Geologic Studies in Alaska by the
U.S. Geological Survey, 1999
U.S. Geological Survey Professional Paper 1633

Snowy Mountain: A Pair of Small Andesite-Dacite Stratovolcanoes in Katmai National Park

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Abstract

Snowy Mountain is a small andesite-dacite volcanic center that originated about 200 ka. Eruptions have taken place from two vents 4 km apart that built contiguous edifices that extensively overlap in age, though only the northeastern vent has been active in the Holocene. Sector collapse of the hydrothermally weakened upper part of the northeastern cone in the late Holocene produced a 22-km^2 debris avalanche and left a 1.5-km^2 amphitheater that was subsequently occupied by a blocky lava dome. Many products of the southwestern vent are olivine-bearing (55.5–62.2 percent SiO_2), whereas those of the northeastern vent are largely pyroxene dacites (61.7–63.7 percent SiO_2). Estimates of eruptive volume yield 8k3 km^3 for the northeastern edifice, 5±2 km^3 for the southwestern, and 13±4 km^3 for the Snowy Mountain center as a whole. Only half to two-thirds of this material remains in place on the glacially ravaged skeletal edifices today. Because subsets of Snowy Mountain's 25–30 lava flows erupted as packages in short episodes, calculation of the volcano's lifetime average volumetric eruption rate (0.04–0.09 km^3/k.y.) is a potentially misleading exercise. Nominally, the lifetime rate for Snowy Mountain is similar to that estimated for each of the cones of nearby Trident volcano (fig. 1), but it is 3–10 times smaller than long-term rates for Mounts Mageik and Katmai. Snowy Mountain is typical of the close-set arrays of small cones characteristic of late Quaternary andesite-dacite arc volcanism in the Katmai district.

Introduction

The Snowy Mountain volcanic center consists of a contiguous pair of andesite-dacite stratocones that straddle the rangecrest of the Alaska Peninsula about 15 km northeast of Mount Katmai. Snowy Mountain is the only late Quaternary eruptive center along the 30-km stretch of the main volcanic line (fig. 1) that separates the closely grouped Katmai cluster (Hildreth and Fierstein, 2000) from the even closer set chain of four stratovolcanoes that begins with Mount Denison (fig. I). Built along the preexisting regional drainage divide in a zone of high precipitation, these volcanoes have suffered intense glacial erosion, not only during the Pleistocene but continuously throughout the Holocene. Snowy Mountain itself, rising to an elevation of 2,161 m (7,090 ft), remains today the source of 10 substantial glaciers (fig. 2). Because glacial ice still covers nearly 90 percent of the edifice, the principal rock exposures are limited to narrow ice-bounded arêtes at higher elevations and ice-scoured lava-flow benches at lower elevations.

Snowy Mountain was named during the National Geographic Society expedition to Katmai in 1917 (Griggs, 1922, p. 131). The name chosen evidently reflected how impressed those explorers were with its extensive mantle of snow and ice as seen from upper Katmai River, which was their closest approach to the edifice and provided a vista similar to that illustrated in our figure 3. They did not identify the mountain as a volcano.

The region around Snowy Mountain is uninhabited National Park wilderness and access is unusually difficult, even for Alaska. The nearest town is King Salmon, 120 km to the WNW. Hikers and climbers are exceedingly rare in the mountains northeast of Mount Katmai, but aerial sightseeing has recently become common. In the many bays along Shelikof Strait (fig. 1), commercial fishing boats are common and aircraft-supported camping, sportfishing, poaching, and ranger patrols take place sporadically.

Our attention was initially drawn to Snowy Mountain by the identification of persistent diffuse seismicity on and northwest of the volcano (Ward and others, 1991). We thought it worthwhile to investigate the volcanological nature of the remote edifice as background for interpreting the seismic activity (Jolly and McNutt, 1999). On investigating, we were surprised to find that Snowy Mountain remained one of the least known volcanoes in the entire Aleutian arc. So little work had been done in the area that the regional reconnaissance geologic map of Keller and Reiser (1959) had designated Snowy Mountain as "igneous rocks, undifferentiated," lumping it with deformed volcanic rocks of Tertiary age. In *Volcanoes*

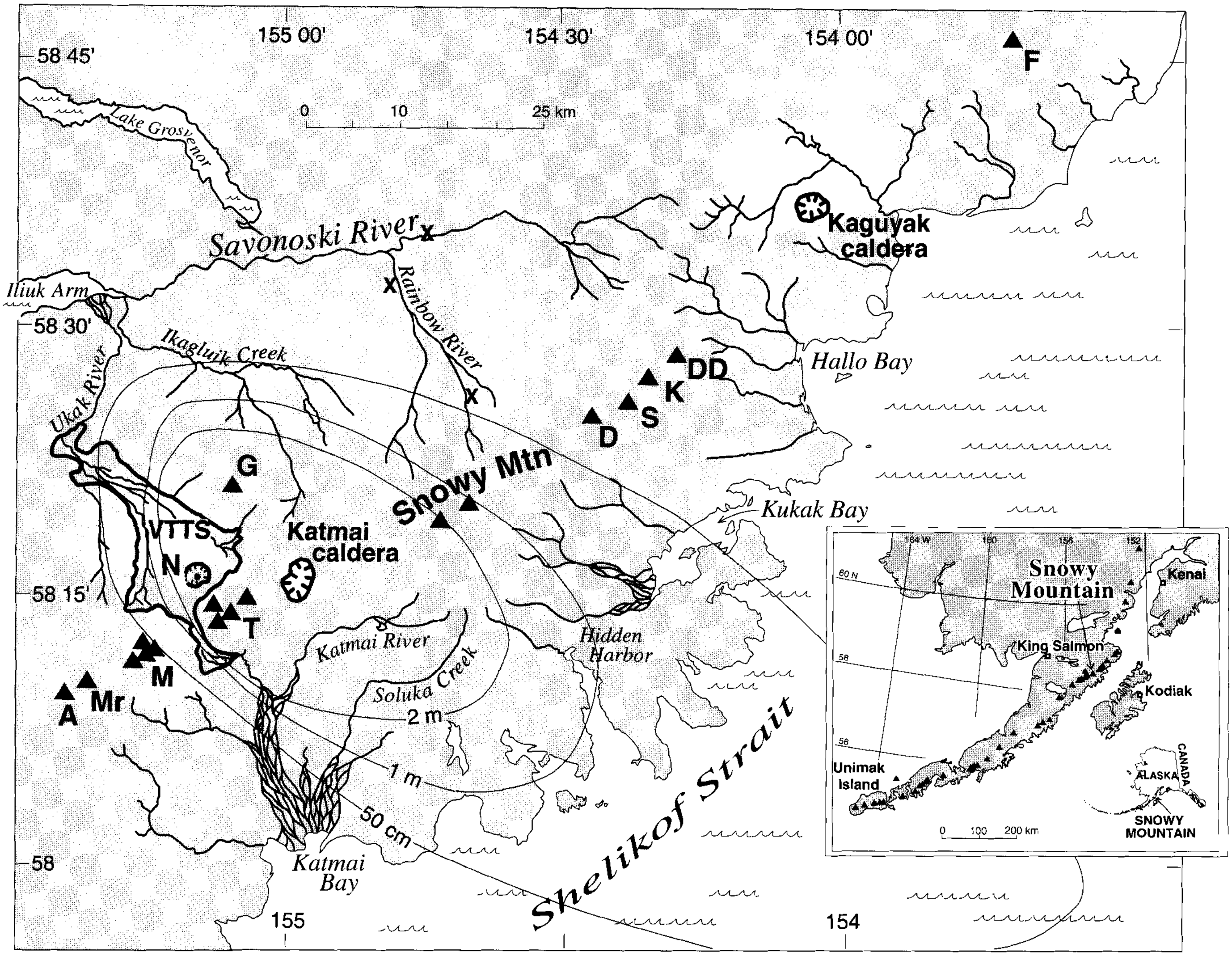

Figure 1. Regional location map showing position of the two Snowy Mountain volcanoes along the late Quaternary volcanic axis, which straddles the drainage divide of this stretch of the Alaska Peninsula. Triangles indicate andesite-dacite stratovolcanoes, identified by letter: A, Alagogshak; Mr, Martin; M, Mageik (cluster of four); T, Trident (cluster of four); G, Griggs; D, Denison; S, Steller; K, Kukak; DD, Devils Desk; F, Fourpeaked. VTTS, Valley of Ten Thousand Smokes ash-flow sheet (outlined area), which erupted at Novarupta (N) in June 1912. Isopachs show thickness of cumulative plinian fallout from Novarupta, originally 1–2 m thick at Snowy Mountain. Were pyroclastic flows or debris flows to originate at Snowy Mountain, after descending glaciers, they could go down Rainbow River, Katmai River, Soluka Creek, or the unnamed drainages ending in Kukak Bay or Hidden Harbor. Bold "X" symbols locate three cutbank exposures of debris-flow deposits mentioned in text.

of the World (Simkin and Siebert, 1994), Snowy Mountain was listed as a stratovolcano, its status given as "Fumarolic," but no further information was provided save location and elevation. The lack of previous attention to Snowy Mountain is especially well illustrated by its entry in *Volcanoes of North America* (Wood and Kienle, 1990, p. 73) where its purported photograph is actually of Mount Denison and its accompanying map polygon represents an area predominantly of basement rocks. The regional 1:250,000 geologic map of Riehle and others (1993), on the other hand, represents the extent of Snowy Mountain's volcanic rocks rather well, though no additional data are given.

Although our own work is no more than a detailed reconnaissance, we did visit most of the outcrops. Our fieldwork was accomplished entirely by helicopter while in transit between Kaguyak and Katmai volcanoes, where we were conducting more detailed volcanological studies in 1998 and 1999.

Basement Rocks

Quaternary volcanic rocks of Snowy Mountain overlie three distinctive suites of basement rocks (Riehle and others, 1993). Most exposures north of the volcano consist of subhorizontal or gently dipping siltstone and sandstone of the Jurassic Naknek Formation (Detterman and others, 1996). Intruding these rocks are several porphyritic granitoid plutons of Tertiary age, into which the glaciers north and northwest of Snowy Mountain have incised spectacular canyons. South and southwest of the volcano, its lava flows rest on altered volcanic rocks that have received little attention. Erupted from several ill-defined centers, these rocks are ordinary arc andesites and dacites, either undeformed or gently warped, slightly to severely altered hydrothermally, and mostly of Neogene (Shew and Lanphere, 1992) and probably in part early Quaternary age.

Like the adjacent volcanic clusters along the Quaternary chain (fig. 1), Snowy Mountain straddles the peninsular drainage divide, having been constructed atop an antecedent rangecrest that had been glacially sculpted from the three basement suites. Although the northwest slope of the range is the steeper at Snowy Mountain, the gentler southeast slope has undergone more severe glacial stripping of the Quaternary volcanic rocks. Moreover, it still retains more extensive ice cover (figs. 2, 3). The asymmetry of erosion may reflect (a) greater precipitation on the Shelikof Strait (Pacific) side of the range, (b) easier relative erodability of the punky Tertiary volcanic rocks underlying the southerly slopes of Snowy Mountain, and (c) early Pleistocene entrenchment of the northwest-flowing glaciers. Concentration of the northwesterly ice tongues within granite-walled gorges apparently helped preserve the Quaternary lavas on the interfluves between them (fig. 2). Finally, (d) ice-sheet movement northward onto the Alaska Peninsula from the icecap over Kodiak Island (Mann and Peteet, 1994) during Pleistocene glacial maxima could have contributed to greater erosion on the south slope of the volcano.

