachatna valley (Meyer and Trabant, this volume). The pyroclastic debris did not spill through the southward gap in the crater rim but was explosively launched east and southeast with enough vol-

Figure 7. View upvalley of mobile-flow deposit of the August 1992 eruption of Crater Peak, Mount Spurr volcano, Alaska, that greatly outdistanced normal pyroclastic flows in gully 2. Margins are low, clasts are sorted (water winnowed), and vegetation is abraded but not charred. Person (to right) is standing in ballistic impact crater. Boulder jam shown in figure 8 marked by arrow. Compare with figure 6.

Figure 8. View downflow of jam of cobbles and small sorted boulders on upstream side of 1.5-m boulder in August 1992 mixed-flow deposit in gully 2. Handle of shovel (center of photograph) is about 50 cm long. Crater Peak, Mount Spurr volcano, Alaska.

ume to erode and melt snow that lingered even in late summer. Ballistic projectiles—lithic clasts as large as 1.5 m and smaller juvenile projectiles—were hurled at least 4 km southeast of Crater Peak (fig. 7) (Waitt and others, this volume). This ballistic shower, which mostly occurred after the pyroclastic flows were emplaced on the same flank, is further evidence that the vent explosively directed debris southeast over the crater rim.

SEPTEMBER ERUPTION

The eruption during the night of September 16–17 sent at least two wet pyroclastic (laharic) flows down the south-southeast and southeast flanks of Crater Peak. In gully 1 a fluid flow with gentle termini fingered out 300 m upgully of the August pyroclastic-flow termini. **A** second deposit in gully 1 has a sharp steep margin 0.5 to 1.5 m high (fig. 9) of several lobes whose crosscutting patterns delineate slight differences in arrival times. That second flow apparently was far more viscous than the slightly earlier flow, and it terminated abruptly about 50 m upvalley of the first wet-flow terminus. The September deposits consist largely of breadcrusted to angular clasts of juvenile andesite pumice superficially resembling pyroclastic-flow deposits. Yet 12 to 15 hours after the eruption both were cool and water saturated (R.M. McGimsey, oral commun., 1992). The younger of the two has arcuate pressure ridges indicating a flow with internal strength (fig. 9). Rather than remaining loose as in typical pyroclastic flows, the matrix hardened within days as the wet clay and silt particles adhered to each other and bound the coarse clasts. Unlike the largely pumiceous August flows, only two-thirds of gravel clasts of the September wet flows are juvenile; the rest are diverse porphyritic andesite clasts of older Crater Peak rocks incorporated upgully.

Figure 10. Low-level aerial views (photographs taken September 29, 1992) of ice scabland produced by flood during September 1992 eruption of Crater Peak, Mount Spurr volcano, Alaska, along west side of Kidazgeni Glacier. ***A***, September pyroclastic-flow deposit veneer stripped along September ice-scabland channels; width between scarps in deposit in lower part of photograph is about 5 m.

Pumice-lithic pyroclastic flows also descended the east-northeast side of Crater Peak cone and turned southeast down Kidazgeni Glacier. An eyewitness situated 18 km to the southeast reported the heaviest incandescent flows of the night eruption on the east flank. At altitude 1,000 m their collective deposit is a poorly sorted pebble gravel that consists mostly of dark brownish gray andesite and lithic clasts. Many ice blocks as large as 1 m were entrained as the flow descended an ice fall. This deposit broadly overlies gently sloping parts of the glacier between altitudes 1,050 and 800 m (fig. 10*B*). Along the west side of the glacier from altitude 2,000 down to 1,000 m (gradients 500 to 150 m/km), meltwater stripped off this deposit along a tract 5 to 15 m wide while eroding a stepped series of cataracts and plunge pools several meters wide and deep (figs. 10, 11). This essentially subfluvial topography is a small-scale scabland with 0.5- to 1-m scarps along its margins, analogous to the bizarre topography of Washington's channeled scabland, two to four orders of magnitiude larger cut in basalt by gigantic floods during the Pleistocene (Bretz, 1928, 1959; Waitt, 1994). Within the ice scabland on Kidazgeni Glacier are pockets of poorly sorted diamict containing lithic boulders as large as 1.5 m indicative of debris flow, and moderately sorted gravel in the form of small expansion bars (also a channeled-scabland analogy) at the lower ends of some eroded ice-scabland channels, indicative of sediment-laden streamflow. The debris flow formed as meltwater mixed with the new pyroclastic-flow deposit; the streamflow ensued as the proportion of meltwater outstripped the available supply of pyroclasts. The watery phase of flow down the glacier closely followed the debris-flow phase.

