ON BATHOLITHS AND VOLCANOES

Intrusion and eruption of Late Cenozoic magmas in the Glacier Peak Area, North Cascades, Washington

GEOLOGICAL SURVEY PROFESSIONAL PAPER 604

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THE GLACIER PEAK AREA
NORTH CASCADES

Glacier Peak from northeast. Chocolate Glacier, far left; Dusty Glacier, middle left; Vista Glacier, right; and Ptarmigan Glacier, far right. Mount Rainier on left horizon. The gullied slopes of the foreground are underlain by pumice. Photograph by Austin Post.

On Batholiths and Volcanoes—Intrusion and Eruption of Late Cenozoic Magmas in the Glacier Peak Area North Cascades, Washington

By R. W. TABOR *and* D. F. CROWDER

GEOLOGICAL SURVEY PROFESSIONAL PAPER 604

Description of the Cloudy Pass batholith, the overlying Gamma Ridge volcanic rocks, and the still younger Glacier Peak volcano with discussion of the source magmas, their genetic ties, and the structures controlling their emplacement and eruption

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ON BATHOLITHS AND VOLCANOES—INTRUSION AND ERUPTION OF LATE CENOZOIC MAGMAS IN THE GLACIER PEAK AREA, NORTH CASCADES, WASHINGTON

By R. W. Tabor and D. F. Crowder

ABSTRACT

In the Glacier Peak area, the three principal episodes of Cenozoic igneous activity have been the intrusion of the tonalite-granodiorite Cloudy Pass batholith in early Miocene time, as shown by potassium-argon radiometric dates of 22 m.y. (million years); the extrusion on and near the exposed batholith of a thick pile of predominantly andesitic to dacitic breccia, tuff, and lava of Gamma Ridge between early Miocene and Pleistocene time; and, in late Pleistocene and Recent time, the growth of the dacitic Glacier Peak volcano, which was accompanied by eruption of small amounts of basalt from separate vents near Glacier Peak.

Much of the Cloudy Pass batholith in the Glacier Peak area lies under a relatively thin roof of regionally metamorphosed rocks, as shown by a retinue of stocks in a zone trending southwest away from the main pluton and by thermal metamorphism and concentrations of alaskite dikes in the roofrocks over this zone. Some of the alaskite dikes are related to earlier regional metamorphism, but many appear to be differentiates of the batholith squeezed out of an adamellite cap—exposed along the northwest margin of the pluton and in small patches farther east—by renewed intrusion of the tonalite-granodiorite core. Hornblende tonalite porphyry dikes and inclusions confined to the adamellite border are probably injections from the core which were partly disrupted by renewed intrusion. The textures of the adamellite and its chemical similarity to the experimentally determined minimum-melting composition of granite indicate that the cap is a normal crystallization differentiate enriched in felsic constituents by settling out of early formed mafic crystals.

Intrusive breccias with aphanitic and protoclastic matrices occur along steep contacts of the main pluton and of a satellitic stock and in small bodies nearby. These breccias resemble many described by F. W. Cater along Phelps Ridge in the Holden quadrangle. Clearly intruded under low lithostatic pressure, the breccias and aphanites may have been vents for errupting gas-charged magma from the core of the batholith.

By the time the coarse volcanic breccias, tuffs, lithic wacke, volcanic wackes, and minor lavas of Gamma Ridge erupted, the Cloudy Pass batholith had cooled at the level now exposed and had been partly deroofed by erosion. Welded tuff in the Gamma Ridge rocks and the considerable local relief under them indicate subaerial eruption in mountains. Basal interbedded volcanic and monolithologic breccias are similar to some of the nearby intrusive breccias that cluster around the Cloudy Pass batholith, and this similarity suggests that the Gamma Ridge rocks erupted from the batholith's still-molten core. However, present drainage patterns appear to have been set by diversion around the Gamma Ridge volcanic center, which suggests the rocks may be latest Pliocene or even earliest Pleistocene in age. If the magma of the batholith's core were the source, it would have had to remain molten an inordinantly long time.