Ice-Mantled Double Edifice

Along the rangecrest, the Snowy Mountain volcanic center exhibits three principal summits (figs. 2, 3), Peaks 6770, 7090, and 6875. Radial dips, vent facies, and intrusive relationships, however, define just two stratovolcanoes. The ice-filled 6,100-ft saddle between Peaks 6770 and 7090 marks the contact between cones, as clearly defined by opposing stacks of lava flows that dip 20°–25° off those peaks and meet each other at the saddle (fig. 2). Peak 6770 is a large remnant of the northerly shell of the southwestern cone; it stands about 500 m northwest of its own eroded vent complex (fig. 3; Knob 6600+) and consists of stacked lava flows that dip radially (W., N., and NE.) away. Peak 7090, true summit of Snowy Mountain, is similarly a large ice-ravaged remnant of the westerly shell of the northeastern cone; the peak stands 900 m west of its vent and its lava flows dip radially from SW. through W. around to N. (fig. 2). Of Snowy Mountain's three rangecrest summits, only Peak 6875 is actually a volcanic vent, being a Holocene lava dome that occupies the crater of the severely eroded northeastern stratovolcano.

The contiguous cones are both predominantly of late Pleistocene age. Judging by its highly and universally eroded condition, the southwestern cone does not appear to have been active in the Holocene. Each volcano has been the source of at least 12–15 andesite-dacite lava flows, a few of which thicken downslope to 50–200 m distally. The scattered present-day outcrops add up to only 2.4 km^2 for the southwestern cone and 6.5 km^2 for the northeastern. Interpolation between outcrops and conservative extrapolation downslope suggest original lava-covered areas of 3 0 4 0 km^2 and 3 5 4 5 km^2, respectively, not counting probable intracanyon lava tongues subsequently removed by glaciers. Nearly 90 percent of the compound edifice is therefore either currently ice covered or has been glacially stripped.

Southwest Snowy Mountain Edifice

The Southwest Snowy cone is exposed in 10 discrete areas of outcrop (fig. 2). Most interesting (and probably worthy of further study) is a remnant of the vent complex, preserved as a SSE.-trending ridge 700 m long and 300400 m wide, just south of Peak 6770 (figs. 2–4). The ridge is bounded on most sides by a 200-m-high cliff (fig. 4), the upper half of which consists of chaotic (or locally crudely stratified) coarse breccia, much of it lightly agglutinated or otherwise indurated. On the east face the breccia is cut by several dikes, and on the west face it is intruded from below by a 300-m-wide, steeply jointed intrusive mass, which is probably a remnant of a vent-filling plug (fig. 4). The poorly sorted fragmental debris is block-rich proximal ejecta, not lava-flow breccia, and the blocks range texturally from scoriaceous and partly glassy to vesicle poor and devitrified. Texturally contrasting blocks sampled on the ridgetop are both olivine-andesite (55.6–55.7 percent SiO_2), the most mafic eruptive material found anywhere at Snowy Mountain.

Immediately north of the vent complex, Peak 6770 exposes a proximal stack of at least six andesitic lava flows on its south-facing 100-m-high scarp (fig. 4). As the largest preserved remnant of the cone, the stack dips radially around the conical sector that swings from west through north to northeast (fig. 2). Most of the cone's surviving mass is concentrated in its northwest buttress, which is ice covered except for two windows of andesite at elevations of 4,700–5,200 ft and 3,8004,900 ft (fig. 2). These windows expose, respectively, one and three NW.-dipping lava flows. The top flow in the lower window is a plagioclase-rich pyroxene andesite (62.2 percent SiO_2), similar to the capping flow on the summit, Peak 6770.

The WNW. arête of Southwest Snowy is an ice-bounded outlier made up of at least three andesitic lava flows (fig. 5). It is separated from the main part of the edifice by an arête of gray-green Tertiary andesite as well as by ice. The arête of Southwest Snowy lavas extends northwest from Crag 5720 and broadens into a cliff-bounded mesa (elevation 5,300

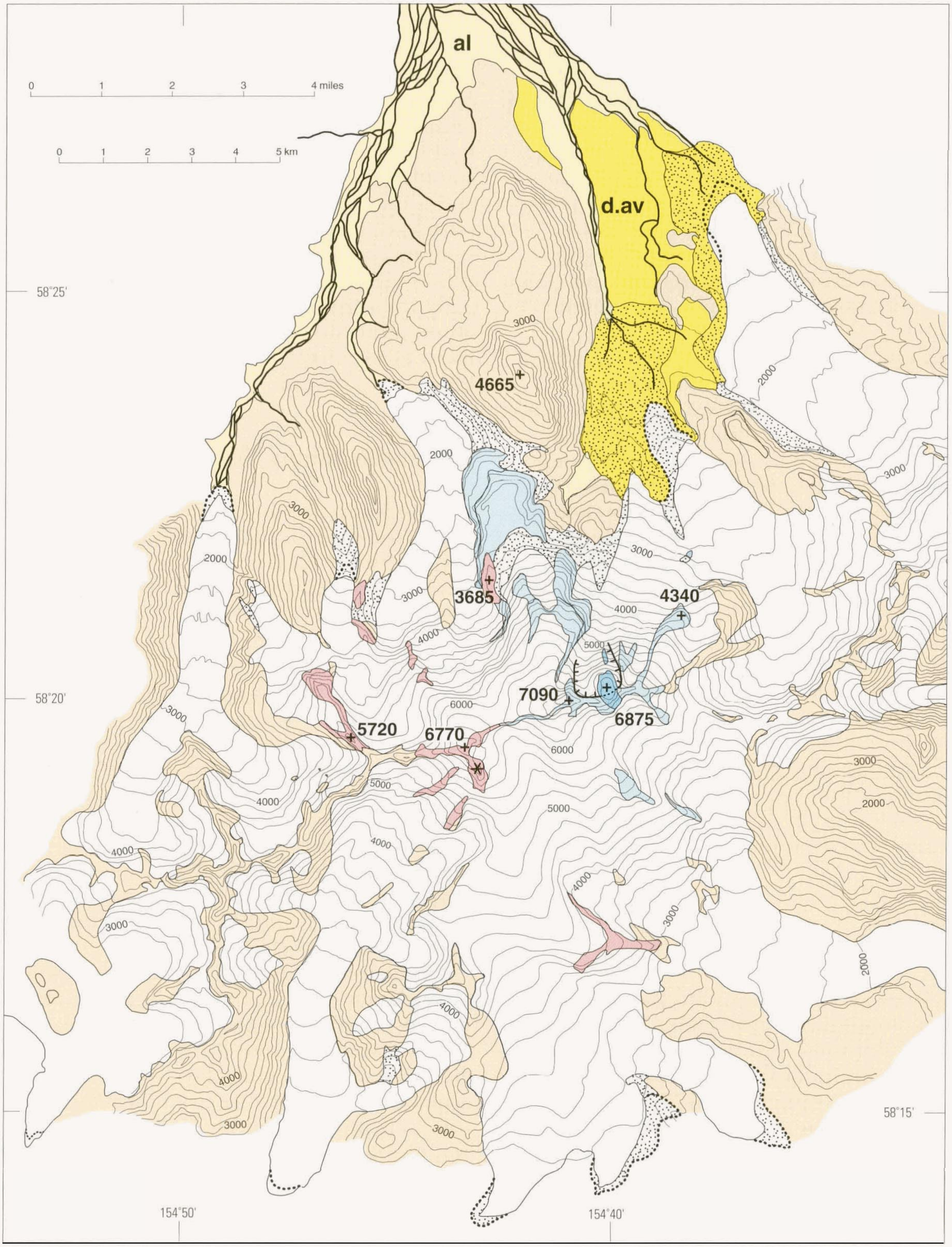

Figure **2A.** Simplified geologic map of Snowy Mountain volcanic center. Exposed lavas of Southwest Snowy volcano in red, of Northeast Snowy volcano in blue. Vent complex of former indicated by "*." Holocene lava dome occupying amphitheater (hachured) of latter is darker blue. Most of both cones covered by glacial ice (white). Basement rocks undivided are beige; they are largely Jurassic sedimentary rocks north of the volcanoes and largely Tertiary volcanic rocks to the south, although Tertiary intrusive rocks are also common in both sectors. Active alluvium (**al**) is pale yellow; debris avalanche deposit (**d.av**) is bright yellow. Glacial till is stippled. Stippled part of debris avalanche deposit was superficially remobilized when overrun by Neoglacial advance (and subsequent retreat) of Serpent Tongue Glaciers. Terminal positions of glacier snouts are dotted for 1951, entire for **1984–87.** Contour interval 200 ft; selected elevations are given in feet (1 m = 3.28 ft).

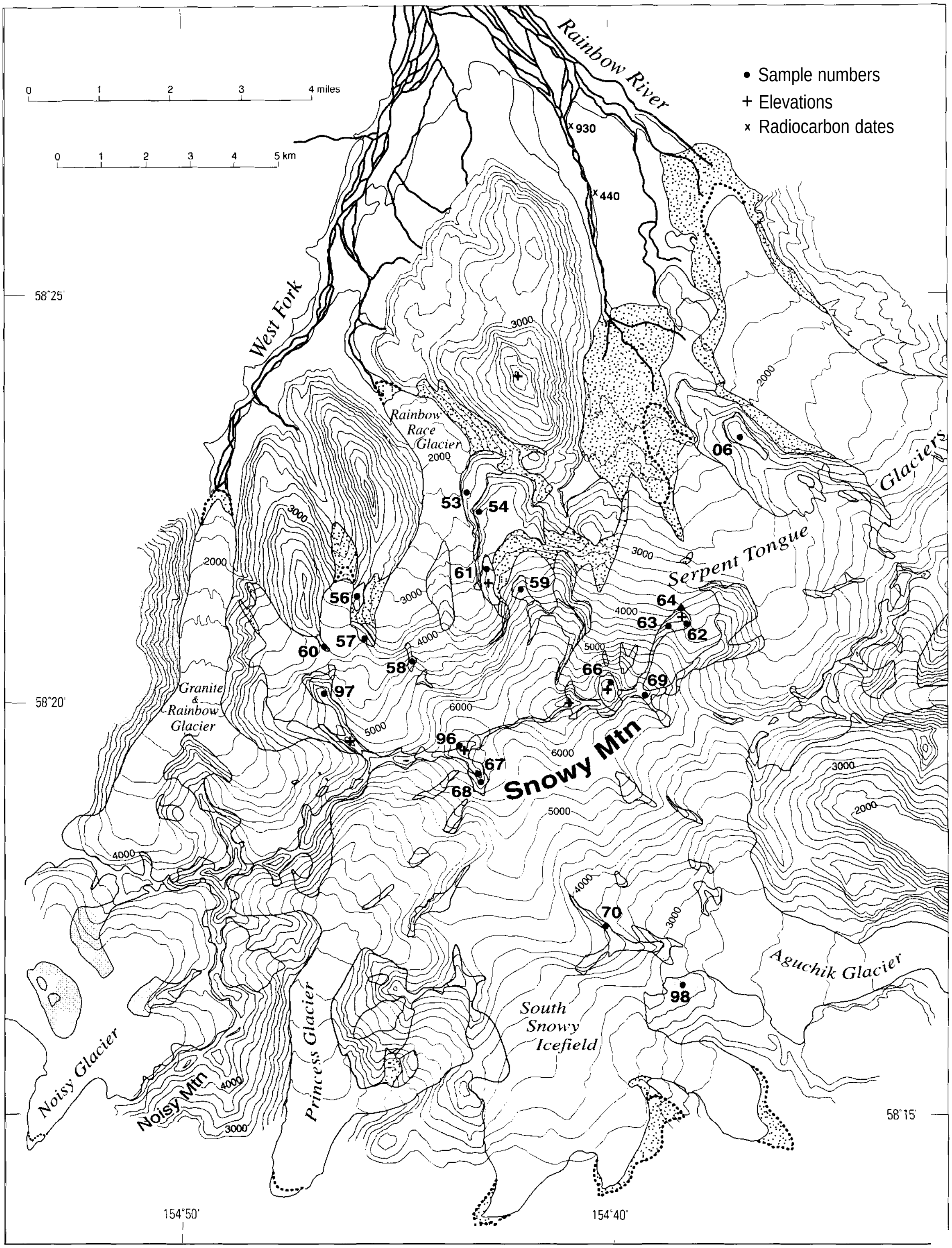

Figure 2*B*. Place names mentioned in text and locations of samples listed in tables 2 and 3. There being no ambiguity, only the last two digits of the sample numbers given in the tables are shown on the map. Same base as panel A. Topography simplified from USGS 1:63,360 quadrangles Mt. Katmai A2, A3, B2, and B3. In northern part of map, sites of two radiocarbon-dated samples atop Rainbow River debris avalanche are indicated by ×440 and ×930, as discussed in text.