Figure 9. Terminus of lobate laharic flow of the September 1992 eruption of Crater Peak, Mount Spurr volcano, Alaska in gully 1. Note delicate pressure ridges on flow surface. Person for scale. Photograph taken September 26, 1992.

From the ice-scabland tract the flows emerged onto a flatter (gradient 100 to 50 m/km) part of the glacier and spread out as a broad fan 50 to 75 m broad. Later incision of this deposit exposed more than 1.2 m of compact, nearly massive pebble gravel (diamict) capped by 20 cm of loose openwork pebble

Figure 10. Continued. **B,** View directly up main ice-scabland tract; width of roughest part of tract about 8 m.

Figure 10. Continued. *C*, Erosional ice-scabland and patches of pyroclastic-flow deposit, view upglacier; height of largest scabland elements about 2.5 m.

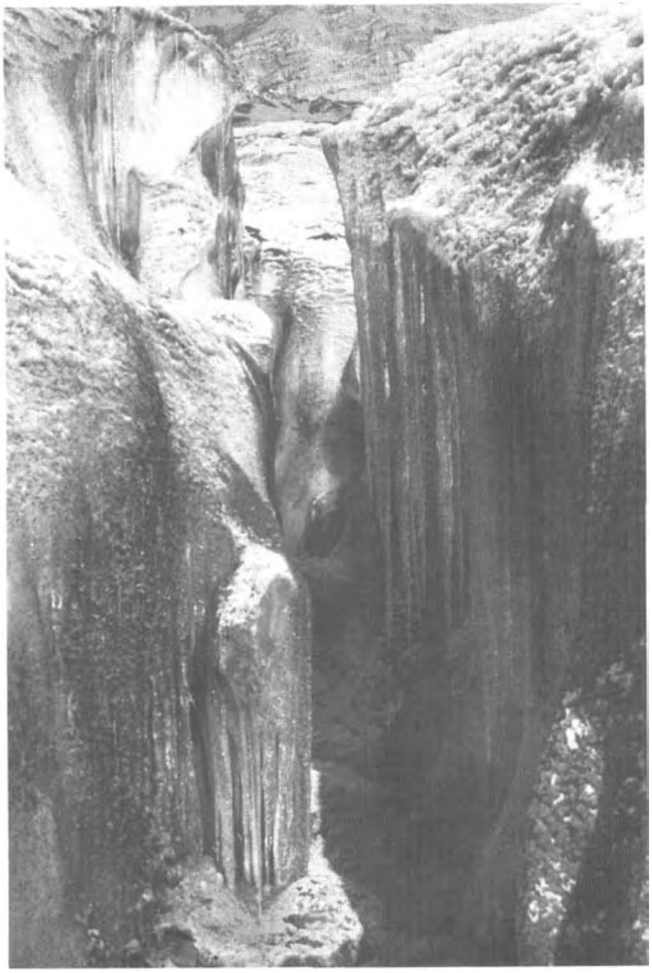


Figure 11. Close view (photograph taken September 29, 1992) upglacier of ice scabland on Kidazgeni glacier produced by flood during September 17, 1992 eruption of Crater Peak, Mount Spurr volcano, Alaska. Depth of scour shown here is about 2.5 m.

gravel (fig. 12). This two-layer deposit bespeaks a voluminous debris flow phase followed by a voluminous watery phase.