The oldest Glacier Peak lavas pooled in valleys on the east side of Lime Ridge, a northwest-trending spur of the Cascade Crest, and now crop out as elongate, locally very thick, ridge caps, owing to inversion of topography by the subsequent erosion. Later flows cling to the sides of present valleys and are moderately dissected; the youngest flows bottom the present valleys and are little dissected. This spectrum of greatly dissected older flows to little dissected younger flows indicates continual uplift and erosion during growth of the volcano. The ridge-capping flows radiate from the present summit area of the volcano and extend nearly to the Suiattle River, which shows that the river was forced into its wide northeast loop around the Gamma Ridge eruptive rocks prior to earliest Glacier Peak time. As Glacier Peak grew by continued eruption of clinopyroxene-hypersthene dacite, the lavas eventually spilled over Lime Ridge into the White Chuck valley.

Late in the life of the volcano, an oxyhornblende-hypersthene dacite dome was extruded near the summit at Disappointment Peak. A second hornblende dacite dome is presumed to have grown and collapsed on the east side of the peak to furnish debris for a giant fan and valley fill in the just deglaciated Suiattle valley. Chocolate Creek was diverted from ancestral Dusty Creek and forced to spill over a confining lava ridge by the growth of the fill. The Suiattle River was dammed and forced farther east.

All the flows of Glacier Peak were erupted within the past 700,000 years, as shown by their normal magnetic polarity, and the latest flows, within the past 17,000 years, after alpine glaciers had retreated. About 12,000 years ago (as shown by a carbon-14 date and correlations of R. Fryxell and other workers for areas far from the Glacier Peak area) pumice was expelled and drifted far, especially to the east. During or soon after this erruption, mudflows and streams on the west side of the peak partly filled the recently deglaciated White Chuck valley with pumice lapilli and other volcanic detritus from the volcano, which formed the White Chuck fill. A nuée ardente rushed valleyward to form a thin cap of vitric tuff on this fill and was later covered by pumice that continued to wash off the mountain. Three hot springs—Kennedy, Sulphur, and Gamma—are the only evidence that hot rocks, perhaps even magma, still exist at depth.

There is some indication that the differentiation index increases in the younger eruptive rocks of Glacier Peak, but the dacite lavas making up the bulk of the volcano are remark-

ably uniform in composition, varying a maximum of only 8.0 percent in silica (as shown by refractive index measurements on fused glass beads) over a period of at least 10,000 years and probably more on the order of 500,000 years.

Basalt is not interlayered with the dacite flows, but late in Glacier Peak time basaltic andesite was extruded near Lightning Creek and basalt was erupted from cinder cones at Indian Pass and the upper White Chuck River. The absence of basalts or intermediate rocks in the dacite cone suggests separate sources for the dacites and basalts.

The intrusion of the batholith appears to have been guided by: (1) Northwest-trending regional foliation, compositional layering in the schist and gneiss host rocks, and (2) northeast-trending joints perpendicular to the regional trends and fold axes (*ac* joints). All the Cenozoic magmas in the Glacier Park area have risen along the intersection of several regional structures: (1) The northwest-trending normal faults of the Chiwaukum graben, (2) a related(?) northwest-trending belt of small pods of sepentinized ultramafic rocks, and (3) a deep fracture(?) that trends north-northeast and underlies a zone of dikes and eruptive rocks. This deep fracture(?) passes under the volcano and, on projection, intersects other Tertiary batholiths and Quaternary eruptive centers (for example, the Snoqualmie batholith and Mount Rainier volcano). It may have led basaltic magma to the surface from the mantle and may have helped localize the emplacement of the more silicic magmas of Cloudy Pass, Gamma Ridge, and Glacier Peak.

INTRODUCTION

PROBLEM

In early Miocene time, the Cloudy Pass batholith intruded the metamorphic rocks of the North Cascades between Glacier Peak and Lake Chelan. Intrusive breccias and hypabyssal phases suggest that the magma came close to the surface and probably erupted. After the cooling of at least the upper part of the pluton, it was exposed by erosion, and volcanic and volcaniclastic rocks were deposited on or near it. In Pleistocene time, a dacitic volcano, Glacier Peak (fig. 1), began to form; its last eruption was about 12,000 years ago. During this last phase of activity of the volcano, basaltic cinder cones grew nearby.