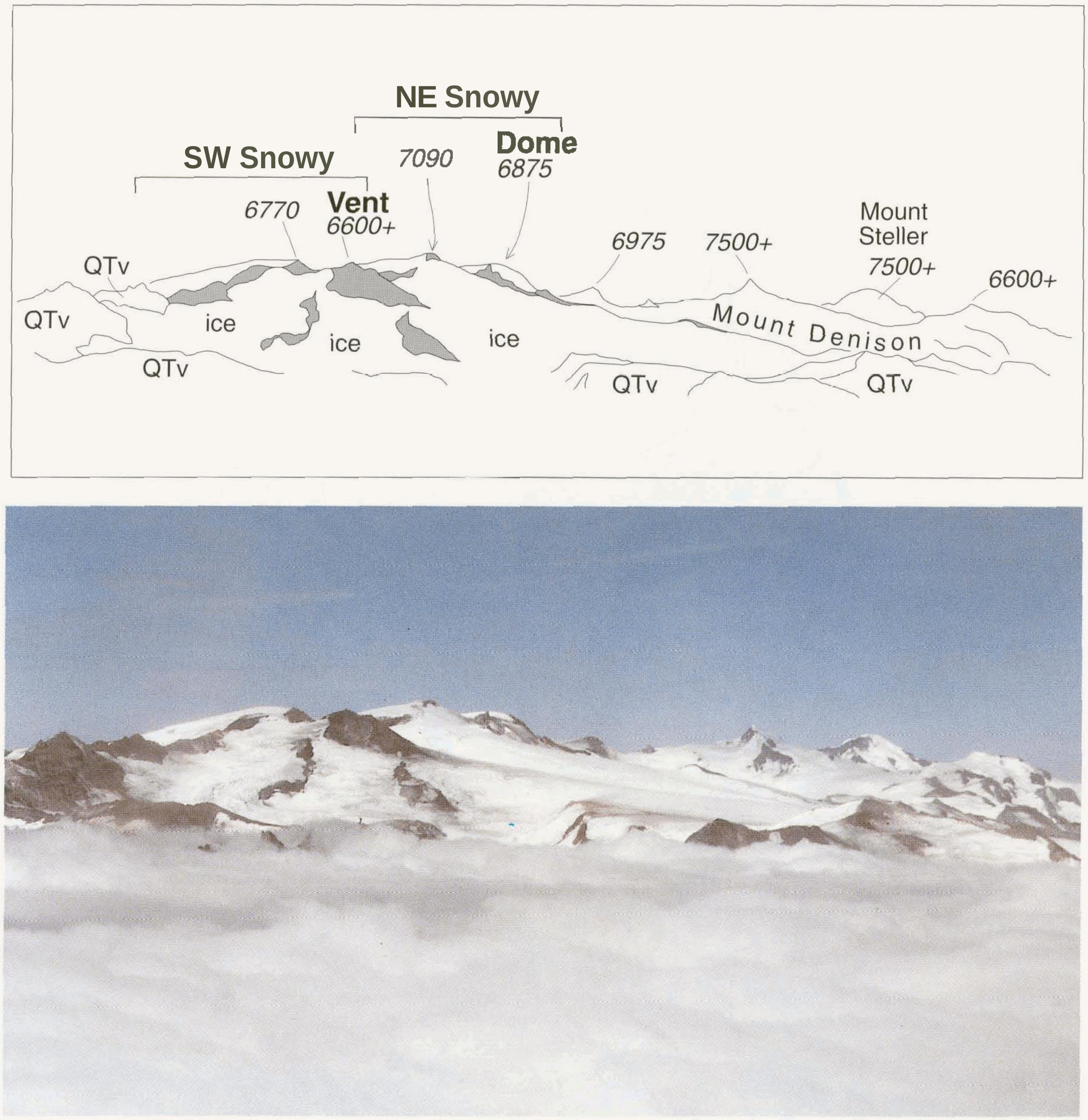

Figure 3. Alaska Peninsula rangecrest, July **1997:** A 25-km-long reach of the main divide as seen northeastward from upper Katmai River (fig. 1). Left half of panorama shows the pair of Snowy Mountain volcanoes; right half shows Denison and Steller volcanoes, as indicated in labeled profile. Mount Steller lies **4 km** behind (ENE of) Mount Denison. Products of the two Snowy Mountain vents are shaded. **QTv,** volcanic rocks, largely andesitic to dacitic, of several unidentified centers, of late Tertiary and possibly early Quaternary age (Shew and Lanphere, **1992;** Riehle and others, **1993).** Elevations in feet (1 m = 3.28 ft).

ft) scoured on an andesite lava flow (60.9 percent SiO_2) that thickens to 100 m distally (fig. 5). This rests on an even thicker andesitic lava flow that was not sampled (fig. 5).

A few kilometers north of this arête, two ridge-capping andesite remnants, each about 700 m long, rest directly on Jurassic basement rocks. Each consists of a single lava flow 60–80 m thick of olivine-bearing pyroxene andesite (59.9, 58.7 percent SiO_2). Although only 4–5 km from the vent complex, these lavas are today the most distal products of the Southwest Snowy cone preserved north of the drainage divide.

South of the divide, a parallel pair of kilometer-long cleavers of rubbly andesite trend and dip southwest away from the vent complex, and a large lava tongue, mostly ice covered, extends about 5 km southeastward (fig. 2). The latter consists of one or possibly two lava flows forming a 150-m-high bench at its eroded terminus, the only good exposure. The rim-forming lava of this 4,000-ft bench (5 km southeast of the vent; sample 2570; 70 in fig. *2B*) is olivine-bearing pyroxene andesite (57.9 percent SiO_2).

Figure 4. Two views of Southwest Snowy edifice, July 1998. *A*, East side of intrusive vent complex (swayback knob 6600+) and, at right, north-dipping stack of lava flows that make up Peak 6770. Vertical exposures visible are, respectively, 225 m and 175 m. View toward WSW. *B*, Southwest face of intrusive complex (knob 6600+), with lava stack of Peak 6770 in background clouds. View toward NNE. Foreground face, about 200 m high, consists below of steeply jointed intrusive andesite, overlain by rim cliff of chaotic vent breccia, which is densely agglutinated and cut by dikes. These rocks are in turn overlain by remnants of three lava flows, each 10 to 15 m thick, that cap knob 6600+.

Figure 5. Three andesite lava flows forming the glacially carved, sinuous, WNW. ridge of Southwest Snowy volcano, July 1999. At right, mesa 5300+ is scoured atop the middle flow, which is only 10–15 m thick at the left but thickens distally to 100 m at its eroded terminus. Ramping over this flow from the left, the top flow (rich in black glassy zones) maintains a 60-m-thick remnant that forms Crag 5720. Base of the lowest flow is ice covered; flow is 60 m thick in foreground and as thick as 150 m distally (below the promontory at far right). Its upper part is brecciated and oxidized, and locally (as at the lower left) the flow appears to be compound. View westward to nameless mountains of pre-Quaternary basement rocks on the Ikagluik-Rainbow divide. Pale-gray veneer on mesa (and on many distant slopes) is pumice-fall deposit of 1912 from Novarupta, which lies 23 km WSW.

Figure 6. Ice-topped Holocene lava dome (Peak 6875) on central skyline, partly filling ice-mantled amphitheater on northeast slope of Northeast Snowy edifice, July 1999. True summit (Peak 7090) lies just behind dome to its right. Radial dips surrounding amphitheater define Pleistocene edifice. Smooth skyline slope at right is north-dipping planeze that extends northward into staircase stack of thick coulees (just out of frame to right), illustrated in figure 10. Amphitheater originated by sector collapse and subsequent modification by ice of the acid-altered core of the edifice. Exposed walls of the amphitheater are hydrothermally altered orange-brown, yellow, and white, severely so in permeable breccia zones. Intact remnant of outward-dipping edifice lavas (surrounded by snow) lies at northeast foot of the lava dome. View southwestward across Serpent Tongue Glacier from ridge 3075 (sample site K-2606; 06 in fig. 2), 6 km from the dome.

Northeast Snowy Mountain Edifice

The northeasterly cone of the contiguous pair is likewise in large part a Pleistocene edifice, but unlike its companion it has erupted at least once during the Holocene. Nearly as ice-ravaged as the other cone, it nonetheless has almost three times more ice-free surface exposure. Most exposures, however, are along or north of the rangecrest, even though the vent itself lies right on the divide. Because such unilateral asymmetry is unlikely to reflect the eruptive behavior of a free-standing unconstrained cone, it seems required that a large fraction of the edifice have been glacially stripped from the south slope (fig. 2).

Holocene Dome

The Holocene lava dome was extruded just inside the headwall of a parabolic amphitheater, open to the northeast (fig. 6), probably directly above the long-term conduit of the stratovolcano. Lavas exposed on the amphitheater walls are severely ice eroded and hydrothermally altered, contrasting with the fresh dome lava, which is coarsely blocky, scoriaceous to densely vitrophyric, black to dark gray-brown, and little eroded (despite its 10- to 30-m-thick cap of ice). The dome has more than 500 m of relief concealed by ice on its north side (fig. 7) and 250 m of relief well exposed on its southeast side (fig. 8). The southeasterly exposure is a stubby exogenous flow lobe that drapes off the dome and distally overlies hydrothermally altered lavas of the crater headwall (fig. 8), perhaps also penetrating a now-concealed breach in that headwall. A smaller exogenous lobe (fig. 9) hangs off the ice-clad southwest face of the dome, and the ice-covered NNW. nose of the dome (figs. 6, 7) might be a third one. A sample from atop the dome is plagioclase-rich pyroxene-andesite vitrophyre, which at 62.8 percent SiO_2 is virtually a dacite. Of all the units we sampled at Snowy Mountain (fig. 2*B*), only the dome lava contains amphibole, and it has only a trace.

Amphitheater

The amphitheater containing the dome occupies a 50° sector high on the cone and widens distally (fig. 6). Such amphitheaters can sometimes be no more than breached summit craters, filled and enlarged by glacial ice, but they also commonly form catastrophically by sector collapse (with or without concurrent eruption), generating debris avalanches and derivative stream-borne debris flows. A hummocky debris-avalanche deposit just beyond the termini of the Serpent Tongue Glaciers (fig. 2) is derived principally from the Northeast Snowy amphitheater, as indicated by its abundance of hydrothermally altered andesitic debris, which imparts a characteristically pale-orange color to the bulk deposit. The avalanche deposit is present only in the valley directly north of the amphitheater, and the altered core of the volcano now occupied by the amphitheater is the only known source for the orange debris.

