Valley of Ten Thousand Smokes, Katmai National Park, Alaska

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LOCATION

The pyroclastic deposits of the Valley of Ten Thousand Smokes (VTTS) lie within Katmai National Park, 450 km southwest of Anchorage and 170 km west of Kodiak (Fig. 1). The only convenient access is by boat or amphibious aircraft from King Salmon to Brooks Camp on Naknek Lake; scheduled commercial service is available during summer months. Brooks Lodge offers a daily commercial shuttle by bus or van to the Overlook Cabin, perched on a scenic knoll near the terminus of the VTTS ash-flow deposit, at the end of a 37-km dirt road from Brooks Camp. Cabins, meals, camping, and National Park Service programs are available at Brooks Camp, but the Overlook Cabin and the Baked Mountain Hut (a day's walk up the VTTS) provide no amenities other than primitive shelter from the normally foul weather. The distal part of the ash-flow sheet can be reached in an hour's walk by rough trail from the Overlook Cabin, but anything more than a brief visit demands a backpack, boots *and* sneakers, high-quality rain gear, a sturdy tent, warm clothing, maps and compass, water bottles, food, an ice axe or staff, goggles for ash storms, a rope for fording streams, and a plan (or philosophy) for dealing with brown bears—which are commonly encountered with little warning. High winds, rain, bears, icy streams, and remoteness make the VTTS a true wilderness, exhilarating but dangerous, occasionally glorious, usually uncomfortable, and never to be trifled with. Information can be obtained by writing to the Superintendent, P.O. Box 7, King Salmon, AK 96613. U.S. Geological Survey 1:62,500 topographic maps, *Mt. Katmai A3, A4, B3, B4,* and *B5,* cover the VTTS and several neighboring stratovolcanoes, and the *Mt. Katmai* 1:250,000 sheet provides a desirable regional perspective.

SIGNIFICANCE

The eruption of 6–9 June 1912 was the most voluminous of the twentieth century, one of the three largest in recorded history, and one of the few historic eruptions to produce welded tuff. Widespread tephra falls, compositionally banded pumice, and the "ten thousand" fumaroles in the ash-flow sheet attracted broad scientific and popular attention, principally owing to the work of the National Geographic Society expeditions of 1915–1919 led by R. F. Griggs (Griggs, 1922). Among historic eruptions, this event was virtually unique in that it generated a large volume of pumiceous pyroclastic flows that came to rest on land. Study of its superbly exposed deposits has strongly influenced our understanding of the eruption, emplacement, degassing, and cooling of silicic ejecta.

INTRODUCTION

A sequence of eruptive pulses (indicated, by the record of discrete ash falls at Kodiak village, to have spanned ~60 hr) produced three principal groups of pyroclastic deposits (Curtis, 1968; Hildreth, 1983): (1) Plinian pumice-fall and surge deposits, dominantly rhyolitic, that preceded and accompanied ash-flow emplacement; (2) a 120-km^2 ash-flow sheet consisting of several flow units and zoned from rhyolite to andesite; and (3) Plinian pumice-fall deposits, dominantly dacitic, that overlie both the ash flow and the stratified rhyolitic tephra. Virtually all of the more than 30 km^3 of pyroclastic material vented within the 2-km-wide Novarupta depression (see Fig. 1, 4), which is thought to be a flaring funnel-shaped structure backfilled by its own ejecta. The small rhyolitic lava dome, named Novarupta, was extruded within the depression after the explosive sequence had ended.

At Mt. Katmai, 10 km east of the 1912 vent, a 3-km-wide caldera (more than 600 m deep) (Fig. 1) collapsed at some unknown time during the eruption, probably in response to withdrawal of magma hydraulically connected with that erupting from the Novarupta flank vent. A small dacite lava dome (the horseshoe island of Griggs, 1922), extruded on the caldera floor and now concealed by more than 250 m of lake water, was the only 1912 eruptive unit confidently attributable to Mt. Katmai itself (Hildreth, 1983).

The five locations described below exhibit some of the best evidence for the sequence and mechanisms of emplacement of the 1912 eruptive products, as well as for subsequent phreatic, fumarolic, and secondary mass-flow processes. The first location requires only half a day from the Overlook Cabin; the second, third, and fourth can be combined into a three-day loop hike; and finally, a visit to the caldera rim of Mt. Katmai would require an additional all-day roped ascent from a camp near Location 3 or 4 (Fig. 1).

LOCATION 1. PYROCLASTIC DEPOSITS NEAR THREE FORKS

Three Forks is the area below the Overlook Cabin where the Ukak River is formed by the confluence of Knife Creek, the River Lethe, and Windy Creek (Figs. 1 and 2). Each of these rushing streams occupies a gorge incised completely through the distal part of the 1912 ash-flow sheet into underlying glacial and fluvial deposits and Jurassic siltstone of the Naknek Formation. A 2-km-long trail winds northward from the Overlook Cabin to a footbridge over the Ukak, and an additional 2-km walk upstream along the east bank brings one to Three Forks. Be sure to ask the National Park Service about the status of the footbridge, which spans a dangerous crossing and is sometimes destroyed in periods of heavy runoff.

