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Disruption of Drift glacier and origin of floods during the 1989–1990 eruptions of Redoubt Volcano, Alaska

D.C. Trabant[a], R.B. Waitt[b], J.J. Major[b]

[a]*U.S. Geological Survey, Alaska Volcano Observatory, Fairbanks, AK 99775, USA*
[b]*U.S. Geological Survey, Cascades Volcano Observatory, Vancouver, WA 98661, USA*

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Abstract

Melting of snow and glacier ice during the 1989–1990 eruption of Redoubt Volcano caused winter flooding of the Drift River. Drift glacier was beheaded when 113 to 121×10^6 m^3 of perennial snow and ice were mechanically entrained in hot-rock avalanches and pyroclastic flows initiated by the four largest eruptions between 14 December 1989 and 14 March 1990. The disruption of Drift glacier was dominated by mechanical disaggregation and entrainment of snow and glacier ice. Hot-rock avalanches, debris flows, and pyroclastic flows incised deep canyons in the glacier ice thereby maintaining a large ice-surface area available for scour by subsequent flows. Downvalley flow rheologies were transformed by the melting of snow and ice entrained along the upper and middle reaches of the glacier and by seasonal snowpack incorporated from the surface of the lower glacier and from the river valley. The seasonal snowpack in the Drift River valley contributed to lahars and floods a cumulative volume equivalent to about 35×10^6 m^3 of water, which amounts to nearly 30% of the cumulative flow volume 22 km downstream from the volcano. The absence of high-water marks in depressions and of ice-collapse features in the glacier indicated that no large quantities of meltwater that could potentially generate lahars were stored on or under the glacier; the water that generated the lahars that swept Drift River valley was produced from the proximal, eruption-induced volcaniclastic flows by melting of snow and ice.

1. Introduction

Redoubt Volcano, about 177 km southwest of Anchorage, Alaska (Fig. 1), is near the northeastern end of the Aleutian volcanic arc. Drift glacier (unofficial name) drains the 1.8-km-wide, ice-filled summit crater of Redoubt Volcano through a breach in the crater's north rim (Fig. 2). Along 5.5 km the glacier descends from the crater at about 2550 m altitude to the head of a piedmont lobe at 650 m. The piedmont lobe is about 3.5 km long, 3.7 km wide, and its terminus at 300 m altitude abuts the Drift River. The recently active volcanic vent was under Drift glacier at the breach in the crater rim at about 2400 m altitude, approximately the same location as the 1966–1968 eruptive vent. (Figs. 2 and 3). The 1989–1990 eruption beheaded Drift glacier, ultimately removing most of the ice between 750 m and 2500 m altitude (Fig. 3). The 1966–1968 eruptive episode similarly beheaded Drift glacier and removed about 60×10^6 m^3 of glacier ice between 1500 and 2500 m altitude (Sturm et al., 1986).

Disruption of the snow and ice on Redoubt Volcano occurred mostly on Drift glacier and in

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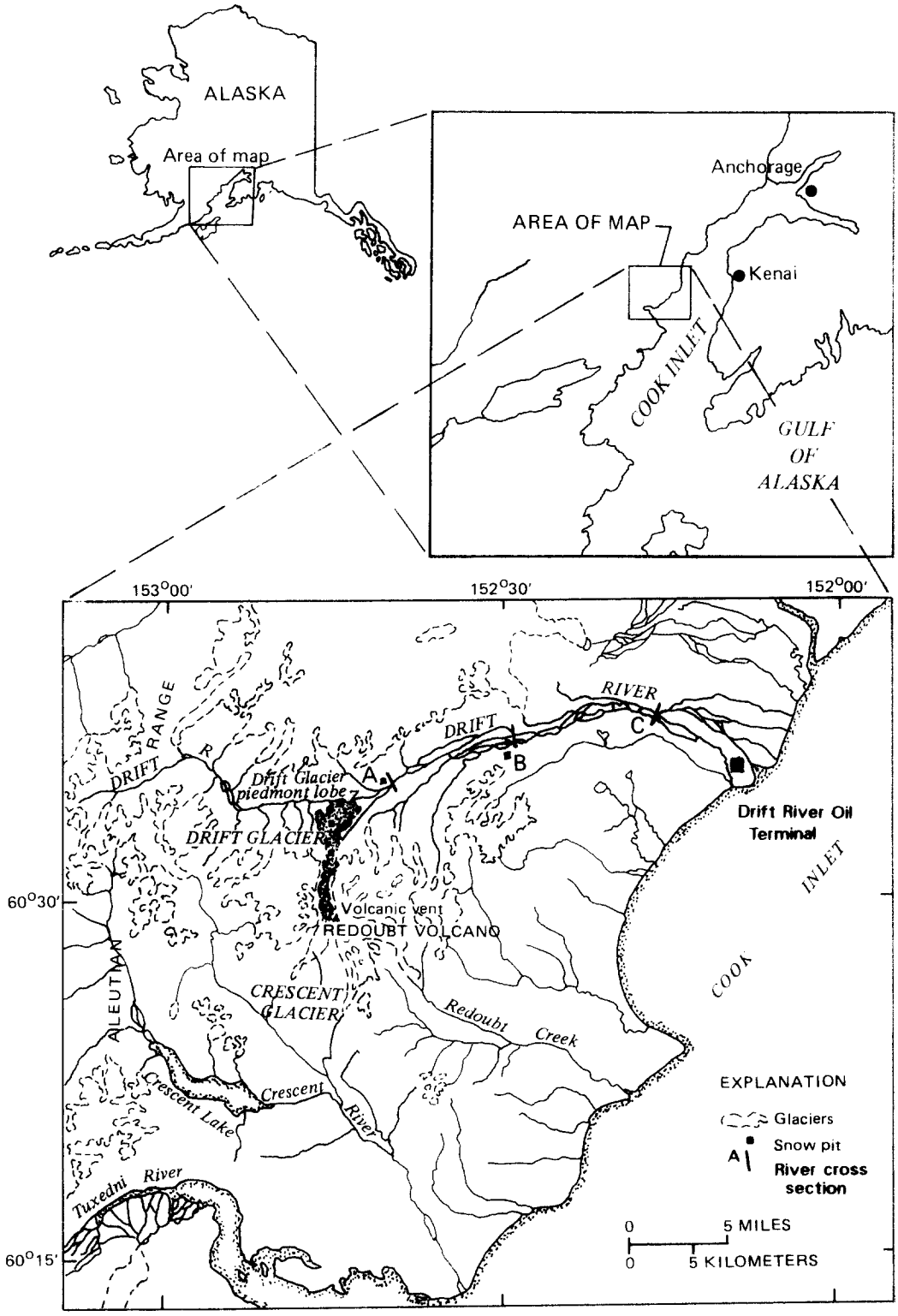


Fig. 1. Maps showing regional context of Redoubt Volcano and Drift glacier.