Detailed grain-size analyses are beyond the scope of this study, but differences obvious in the field are quantified by histograms and cumulative-frequency grain-size distributions obtained by sieving representative samples (fig. 13*A*,*B*). Mass-flow deposits are poorly sorted, the water-flow deposit moderately sorted (tables 1,2). In Folk's (1980) classification the pyroclastic-flow deposit is medium-pebble gravel, the debris-flow deposit sandy small-pebble gravel (but both are diamicts), and the watery flow deposit a large-pebble gravel (fig. 13*C*). The large deviation in clast sizes within the pyroclastic-flow deposit bespeaks its polymodal source and lack of winnowing during flow. The even poorer sorting of the debris-flow deposit probably reflects its incorporation of supraglacial de-

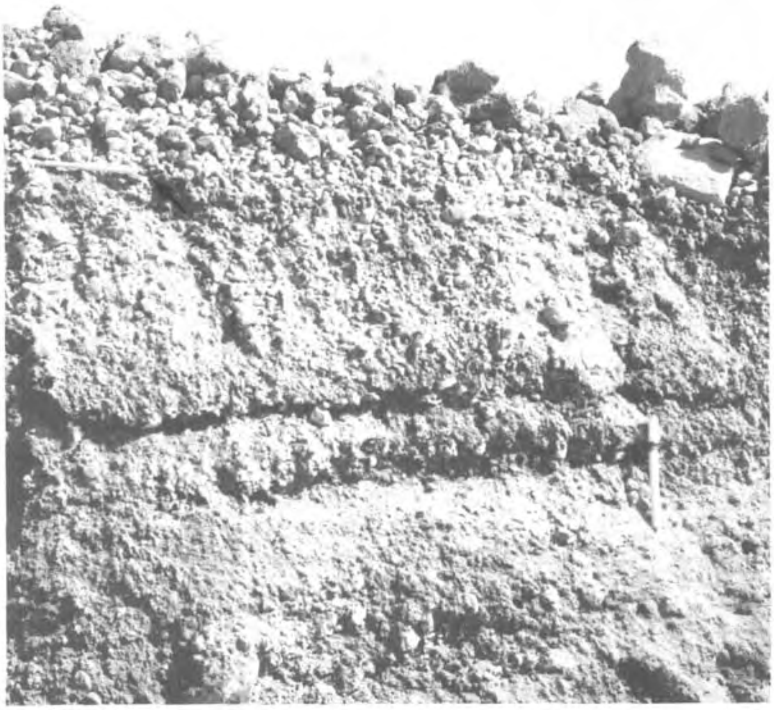


Figure **12.** Section exposing September 13, 1992, flowage deposits overlying Kidazgeni Glacier, Crater Peak, Mount Spurr volcano, Alaska. Matrix-bearing debris-flow deposit with poorly developed plane bedding is overlain at pencil (arrow) by openwork pebble-cobble gravel watery-flow deposit. Pen to right is 13 cm long.

bris; the far lower deviation of the waterlaid deposit demonstrates a winnowing out of the fines and perhaps also the coarsest clasts.

The composite debris and watery flow descended to the glacier side and through an existing breach in the right-lateral moraine about at altitude 1,068 m. The flow apparently greatly enlarged the erosional gash, where it incorporated much coarse sediment before spreading gravel across a fan west of the glacier at altitude 825 to 670 (fig. 14). From there a small lahar tongue descended to the Chakachatna River (Meyer and Trabant, this volume).

The September pyroclastic flows and derivative water-containing flows were concentrated on the east-northeast through south-southeast segment of the cone rather than downslope from the south-facing crater breach. This distribution indicates that the pyroclasts were launched by directed explosions, as they were during the June and August eruptions. Over the course of the three eruptions the vent was observed to migrate progressively west, and so after the September eruption it was tight against the west-northwest crater wall (T.P. Miller, oral commun., 1992). With each eruption the migrating vent directed energetic explosions successively farther counterclockwise, from south-southeastward to eastward, obliquely away from the south-facing crater-rim breach.

Table **1.** Sieve analyses for three samples of flows of the September 1992 eruption of Crater Peak, Mount Spurr volcano, Alaska.

[Values are weight percent of entire sieved sample.]

Size class in phi (ø)	Pyroclastic flow	Debris flow	Watery flow
-6	11.5		
-5	5.8	5.3	34.5
-4	11.8	10.9	51.0
-3	22.1	25.3	12.7
-2	17.5	20.7	0.1
-1	16.7	12.9	0.0
0	10.9	8.7	0.0
1	2.7	5.1	0.0
2	0.7	7.3	0.1
3	0.3	3.3	0.2
4	0.1	0.1	0.3
>4	0.0	0.4	1.2
Total -----	100.0	100.0	100.0

Table 2. Statistical data from sieved samples of flows of the September 1992 eruption of Crater Peak, Mount Spurr volcano, Alaska.