Deposits present here, 16 km from the Novarupta vent, include (1) the distal tongue of the main ash-flow deposit, here nonwelded, largely rhyolitic, and only 10 to 20 m thick, resting

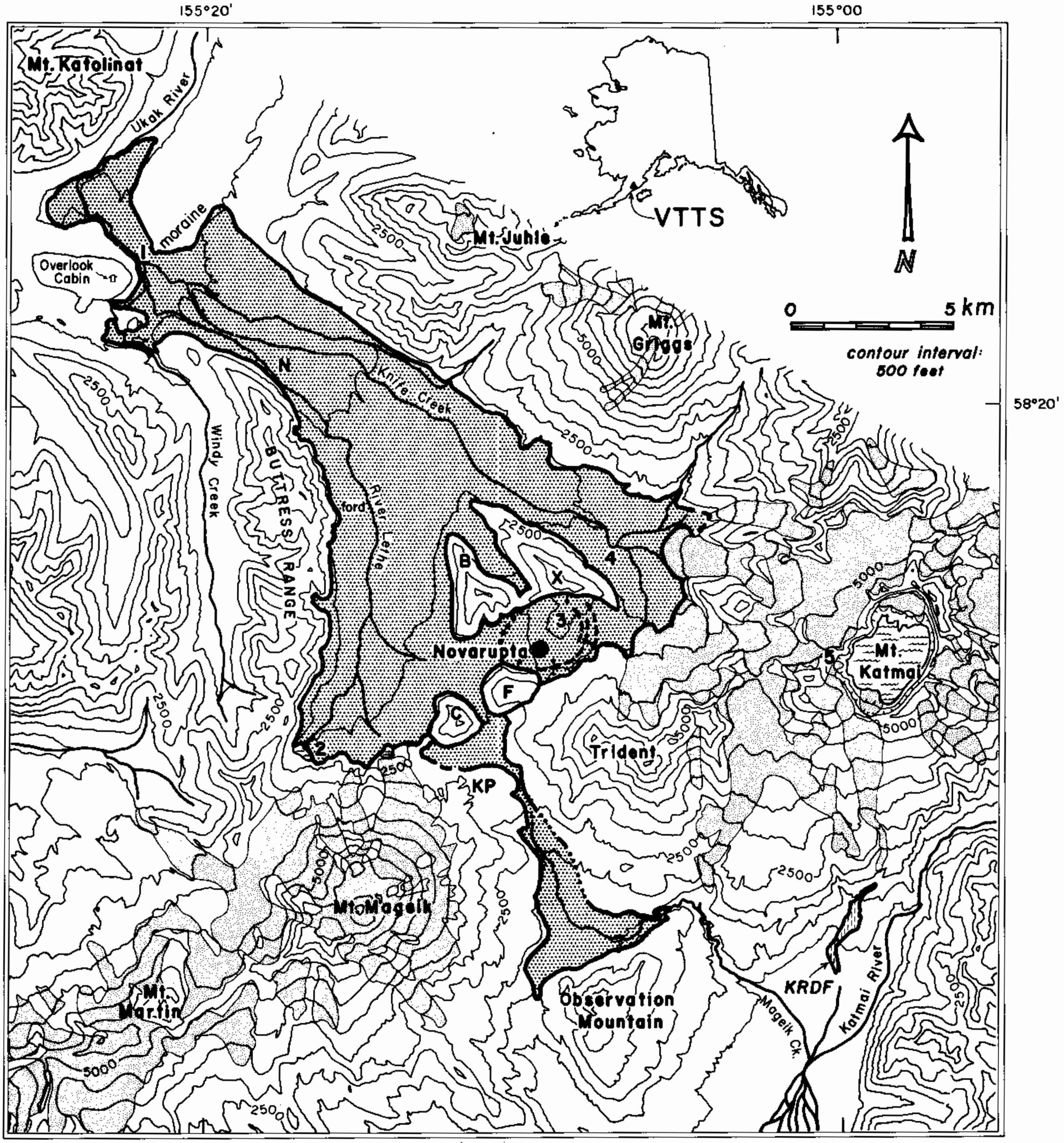

Figure 1. Location map for the Valley of Ten Thousand Smokes (VTTS), Alaska (inset), showing the 120-km^2 extent of the 1912 ash-flow sheet and its source area at Novarupta. One lobe penetrated Katmai Pass (KP) and flowed down the Pacific slope of the volcanic chain. Mts. Griggs, Katmai, Trident, Mageik, and Martin are all andesite-dacite stratovolcanoes, each of which has active fumaroles and has experienced Holocene eruptions. Lighter pattern on stratovolcanoes indicates glaciers. Mt. Cerberus (C) and Falling Mountain (F) are Holocene dacite domes adjacent to the 1912 vent. The Overlook Cabin is the starting point for almost all hikes in the VTTS. Locations 1 through 5 are discussed in the accompanying text. Baked Mountain (B), Broken Mountain (X), the Buttress Range, and most of Mts. Katolinat and Juhle consist of Jurassic sedimentary rocks. The Katmai River debris flow (KRDF) and ash-flow depositional features related to narrowing of the valley near location (N) are discussed in Hildreth (1983). The indicated ford is a rare place where the River Lethe can be waded.

upon charred remnants of willow thickets that grew on the overrun moraine now exposed at creek level; (2) an overlying, dark gray to brown, ash-flow unit, generally only 3 to 5 m thick, consisting of a mixture of andesitic, dacitic, rhyolitic, and banded pumice and occupying a broad shallow swale it scoured into the subjacent flow unit; (3) dacitic airfall strata consisting of four graded couplets of coarse to fine ash, altogether only 40 to 45 cm thick here, but equivalent to the 10-m pumice-fall section (layers C to H of Curtis, 1968) to be visited at Location 4; and (4) a few meters of capping debris-flow deposits, consisting largely of remobilized ash and pumice lumps but also containing blocks of welded tuff from far upvalley and scattered rip-ups of fine-grained airfall strata.