Evidence against forming the ***entire*** amphitheater by sector collapse, however, is the intact planeze of edifice lavas (surrounded by ice) at the northeastern foot of the dome (figs. 6, 7). This NE.-dipping remnant of the original shell of the cone, located at the northeast edge of the amphitheater, was evidently bypassed by the avalanche, which can thus be inferred to have issued only from the western two-thirds of the amphitheater. The western and southern headwalls of the amphitheater are higher and more pervasively altered than the eastern wall, consistent with the inferred source asymmetry. The sector collapse greatly enlarged what was probably a former crater, and the amphitheater has itself been enlarged by subsequent glacial erosion.

The amphitheater thus circumscribed occupies an apparent collapse area of about 1.5 km^2, whereas the avalanche deposit (described more fully in a later section) originally covered an area of at least 22 km^2 and ranged from 5 to 50 m in thickness. If the ***average*** thickness of the whole deposit were in the range 10–20 m, then its (pre-erosional) volume would have been between 0.2 and 0.45 km^3. Derivation of such a volume entirely from the 1.5-km^2 amphitheater therefore requires that the average original thickness of the mass displaced need only have been 150–300 m. As the present-day relief on the south and west walls of the amphitheater is 100–300 m (plus an unknown thickness of ice infilling its floor), the volumetric match is satisfactory despite the uncertainties.

Prior to extrusion of the Holocene dome, the previous summit vent (probably an ice-filled crater) had been the focus for long-term hydrothermal weakening of the upper part of the cone. The crater and much of its altered envelope slid away northward, plausibly destabilized by intrusion of magma that subsequently produced the lava dome, leaving behind an amphitheater much larger than any original crater. After extrusion of the dome inside the amphitheater, accumulation of ice produced three discrete glacial tongues, one descending along each side of the dome, a third separating the dome from the isolated remnant planeze, and all three merging downslope into the main glacier (figs. 6, 7).

Cone-Forming Lavas

The stacks of lava flows exposed in several ice-free segments around the rim of the amphitheater all dip radially away at 20°–45° (figs. 2, 6–9). Some of the steepest dips, adjacent to the dome, may have been increased slightly by tilting during dome extrusion. Steeply dipping ultraproximal lavas are dominated by flow-breccia zones (figs. 8, 9); the accompanying massive interior zones are generally only 5–10 m thick proximally but thicken downslope as dips diminish. Such breccia zones provide the main avenues of permeability for acid fluids to spread away from the conduit and crater,

Figure 7. Southeastward view of Holocene lava dome (Peak 6875) extruded at head of amphitheater seen in figure 6. Icy summit on right skyline is Peak 7090, part of the headwall. Its lavas, like those of the two prows at the left and the 300-m cliff at the right, dip radially away from the dome, serving to define the gutted center of the Northeast Snowy edifice. Relief on the ice-covered north face of the dome exceeds 500 m. Reddish-brown discoloration of glacier surface at right is caused by rockfall and windblown sand and silt from disintegrating cliff of hydrothermally altered andesite at right. Upper part of Serpent Tongue Glacier in foreground. Photo July 1998.

Figure 8. Steep exogenous lava lobe that drapes 250-m-high southeast face of Holocene lava dome (Peak 6875) occupying gutted core of Northeast Snowy edifice, July 1998. Best exposures of ice-mantled but little-eroded blocky lava dome are here on its southeast side. Remnants of stacked lava flows that built the ice-ravaged Pleistocene edifice dip 25° E. at right, 45° WSW. on crag at upper left. Within the lava stacks, permeable breccia zones are hydrothermally altered rusty orange- and yellow-brown; massive zones (flow interiors) are fresh and dark gray. View northwestward.

Figure 9. View northeastward past Crag 6700+ to southwest face of Holocene dome (Peak 6875), which exposes a 25-m-thick stubby lobe of fresh, little-eroded, blocky andesite. Crag at left lies on south rim of cirque-amphitheater and midway between the dome and Peak 7090 (fig. 2); it consists of coarse lava-flow breccia that dips as steeply as 45° WSW., away from the dome. Smoothed and corniced snow surface atop dome is a transient eolian feature that conceals a capping of crevassed ice as thick as 30 m. Foreground snow saddle is about 100 m below top of dome and about 70 m below top of Crag 6700+. Photo July 1998.

Figure 10. Glacially scoured staircase of andesite-dacite lava flows that descends northward from Northeast Snowy volcano and divides the forks of Rainbow River, July 1999. Lowest and second benches are compositionally identical dacite lavas, each 150 m thick. Small mesa right of center (Bench 3685) is a third (andesitic) lava flow 30–50 m thick, apparently banked in against the stack of thicker flows and probably derived from the other (southwest) cone. Still higher bluff (above snow slope at the right margin) is another dacite flow about 200 m thick. Forming the broadest bench, the second flow of the stack yields a K-Ar age of 171±8 ka (table 1). At left in middle distance, smooth-sloping Peak 4665 consists of pre-Quaternary basement rocks, as do most of the skyline peaks and ridges. View is northeastward across head of Rainbow Race Glacier from sample site K-2597 (97 in fig. 2) on WNW. ridge of Southwest Snowy edifice.

promoting hydrothermal alteration within the cone's outward-dipping lava stacks for as much as 2 km radially (e.g., fig. 6).

Three samples from two of the NE.-dipping flows in the stack that extends from the cirque rim 2.5 km northeastward to bench 4340 (figs. 2, 6) are mutually similar pyroxene andesites (61.7–61.8 percent SiO_2). The top flow on the east shoulder of the amphitheater (fig. 8) is plagioclase-rich pyroxene dacite (63.7 percent SiO_2), slightly more evolved than the adjacent Holocene lava dome.

Most of the surviving volume of the Northeast Snowy cone forms a great staircase of thick lava flows that descends 6 km northward from Peak 7090 (figs. 2, 6, 10). Proximal exposure is limited by ice cover, so only a single, vertically jointed lava flow, 100 m thick, crops out along the amphitheater's west wall above the 6,000-ft level. Farther down that sidewall, just below the strongly altered zone shown in figure 6, N.-dipping stacks of at least six lava flows are exposed on cliffs below lava benches at 5,400 ft and 4,600 ft (fig. 6). As much as half the material in these 300-m cliff sections along the western Serpent Tongue Glacier is flow breccia, many zones of which have been selectively discolored yellow- or orange-brown by hydrothermal fluids that visibly affected them for as far as 3 km north of the vent-plugging dome. A few kilometers northwest, the (unaltered) west side of this same stack of flows is well exposed as a series of cliff-bounded lava benches that extends to an elevation as low as 2,000 ft along the eastern wall of Rainbow Race Glacier (fig. 10). Three of these bench-forming distal lava flows, each 150–200 m thick, are pyroxene dacite (63.1–63.6 percent SiO_2) and are among the most evolved products identified at Snowy Mountain. An accompanying flow only 30–50 m thick (figs. 2, 10) is olivine-bearing pyroxene andesite (57.7 percent SiO_2) that banked against the stack of dacites and probably erupted from the Southwest Snowy vent, 4 km south.

The great thickness of these lava flows at their eroded termini, which are today just upstream of a granite-walled glacial gorge (fig. 2), suggests that some or all of them could originally have extended many kilometers farther down Rainbow River.

Fumaroles

No fumaroles have been observed on Southwest Snowy, but two separate areas on Northeast Snowy were reported to have been steaming in the summer of 1982 (Motyka and others, 1993). They recorded diffuse steam emissions issuing at 89°C from holes melted in the ice capping Peak 7090, and they mentioned steaming ground on the dome, Peak 6875. On helicopter flights in late July of both 1998 and 1999, we looked closely at Peak 7090, hovered all the way around Peak 6875, and landed atop the latter without seeing any emissions or detecting any fumarolic odors. Either the emissions have diminished, or we overlooked them, or thickening icecaps have suppressed them. The ice capping the dome in 1998–1999 (figs. 6–9) was many times more voluminous than that visible in aerial photographs taken in July 1951 (such details are obscure in the 1984 aerial photographs in our possession), so the third possibility seems not unreasonable.

Debris Avalanche and Debris Flows

Rainbow River Debris-Avalanche Deposit

A hummocky debris-avalanche deposit is well preserved between the eastern forks of Rainbow River (fig. 2) as far as 14 km north of the amphitheater headwall at Peak 7090. Though extensively overgrown with scrub alder, exposures of the deposit are abundant and are generally pale orange-brown, reflecting derivation principally from the hydrothermally altered core of the edifice. The present-day headwall and western sidewall of the amphitheater consist of altered andesite of similar color (fig. 6). Block-rich hummocks, many of them 100–400 m across, stand as high as 30 m above adjacent depressions on the deposit surface. Relief adjacent to glacier-fed stream gorges incising the medial part of the deposit reaches 40 m and locally may even exceed 50 m. The avalanche sheet generally thins northward, but even distal remnants have hummocks and ridges 20–30 m high. The moving avalanche was generally valley confined, not climbing the sidewalls appreciably. though it did apparently overrun three bedrock ridges in its path (fig. 2A) that stand 100 m or more above the surface of the deposit.

The main glacier-fed streams have cut channels right through the deposit and a few lesser streams head in the deposit itself. Much of the sheet, however, still lacks integrated drainage and remains marked by numerous depressions (20–400 m wide), many of which are pond filled and lack surface outlets. An unknown fraction of the distal part of the sheet has been removed, principally having been reworked as alluvium on the braided outwash plain of Rainbow River (fig. 2). Proximally, any avalanche debris that may have been deposited supraglacially has since been swept away by glacial transport. Medially, the deposit was overrun by Little Ice Age (A.D. 1400–1900) advance of three lobes of the Serpent Tongue Glaciers (fig. 2). Recession of those ice tongues during the last century or so has exposed overrun swaths of the avalanche deposit extending 1.5–2.5 km beyond present glacier termini that were superficially remobilized as till (fig. 2). Below the modem glacier termini, about 10 km^2 of the deposit are little modified, 7 km^2 have been overrun and re-exposed by glacier fluctuations, and at least 5 km^2 have been reworked as alluvium. The original area of the deposit was thus no less than 22 km^2, not including distal runout facies or the proximal devastated area (about 7 km^2) now swept clean by younger ice.

Though it obviously postdates withdrawal of the regionally extensive late Pleistocene alpine valley glaciers (Riehle and Detterman, 1993), the emplacement age of the avalanche is poorly known. Because the deposit was overrun by the Little Ice Age advance of the Serpent Tongue Glaciers, it is likely to be older than 500 years. Poorly integrated surface drainage, meager soil development, and immature vegetation on the deposit, as well as scant erosion of the lava dome emplaced in its source amphitheater, are features that suggest a late Holocene age for the collapse.