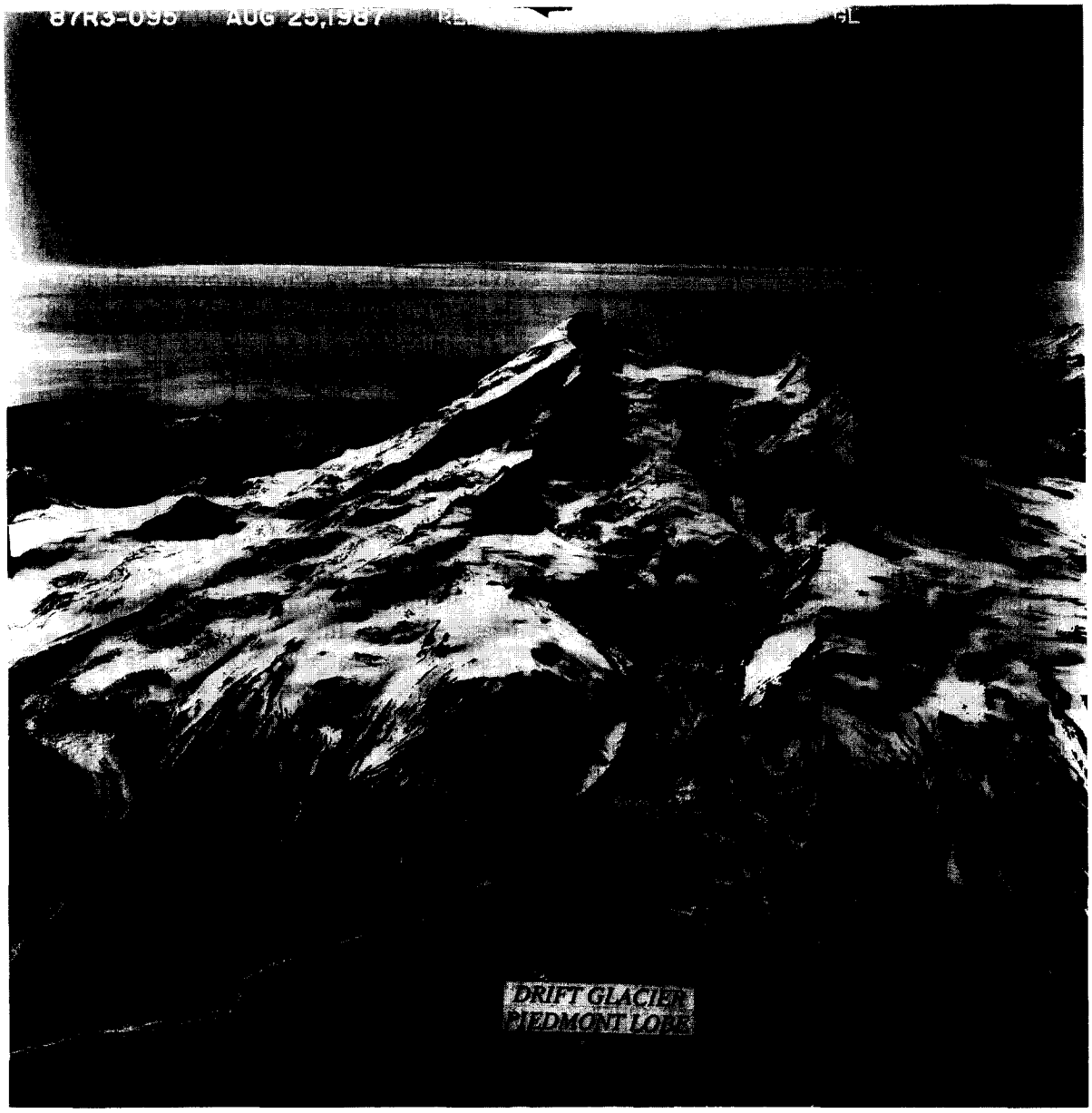


Fig. 2. View southward, of pre-eruption Redoubt Volcano. Drift glacier descends from the breached summit crater. Photograph by Austin Post, August 27, 1987 (photo number 87R3-095).

the Drift River valley downstream from Drift glacier. A single avalanche of mixed snow and volcanic debris also descended to about 1200 m altitude on the southwest-flowing Crescent glacier (unofficial name) and formed a deposit low on the glacier. Most of the remaining snow and ice on Redoubt Volcano received a few centimeters or less of tephra or surge deposit and shows little disturbance or disruption.

Unusual midwinter flooding of the Drift River resulted when hot volcanic debris incorporated and rapidly melted snow and ice during the

Fig. 3. Photograph of north flank of Redoubt Volcano and Drift glacier showing the deep, narrow canyon carved into the glacier (arrow 1). The dark areas are thick pyroclastic-flow deposits from the February 28 eruption. Above the dark patches Drift glacier is largely removed. The former glacier bed is blanketed by fresh snow (arrow 2). The 1989–1990 volcanic vent is at arrow 3. Photograph by R.B. Waitt, March 4, 1991.

1989–1990 eruptions of Redoubt Volcano. The eruptions generated various types of volcaniclastic flows that swept across Drift glacier and entered the upper reaches of Drift River valley. Commonly, these flows underwent transitions from hot, dry flows in proximal areas to cold, wet flows (lahars) in distal reaches of the valley owing to incorporation of snow and glacier ice along the flowpath. Gardner et al. (1994-this volume) discuss proximal pyroclastic flows; Waitt et al. (1994-this volume) discuss avalanches of mixed snow, ice, and volcanic debris; and Dorava and Meyer (1994-this volume) discuss the characteristics and evolution of lahars. The largest floods on the Drift River were associated with the four most seismically energetic eruptions: December 14–15, 1989, and January 2, February 15, and March 14, 1990 (Dorava and Meyer, 1994-this volume; Miller and Chouet, 1994-this volume). The floods forced several temporary evacuations of the Drift River Oil Terminal (DROT) located near the river mouth 34 km from the volcano (Fig. 1) (Brantley, 1990).

This paper documents the effects of the 1989–1990 eruptions on snow and ice and discusses the general processes by which volcaniclastic flows ravaged the Drift glacier, incorporated snow and ice, and produced large-magnitude flooding on the Drift River.

2. Measurements and data

Analysis of the eruption-induced changes in the snow and ice mass following the four principal eruptions was based on aerial and ground observations, video recordings, oblique and vertical photography, snow pits, and glacier-thickness measurements. Intensified photographic and video coverage at Redoubt Volcano began on December 14, a few hours before the onset of eruptive activity, and continued on most good-weather days through the first 3 months of the eruption. Two time-lapse cameras began to intermittently photograph Drift glacier on March 22 and May 22 1990. Four sets of geodetic-quality vertical-aerial photographs were made: January 9, May 5, May 31, and August 29, 1990. Detailed geomorphic maps were made from the photos of January 9 and May 31 (Fig. 4). Two snow pits along the Drift River valley and three in unperturbed areas on the piedmont lobe of Drift glacier (Fig. 1) were used to determine the water equivalent of the seasonal snow between datable ash layers from the four major eruptions. The snow-pit studies revealed that only the rare ejecta coarser than about 5 mm had melted snow. Finer-grained tephra deposits a few millimeters thick induced no melting and commonly were mixed with snow. Because the snow had been below the melting point continuously, we assumed that there had been no change in the mass between ash layers. We therefore used the water-equivalent values of the snow layers to estimate the volume of water incorporated by flows that

scoured snow from the glacier surface and the valley floor.

Glacier thicknesses at Redoubt Volcano were measured in August 1989 as part of an ongoing volcano-hazards assessment, 4 months before the beginning of the volcanic activity. Of the sixteen ice-radar thickness measurements made on Drift glacier, four are applicable to estimates of ice-volume change. Additional ice-thickness information was obtained from aerial photographs made within days of the initial eruptions and from direct field observations in canyons eroded through the glacier ice. Ice-volume changes were estimated from the ice-thickness information and from changes in ice boundaries that were digitized from successive aerial and ground-based photographs made during the 1989–1990 eruptions. The ice-volume-change estimates are preliminary owing to incomplete geodetic control and unfinished remapping of the area, yet they are better than order-of-magnitude accuracy.