All parts of the ash-flow deposit near Three Forks contain rhyolitic, dacitic, andesitic, and banded pumice lumps in various proportions (Hildreth, 1983). The rhyolite (77% SiO_2) is white and contains only 1–2 wt% phenocrysts, whereas the light-gray dacite (64-66% SiO_2) and black andesite (58–62% SiO_2) both have 30–45 wt% phenocrysts. All 1912 ejecta contain plagioclase, hypersthene, titanomagnetite, ilmenite, apatite, and pyrrhotite; in addition, quartz is present in the rhyolite and augite, and traces of olivine are present in the andesite and dacite.

An ash-flow sheet (ignimbrite) usually consists of multiple flow units, each of which is generally made up of a poorly sorted, unstratified mixture of accidental lithic fragments, juvenile pumice fragments, and crystal-vitric ash produced by explosive and abrasive comminution of the pumice. If a flow travels far enough, however, it commonly develops a measure of crude internal sorting that is best displayed at the base and top of its deposit (Sparks, 1976; Wilson, 1984). Three common manifestations of such sorting can be seen between Three Forks and the footbridge site: (1) fine-grained basal layers, typically 5 to 30 cm thick and gradational into the main deposit, probably produced by grain-dispersive forces that result in the coarser fragments being driven away from the base of each moving flow; (2) density dependent grading of coarse fragments—normal grading for dense lithics but inverse grading for buoyant pumice—sometimes culminating in concentrations of coarse pumice blocks at tops and toes of flow units; (3) a discontinuous ground layer, typically a few centimeters thick, enriched in crystals and lithics but depleted in fine ash relative to the main deposit. Normally in sharp contact beneath the fine-grained basal layer, a ground layer is thought to result from rapid sedimentation from the fluidized head of the moving flow, which may become highly expanded as it ingests air during turbulent encounters with willow thickets, bears, and rough terrain.

In addition to flow units, segregation units a few centimeters to a few meters thick are unusually well developed in the Three Forks area. Defined by alternating enrichments and depletions of pumice lapilli, and ranging from vague grading to abrupt stratification that simulates true flow units, they are thought to result from internal shear promoted by vertical velocity gradients that develop within ash flows as they slow to a halt—rather like a sliding deck of cards. Of the many apparent subunits exposed

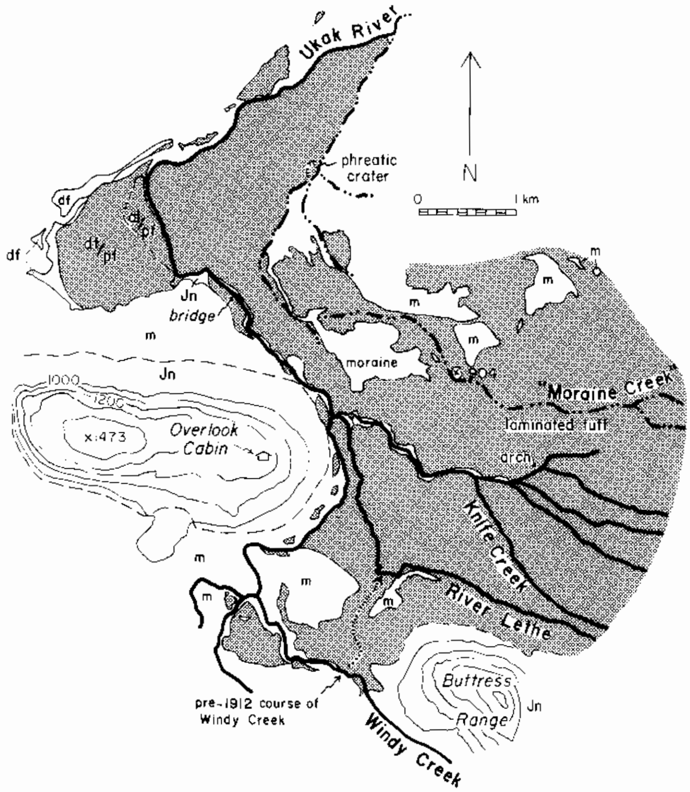

Figure 2. Simplified map of the Three Forks area, Location 1. The pattern indicates areas underlain by the 1912 ash-flow deposit, which is discontinuously mantled by as much as a few meters of alluvial, debris-flow, and airfall deposits. The base of the tuff is generally accessible between the site of the foothridge and the natural arch 4 km up Knife Creek. Check with the National Park Service about the status of the footbridge. Symbols: *al* = alluvium; *df* = debris-flow deposits; *pf* = pyroclastic-flow deposits; *m* = moraine, probably largely Neoglacial in age; *Jn* = Jurassic marine strata of Naknek Formation, largely siltstone. The morainal exposure just south of the sharp bend in the River Lethe includes glaciofluvial beds rich in reworked dacite pumice, probably representing a Holocene eruption of Mt. Mageik.

near Three Forks, only the dark-colored top one and a subjacent light-gray one (prominent along lowermost Knife Creek) independently flowed the length of the VTTS. Most originated within the main rhyolite-rich ash flow not long before it came to rest; a few traveled far enough as coherent pulses, following segregation, that their internal sorting characteristics are as well developed as those of true flow units that originated near the vent. Transition from virtually structureless tuff to extreme laminar segregation can be examined about 2 km east of Three Forks by comparing exposures near the natural arch along a Knife Creek tributary with those in the deep gorge of "Moraine Creek" 700 m northward (Fig. 2).