We earlier suggested (in Hopson and others, 1966) that the proximity of the batholith to most of the volcanic rocks and their chemical similarity indicate a genetic relationship. Batholithic magmas which erupted are no strangers to the Cascades of Washington. Fuller (1925) described the explosive deroofing of the Snoqualmie batholith to form flows and volcaniclastic rocks of late Miocene and early Pliocene age. Details of the eruptive history of the Miocene Tatoosh pluton in the Mount Rainier area were aptly given by Fiske, Hopson, and Waters (1963, p. 52–63), who postulated a possible genetic tie between the batholith and the volcano of Mount Rainier (p. 91). Cater (1960; 1969,) described a link between the Cloudy Pass batholith and volcanism in the Holden quadrangle. This paper

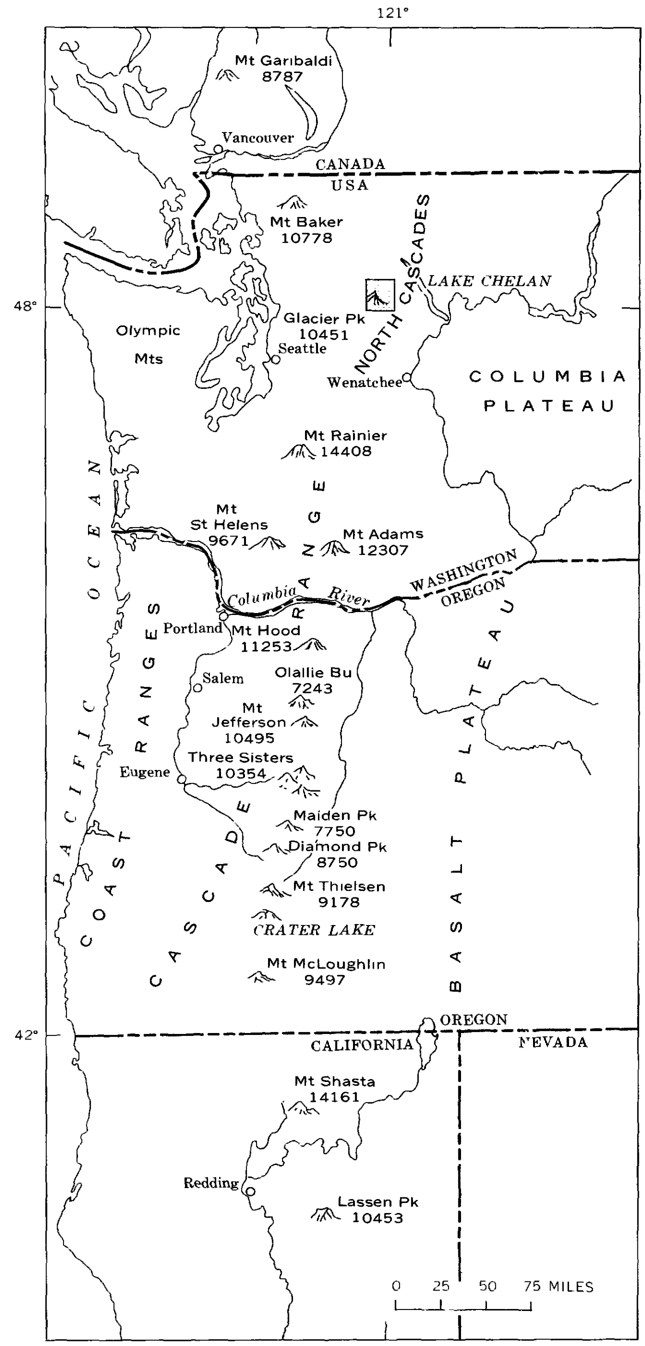


FIGURE 1.—Quaternary volcanoes of the Cascade Range and area of figure 2. Adapted from Williams (1944, fig. 1).

describes the batholith and the volcanic rocks that occur in the adjoining Glacier Peak quadrangle and examines the evidence for kinship of these rocks. The volcanic rocks of the early episode of volcanism on Gamma Ridge may well be derived from the batholith. Such an origin for the later lavas of Glacier Peak is unlikely, although there may well be a genetic relationship in ultimate source or process.