3. Chronology and interpretation of major eruptions and flows

3.1. December 14–15, 1989

Drift glacier had completely covered the 1966 vent plug for several years (Fig. 2). Photographs made hours before the vent-clearing eruption on December 14, 1989 show a new circular opening in the ice and snow around the 1966 vent plug. The apparently empty moat that developed around the old plug represented a loss of about 13 to 14×10^6 m^3 of perennial snow and ice. Most of the water generated by the loss of that snow and ice probably entered the volcano's groundwater system; the rest was lost mostly as vapor, and minor amounts of water probably wetted the perennial ice and snow. Absence of sink holes in the glacier, of high-water marks in the moat or crevasses, and of surficial runoff from the crater indicated that no large quantities of water had been stored subglacially or englacially and subsequently released. Steam clouds reported by pilots on 20 November and December 3, 1989 and a steam plume visible from Anchorage on December 8, 1989 (Brantley, 1990; Miller and Chouet, 1994-this volume) probably represent minor evaporative losses.

Multiple eruptions on December 14–15 removed 65 to 67×10^6 m^3 of snow and ice from the summit crater and the connecting outlet glacier. The eruptions produced a succession of avalanches composed of a mixture of snow, slush, ice, fresh pyroclasts, and old rock (Waitt et al., 1994-this volume). The avalanches removed much of the roughest and steepest glacier ice and snow between 2200 and 1500 m altitude, and eroded deeply incised channels into the smoother glacier ice below 1500 m altitude (Figs. 4 and 5). The incised channels terminated on the east edge of the glacier at about 600 m altitude. The channels were 10–30 m wide and 10–40 m deep. The snow and ice mobilized and removed during the December 14–15 eruption was not melted in place, nor was it mobilized by release of subglacially or englacially stored water (confirmed by the absence of subsidence crevasses). Rather, most of that snow and ice was mechanically disrupted and entrained by avalanches initiated by pyroclastic flows that descended a highly crevassed 1500-m-high icefall.

Entrainment of snow and ice was evident in three successive ice-diamict deposits composed of snow blocks, glacier ice, and subordinate rock mixed in a matrix of snow and ice grains, volcanic ash, and frozen pore water, and by large glacier-ice boulders transported by the avalanches that produced those deposits (Waitt et al., 1994-this volume; Gardner et al., 1994-this volume). More or less continuous ice-diamict deposits extended about 6 km down the east half of Drift glacier from 850 m altitude (Fig. 6). We observed isolated remnants of ice diamicts as high as the volcanic vent at 2400 m altitude. Subsequent pyroclastic flows, avalanches, and debris flows incised the multi-layered diamict deposit (Fig. 7) that was as thick as 8 m but averaged about 2 m. Altogether, the ice-diamict was 80–90% ice and snow and had a volume of about $15–16\times10^6$ m^3, about 20% of the total volume of snow and ice disrupted by the eruptions on December 14–15.

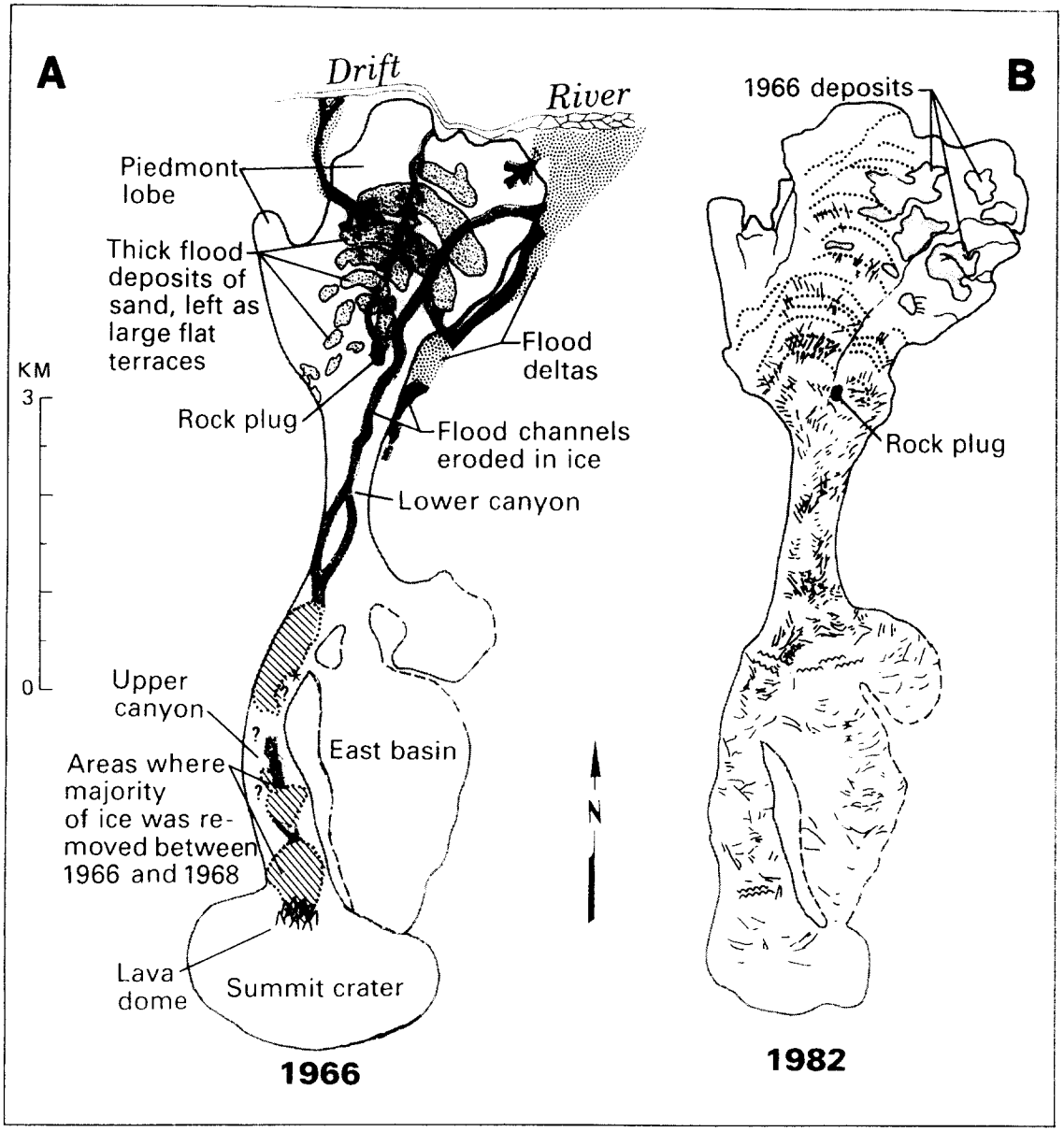
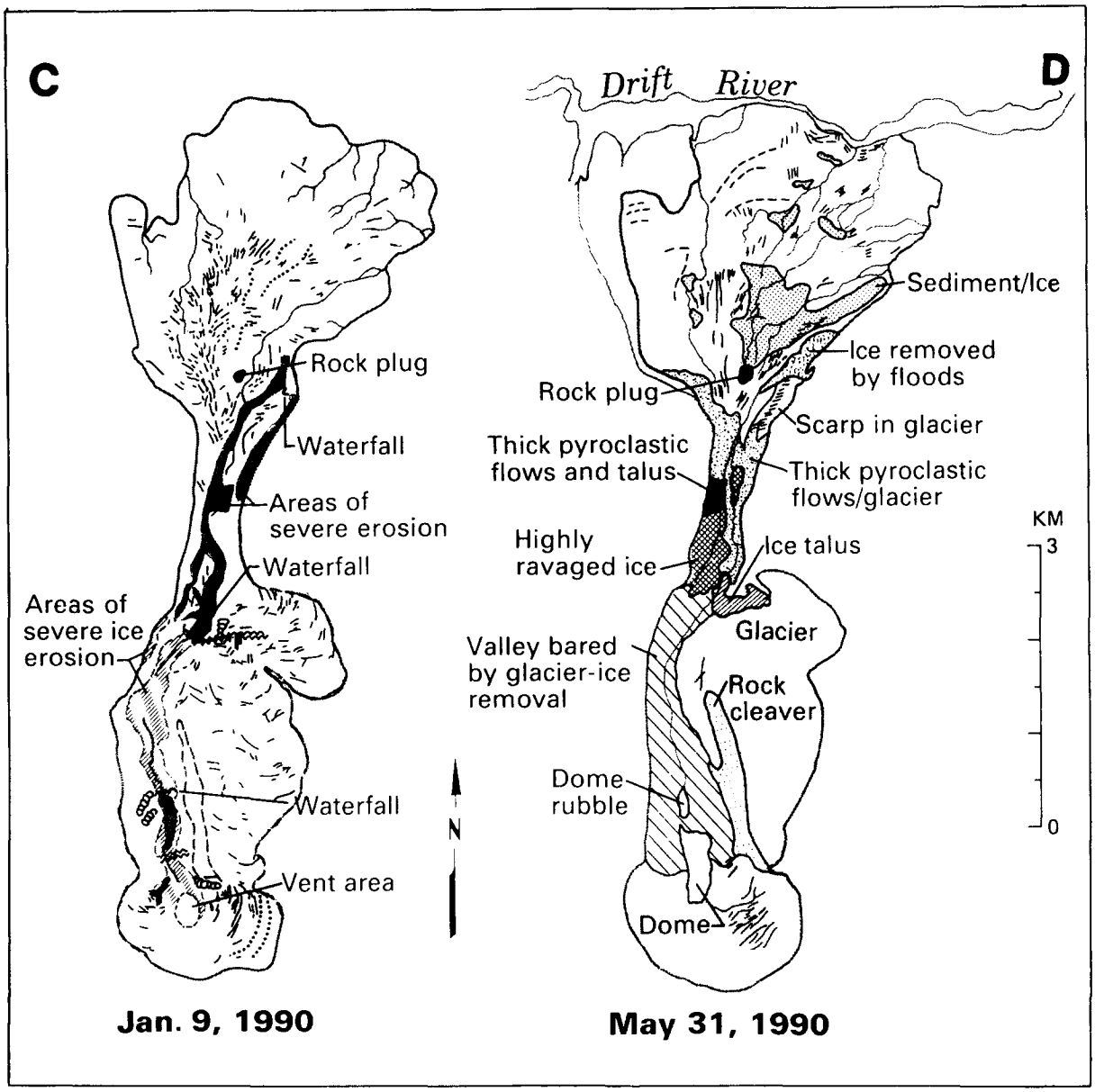