Surprisingly sluggish emplacement of the 1912 ash flows is indicated by relations between the deposits and the partially engulfed moraine that extends across the VTTS northeast of Three Forks (Fig. 2). In contrast to high-velocity and strongly fluidized

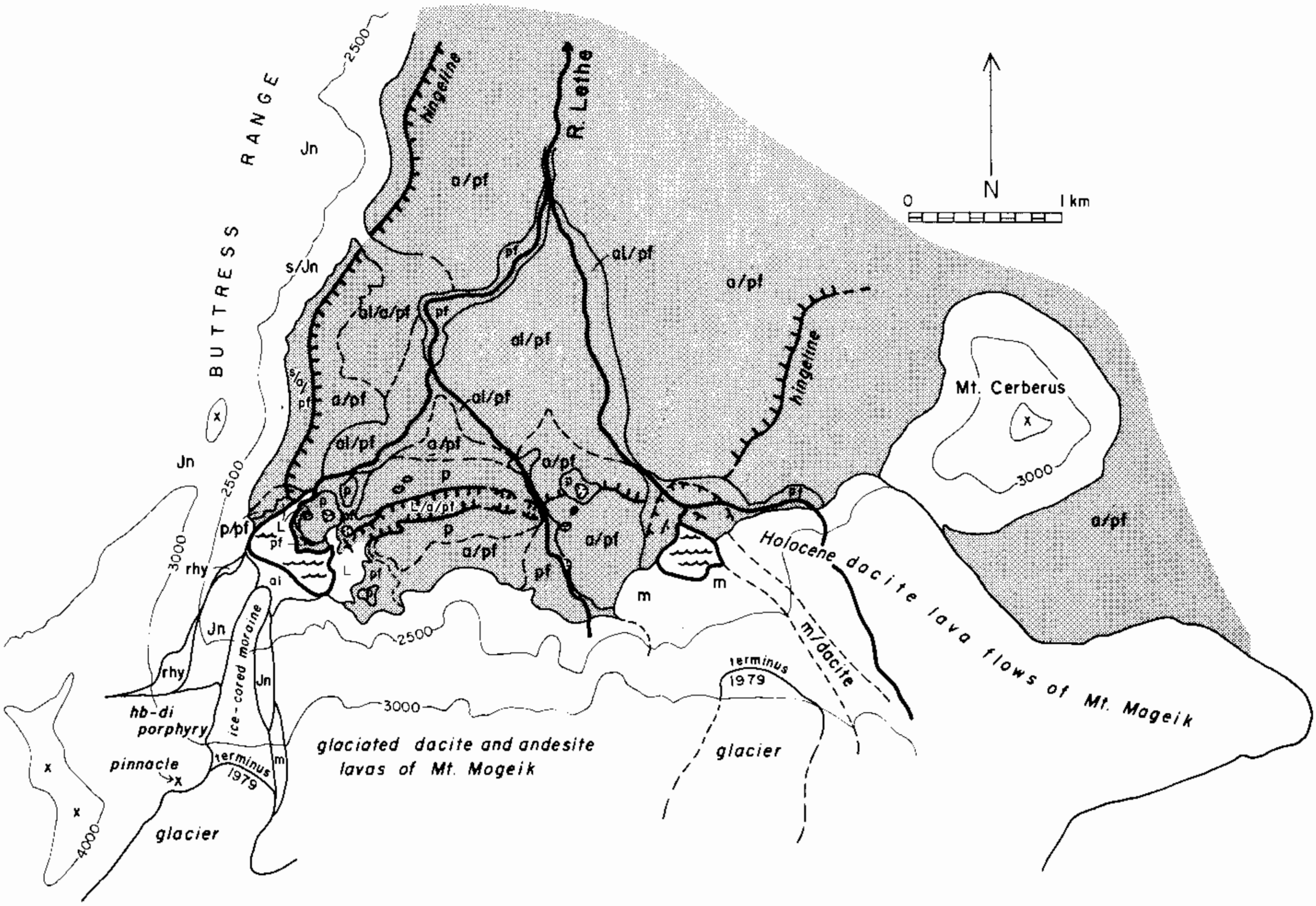

Figure 3. Simplified map of southwestern corner of the VTTS, Location 2. Sites of the two lakes were occupied in 1912 by snouts of glaciers that have since receded. Differential compaction of thick tuff beneath the valley floor produced the marginal bench and its fissured hingeline, which was the locus of many large fumaroles and phreatic explosions. Elongate valley extending northeast from the western lake was excavated along the hingeline by such explosions; called "Fissure Lake" by Griggs (1922), it is now filled with ashy sediments. Dip symbols indicate deformation of the tuff, both hy compaction and by marginal downwarping in former ice-contact areas. Symbols: s = pumiceous scree; a = airfall deposits; rhy = rhyolitic sill; p = phreatic explosion deposits; L = lake deposits; others as in Figure 2. The undated "pinnacle porphyry" is hornblende diorite.

ash flows (Wilson, 1984), the 1912 flows were too slow and deflated to surmount this 30-m-high obstacle perpendicular to its path (Hildreth, 1983). One flow passed through saddles along the moraine crest, and some were diverted around its low western end, but much of the 20 to 30-m-thick tuff simply wedges out against the till. Low velocity, poor fluidization, and deflection around obstacles may have helped promote the internal shear thought responsible for the remarkable degree of laminar segregation in this area.