The wind-scoured surface of the avalanche is generally barren or is directly overlain by remnants of the Novarupta ash fall of 1912. Distally, however, where the surface is protected by alders and willows, a few centimeters of eolian silt (incipiently transforming into soil) had accumulated atop the avalanche prior to deposition of the 1912 ash. At two distal bluff-rim sites (fig. 2*B*), we obtained radiocarbon ages from the base of such an organics-bearing silt. At the southerly site (fig. 2*B*), the basal 3–4 cm of incipient soil developed on the reworked top of the avalanche deposit yielded an AMS age of 440±40 ^{14}C yr B.P., which calibrates to a calendar age in the interval 1433–1471 A.D. At the northerly site, the basal 4 cm of a 10- to 13-cm accumulation of silty soil (resting directly on the primary avalanche deposit) yielded a conventional age of 930±120 ^{14}C yr B.P., which calibrates to a calendar age in the interval 997–1240 A.D. About 500 m downstream from the latter site, the avalanche deposit banks against a postglacial landslide deposit of local derivation and nonvolcanic composition. Atop this slide mass, the accumulation of Holocene eolian silt is as thick as 80 cm, at least six times greater than the maximum thickness found atop the adjacent debris avalanche. We conclude that the Rainbow River debris avalanche broke loose from Snowy Mountain in the late Holocene, roughly 1,000–1,500 years ago.

Debris Flows

The glaciers of Snowy Mountain drain directly into no fewer than nine separate river valleys (fig. 1)—three forks of Rainbow River, two tributaries of Katmai River, the canyon of Soluka Creek, an unnamed gorge that runs to Hidden Harbor, and two canyons that drain to Kukak Bay. Just 4–12 km east of the volcano, three additional glacier-fed canyons run down to Kukak Bay, and a fourth drains to Rainbow River (fig. 1). All 13 drainages are susceptible to the flooding or debris-flow inundation that might be initiated by eruption or avalanching of the edifice or by fallout of proximal tephra on the ice. As the area is uninhabited, the main debris-flow hazard is to fish and wildlife resources.

We reconnoitered all the drainages just mentioned by means of low-altitude helicopter flights, searching for debris-flow deposits that might have originated at Snowy Mountain. The outwash-laden braided streams occupying these canyons have vigorously reworked such material into alluvium, leaving very few cutbanks in Holocene mass-Row deposits. Scattered remnants of 1912 or younger pumiceous debris flows and hyperconcentrated (phenocryst-dominated) sandflows reworked from the regional Novarupta fallout blanket of 1912 are present, but mass-flow deposits potentially attributable to Snowy Mountain are rare. In particular, primary runout deposits from the Holocene debris avalanche were sought but not identified downstream on the Rainbow and Savonoski Rivers (fig.1).

Debris-flow deposits several meters thick do form steep cutbanks at two isolated sites 23 km and 27 km north of Snowy Mountain's summit (fig. 1). Recognized from the air, neither site was visited owing to difficulty of access, so their age and provenance remain unknown. A third mass-flow deposit 11 km north of the summit banks against the debris-avalanche deposit on a local right-bank terrace of Rainbow River at an elevation of 950 ft (figs. 1, 2). The massive orange-brown sandy deposit is 2–3 m thick, has a median grain size diameter of only 2.1 mm, and contains only 10 weight percent clasts larger than 8 mm and merely one percent silt and clay (particles smaller than 0.063 mm). Identifiable clasts are mostly phenocryst-rich andesites, about a third of them hydrothermally altered, along with fewer than 5 percent nonvolcanic basement rocks. Although the material certainly came originally from Snowy Mountain, the sandy deposit itself probably resulted from stream flow that transported material remobilized from the avalanche and flushed it of fine-grained constituents.

Behavior of Glaciers

The icefields blanketing Snowy Mountain distribute outward into 10 valley glaciers (fig. 2), altogether representing about 155 km^2 of present-day ice. On Mount Mageik, another ice-clad volcano, similar in elevation to Snowy Mountain and only 35 km southwest along the rangecrest, we found the ice volume to have been shrinking substantially and the termini of all glaciers to have receded during the interval of 20th-century observation (Hildreth and others, 2000). Comparison of aerial photographs of Snowy Mountain taken in 1951 and 1983–84, however, reveals no similarly consistent pattern. (The following notes refer to behavior of glacier termini only during the 33-year interval 1951–1984. We know of no pre-1951 photographic record for Snowy Mountain, and our own 1998–99 observations yielded no quantifiable changes of terminal positions from those of 1984.)

To the northeast, the three lobes of the Serpent Tongue Glaciers behaved independently between 1951 and 1984. The terminus of the southwest lobe did not change position, that of the central lobe retreated 1,200 m, and that of the larger northeast lobe (which originates on Mount Denison) retreated 400 m. Prior to 1951, the three lobes had retreated 1.5 to 2.5 km from their Neoglacial (probably Little Ice Age) maxima (fig. 2).

To the southeast of Snowy Mountain, the terminus of Aguchik Glacier (fig. 2), which fronts on a great outwash plain at the head of Kukak Bay, retreated 1,000 m between 1951 and 1984. To the south, the extensive South Snowy Icefield (fig.

2) trifurcates distally into three modest ice tongues (fig. 2). The southwestern and central tongues each retreated only 200 m from 1951 to 1984, while the longer southeastern tongue retreated more than 600 m. In contrast, only 4–5 km farther west, Princess Glacier (so named by Griggs, 1922, p. 131–132) has actually advanced 150 m since 1951 (fig. 2). A few kilometers still farther west, the East Katmai Icefield (fig. 2) contributes both to Noisy Mountain Glacier, which likewise advanced 150 m since 1951, and to north-flowing Ikagluik Glacier (just west of fig. 2), the terminus of which is unchanged since 1951.

Four glaciers on the northwest side of Snowy Mountain occupy canyons that converge into the west fork of Rainbow River (fig. 2). The westernmost and largest of the four (Granite & Rainbow Glacier, confined in a granite-walled gorge) retreated 200 m between 1951 and 1984. The easternmost (Rainbow Race Glacier, likewise a large intracanyon ice tongue with a churning millrace of an outlet stream) retreated about 500 m, although the exact position of its terminus is rendered ambiguous by extensive ice-cored moraine. As for the two lesser glaciers between these (fig. 2), the western terminus has remained virtually stationary, while the eastern has retreated 250 m since 1951 and at least 1,500 m from its Little Ice Age maximum (fig. 2). Only for this small glacier and for the three Serpent Tongue Glaciers is good evidence preserved for terminal positions of the Little Ice Age advances. Most of the other glaciers in the district terminate on valley floors filled with braided outwash gravels where vigorous fluvial reworking has removed any Neoglacial moraines.

The marked inconsistency of 20th-century glacier behavior in the Snowy Mountain area may in part reflect distribution of the 1912 Novarupta ash cover, superimposed on the climatically controlled, generally negative, regional ice budget. The blanket of crystal- and pumice-rich fallout of 6–9 June 1912 had a cumulative thickness of 1–2 m on Snowy Mountain. As the principal dispersal sector from Novarupta was toward the ESE. (Fierstein and Hildreth, 1992), the primary fall deposit thinned northward and eastward, respectively, to about 50 cm around both upper Rainbow River and Kukak Bay (fig. 1). Southwest of Snowy Mountain, however, the deposit thickened to more than 3 m at Katmai River and on Mount Katmai (fig. 1). During the 9 decades since the great eruption, glacier flowage and surface erosion have stripped most of the 1912 ash from the glaciers northeast, east, and southeast of Snowy Mountain, but glaciers to the west and southwest retain thick fallout blankets, especially on their distal reaches. Of the 14 glaciers just mentioned, the ash-covered ones to the west have generally advanced or stagnated historically, whereas the ash-free glaciers farthest east have all receded. The buff pumice mantle apparently retards glacial ablation.

Exhibiting comparable behavior still closer to Novarupta, where the 1912 pyroclastic blanket is several meters thick, the termini of three of the five Knife Creek Glaciers advanced about 100 m between 1951 and 1987, actually edging out over the adjacent 1912 ash-flow sheet at the head of the Valley of Ten Thousand Smokes (Hildreth and others, 2000). Positions of the other two termini did not change. The heavily ash-covered advancing glaciers did so despite the fact that two of them had been partially decapitated by the 1912 collapse of Katmai caldera. In contrast, the largely ash-free glaciers of Mount Mageik, which lies just upwind of the principal 1912 fallout sector, have all retreated since 1912 (Hildreth and others, 2000).

Despite the advances of several ash-insulated ice tongues, the ice budget for most glaciers in the region has clearly been negative during the last century or so. As little as 8000 years ago, moreover, these glaciers were far thicker and, coalescing with numerous others, extended many tens of kilometers beyond their recent termini (Riehle and Detterman, 1993). Holocene shrinkage of the glacial cover on steep parts of an edifice like Snowy Mountain elevates the likelihood of failure of oversteepened glacial deposits, cliffy stacks of rubbly lava flows, and hydrothermally altered parts of the volcano. By lifting the deformable ice envelope sealing such unstable materials, the retreat of glaciers can actually increase the hazards of debris avalanches and derivative downstream debris flows.

Geochronology

Northeast Snowy volcano erupted at least once during the Holocene, as shown by its "postglacial" vent-plugging lava dome, but most of the edifice is severely eroded glacially. To determine how long the volcano has been active, we sought to date some of its oldest lava flows by the K-Ar method. Because the northward-descending staircase of lava flows (figs. 2, 10), which extends from the present summit all the way down to an elevation of 2,000 ft, represents the largest surviving fraction of the edifice, it seemed likely that the basal flow of the stack could be one of the earliest products of the volcano. Our sample of that (dacitic) flow was partly glassy so instead we dated a fully devitrified sample from the compositionally identical overlying flow (K-2554; 54 in fig. 2), determining a high-precision age of 171±8 ka (table 1).

Sample selection criteria and analytical methods were identical to those described by Hildreth and Lanphere (1994). Because we were seeking high-precision age determinations for late Pleistocene rocks, we employed the multiple-collector mass spectrometer (Stacey and others, 1981) at the U.S. Geological Survey in Menlo Park.

In contrast to Northeast Snowy, there is no evidence that the Southwest Snowy volcano has erupted in the Holocene, as all its products are severely eroded (figs. 4, 5). The paired edifices occupy adjacent but virtually exclusive areas, so stratigraphic evidence of relative ages by overlap or interfingering is generally lacking. At their mutual saddle, which is largely ice covered (fig. 2), their lava flows appear to abut directly, and exposure is inadequate to discern a relative age. Along the narrow strips of exposure adjacent to the saddle (fig. 2), the lava flows from Northeast Snowy are notably more altered hydrothermally. At a single location (Bench 3685; fig. 2), 4 km north of the summit of Southwest Snowy, a lone lava flow apparently derived from that edifice banked against the previously eroded staircase of flows from the other (northeast) edifice (fig. 10). That flow (sample K-2561; tables 2, 3) is olivine bearing, more mafic (57.7 percent SiO_2), and much thinner than the stack of thick dacite lavas against which it banks. This relationship, if correctly interpreted, provides the only direct stratigraphic evidence for temporal overlap of the active lifetimes of the adjacent ice-mantled edifices.

This stratigraphic inference is supported by a K-Ar age of 92±10 ka (table 1) for the major southeast-trending lava lobe erupted from Southwest Snowy (fig. 2). This flow (sample K-2570; tables 1–3) is compositionally similar to the northerly flow just discussed (K-2561; 61 in fig. 2), and it may be the basal Quaternary lava flow on the south side of the edifice. Where its ice-mantled snout crops out on a bench at 4,000 ft, exposure during our visits was inadequate to discern whether the flow rests directly on the Tertiary andesites exposed downslope or whether another lava flow from Southwest Snowy separates them.