ACKNOWLEDGMENTS

We owe much to fellow students of North Cascade geology for both fundamental work and valuable discussion, in particular to Fred Cater, Cliff Hopson, Art Ford, Bob Grant, and Ray Wilcox. Others who have given pertinent advice and opinions are Paul Bateman, Dave Hopkins, Jack Lockwood, George Walker, Don Swanson, Don Tatlock, and Ron Kistler. We especially thank Art Ford, who loaned us his specimens of Glacier Peak lavas, and George Tilton, who furnished unpublished data on lead isotopes.

CLOUDY PASS BATHOLITH AND ASSOCIATED ROCKS

GEOLOGIC SETTING AND AGE OF INTRUSION AT THE LEVEL EXPOSED

The Cloudy Pass batholith and its associated rocks were first mentioned in the geologic literature by Youngberg and Wilson (1952, p. 5). The extent and nature of the batholith has been established by subsequent studies of the U.S. Geological Survey and of students from the University of Washington working under the supervision of Peter Misch (fig. 2). A description of the batholith and its structural setting has been published by Grant (1969). Of timely interest is Grant's discussion of transverse structural belts controlling ore deposition.

The metamorphic and granitoid rocks intruded by the batholith strike northwestward, forming the core of the North Cascades. They consist of steeply dipping biotite and hornblende gneisses and schists, granitoid gneissic plutons, minor quartzite, and scattered thin lenses of marble (Crowder and others, 1966; Cater and Crowder, 1967). The age of deposition of the metasedimentary rocks is unknown but has been estimated to be pre-Ordovician (Waters, 1932, p. 608) to pre-Late Jurassic (Misch, 1966, p. 113).

Unconformably overlying the metamorphic country rocks is the Upper Cretaceous and Paleocene Swauk Formation. These sedimentary strata do not lie on the Cloudy Pass batholith itself, but faults that have downdropped the Swauk in the Chiwaukum graben are cut off by the pluton (Cater and Crowder, 1967, and fig. 61). Radiometric age determinations (table 1) show that the pluton now exposed was intruded about 22 m.y. (million years) ago, in the early Miocene Epoch.

Most of the intrusive rocks of volcanic aspect (that is, aphanitic and porphyritic-aphanitic rocks) associated with the Cloudy Pass batholith are exposed in the Holden quadrangle and have been described by Cater (1969). These rocks occur in a border zone on the east side of the batholith (the complex of Hart Lake) and

TABLE 1.—*Potassium-argon and lead-alpha radiometric age determinations of the Cloudy Pass batholith and its thermally metamorphosed host rock*

[Analysts: Biotite, Harold Thomas, Richard Marvin, and John Obradovich; zircon, T. W. Stern]

Biotite [1]

Sample	K_2O (percent)	Ar^{40} (ppm)	Radiogenic Ar^{40} (percent)	Age (m.y.) [2]
DFC-1e-60	8.14	0.0107		22.1±2.2
180-61	8.50	.0114	75.8	22.5±0.0
179-61	8.82	.0107	69.0	20.4±2.0

Zircon [3]

Sample	Size fraction	Milligram hour	Pb (ppm)	Age (m.y.) [2]
DFC-1e-60	−80 +150	192	1.9	20±20
1e-60	−150	367	3.8	30±20
180-61	−115+200	111	1.4	30±20

[1] Constants used: $\lambda_\epsilon=0.585\times10^{-10}$ yr^{-1}; $\lambda_\beta=4.72\times10^{-10}$ yr^{-1}; $K^{40}/K_{rT}=1.216\times10^{-4}$ g/g.
[2] These ages are slightly different than those previously published, owing to revision of constants.
[3] Constants used: U:Th=1; C=2485; $K=1.56\times10^{-4}$.

Sample locations:
- DFC-1e-60: Granogabbro from talus below bench mark 5248 on Railroad Creek trail near Crown Point Falls, Holden quadrangle.
- 180-61: Granogabbro from just north of Railroad Creek trail 0.25 mile northeast of bench mark 3989, near Hart Lake, Holden quadrangle.
- 179-61: From thermally metamorphosed Swakane biotite gneiss, altitude 6500 feet on stream 0.5 mile north of Plummer Mountain, Holden quadrangle.

in porphyry plugs and intrusive breccias that pierce the batholith and its roof. In the Glacier Peak area there are a few intrusive breccias, but the principal batholithic rocks occur in the main pluton and in a host of granitoid stocks which we contend are cupolas.