[Parameters of Folk, 1980]

Parameter	Pyroclastic flow	Debris flow	Watery flow
Weight percent gravel	85.4	75.1	98.3
Weight percent sand	14.6	24.5	0.6
Weight percent mud	0	0.4	1.1
Mean (ø)	-3.1	-2.2	-4.8
	medium pebble	*small pebble*	*large pebble*
Sorting (ø)	1.8	2.1	0.8
	poor	*very poor*	*moderate*
Skewness	0.02	0.29	0.0
	symmetrical	*fine skewed*	*symmetrical*

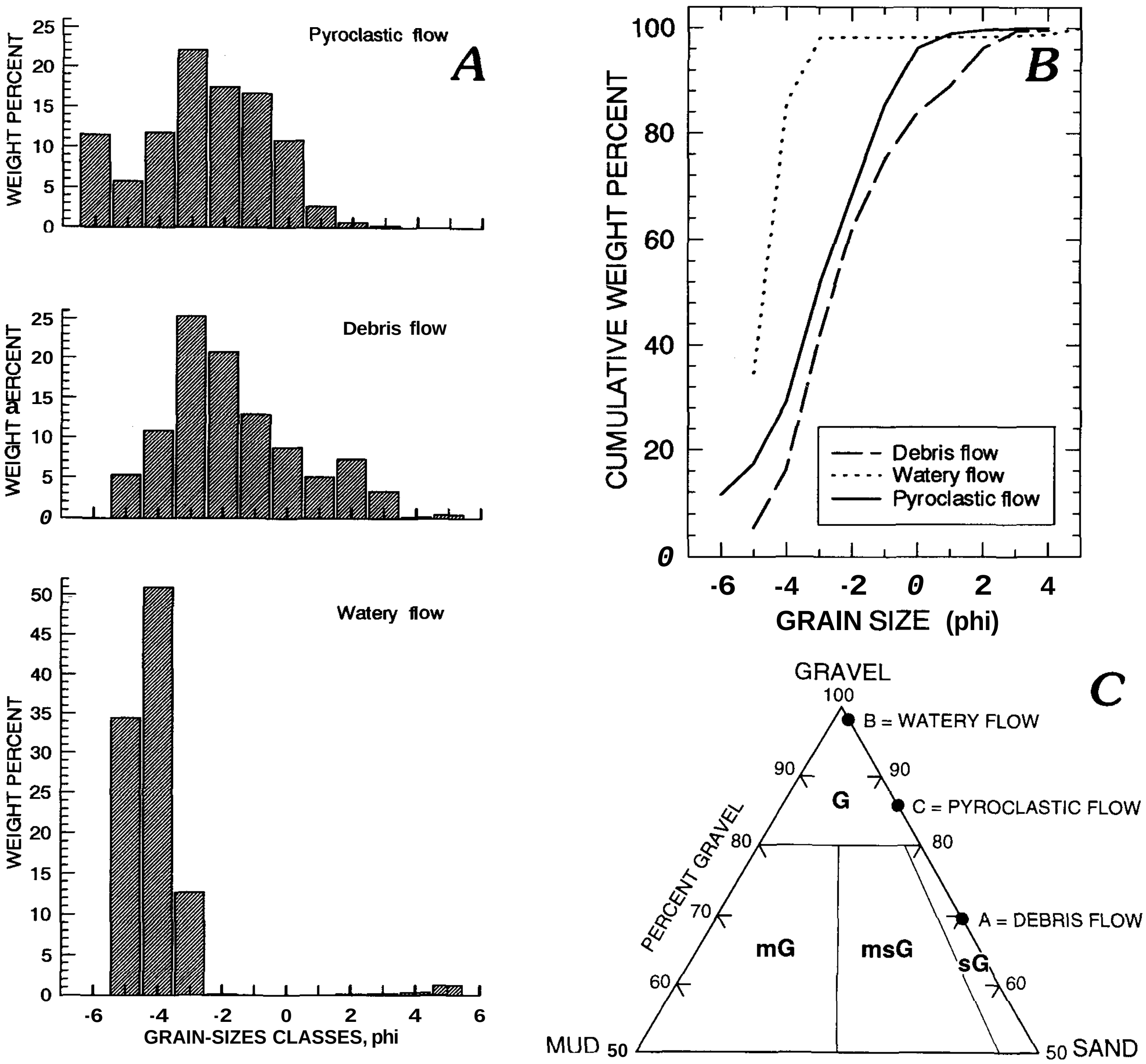


Figure 13. Grain-size character of pyroclastic-flow deposit of August 18, 1992, eruption on Kidargeni glacier and deposits derived from it by water-flow processes. Crater Peak, Mount Spurr volcano, Alaska. *A*, Histographs showing grain-size distributions. B, Cumulative grain-size-frequency distributions. *C*, Names according to Folk's (1980) classification. Only top (gravel) portion of Folk's classification triangle shown. G, gravel; sG, sandy gravel; msG, muddy sandy gravel; mG, muddy gravel.

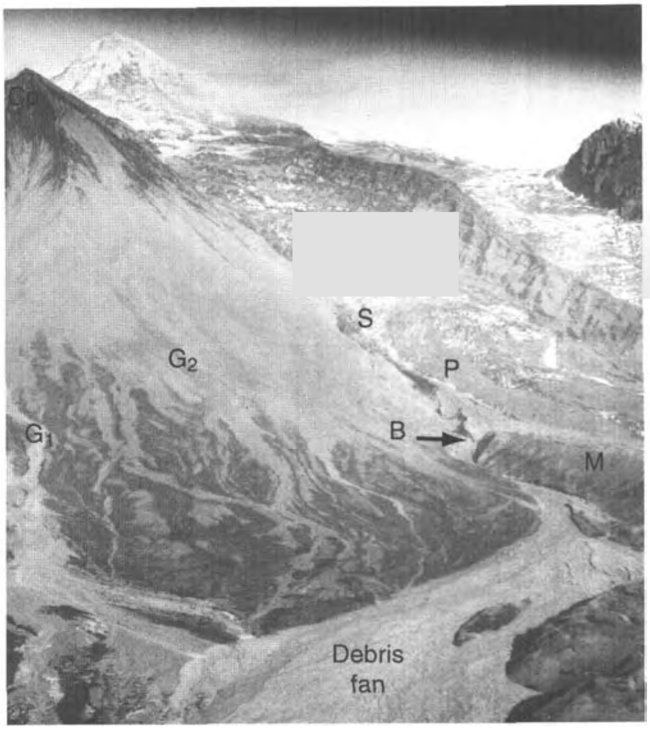


Figure 14. View north showing fan of flood debris below the right-lateral moraine of Kidazgeni Glacier and other effects of September 16–17, 1992, eruption of Crater Peak, Mount Spurr volcano, Alaska. Mount Spurr is high, snow-capped peak to upper left; Crater Peak is peak on far left. G1, gully 1; G2, gully 2; P, pyroclastic-flow deposit on glacier; S, water-scoured west side of glacier. B, breach enlarged by flood through lateral moraine. Debris fan resulted from distribution of material from moraine breach. At the mouth of gully 1, the September fan cuts across small fan of June flow that descended gully 1.

COMPARISON WITH ERUPTIONS AT OTHER SNOWCLAD VOLCANOES

The deposits of hybrid flows from Crater Peak resemble those of mixed pyroclast-snow flows during several other recent eruptions. Swift pyroclast-snow mixing occurred at the base of the huge pyroclastic surge off Mount St. Helens during the first minutes of the cataclysmic eruption of May 18, 1980. Stratigraphy shows that large laharic flows down the east and west volcano flanks trailed the pyroclastic surge and were clearly caused by it (Waitt, 1989). Between 1981 and 1991 many small to moderate explosive eruptions at Mount St. Helens caused turbulent, rapid mixing of hot pyroclasts with snowpack on the crater walls and floor to form various mixed flows (Waitt and others, 1983; Waitt and MacLeod, 1987; Mellors and others, 1988). Each mixed-flow deposit included a relatively dry marginal facies consisting largely of snow that did not melt and which froze soon after emplacement. Many pyroclast-snow mixing events also produced far more mobile slushflows along deeper and more axial parts of flowpath. Further melting transformed some of them into watery flows that deeply channeled snowpack along the lowest axial part of the flowpath.