Fig. 4. Geomorphic maps rendered by Kern PG-2 plotter from aerial photographs taken before and during the 1989–1990 eruptions. (A) 1966–1968 (from Sturm et al., 1986); (B) 1982 (JJM); (C) January 9, 1990 (JJM); (D) May 31, 1990 (RBW). Slight differences in parts of the glacier outline in B, C and D are due to obscure glacier margins on some of the photos.

3.2. January 2, 1990

Nearly 25×10^6 m^3 of ice was removed from Drift glacier during the most energetic of the 1989–1990 eruptions when part of the newly emplaced lava dome collapsed and avalanched down the Drift glacier gorge. Pyroclastic flows resulting from that dome collapse removed the remnants of Drift glacier ice below 2200 m altitude and extended the wholesale destruction of the glacier down to about 1300 m altitude (Fig. 4C). Channels incised in the glacier varied in



EXPLANATION

? Uncertainty in location or extent

* Large kettle holes

Areas of major fractures and crevasse

Pressure ridges

Ice falls

Ice avalanches

Swales between pressure ridges

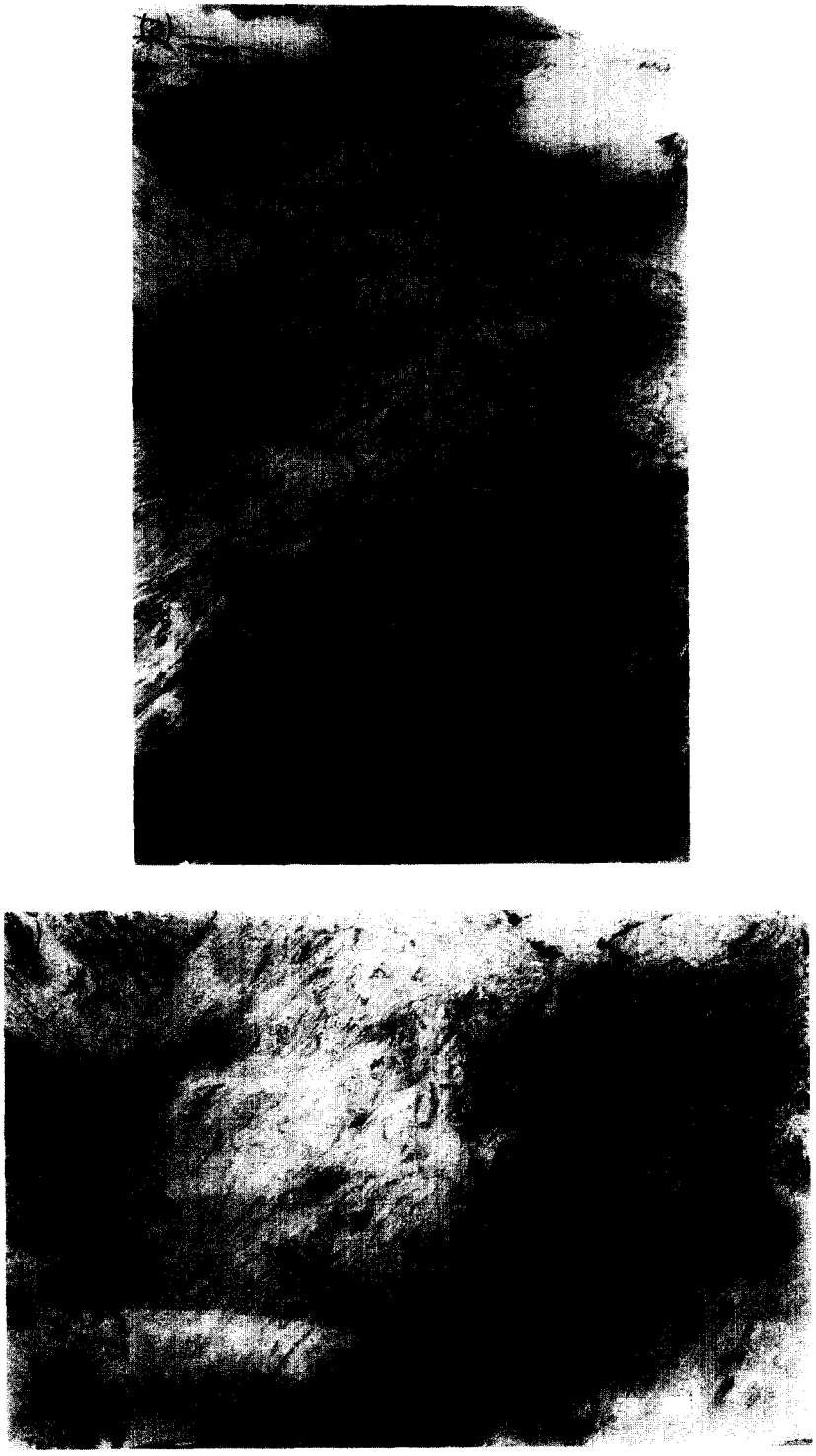


Fig. 5. Photographs of channel incised in the Drift glacier which is 10 to 30 m wide. (a) View southwest up the apex of the piedmont lobe; (b) view southwest into the outlet of the incised channel at 600 m altitude. Compare with Fig. 11 made about 100 days and 14 eruptive events later. Photographs by T.C. Pierson, December 26, 1989.