Additional features to note in the Three Forks area include: (1) upright charred trees enclosed in the tuff along Windy Creek and near the cross-valley moraine; (2) compaction faults in the tuff, typically having approximately 1 m displacement; (3) preferential salmon-pink oxidation of upper and/or coarser grained zones of flow units; (4) multicolored zones of fumarolic alteration controlled by gas-escape pipes, faults, and contraction cracks in indurated tuffs, and wavy irregular conduits in permeable tuff. The ash-flow corridor near the footbridge (Fig. 2) follows a buried pre-1912 channel of the Ukak River; the old course is marked by a compactional swale atop approximately 25 m of infilling tuff that thins drastically toward the present-day riverbed only 300 m westward. A similarly buried pre-1912 course of Windy Creek lies about 3 km southward (Fig. 2).

LOCATION 2. SOUTHWEST CORNER OF THE VTTS

The scenic lake basin at the northwest toe of Mt. Mageik, a full day's walk from the Overlook Cabin, displays striking evidence for welding, alteration, and deformation of the tuff and for violent tuff-water interactions. A trail southeast of the Overlook Cabin descends to a shallow ford on Windy Creek, beyond which the simplest route hugs the eastern base of the Buttress Range all the way to the southwest corner of the VTTS (Figs. 1 and 3).

The bench ringing the Lethe arm of the upper VTTS, called the "high sand mark" by Griggs (1922), resulted neither from the passage of a highly inflated ash flow nor by axial drainaway of a high-riding flow. Rather, it reflects differential compaction and welding of tuff that may be as thick as 200 m along the axis of the buried glacial valley (Curtis, 1968; Hildreth, 1983). Along the hingeline of the beach, the dip of the tuff toward the valley floor steepens abruptly from approximately 5° to 20°, and numerous faults (many of them antithetic) displace both the ash-flow and overlying air-fall deposits. About 500 m north of the lake, the dacite air-fall strata (here about 80 cm thick) are stepped down about 4 m into a 30-m-wide hingeline graben walled by partially welded and fumarolically indurated ash-flow tuff. Offset of even the youngest air-fall strata along the hinge shows that ash-flow compaction lasted for at least a few days, whereas channeling of late flow units along axial swales on the valley floor suggests that it had been underway immediately after emplacement.

The faults focused such vigorous fumarolic discharge along the hingeline that the top few meters of nonwelded deposits are commonly burnt orange and indurated by vapor-phase crystallization; in slightly deeper exposures the tuff is partially welded and commonly brick red. For comparison, fresher exposures of dark-gray welded tuff rich in andesite and dacite pumice can be examined on the valley floor along the nearby gorge of the upper Lethe.

The chaotically disintegrating tuff bluffs just west of the lake provide a rare upvalley exposure (Hildreth, 1983, Fig. 5) down into the rhyolite-rich flow units that underlie the little-incised andesite-dacite welded tuffs sealing much of the upper VTTS.

The lake basin was occupied in 1912 by a glacier, which had melted back sufficiently to produce the single modern lake only by the 1950s. The ash flows banked against the glacier and probably smothered adjacent snowbanks and ice-cored moraine. Evidence for resulting ash-water interactions includes (1) at least six phreatic craters close to the present north shore of the lake; (2) a fringing apron, 1 to 5 m thick, of pumiceous diamicton and cross-bedded ejecta, containing many blocks that had been welded and fumarolically altered prior to ejection, some of which were still hot enough to develop prismatic joints after redeposition; and (3) peripheral fissuring, slumping, and lakeward tilting of the ash-flow sheet, as a result of the melting of subjacent and adjacent snow and ice. When first visited in 1917, an elongate lake had developed between the ice front and the steaming tuff margin (photo in Griggs, 1922, p. 212). The lake also extended 600 m northeast of the present lake, confined along a narrow cleft that had been explosively excavated by a chain of coalescent phreatic craters along the fissured hingeline of the compactional bench. Called "Fissure Lake" by Griggs, this extension ultimately silted up, and today more than 10 m of its ashy lacustrine and alluvial fill have been incised by a stream flowing back into the modern lake.

LOCATION 3. NOVARUPTA CALDERA: THE 1912 VENT

From the last stop, the 8-km trek to Novarupta is most informatively made by staying up on the bench below the cliffy andesite lavas of Mt. Mageik, first to another lake (having a history much like that of the lake just visited) and then along the northern bases of Mt. Cerberus and Falling Mountain, both of which are Holocene domes of pyroxene dacite (Figs. 1 and 4).

The 2-km-wide depression separating Falling and Broken mountains is thought to be a funnel-like vent structure nearly filled with its own fallback ejecta (Hildreth, 1983). The sheared-off face of Falling Mountain is one margin and, although relations are now concealed, the Naknek siltstones of Broken Mountain and andesitic lavas of Trident are also truncated by the steep walls of the vent. Lithic fragments of these lithologies are abundant among the ejecta. The oval vent area is outlined in plan (Fig. 4) by arcuate fractures and compaction-related faults in the deposits; the oval is partly occupied by a 250-m-high mound of coarse ejecta (the "Turtle"), in which the small hollow containing the Novarupta dome is eccentrically nested.

The blocky lava dome is 380 m wide, 65 m high, and consists mostly of glassy, phenocryst-poor rhyolite that was extruded after the main pyroclastic outbursts had ceased. Flow banding is defined largely by variable vesicularity, oxidation, and microlite growth in the rhyolite, but approximately 5% of the bands are dacite and andesite, which both contain conspicuous plagioclase and pyroxenes and crop out most abundantly along the dome's southeast margin.