On the north side of Southwest Snowy, a basal lava flow that rests on Jurassic basement 3.3 km northwest of the summit yielded an age of 199±9 ka (table 1). Somewhat surprisingly, the uppermost lava flow of the summit-forming stack atop Peak 6770 gave an (analytically indistinguishable) age of 196±8 ka (table 1). As these lava flows bracket most others preserved on Southwest Snowy, it seems apparent that much of the small cone grew very rapidly. More than 100 k.y. of glacial erosion ensued, however, scouring away much of the southern flank of the volcano before the big southeast-trending lava lobe was emplaced at 92±10 ka. No younger units are recognized at Southwest Snowy.

In summary, it is inferred from present data that eruptive activity began by 200 ka at Southwest Snowy and by 170 ka at Northeast Snowy. Lava-producing eruptions have been few and widely spaced at both cones. The latest activity recognized at Southwest Snowy took place about 92 ka, whereas Northeast Snowy has been active as recently as the late Holocene.

Composition of Eruptive Products

All samples taken from Snowy Mountain are andesites and dacites, the great majority being plagioclase-rich two-pyroxene andesites (table 2). Most rocks have 20–40 percent plagioclase phenocrysts as large as 3 mm, about 10 percent pyroxene phenocrysts (orthopyroxene and clinopyroxene in varied but subequal proportions), and 1–3 percent opaque oxide microphenocrysts—largely titanomagnetite. A few lava flows also contain small amounts of olivine, and some of the more mafic products of the Southwest Snowy cone have

Table 1. Whole-rock potassium-argon ages and analytical data

[Analysts: Potassium by D.F. Siema; Argon by F.S. McFarland and J.Y. Saburomaru. Constants: $\lambda = 0.581\times10^{-10}y^{-1}$; $\lambda_\beta = 4.962\times10^{-10}\ y^{-1}$; $^{40}K/K = 1.167\times10^{-4}$ mol/mol]

Sample number	Location (see fig. 2)	Weight percent SiO_2	Weight percent K_2O	Radiogenic ^{40}Ar (10^{-13} mol/g)	Radiogenic ^{40}Ar (percent)	Calculated age
K-2554	NE Snowy volcano. Second flow of stack to north; 3000-ft rim facing Rainbow Race Glacier; 4.9 km NNW. of Peak 7090.	63.6	2.083±0.008	5.132	10.5	171±8 ka
K-2557	SW Snowy volcano. Basal lava flow on basement at 4000-ft point, 3.3 km NNW. of Peak 6770.	58.7	1.405±0.002	4.034	18.8	199±9 ka
K-2596	SW Snowy volcano. Top lava flow on SW Summit, Peak 6770.	61.4	1.740±0.006	4.899	16.5	196±8 ka
K-2570	SW Snowy volcano. 4000-ft rim of ice-mantled lava flow, 5.2 km SE. of Peak 6770.	57.9	1.217±0.003	1.618	6.8	92±10 ka

Table 2. Estimated phenocryst contents of eruptive products of Snowy Mountain volcanic center.

[Data are visual estimates based on thin-section examination. For each phenocryst species, approximate volume percentage (%) and maximum size (max) are given. SiO_2 is weight percent SiO_2 of each sample; data from table 3. Pyroxenes includes subequal amounts of clinopyroxeue and orthopyroxene—except K-2558i, K-2567, and K-2568, which have only clinopyroxene. Clots refers to oxide-pyroxene-plagioclase aggregates, typically with grain-size range similar to or smaller than that of coexisting free phenocrysts. Sieved plag refers to sieve-textured cores or concentric zones within plagioclase phenocrysts; P, present in a few grains; C, common in many grains (but not most). Cone (NE or SW) and sector are given to assist reader in locating sample number on figure 2]

Sample	Cone	Sector	SiO_2	Plagioclase		Pyroxenes		Oxides		Olivine		Clots	Sieved plag	Notes
				%	max (mm)	%	max (mm)	%	max (mm)	%	max (mm)			
K-2553	NE	N	63.6	25-30	3	10	2	2-3	0.4	0		x	no	
K-2554	NE	N	63.6	25-30	2.5	10	3	1-2	0.4	0		x	no	
K-2556	SW	NW	59.9	20	3	10	3	1-2	0.4	0		x	P	
K-2557	SW	NW	58.7	15	2.5	5-7	2	1	0.3	trace(?		x	P	
K-2558	SW	NW	62.2	20-25	2.5	10	1.5	2-3	0.5	0		x	P	
K-2558i	SW	NW	55.5	30-40	1	15 (?)	<0.1	5(?)	<0.1	0 (?)		no	no	Non-vesicular 10-cm enclave. Small plag laths dominant; Mafics very fine grained.
K-2559	NE	N	63.1	25	3	8-10	2	1-2	0.3	0		x	P	
K-2561	SW	N	57.7	10-15	3	5	1	1	0.3	trace	1	x	P	Olivine iddingsitized.
K-2562	NE	NE	61.8	20	2.5	12-15	2.5	1-2	0.3	0		x	P	
K-2563	NE	NE	61.8	20-25	3	10-12	2	1	0.5	0		x	P	
K-2564	NE	NE	61.7	25-30	3	10	2	<1	0.3	0		x	P	
K-2566	NE	dome	62.8	20	3	8-10	1.5	2-3	0.5	0		x	P	Trace of oxidized hornblende.
K-2567	SW	vent	55.6	5	2.5	2-3	1.5	tr	0.1	5-7	2	x	P	
K-2568	SW	vent	55.7	5	2	2-3	1.5	tr	<0.1	5-7	2	no	P	
K-2569	NE	E	63.7	20-25	2.5	10	3	2	0.4	0		x	P	
K-2570	SW	SE	57.9	20-25	3	10	2	1	0.2	2	1.5	x	P	
K-2570i	SW	SE	58.3	10-15	2.5	5-7	1.5	tr	0.1	1	1	x	C	Non-vesicular 30-cm enclave.
K-2596	SW	summit	61.4	30-35	3	10	2	1-2	0.4	0		x	C	
K-2597	SW	WNW	60.9	25-30	3	8-10	2.5	1	0.4	0		x	C	
Pre-Snowy Mountain volcanic rocks														
K-2560	QTv	NW	65.05	10-15	3	5	1	1	0.5	0		no	P	
K-2598	QTv	SE	63.14	15-20	2.5	5-7	1	1	0.5	0		x	P	Altered pyroxenes coexist with fresh generation.
K-2606	QTv	NE	62.83	35-40	4	10	1.3	1-2	0.4	0		x	P	

Table 3. Chemical analyses of eruptive products.

[The ten major oxides (reported in weight percent) are normalized to H_2O-free totals of 99.6 weight percent (allowing 0.4 weight percent for trace oxides and halogens). Determinations by wavelength-dispersive XRF in USGS laboratory at Lakewood, Colorado; D.F. Siems, analyst. Precision and accuracy are discussed by Bacon and Druitt (1988) and Baedecker (1987). FeO* is total iron calculated as FeO. "Original total" is the volatile-free sum of the ten oxides, as analyzed, before normalization, with total iron calculated as Fe_2O_3. LOI, weight loss on ignition at 900°C. Cone and sector are given to assist reader in locating sample number on figure 2]

Sample	Cone	Sector	SiO_2	TiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Original total
Snowy Mountain														
K-2553	NE	N	63.6	0.69	15.74	5.67	0.11	2.69	5.36	3.62	1.92	0.21	0.54	98.83
K-2554	NE	N	63.6	0.67	15.84	5.51	0.11	2.71	5.45	3.62	1.91	0.20	0.03	99.33
K-2556	SW	NW	59.9	0.70	16.67	6.54	0.12	3.83	6.77	3.41	1.46	0.19	-0.04	99.68
K-2557	SW	NW	58.7	0.70	16.69	6.86	0.13	4.32	7.41	3.25	1.34	0.18	-0.14	99.47
K-2558	SW	NW	62.2	0.66	16.11	5.89	0.12	3.17	6.01	3.50	1.72	0.18	0.11	99.16
K-2558i	SW	NW	55.5	0.75	17.41	8.08	0.14	5.18	8.71	2.73	1.03	0.12	0.24	99.18
K-2559	NE	N	63.1	0.62	16.51	5.54	0.10	2.84	5.42	3.55	1.76	0.18	1.27	98.48
K-2561	SW	N	57.7	0.74	16.88	7.15	0.13	4.89	7.46	3.27	1.21	0.18	0.49	99.01
K-2562	NE	NE	61.8	0.61	16.56	5.72	0.12	3.26	6.11	3.66	1.55	0.20	0.25	98.20
K-2563	NE	NE	61.8	0.60	16.75	5.69	0.11	3.21	6.01	3.70	1.51	0.20	0.26	99.45
K-2564	NE	NE	61.7	0.61	16.58	5.77	0.12	3.32	6.09	3.65	1.52	0.20	0.26	99.31
K-2566	NE	dome	62.8	0.57	16.49	5.21	0.11	3.02	5.88	3.79	1.53	0.19	0.41	99.29
K-2567	SW	vent	55.6	0.70	16.21	7.16	0.13	7.16	8.50	3.08	0.85	0.20	0.36	99.18
K-2568	SW	vent	55.7	0.69	16.18	7.14	0.13	7.14	8.47	3.04	0.87	0.20	0.35	98.90
K-2569	NE	E	63.7	0.61	16.08	5.22	0.11	2.75	5.47	3.78	1.72	0.20	0.19	99.17
K-2570	SW	SE	57.9	0.72	16.81	6.59	0.13	4.88	7.82	3.37	1.13	0.21	0.49	99.38
K-2570i	SW	SE	58.3	0.74	16.44	6.56	0.12	5.10	7.82	3.16	1.29	0.13	0.68	99.05
K-2596	SW	summit	61.4	0.67	16.17	6.14	0.12	3.46	6.37	3.49	1.63	0.18	0.04	99.15
K-2597	SW	WNW	60.9	0.71	16.91	6.10	0.12	3.13	6.43	3.59	1.54	0.20	1.00	98.35
Pre-Snowy Mountain volcanic rocks														
K-2560	QTv	NW	65.0	0.52	16.11	4.41	0.09	2.49	5.54	3.79	1.38	0.22	1.71	97.69
K-2598	QTv	SE	63.1	0.68	15.89	5.16	0.10	3.74	5.53	3.61	1.56	0.19	1.81	97.17
K-2606	QTv	NE	62.8	0.65	16.37	4.91	0.09	3.30	5.89	3.89	1.47	0.18	2.16	97.33

several percent olivine phenocrysts as large as 2 mm. Amphibole was found only in the Holocene lava dome, and in our sample it is rare and opacitized. Quartz, sanidine, and biotite are absent. Groundmass textures are normal for intermediate lavas, ranging typically from partly glassy and vesicular in ejecta and in flow exteriors to crystalline and massive in thick flow interiors. As in many andesites, the plagioclase phenocrysts typically make up two or several coexisting populations. Some crystals are weakly zoned and relatively uncomplicated whereas others variously exhibit oscillatory zoning, dissolution surfaces with overgrowths, sieve-textured zones or cores, intergrowths with other grains, or polycrystalline clots (usually including pyroxenes and oxides). Such complexity preserves evidence for multistage pre-eruptive thermal and ascent histories generally involving magma mixing and remobilization of stalled crystallizing batches (e.g., Singer and others, *1995;* Coombs and others, *2000).*

Major-element determinations by X-ray fluorescence spectroscopy are given for *19* Snowy Mountain samples in table *3;* the data are illustrated in figure 11 and the sample locations shown in figure *2B.* Four additional analyses (fig. *11)* of samples said to be from Snowy Mountain were tabulated by Kienle and others (1983), but neither sample locations, analytical methods, nor laboratory were specified. No other chemical data for the Snowy Mountain volcanic center are known to us.