During the eruption of Nevado del Ruiz, Colombia, in November 1985, initial pyroclastic surges dynamically mixed with snowpack, firn, and ice to form unusual, mixed ice-debris deposits (Pierson and others 1990, figs. 8, 9). Ensuing pyroclastic flows did far more turbulent mixing and melting to form lahars that flowed down surrounding valleys, where they enlarged with debris and streamwater into huge lethal flows.

At Augustine Volcano, Alaska, pyroclastic flows of two recent eruptions turbulently mixed pyroclasts with snowpack to yield watery flows. During the 1976 winter eruption, pumiceous pyroclastic flows incorporated winter snowpack to form pumiceous deposits more sorted and with more rounded clasts than adjacent pyroclastic-flow deposits (Kamata and others, 1991, fig. 9). The 1986 spring eruption produced typical pumiceous pyroclastic flows that merge downslope into small scabland erosional tracts overlain by patchy, matrix-free water-washed coarse gravel (unpub. data, 1988), evidence that pyroclastic flows swiftly melted snowpack they overrode.

During the 1989–90 eruptions of Redoubt Volcano, Alaska, repeated collapses of fragmented hot dome rock onto glacier ice formed debris flows and watery floods. The initial eruption of December 15, 1989, formed an expansive "dry" ice-diamict deposit on both the north and south volcano flanks (Waitt and others, 1994). The degree of melting was small because pyroclasts were swiftly cooled by a huge volume of readily incorporated snow and firn. But during many later dome collapses, fragmented dome rock swiftly interacted with and greatly eroded the northside Drift glacier (Trabant and others, 1993) to yield large watery floods.

At Crater Peak the wet, mixed flows were fairly small. The dry-appearing hybrid-flow deposit of June 27 closely resembles the surface texture of the "dry" phases of mixed-flow deposits at Mount St. Helens between 1982 and 1986 and also the melted ice-diamict surface at Redoubt (Waitt and others, 1994, figs. 11, 12). The small scabland eroded into Kidazgeni Glacier in September was similar to the ice-erosional forms carved in Drift glacier by the 1989–90 Redoubt eruptions (Trabant and others, 1994).

Hybrid flows are probably far more common than past reports suggest. Those from Crater Peak and the other cited eruptions were documented because of access by helicopter soon after eruption. Because the flows are cool or cold, snowfall quickly obscures them in winter. Because some of the flows contain much snow, much of the original volume disappears and the resulting deposit can resemble a typical pyroclastic-flow or lahar deposit. The subtle evidence of wetness can be mostly lost in the geologic record, indeed easily overlooked even in recent surface deposits.

HAZARDS

Had the wet or snowy flows at Crater Peak been larger they might have dammed Chakachatna River and induced large floods, but they would not have endangered life or property in that remote setting. Yet these small hybrid flows illustrate a hazard common to snowclad volcanoes. When hot pyroclasts turbulently mix with snow or flow over glacier ice, they swiftly generate wet flows that can soon travel beyond the limits of dry, hot pyroclastic flows. Thus their damaging effects extend beyond the mountain flanks. At volcanoes in Indonesia and the Phillipines that are affected by monsoons, most lahars initiate secondarily when torrential rains act on loose, hot, unstable pyroclastic debris (Rodolfo and Arguden, 1991; Pierson and others, 1992). The type of snowflows and floods produced at Mount Spurr volcano, Mount St. Helens, Redoubt Volcano, and other snowclad volcanoes, are ***primary,*** produced as they are swiftly ***during*** a pyroclastic eruption by turbulent hot flows moving over snow or ice. Large, lethal examples of such floods originated at Öræfajökull in Iceland in 1362 (Thorarinsson, 1958), at Cotopaxi in Ecuador in 1877 (Wolf, 1878), and at Nevado del Ruiz in Colombia in 1985 (Pierson and others, 1990). In a literature review, Major and Newhall (1989) compiled data on historical eruptions at snowclad volcanoes, concluding that pyroclastic flows and surges acting on ice and snow are the most important processes generating ***primary*** large lahars and floods.

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