In this report, the contiguously exposed part of the batholith is referred to as the Cloudy Pass pluton, and the term "batholith" is used for the entire assemblage of granitoid rocks, that is, for the pluton and stocks as well as their subsurface connections.

STRUCTURE AND CONTACT RELATIONS

GENERAL FEATURES

In the Glacier Peak quadrangle, the Cloudy Pass pluton is clearly discordant (pl. 1). The contacts, though poorly exposed, appear abrupt and are steep except in local places north of the mouth of Canyon Creek.

The likely relatives of the main pluton south and west of Glacier Peak show both a southwesterly and a northwesterly alinement. The northwesterly elongation of the Sitkum stock and the presence of the White Chuck stock along its southeast projection indicate that emplacement was locally controlled by the layering and foliation of the host rocks. The Milk Creek stock, Sitkum stock, and small bodies and dikes in the Lost Creek area form a belt trending northeastward toward the west border of the exposed batholith, approximately at right angles to the regional foliation. The Cool stock and several dikes as much as 50 feet thick that crop out on Sulphur Mountain and White Mountain are probably offshoots of the Cloudy Pass

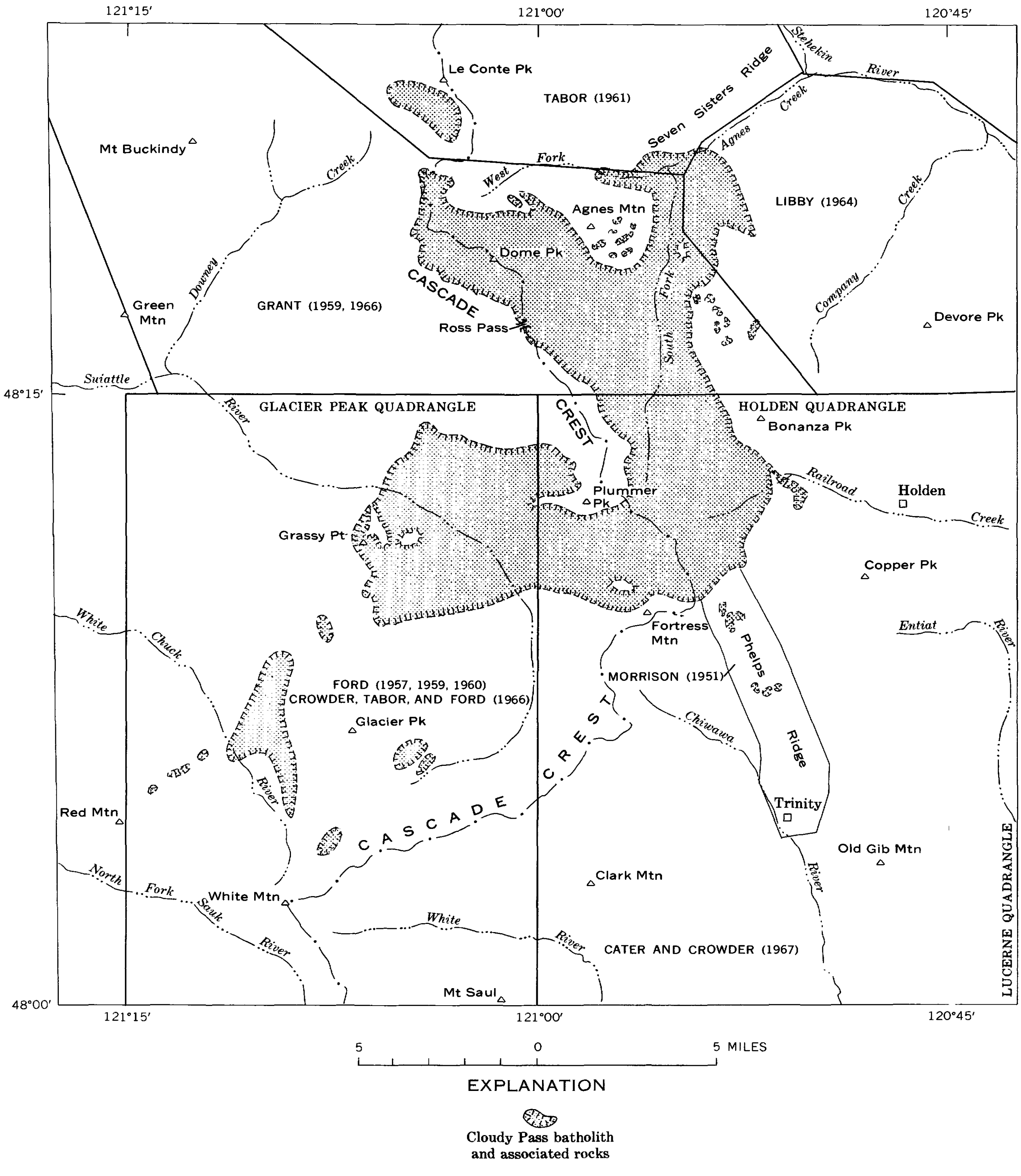


FIGURE 2.—Cloudy Pass batholith and associated rocks as determined by workers shown.

pluton, but they are not confined to this northeasterly belt and appear to be independent of the northwesterly structural grain.