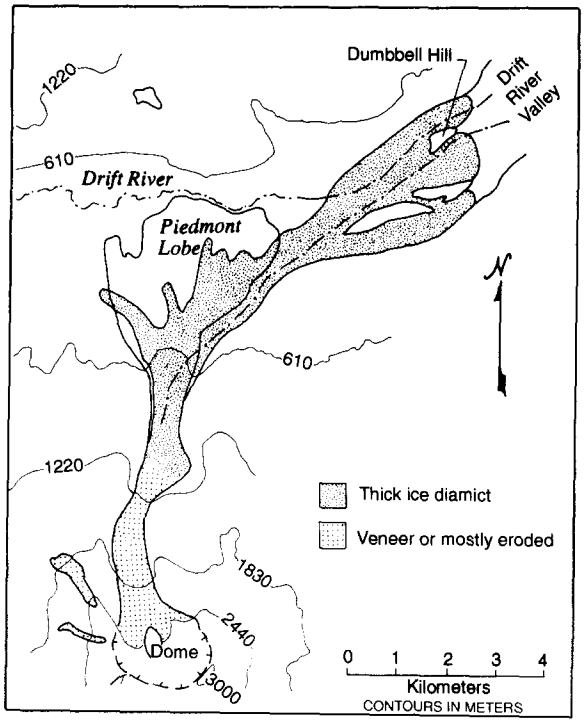


Fig. 6. Map showing the distribution of the ice-diamict formed on December 14–15, 1989. Redrawn by RBW from earlier version by T.C. Pierson.

width from 30 to 100 m, and depths reached the full ice thickness of 30 to 70 m along the lengths of most of the channels (Figs. 8, 9, 10 and 11). A lahar caused by mixing of pyroclasts with ice and snow further entrained an estimated 4×10^6 m^3 of water equivalent of new snow from the glacier surface and the river valley and initiated downvalley flooding having a peak discharge between 10,000 and 70,000 $m^3 s^{-1}$, 22 km downstream from the volcano (Dorava and Meyer, 1994-this volume). This was the greatest peak discharge produced by flooding during the 1989–1990 eruptions, and it represents the largest flood to sweep the Drift River valley this century (Major and Janda, 1990).

Much of the easily erodible snow and highly crevassed ice along the flow path on Drift glacier was removed following the January 2 eruption. Between December 14, 1989 and January 2, 1990, about 15% of Drift glacier and 60% of the perennial ice mass in the summit crater had been removed by the eruptive activity.

3.3. February 15, 1990

The third most seismically energetic eruption produced a pyroclastic flow and pyroclastic surge

Fig. 7. View southwest showing dark ice diamict overlying glacier ice in canyons and covered by pyroclastic flows and lahars near the head of the Drift glacier piedmont lobe. The maximum thickness of the ice-diamict was about 8 m. Photograph by R.B. Waitt, August 3, 1990.

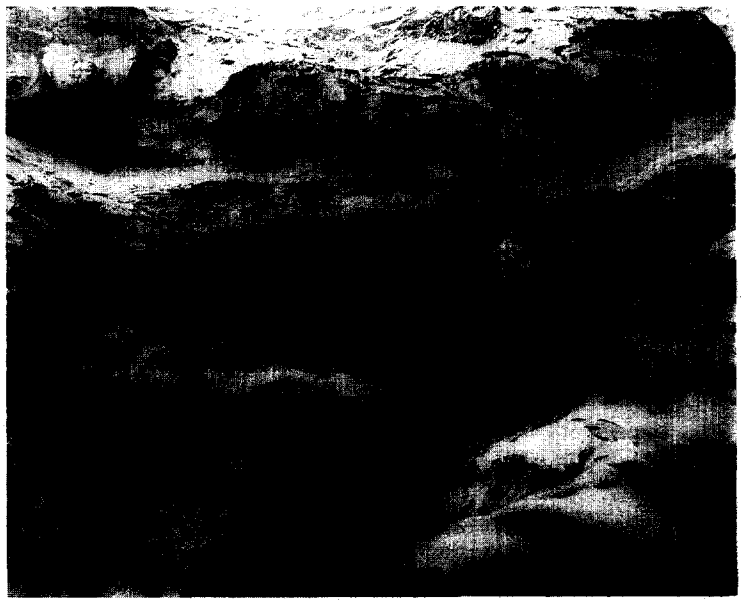


Fig. 8. View looking northwest across the ice canyon near the centerline of Drift glacier at about 760 m altitude. The canyon is narrow because the bottom has not reached bedrock. Photograph by R.B. Waitt, March 4, 1990.

Fig. 9. View of the minor 'scabland' channel on glacier surface. Quarried ice blocks several meters in diameter (arrow) litter the channel; view to south. Photograph by R.B. Waitt, February 15, 1990.

(Miller and Chouet, 1994-this volume; Gardner et al., 1994-this volume) that not only swept through previously affected areas but also deposited hot debris on some snow-covered areas not previously overrun. A pyroclastic flow destroyed the continuous glacier ice between 1300 and 750 m altitude, further enlarged the channels incised in the glacier, and removed an estimated 10–15$\times 10^6$ m^3 of glacier ice.

Along a small distributary channel trending

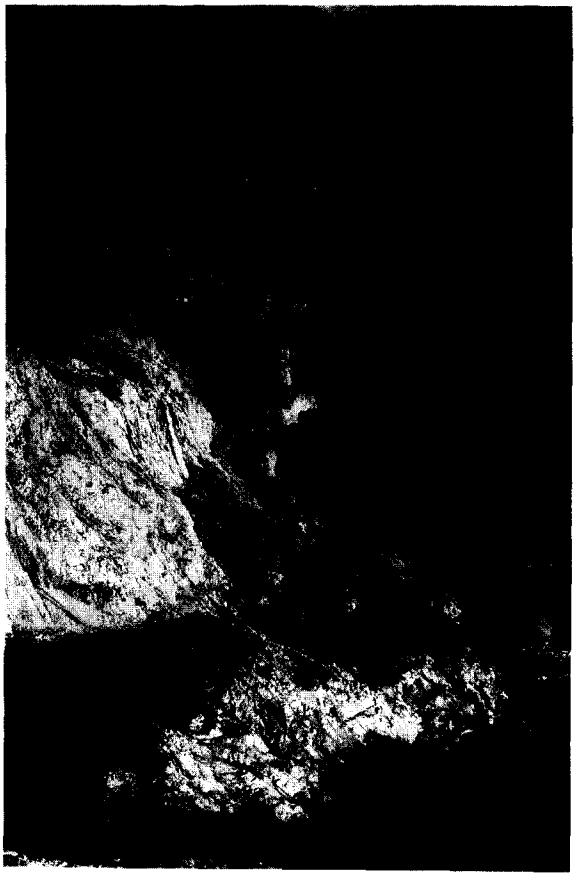


Fig. 10. View northward down the deglaciated valley to the ravaged middle segment of Drift glacier between 900 and 600 m altitude and across the piedmont lobe to the Drift River against the far valley wall, about 6 km away. Photograph by R.B. Waitt, August 3, 1990.