All Snowy Mountain samples plot in the medium-K field (fig. 11*A*) and far into the calcalkaline field on a conventional FeO*/MgO vs. SiO_2 diagram (fig. 11*B*). An alkali-lime intersection (fig. 11*C*) at *63.5* percent SiO_2 defines a calcic suite (Peacock, 1931), as previously also determined for Novarupta (Hildreth, *1983)* and for nearby Mageik, Martin, and Alagogshak volcanoes (Hildreth and others, *1999; 2000).* The SiO_2 contents of lava flows range from *55.6* to *63.7* percent, and the two magmatic enclaves analyzed gave *55.5* and *58.3* percent. This range is comparable to those of suites from Trident,

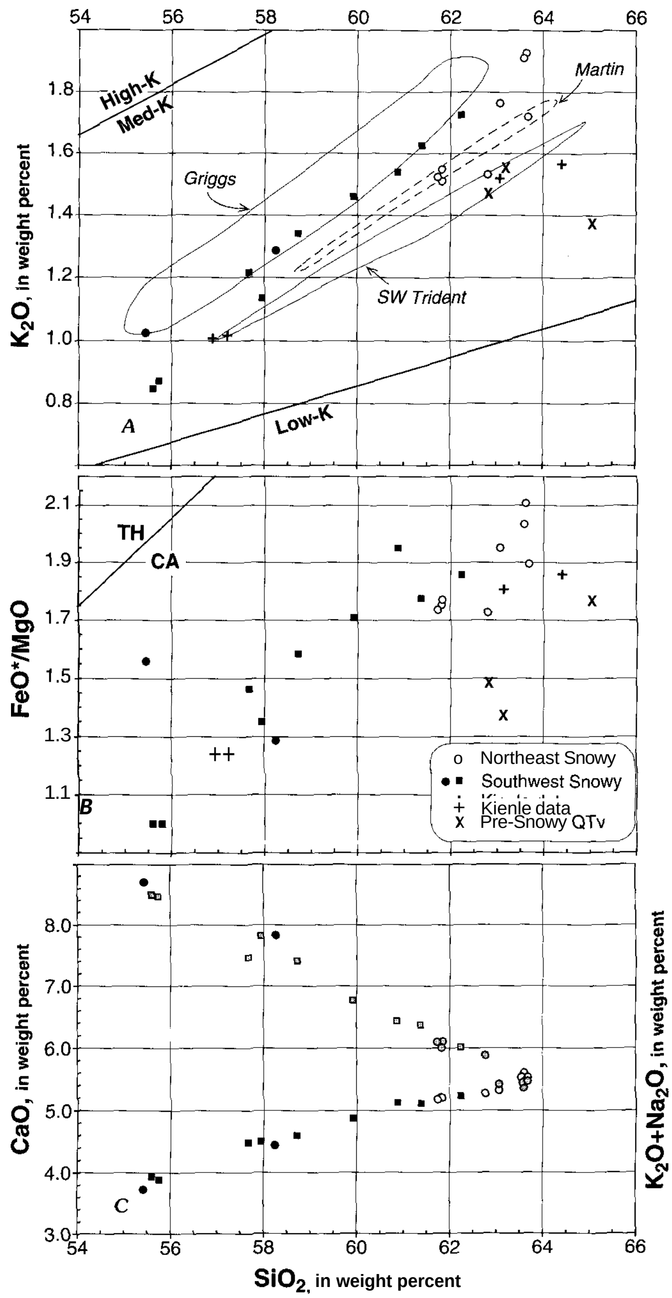

Figure 11. Whole-rock compositional data for Snowy Mountain samples as identified in inset. Filled circles for Southwest Snowy are magmatic enclaves (tables 2, 3). "Kienle data" (+) are four analyses reported by Kienle and others (1983) for unlocated samples said to have been taken from Snowy Mountain. In addition to Snowy data, fields outlining the compositional ranges determined for our suites of samples from nearby Mount Griggs (n = 75), Mount Martin (n = 13), and Southwest (New) Trident (n = 15) are shown for comparison. *A*, K_2O vs. SiO_2. *B*, FeO*/MgO vs. SiO_2. *C*, CaO (upper array) and total alkalis (lower array) vs. SiO_2. Data from Hildreth and others (1999, 2000); Hildreth and Fierstein (2000); and table 3 of this report. TH/CA is conventional field boundary between tholeiitic and calcalkaline suites. FeO* is total iron calculated as FeO. The nomenclatural division between andesite and dacite lies at 63 percent SiO_2 and is simply a conventional tick on a natural continuum in many arc suites.

Martin, and Alagogshak but much more restricted than those of Novarupta and Mount Katmai (Hildreth, 1987; Hildreth and others, 1999; Hildreth and Fierstein, 2000). Snowy Mountain eruptive products form a typical low-Ti arc suite, containing only 0.57–0.75 percent TiO_2. Contents of Al_2O_3 are ordinary for arc suites, ranging from 15.7 to 17.4 percent. Relatively primitive material has not erupted at Snowy Mountain, most samples having less than 5.2 percent MgO, but (at 7.1 percent MgO) the olivine-bearing scoria blocks from the vent complex of Southwest Snowy do rank among the most magnesian Quaternary volcanic products yet recognized in the Katmai district.

Figure 11 shows that products of Southwest Snowy (55.5–62.2 percent SiO_2) are generally less silicic than those of Northeast Snowy (61.7–63.7 percent SiO_2) and that they also tend to have slightly higher K_2O at equivalent values of SiO_2. The Holocene lava dome (at 62.8 SiO_2, 1.53 K_2O; fig. 11*A*) is less silicic than several older lava flows from Northeast Snowy and is, relatively, one of the least potassic.

Three samples of the highly eroded basement volcanic suite directly underlying the Snowy Mountain lavas were studied and analyzed (tables 2, 3). All three are pyroxene dacites, petrographically and chemically rather similar to silicic members of the Snowy Mountain suite, though relatively less potassic and distinctively more hydrated (see LOI, table 3). Thought to be of early Quaternary or late Tertiary age, these rocks are slightly altered remnants of a previous generation of arc volcanoes that apparently lay along or close to the same alignment as that of the modern volcanic chain (figs. 1, 2).

Volume Estimates

Owing to the extensive glacial erosion and the present-day ice blanket, estimates of eruptive volume are not very accurate for these cones. Exposures of Quaternary volcanic rocks today add up to about 6.5 km^2 for Northeast Snowy and only 2.4 km^2 for Southwest Snowy. Extrapolation beneath the ice between outcrops yields minimum areas originally lava-covered of 31 km^2 and 36 km^2, respectively. Conservative estimates of lost volumes of distal lavas, not counting probable intracanyon lava tongues, could raise total areas to 40 km^2 and 45 km^2, respectively.

For converting such areas to volume estimates, a cone model is inappropriate because the volcanoes straddle a narrow rangecrest ridge of pre-Quaternary basement rocks and because their bilaterally emplaced lavas draped irregularly rugged topography on both flanks. Along the main drainage divide, Tertiary rocks crop out as high as 5,500 ft only 1 km east of the vent-plugging 6,875-ft dome of Northeast Snowy and as high as 6,000 ft only 1.5 km west of the vent of Southwest Snowy (fig. 2). Although Snowy Mountain lavas are preserved on the north flank down to elevations as low as 2,000 ft, they are flanked there by ridges of basement rocks higher in several places than 4,000 ft. The volume approximation is best treated, therefore, in several parts—two thick near-vent piles and several separate stacks of outflow lavas that infilled paleotopography north and south of the divide.

The thick proximal part of the Northeast Snowy cone had an original area of about 10 km^2 and that of the Southwest Snowy cone about 6 km^2. The present-day summits, Peaks 7090 and 6770, respectively, do not appear on structural grounds to be eroded much below their original elevations. If this be true, primary relief on the two proximal piles might have averaged about 650 m and 450 m, respectively. On this basis, cone-model calculations yield volumes of 2.2 km^3 for the northeast proximal pile and 0.9 km^3 for the southwest.

Volumes of outflow stacks are even harder to approximate because the deeply incised (pre-volcano) bedrock surface is so discontinuously exposed beneath the lavas and ice. Where they issue from the proximal piles some lava-flow stacks appear to be 400–600 m thick, but (in contrast to individual lava flows that commonly thicken downslope) the stacks tend to thin distally, probably owing to spreading and shingling during outflow and to more rapid erosion along paleovalleys. At their eroded termini today, radially emplaced stacks of lava flows are no thicker than 300 m on the north slope and as thin as 100–150 m on the south slope. On the basis of all these weakly constraining observations, we estimate the original outflow volume of Northeast Snowy to have been in the range 4–8 km^3 and that of Southwest Snowy in the range 3–6 km'. Adding these crude estimates to the proximal-pile volumes given above yields 8±3 km^3 for the northeastern edifice, 5±2 km^3 for the southwestern, and an eruptive volume of 1324 km^3 for the Snowy Mountain center as a whole. Only half to two-thirds of this material has survived glacial erosion and remains in place on the skeletally sculpted edifices today.

Discussion

Snowy Mountain is a small andesite-dacite arc volcano that apparently originated at least 200 k.y. ago. Eruptions have taken place from two vents 4 km apart. Their eruptive lifetimes overlapped extensively, though only the northeastern vent has erupted in the Holocene. Products of the southwestern vent are generally more mafic than those of the northeastern, which extend to dacite. No dacitic pumice deposits were seen proximally, and no regionally widespread ash layer has been tied to Snowy Mountain. Although we found no evidence for major explosive events, the modem ice cover and the recurrent regional glaciations of the past dissuade us from concluding firmly that no such activity ever took place here during the Pleistocene.

The modest eruptive volume (I 3+4 km^3) and the longevity of the volcano (19929 k.y.) make the calculation of an average volumetric eruption rate (0.04–0.09 km^3/k.y.) a potentially misleading exercise. Nominally, the lifetime average eruption rate for Snowy Mountain is similar to that estimated for each of the cones of Trident volcano (fig. 1), but it is 3–10 times smaller than the long-term rates for Mounts Mageik and Katmai (Hildreth and Fierstein, 2000; Hildreth and others, 2000). Many or most andesite-dacite stratovolcanoes, however, erupt in spurts (Hildreth and Lanphere, 1994), and there is little evidence for volumetrically steady-state production, storage, or eruption of magma at such centers. At the extreme, 13 km' of magma (equivalent to the entire volume of Snowy Mountain) erupted at nearby Novarupta in 60 *hours* in June of 1912 (Fierstein and Hildreth, 1992).

Accordingly, the evidence (albeit modest and inconclusive) at Snowy Mountain suggests that much of its eruptive volume could have been produced during a limited number of events widely separated in time. The pair of Snowy Mountain cones consist altogether of only about 25–30 lava flows, so even if these were ideally spaced, gaps between eruptions would be as long as 6,000 years. Pairs or stacks of conformable lava flows of closely similar composition suggest that there were in reality far fewer eruptive episodes and therefore at least some breaks much longer in duration. (This analysis ignores minor ash outbursts that leave no substantial depositional record in such terrain.) Production of multi-flow stacks during episodes lasting a few years to decades is a common mode of stratovolcano behavior, as illustrated locally by the eruption in 1953–60 of four overlapping andesite-dacite lava flows at Southwest Trident volcano (Hildreth and others, 2000; Coombs and others, 2000).