These isolated stocks, dikes, and small bodies, which crop out to the southwest of the main Cloudy Pass pluton, are lithologically and chemically similar to it. The distribution of contact metamorphism and alaskite dikes related to the batholith, as discussed below, suggests that the batholith connects with them below the surface. Furthermore, lead-isotope ratios of the main Cloudy Pass pluton and the largest of these satellitic bodies, the Sitkum stock, are essentially identical (table 6) and are uniquely different from lead-isotope ratios of other Tertiary plutons in the northwest (compare table 6 with Davis and others, 1966, table 13, p. 172).

Most of the observed contacts of the stocks are steep, although we infer from limited exposures on Milk Creek that the Milk Creek stock may be the flattop of the batholith (section *B–B′*, pl. 1). The parts of the Cloudy Pass batholith now exposed in the Holden quadrangle (fig. 2) are near its top, judging from the presence of the flat roof around Plummer Mountain. A zone of satellitic (Cater, 1969, p. 50) instrusive breccias and porphyry plugs extending down Phelps Ridge suggests a south-plunging nose which parallels regional foliation. This zone lies within the Chiwaukum graben, which extends southeast from the pluton (figs. 2 and 4). The presence of a flat roof has been established by Grant (1966, p. 208) north of the Glacier Peak area, where the pluton floors the valley of the South Fork of Agnes Creek and plunges beneath the schists and gneisses of Seven Sisters Ridge (fig. 2). Indeed, because the schist and gneiss northwest of Seven Sisters Ridge are thermally metamorphosed and hydrothermally altered, Tabor (1961, p. 180) suggested that the very large dike of similar age at Cascade Pass, for which Misch (1966, p. 141) reported a potassium-argon biotite age of 20 m.y. (Tabor, 1963, and fig. 60), is an offshoot of the Cloudy Pass batholith.