The "Turtle" is a thick pile of coarse fallout, predominantly dacite pumice but including breadcrusted and vitrophyric blocks of dacite, reejected blocks of agglutinate and welded tuff, basement lithics, and a few layers rich in black andesitic scoria. Rhyolite is rare except as tumbled blocks adjacent to the dome. Whether some of the Turtle's elevation is a result of a buried basement high is unknown but is thought unlikely. Mutually cross-cutting sets of faults on its summit (Fig. 4) suggest the possibility of some distensional uplift by intrusion of a cryptodome. Faulting postdated the final pumice-fall layers and, apparently, formation of the hollow containing Novarupta.

The stratified pyroclastic deposits exposed on the Turtle and in the ejecta ring extending around Novarupta postdate the ash-flow phase of the eruption. Most probably fell on the second and third days when regional fallout continued to rain down on Kodiak, but less dispersed outbursts may have taken place much later. Fine exposures of these proximal andesite-dacite-fall deposits, more than 12 m thick, can be visited in gulches 1 km east and 700 m south of the dome. Along the great cleft just east of Falling

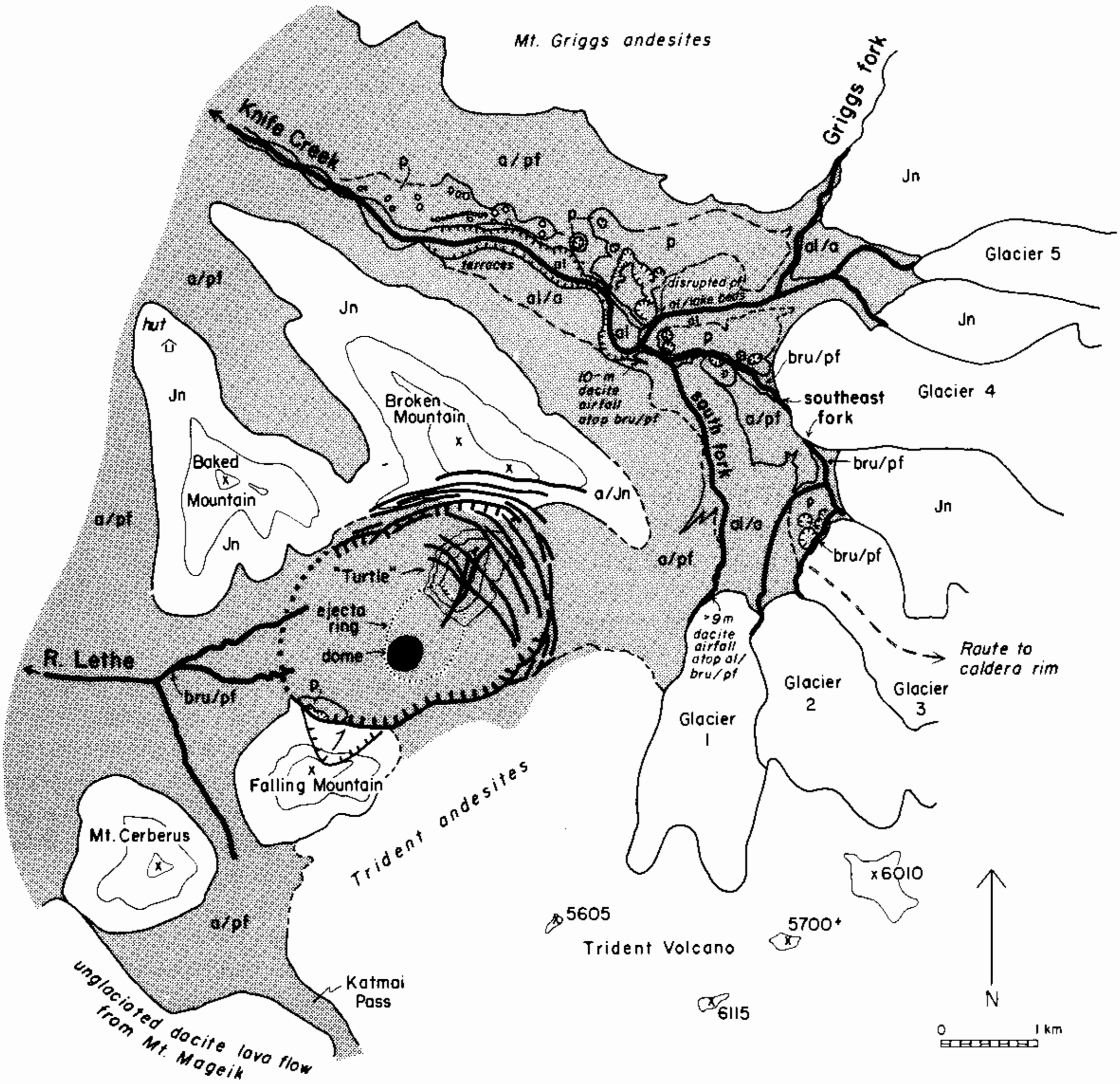

Figure 4. Simplified map of Novarupta caldera and upper Knife Creek, Locations 3 and 4, respectively. The "Turtle" is a 250-m-high hill of coarse 1912 ejecta, discussed in the text. Knife Creek is fed by meltwater from the five Knife Creek Glaciers, and its course across the ash-flow surface is adjoined by numerous phreatic craters and their stratified deposits (p). Block-rich pumice-flow units (bru) overlying the main ash-flow deposit (pf) are discussed in the text. Thick dacite airfall deposits (a) mantle much of the upper VTTS. Other symbols as in Figure 2. Route up Glacier 3 to Location 5 is indicated.