Another example is Mount Martin, 40 km southwest of Snowy Mountain (fig. 1), which consists of a small fragmental cone and a staircase of 10 overlapping coulees of blocky dacite, each 75–100 m thick, that descend northwestward for 10 km. The extremely asymmetrical distribution of lava flows with respect to the summit vent (fig. 12) resembles the stacked array of Southwest Trident, the Holocene array of flows from the East Summit of Mount Mageik (Hildreth and others, 2000), and the staircase of flows on the north side of Snowy Mountain (fig. 12). Interflow conformity within parts of such stacks and the compositional similarities of subsets of successive flows within such stacks suggest rapid sequential emplacement. At Mount Martin, the whole pile is Holocene and much or all of it could have erupted on a timescale of decades to centuries (fig. 12). At Snowy Mountain, the three thick conformable dacites at the bottom of the stack (fig. 12) could likewise have been emplaced in rapid succession.

The small adjacent cones of Snowy Mountain are characteristic of late Quaternary andesite-dacite arc volcanism in the Katmai volcanic district. Along the same rangecrest (fig. 1), four discrete cones of Mount Mageik, four cones of Trident, and two of Mount Katmai, as well as Alagogshak volcano, Mount Martin, and several peripheral lava domes, form a chain only 30 km long, display eruptive volumes of 1–30 km^3 each, and have mutual spacings of only 1–8 km. The close-set array of small cones contrasts strikingly with such giant stratocones as Veniaminof and Shishaldin (each well over 100 km^3) farther down the chain, and it conflicts with the conventional myth of evenly spaced arc volcanoes 40–70 km apart. Additional, comparably close-set arrays of stratovolcanoes on the Alaska Peninsula include the Pavlof and Stepovak Bay groups (Wood and Kienle, 1990) and, just northeast of Snowy Mountain (fig. 1), the Denison-Steller-Kukak-Devils Desk chain. Although the last-named chain is very poorly known, eruptive volumes of the four contiguous cones probably fall in the range 5–15 km^3 each, and the mutual spacing of their vents is 3-4 km. (Mount Steller is not even spelled correctly on many published maps; it is named for Georg Wilhelm Steller, 1709–1746, naturalist on the 1741 voyage of Vitus Bering.)

Why are so many, closely spaced, mostly small, andesite-dacite volcanoes perched directly atop the peninsular drainage divide from Alagogshak to Devils Desk (fig. 1)? It has been suggested (e.g., Keller and Reiser, 1959; Kienle and others, 1983) that the volcanic chain in the Katmai district is built on the crest of a regional anticline in the Mesozoic basement rocks. Examination of the geologic map and structural cross sections of Riehle and others (1993), however, shows that the volcanoes do not necessarily lie right along the ill-defined structural crest and that the "anticline" is at best a broad regional warp defined by strata dipping only 5°–20° and complicated by a variety of oblique lesser folds. Additionally complicated by the intrusion of numerous Tertiary plutons into the warped Mesozoic strata, it seems very unlikely that any such upper-crustal structure controls the linear alignment of the Quaternary volcanic chain illustrated in figure 1. Alternatives to upper-crustal control include (1) a narrowly linear pattern of fluid release from the subducting slab, (2) a sharp convecting corner or some other mechanism producing a narrowly linear curtain of magma generation and ascent in the mantle wedge, or (3) some linear structure in the deep crust that traps and stores mantle-derived magma batches long enough for assimilation, fractionation, and admixture of local partial melts to reestablish buoyant ascent (Hildreth and Moorbath, 1988). The observation that Mount Griggs, a 20- to 25-km^3 stratovolcano 12 km behind the main volcanic chain (fig. 1) has produced an eruptive suite significantly more potassic (fig. 11) than any of the contemporaneous centers along the chain

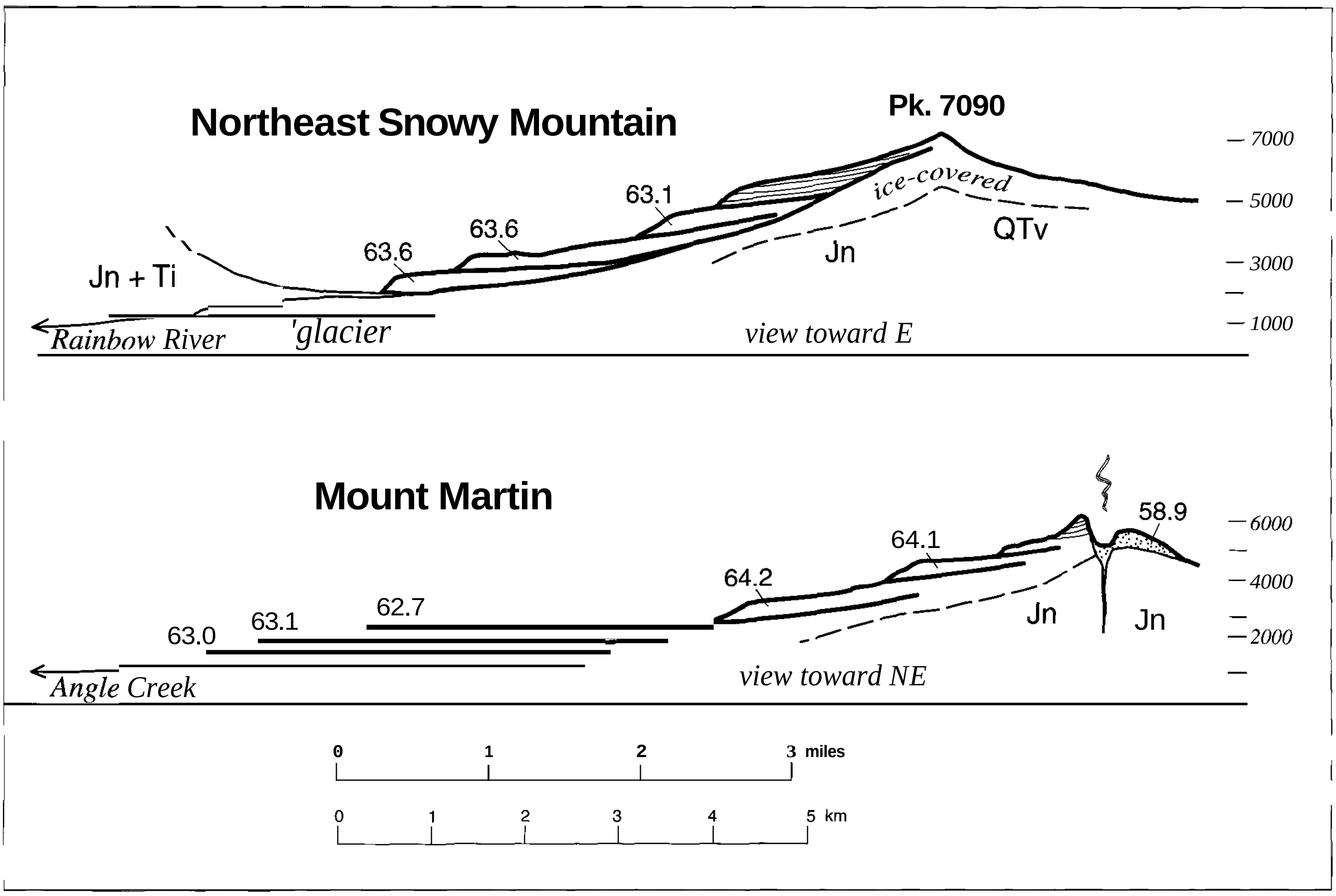

Figure 12. Comparative profiles of conformable staircase stacks of dacitic lava flows on north flanks of Snowy Mountain and Mount Martin, which lie along the same rangecrest 44 km apart (fig. 1). Weight percent SiO_2 (63, 64) is indicated for most flows. Although lavas of the two centers are compositionally similar (fig. 11), the three distal coulees from Northeast Snowy are 150–200 m thick, those from Mount Martin about 100 m thick. Lavas higher in the stacks are thinner at Northeast Snowy, thicker at Mount Martin. Elevations are in feet (1 m = 3.28 ft). No vertical exaggeration. Jn, Jurassic Naknek Formation; Ti, Tertiary intrusive rocks; QTv, pre-Snowy Mountain altered volcanic rocks.

itself generally supports the notion of deep influence. Perhaps an unusually narrow belt of magma storage in the deep crust or mantle-crust transition zone leads to some degree of mixing and modulation of any mantle-derived compositional diversity beneath the main chain. Antecedent to renewed dike transport toward the upper crust and distribution into discrete eruptive centers, such deep-crustal storage and modulation might account for the grossly similar compositional trends of Snowy Mountain and many of the Katmai cluster volcanoes nearby (Hildreth and Fierstein, 2000).

Although the along-arc distribution of andesite-dacite magma into many small, close-set eruptive centers, as observed in the Katmai district and in a few other stretches of the Alaska Peninsula–Aleutian arc, is not a general feature of the whole Quaternary arc, the extremely linear arrangement is. The single-file chain of volcanoes that stretches 2,500 km from Cook Inlet to Buldir Island (Miller and others, 1998) contrasts drastically with the Japanese, Cascadian, Mexican, and Andean arcs, where the Quaternary volcanic zones are typically several tens of kilometers wide and where numerous volcanoes scatter far behind the volcanic front. In the Alaska Peninsula–Aleutian arc, instead of hundreds of volcanoes behind the volcanic front, there are only a handful of Quaternary centers (e.g., Griggs, Ukinrek, Amak, and Bogoslof; Simkin and Siebert, 1994). Although offsets of alignment do divide the chain into several segments, some process or deep structure imposes on this arc an extraordinarily narrow linearity that is not typical of arcs worldwide.

Volcano Hazards

The principal volcano hazards in this wilderness region are to aviation, fish and wildlife resources, and backcountry travelers. The volcano is so remote that a future eruption as large as any past event at Snowy Mountain is unlikely to have any impact on ground-based people or property. Another large debris avalanche might muddy the waters in a coastal harbor or downstream on the Savonoski River for a season or two. The principal danger is from phreatomagmatic and magmatic eruptions that can reasonably be anticipated to produce ash clouds that could rise to altitudes of 5–12 km, i.e., as high as 40,000 ft, endangering any passing aircraft. It is unlikely that ashfall from such an eruption at Snowy Mountain would produce more than a light dusting at Kodiak or Cook Inlet settlements. Many other volcanoes nearby are characteristically more explosive than Snowy Mountain appears to have been and thus pose greater ash-cloud hazards to aviation.

In all probability, renewed eruptive activity at Snowy Mountain or any of its companion volcanoes would be preceded by days to months of increased seismicity. A persistent cluster of shallow earthquakes north and west of Snowy Mountain has been recognized since at least 1965 (Ward and others, 1991), at depths of 5–10 km in basement rocks, 5–20 km from the volcanic line. A few shallow earthquakes (magnitudes 1–2) have also taken place beneath or close to the Snowy Mountain edifice itself. In 1998, Alaska Volcano Observatory (AVO) expanded its Katmai seismic network to deploy several seismometers north of Snowy Mountain, thus sharpening the precision of locating small earthquakes and improving the ability to detect seismic activity potentially precursory to eruptions. Were signs of unrest to be detected, AVO would implement additional instrumental and observational monitoring and would notify various authorities, the media, and the aviation community of the impending hazard.

Acknowledgments

Tracey Felger and Dave Tucker helped with the fieldwork, James Saburomaru and Forrest McFarland with K-Ar dating, and John Paskievitch with field logistics. Helicopter pilots Bill Springer and Jim Sink took us safely to outcrops that would have been a helluva hike. We thank Game McGimsey and Manuel Nathenson for careful reviews of the manuscript.

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Reviewers: G. McGimsey, M. Nathenson