north-northwest on the upper part of the piedmont lobe (Fig. 4C), large ice blocks were quarried from constrictions and deposited in wider segments downstream (Fig. 9). These small tracts are reminiscent of the Pleistocene 'scabland' topography in eastern Washington (Bretz, 1923), though one or two orders of magnitude smaller in scale. This landscape shows that highly crevassed glacier ice is easily quarried even by relatively small channelized flows. Had much of the highly crevassed ice along the primary flow path on Drift glacier not been removed during the previous eruptions, it is probable that the lahar produced by the February 15 eruption would have been larger.

3.4. March 14, 1990

The most significant eruption after February 15 occurred on March 14. It produced only small changes in Drift glacier and generated a water flood having a peak discharge of about 2500 $m^3 s^{-1}$ at a distance of 24 km from the vent. The flood incorporated an estimated 2×10^6 m^3 of water equivalent from snow newly deposited along the flow path.

3.5. Other eruptions and flows

Pyroclastic and laharic flows from several less-energetic eruptions affected the Drift glacier. All of them generated small floods that swept down the Drift River valley. The narrow segment of glacier ice between about 800 and 1050 m altitude was progressively ravaged (Fig. 4D) as the ice canyons expanded, leaving about half of the original glacier ice by the end of the eruptions in late April 1990 (Figs. 5, 7, 8 and 10). Below 800 m altitude, the central ice canyon deepened and widened with the passage of successive pyroclastic flows and lahars. At the mouth of the ice canyon, the upper limits of two successively smaller eruption-generated laharic flows on April 6 and 15, 1990 were marked by proximal concentrations of ice blocks as large as 4 m in diameter. The ice-block deposits extended several kilometers down the Drift River valley where the maximum block size was as large as 0.75 m. The April 15 flood was less than half the peak discharge of the April 6 flood. The ice-block deposit from the April 15 flood reveals that large blocks of ice were readily incorporated even by relatively small flows late in the eruption sequence. The large ice blocks may have originated as ice talus in the canyons and as newly quarried blocks.

4. Processes within the ice canyons

Rapidly fluctuating discharge of meltwater that emanated from Drift glacier between and during some eruptions was caused primarily by restriction or temporary blockage of flow by ice talus within the incised ice canyons rather than by

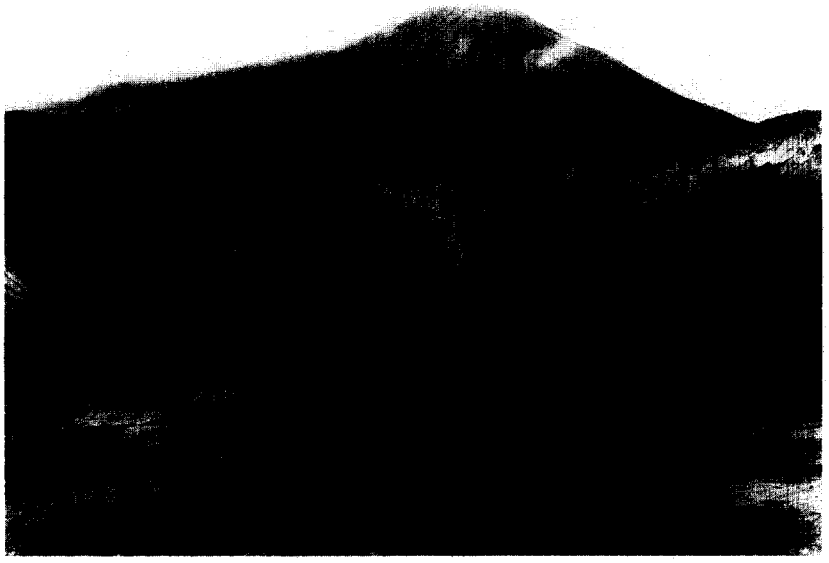


Fig. 11. View looking southwest into the mouth of the ice canyon where it emerges from the glacier onto bedrock at the east edge of Drift glacier at about 550 m altitude. The bottom of the canyon is flat because the floor is an alluvial veneer over bedrock (contrast with canyon in Fig. 8). The canyon is about 40 m wide and about 15 m tall in the central part of the view. Ice blocks lie among the flood-borne gravel in the foreground. Photograph by R.B. Waitt, April 10, 1990.

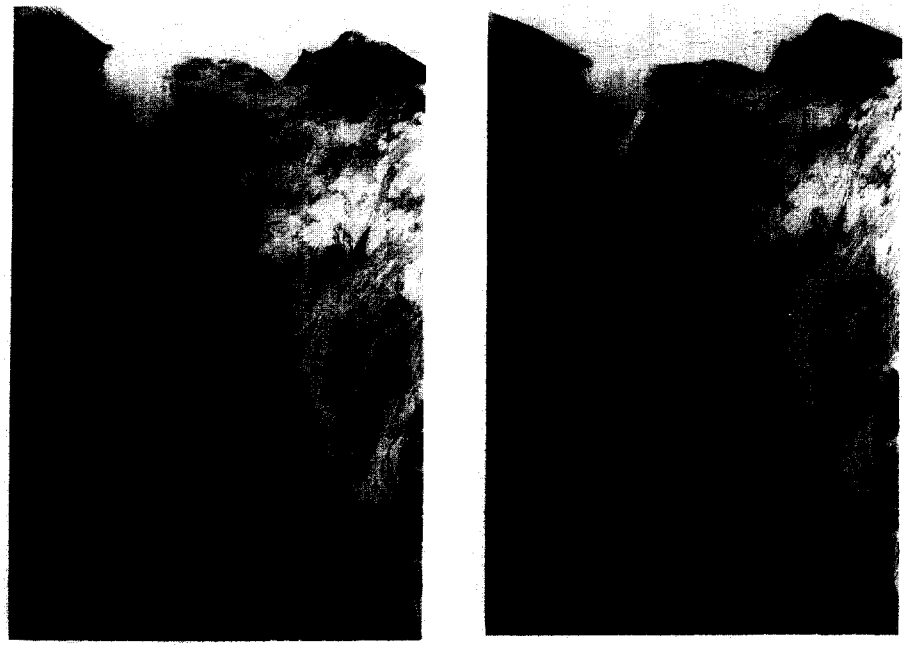


Fig. 12. Stereographic photographs southward showing the bedrock valley formerly occupied by upper Drift glacier between 2500 and 1700 m altitude. Arrow points to the new lava dome. Photograph by R.B. Waitt, April 10, 1990.