Mountain, inboard-dipping strata drape the sharp rim of the vent funnel.

Along the pair of gullies that converge 2 km west of the dome (Fig. 4) are extensive exposures of two andesite-dacite ash-flow units, each 1 to 3 m thick, intercalated within the 7 to 8 m stack of Plinian dacite fall units. A third local flow unit, extraordinarily rich in dacite pumice blocks, crops out near the confluence of the gullies, only about 1 m above the partially welded surface of the main ash-flow sheet that extends down valley. The three intraplinian ash flows were swale-confined and extended only a few kilometers from source, yet developed pronounced pumice-block concentrations at their upper and marginal surfaces.

Near-vent exposures of deposits representing the earliest phases of the eruptive sequence are sparse, the most accessible being on the three steep southerly spurs of Baked Mountain (Fig. 4) and along the brink of the Falling Mountain scarp. On Baked Mountain, 0.5 to 2 m of tan to light-gray, rhyolite-rich, cross- to plane-bedded surge and fall deposits are variably preserved beneath 1 to 3 m of brick-red to terra cotta cross-bedded surge and flow deposits rich in lithics and in andesite and dacite pumice. These units are interpreted as products of near-vent blasts and as lag veneers left behind by the zoned sequence of ash flows that moved on to fill the VTTS.

The strongly oxidized surge and flow veneers apparently inspired the naming of Baked Mountain, as neither its gray Naknek siltstones nor the widely mantling light-gray dacite fall units are oxidized, except within the vent area and on the valley floor where fumaroles rooted in the ash-flow sheet permeated the overlying air-fall strata for years.

Truncation of Falling Mountain probably took place on the first day (June 6th), just after the dominantly rhyolitic phases of the eruption had ended, as the brow of its inward-facing scarp is mantled only by the rhyolite-poor surge deposits and the later dacite fall units. The base of the scarp is marked by shallow craters ringed by as much as 4 m of surge-bedded phreatic deposits resting atop the dacite airfall; there is also a litter of rockfall debris made up of Falling Mountain dacite (still falling today), some of it in shattered disintegrating piles as high as 12 m. Another interesting aspect of Falling Mountain (and Cerberus) is its chemical and mineralogical similarity (64% SiO_2; plagioclase and two pyroxenes) to the 1912 dacite pumice. Because Falling Mountain dacite erupted at the site of the 1912 vent during Holocene time, either the rhyolitic magma of 1912 evolved within a few thousand years or the rhyolitic reservoir lay elsewhere and was separate from the reservoir yielding the dacite domes.

LOCATION 4. UPPER KNIFE CREEK

From Novarupta, a 3-km eastward hike to the snout of Glacier 1 positions one for a fascinating 4-km walk adjacent to the termini of Glaciers 1, 2, 3, and 4 and on down Knife Creek's southeast fork to the junction with its Griggs fork (Fig. 4). From the junction, plan on a full day's walk back to the Overlook Cabin, either by recrossing the River Lethe and Windy Creek or by following the valley's northeast margin down to the Ukak footbridge. (Be sure to check with the National Park Service about the status of the footbridge before attempting the latter route.)

Where the south fork emerges from its steep slot along the northwest snout of Glacier 1 (Fig. 4), about 9 m of stratified dacite airfall (Curtis' layers C through H) rest upon more than 12 m of pumiceous alluvium that had been immediately reworked by torrential runoff of meltwater from glacial surfaces overridden by the pyroclastic flows. Near the base of the fluvial section here and for 3 km along the southeast fork from Glacier 3 to the junction, are exposures of a partially welded pyroclastic flow, which is 2 to 3 m thick and extremely rich in coarse blocks of dacite pumice. Though intercalated with fluvially reworked ejecta here in proglacial Knife Creek, this late flow unit (*bru* in Fig. 4) is otherwise stratigraphically, compositionally, and lithologically similar to the lowest of the intraplinian units west of Novarupta (see Location 3); it similarly lies only about 1 m above the main welded ash-flow deposit, and was similarly swale-confined, probably owing to differential compaction of the thick subjacent welded tuff filling a pre-1912 ice-marginal stream channel. Lateral pinch-outs of the block-rich unit are exposed in cross section 150 m below Glacier 4 on the southeast fork and 100 m above the junction on the Griggs fork.

Only the top few meters of the ash-flow deposits have yet been incised in the upper Knife Creek area. Best exposed along the margins of Glaciers 3 and 4 and near the confluence of the south and southeast forks, the tuff is dark gray, partially welded, rich in both andesite and dacite pumice, shows widespread fumarolic alteration, and forms the fluted walls of shallow but treacherous stream gorges. Glaciers 4 and 5 have each advanced several hundred meters since first photographed in 1917, and Glacier 3 (although partly beheaded by the caldera collapse atop Mt. Katmai) has also advanced slightly. As a result, active glacial ice overlies the welded tuff at stream level along the snouts of both Glaciers 3 and 4.

Phreatic craters ringed by aprons of cross-bedded ejecta 1 to 15 m thick are abundant along the southeast fork and along Knife Creek for another 5 km below the junction (Fig. 4). Deposits contain blocks of welded tuff as large as 2 m, some more densely welded than any tuff yet exposed in place. All the craters cut the dacite air-fall layers and spread their ejecta blankets on top of them, indicating that phreatic explosions from within the ash-flow sheet were delayed for at least the two additional days (7–8 June) during which the dacite pumice falls accumulated. Time may have been required for compaction and welding to reduce permeability, enhancing confinement, and to generate fractures providing access for water to the hot interior of the tuff.

The thickest phreatic deposits dip radially away from the lower Griggs fork just above its junction with the southeast fork, an area marked by a cluster of about 20 craters and by chaotic disruption of the welded-tuff sheet. It is thought that all this debris temporarily dammed the Griggs fork, impounding a 1.5-km-long lake in which more than 10 m of mudflow, lacustrine, and fluvial deposits accumulated prior to breaching. Catastrophic breakout (probably in the summer of 1912) was apparently responsible for the debris-flow deposit that mantles much of the lower VTTS (Hildreth, 1983). The flood scoured part of the central VTTS, transported coarse lithics, dacite pumice, and welded-tuff blocks all the way to the lower VTTS and actually outdistanced the ash-flow sheet, dumping debris as thick as 8 m atop its northwest terminus and running on out into the woods where it engulfed upright uncharred trees.

Remnants of the lake deposits not swept away form the lower bluffs along the Griggs fork, whereas the higher bluffs and hills are mostly phreatic deposits atop the air-fall strata. A gulch 200 m south of the junction provides splendid exposures of a 10-m-thick section of dacite fall units C through H, resting atop pumiceous alluvium and the block-rich pyroclastic-flow unit. The same set of air-fall strata was 45 cm thick at Three Forks (Location 1) and 80 cm thick near the western Mageik lake (Location 2).

LOCATION 5. MT. KATMAI CALDERA RIM

From upper Knife Creek, the west notch on the caldera rim of Mt. Katmai can be reached by a roped hike up Glacier 3 (Figs. 1 and 4). The 3–5 hour ascent should not be undertaken lightly, as the weather is treacherous, progress tedious on hummocky ash-covered ice, and the kettles, crevasses, and englacial rivulets hazardous. If you have little climbing experience, charter a scenic flight at Brooks Camp; you're likely to see more from the air, anyway.

Exposed parts of the unstable caldera wall appear to be entirely andesite and dacite, but Naknek siltstone, which crops out as high as the 4,500 ft contour on the cleaver between Glaciers 3 and 4, could conceivably intersect the wall near or beneath lake level. The stratified (and glacially striated) pyroclastic unit forming much of the surface along the west rim is poorly sorted andesite-dacite airfall that ranges from loose scoria to eutaxitic agglutinate. As far as the tooth near the south notch, the southwest wall also appears to be rimmed by pre-1912 agglutinates. The 1912 fallout has largely been blown away or reworked into ashy periglacial diamicton, but pumice lapilli remaining on the caldera rim seem to be entirely ordinary 1912 ejecta from Novarupta. Apart from the small dacite lava on the caldera floor that briefly formed the "horseshoe island" (Griggs, 1922), there is no good evidence that any 1912 eruptive products vented at Mt. Katmai.

Intracaldera glaciers have gradually accumulated atop slump-block benches on the north and south walls, and another ice tongue now flows back into the caldera from the southwest-rim icefield. Calving of icebergs supplements the ample precipitation in sustaining the caldera lake, which is now more than 250 m deep and still adding a meter or two each year. On the lake's blue-green surface, patches of yellow sulfurous froth and sporadic bubbling attest to sublacustrine fumaroles, as does the persistent odor of H_2S. R. J. Motyka measured summer water temperatures of 5°-6°C and pH values of 2.5–3. The lake surface has frozen during some recent winters, at least intermittently.

THE TEN THOUSAND SMOKES

Most fumaroles in the ash-flow sheet had died out by 1930, and those remaining today are odorless wisps of water vapor that issue along faults in the vent region, notably atop the Turtle. Seven years after the eruption, some fumarolic orifice temperatures were still as hot as 645 °C, but recent measurements by T.E.C. Keith indicate none hotter than 90 °C.

Soluble high-temperature fumarolic chlorides, fluorides, and sulfates (Zies, 1929) have been extensively leached, and the vapor-deposited oxide and sulfide minerals generally retrograded as discharge temperature declined. Around Novarupta, low-temperature hydrothermal alteration of the glassy ejecta to clays is actively overprinting the vapor-phase alteration; Keith's work there indicates abundant silica, kaolinite, amorphous clay precursors, and minor smectite, the resulting warm goo being thoroughly mixed with colorful goethite and amorphous iron-hydroxides and locally with gray, amorphous iron sulfides.

Despite retrogression and leaching, many fumarolic deposits retain spectacular zoning in color, mineralogy, and composition. Irregular, pipelike, and funnel-shaped fossil fumaroles are readily accessible in nonwelded tuff near Three Forks and along the lower gorge of the River Lethe, whereas the best exposed fissure fumaroles (controlled by cooling joints in welded tuff) are along the upper River Lethe opposite Baked Mountain. Red coloration of crusts and altered ejecta is caused by hematite or by goethite and amorphous iron hydroxides, which can also yield oranges and yellows—as can sulfur and arsenic sulfides. Black fumarolic coatings are mostly vapor-phase magnetite; white material is predominantly silica and aluminum fluoride hydroxyhydrate, but includes fluorite, kaolinite, alunite, and gypsum.

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