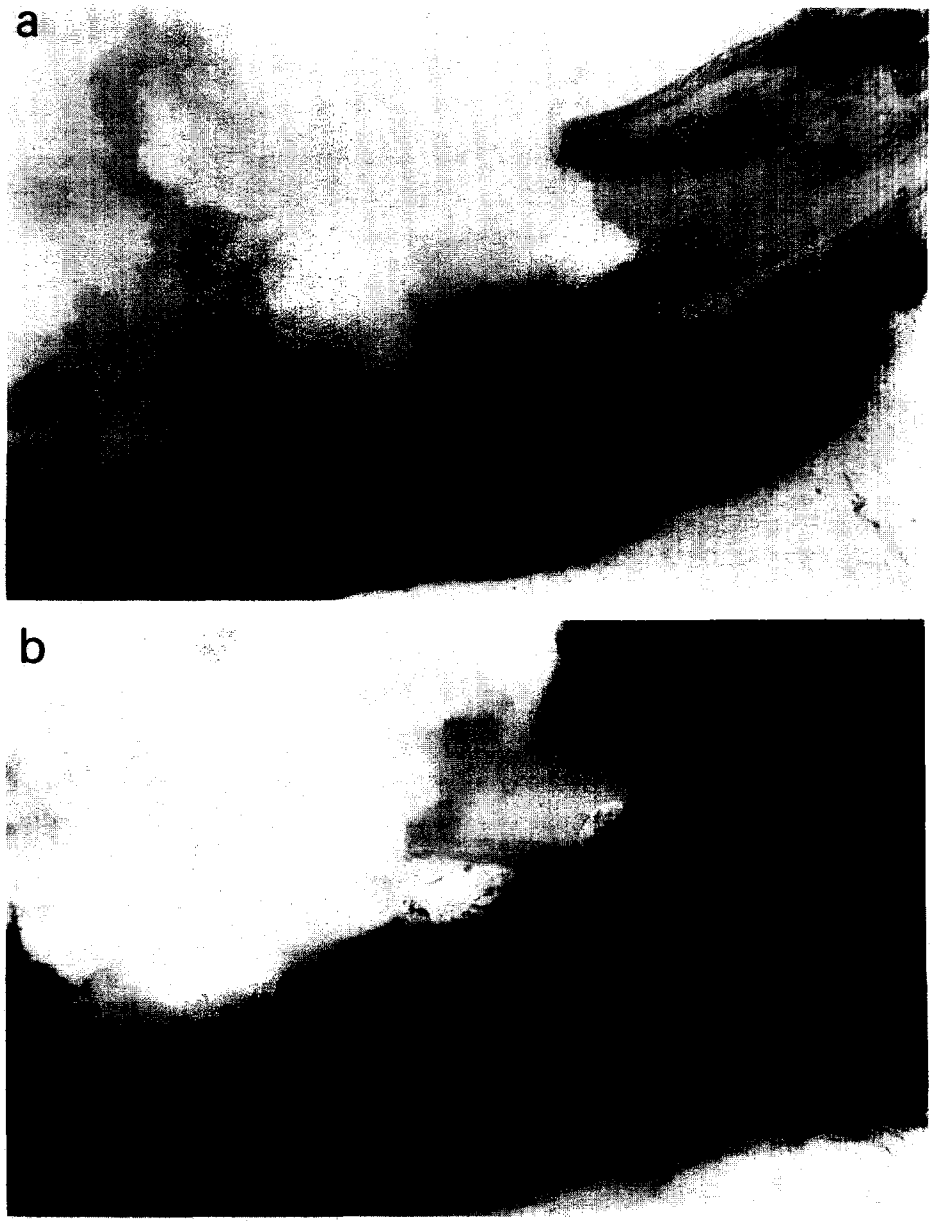
Fig. 13. Upslope view south-southwestward showing the valley formerly occupied by Drift glacier between 1500 and 950 m altitude. Fig. 11 is a downslope view to the north across the same valley segment. Photograph by R.B. Waitt, April 10, 1990.

fluctuations of melting rate at the vent or by episodic release of glacially stored water. On February 28, 2.5 hours after the beginning of an eruption, a DROT crew observed that the flow of water in the Drift River valley had stopped 4 km below Drift glacier, indicating that the river was blocked somewhere upstream. But 24 hours later the Drift River resumed flowing past DROT. On March 4, water was observed flowing under and through ice-avalanche deposits several meters thick within the main ice canyon. Slumping of glacier walls and deposition of ice talus in channels incised in Drift glacier presumably impedes meltwater flow from the crater, leading to unsteady surges on Drift River, and occasionally blocks flow temporarily, which is probably what happened during the February 28 eruption.

On March 15, river discharge approximately doubled over a period of several minutes at a point 3 km below the glacier terminus (near channel cross-section A; Fig. 1) and numerous ice blocks as large as 0.2 m in diameter (mean diameter 0.05–0.1 m) floated in the increased flow that lasted 20–30 minutes. Although no eruptive activity was observed in the field, prolonged low-level seismic activity occurred 20–30 minutes before the river flow increased. On April 7, about 22 hours after an eruption, the discharge at the mouth of the ice canyon (Fig. 11) increased sharply 1.5 to 4 times the base discharge during four episodes lasting 1–3 minutes each during a 15-minute interval. Each peak flow, especially the largest, carried hundreds of small ice blocks. Prior to these fluctuations, there had been neither seismic nor visual indication of energetic vent activity.

6. Discussion and conclusions

The location of the incised channels in Drift glacier was strongly influenced by the pre-eruption topography and by the presence of longitudinal crevasses that were particularly well developed in the compressional-ice-flow area at the head of the piedmont lobe (Fig. 4A). Maps based on aerial photography (Figs. 4A and B) show that the major ice canyons began at the bases of steep icefalls where both the slope of the pre-eruption glacier surface and the isotropic crevassing abruptly decreased. Regions of abrupt change in glacier morphology were the focal points where pre-eruption topographic lows and longitudinal



crevassing directed pyroclastic flows and lahars that swept Drift glacier, concentrated erosion along a central path, and influenced the distribution of the ice diamict and succeeding deposits. Subsequent pyroclastic and laharic flows exploited the developing axial canyon, enlarged longitudinal crevasses, and eroded an anastomosing network of steep-walled gullies that developed into the ice canyons (Fig. 4C). Ice-talus deposits in the steep-walled canyons were a source of ice that was easily entrained by later flows.

The disruption of Drift glacier was dominated by mechanical entrainment of snow and glacier ice by pyroclastic flows, which initiated mixed avalanches of snow and debris and more water-rich debris flows. The entrainment process was accentuated by the highly crevassed icefall over which the pyroclastic flows moved. The ice-diamict deposits and large (>4 m) rounded

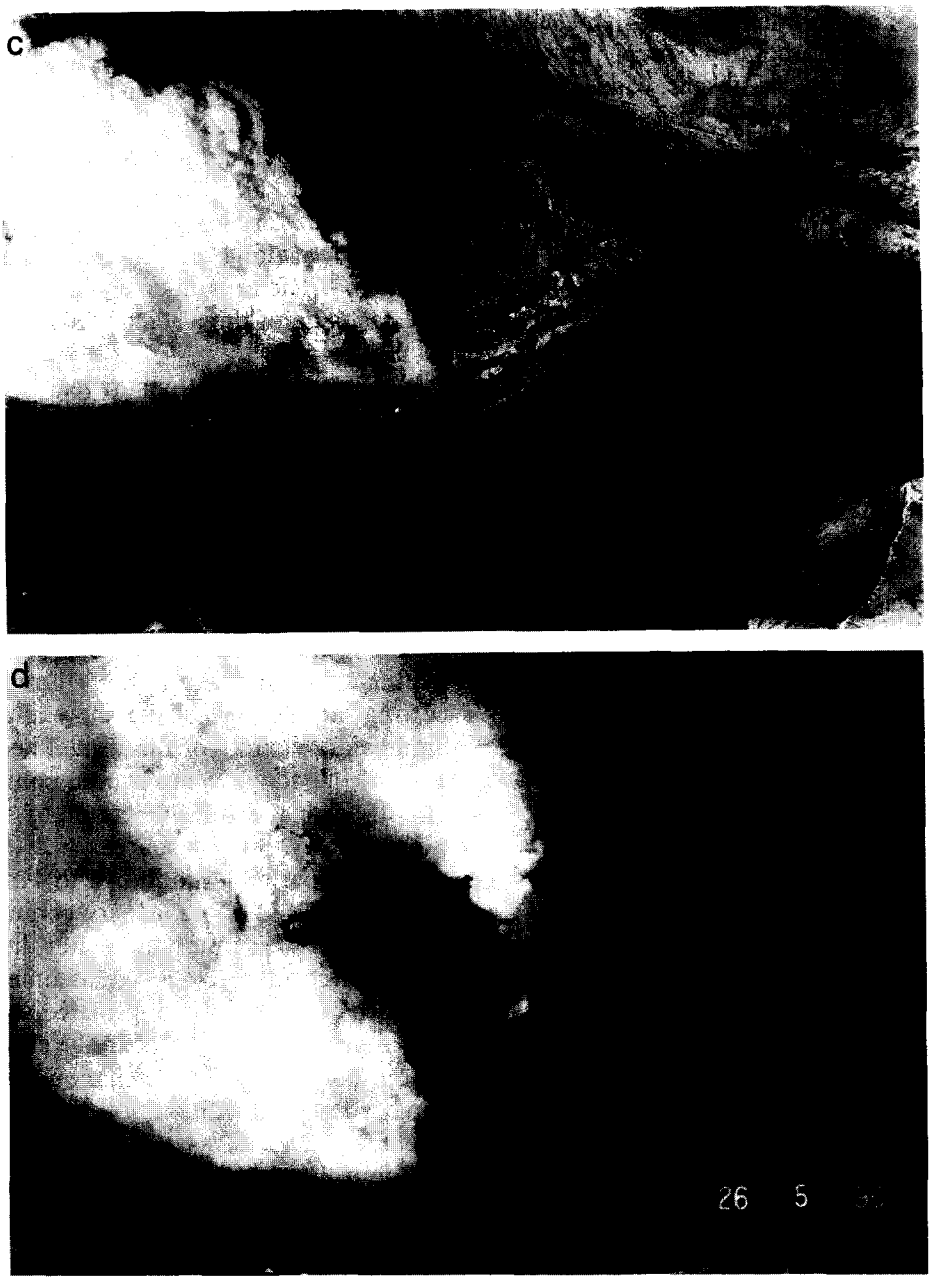


Fig. 14. Views of ice in the summit crater of Redoubt Volcano showing progressive development of the crevasse field concentric to the vent. Photographs: (a) December 26, 1989 and (b) January 25, 1990 by D.C. Trabant; (c) March 20, 1990 by C.A. Gardner; and (d) May 26, 1990 by T.P. Miller.

boulders of glacier ice deposited kilometers beyond the glacier terminus attest to the ease of entrainment of snow and ice. The generally decreasing volumes of glacier ice incorporated by subsequent volcaniclastic flows indicate that entrainment was enhanced when pyroclastic debris moved over rough ice surfaces. The decreasing entrainment volumes were not due to a lack of

ice available for entrainment by later pyroclastic and debris flows, but rather to a diminishing area of highly crevassed glacier surface. This conclusion supports the findings of Pierson et al. (1990) at Nevado del Ruiz volcano. They concluded that the area of the summit ice cap at Ruiz available to attack by pyroclastic flows and surges was more important than the volume of ice in the summit ice cap for the initiation of the devastating lahars during the 1985 eruption.

At the conclusion of the 1989–1990 eruptions of Redoubt Volcano, less than 20% of the ice volume of Drift glacier had been removed. The specificity of the attack on Drift glacier was directed by the breach in the summit crater rim through which the glacier enters a deep narrow gorge that leads to the head of the piedmont lobe. The crater-rim breach and the downslope gorge directed pyroclastic flows onto Drift glacier.

The relatively large eruption on February 15 initiated a pyroclastic and laharic flow that incorporated the snowpack along the entire flowpath and produced the third largest flood of the 1989–1990 eruption series (Dorava and Meyer, 1994-this volume). Yet a relatively small dome collapse and pyroclastic avalanche nine days later, which encountered very little snow along the flowpath, produced a smaller flood, but one that reached the sea. This pair of events illustrates that a flood can be generated by hot materials scouring the ice talus and walls of the canyons incised in the glacier with little water volume added by incorporated seasonal snow. Had the proportion of highly crevassed ice along the primary flow path not been reduced by the eruptions of December 14–15, 1989 and January 2, 1990, these smaller laharic flows undoubtedly would have been substantially larger. Although the eruptions of December and January did not eliminate the threat of large-magnitude flooding on the Drift River they probably reduced the threat by removing much of the easily erodible highly crevassed ice on Drift glacier.

The 1989–1990 eruptions of Redoubt Volcano removed a total of $113–121 \times 10^6$ m^3 of perennial ice and snow from Drift glacier. If the mean density of the disrupted snow and ice was 0.8 Mg m^{-3} (adjusting for severely crevassed ice and low-density snow), the disrupted material amounted to $90–97 \times 10^6$ m^3 of water equivalent.

By mid-March the gorge that Drift glacier occupied was almost entirely stripped of ice from the vent at 2500 m altitude down to 730 m altitude (Figs. 12 and 13). Below 730 m altitude, a narrow canyon was progressively eroded approximately along the center line of the glacier (Fig. 10). The canyon emerged onto bedrock at the east side of the glacier at about 550 m altitude (Fig. 11).

Repeated observations revealed no subsidence crevasses to indicate storage and release of large volumes of subglacially or englacially stored meltwater at any time during the eruptive series. Subsidence crevasses did form in Drift glacier ice east and south of the vent, where concentric crevasses developed progressively during the 1989–1990 eruption series (Fig. 14A–D). The crevasses reflect the deformational collapse of the remnant snow and ice in the summit crater following the removal of the snow and ice in the immediate vicinity of the vent. The flow of ice toward the active vent ensured continued melt runoff from the summit crater by moving ice closer to the vent heat source.

Continuous melt runoff of 1 to 4 m^3 s^{-1} (T.P. Brabets and J.M. Dorava, pers. commun., 1991) began from the summit area after the first eruption in December 1989. We assume the runoff resulted from the melting of ice owing to the nearness of hot rock to ice in the summit crater. The runoff helped incise channels in the ice at the head of the piedmont lobe between eruptive events.

Rapid fluctuations in discharge near and beyond the glacier during eruptions in late February and between eruptions in March and April 1990 evidently were caused by secondary processes within the ice canyon rather than by fluctuations in vent emissions. Small ice avalanches from the near-vertical canyon walls impeded or temporarily blocked streamflow. Water probably ponded until the restricting piles of ice talus failed and released small floods of water and ice blocks. This process may also be responsible for the ice-boulder deposits left by some of the erup-

tion-initiated floods during the wane of eruptions after April 6, 1990.

Acknowledgments

The photographic and videotaped record of the eruption of Redoubt Volcano was compiled by the staff of the Alaska Volcano Observatory in Anchorage and Fairbanks, Alaska.

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