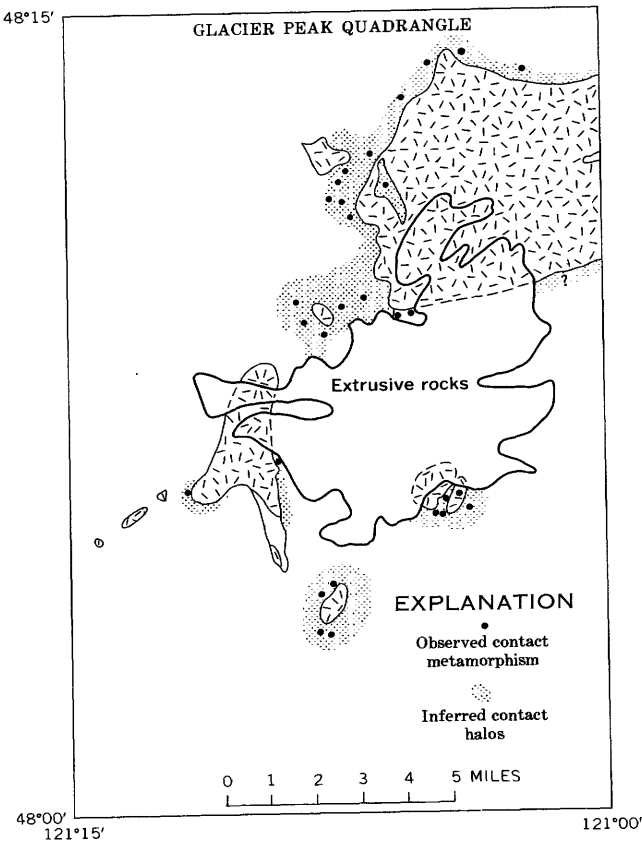


Figure 3.—Distribution of thermal metamorphism around the Cloudy Pass pluton and nearby stocks.

CONTACT METAMORPHISM

Thermal metamorphic effects are variable adjacent to the pluton and stocks (fig. 3). Within the aureole, textures indicative of thermal metamorphism are recognized in the tonalite-gneiss, biotite-quartz-oligoclase schist, hornblende schist, and granitoid alaskite dikes that cut the schists and gneisses. In the medium-grained gneisses, these textures are much harder to recognize than in finer grained schists. On Grassy Point the grain size of granitoid tonalite-gneiss near the pluton has been reduced by cataclasis, and the gneiss is locally recrystallized and contains aggregates of biotite and hornblende in place of original single crystals. In this area the granitoid gneiss is also altered (chlorite and saussurite), and in one specimen, untwinned potassium feldspar replaces and cements the fragments. This potassium feldspar may have emanated from the batholith or may have formed during contact metamorphism by the redistribution and annealing of the microcline locally prominent in the granitoid gneiss. On the north side of the Canyon Creek and within 1,500 feet of the contact, this granitoid gneiss has lost its pronounced foliation and is mottled by patches and veins of recrystallized hornblende. Near the steep contacts of the White Chuck stock, the light purple hornfels schist of the aureole contains clinopyroxene or andalusite; one specimen of hornfels schist bears the unusual association of cordierite and spinel. Near the contact of the Cool stock, the enveloping tonalite-gneisses are highly hornfelsed. Contact metamorphism of the biotite gneiss adjacent to the small bodies in the Lost Creek area disappears within a few tens of feet from the contacts. The extensive brecciation and oxidation prominent nearby may be related to the underlying intrusive rocks that probably connect these small bodies. In the upper reaches of Milk and Pumice Creeks, the schists and gneisses in places contain small aggregates or poikiloblasts of biotite, which strongly suggest contact metamorphism; the wide extent of the aureole recognized in these areas suggests that the batholith lies close below. In the Dome Peak area, contact metamorphism of even greater intensity is common adjacent to the batholith (Grant, 1966, p. 235–246), and incipient hornfels extends to 4 miles west of the pluton.

LITHOLOGY

GENERAL FEATURES

The rocks comprising the Cloudy Pass pluton and associated stocks in the Glacier Peak quadrangle have been previously described by Ford (1959, p. 182–236, 242–244, 247–249; 1960) and those in the Holden quadrangle, by Cater (1969). Grant (1966, p. 207–235) has described the batholith exposed to the north. The summary given here stresses new data and interpretations from our additional work in the Glacier Peak quadrangle.

We distinguished and mapped two phases of the main pluton and of the Sitkum stock—a light-colored, predominantly adamellite phase and a dark-colored phase ranging from granodiorite to gabbro. Corresponding to our light-colored phase are the "leucocratic facies" of Cater (1969, p. 17), the "deuterically altered phase" of Grant (1966, p. 219), and the "rocks of granodioritic, quartz monzonitic and granitic composition" of Ford (1959, p. 104). Corresponding to our dark-colored phase are the "labradorite granodiorite" of Cater (1969), the "main intrusive phase" (quartz diorite) of Grant (1966, p. 314), and the "Miners Ridge quartz diorite" of Ford (1959, p. 182).

The light-colored phase is confined to the northwestern border zone of the pluton and to the north end of the Sitkum stock, but the subsurface part of the batholith, which is thought to connect the stock with the main pluton, would presumably also be of this rock type. The one examined specimen of the Milk Creek stock, a body lying between the main pluton and the Sitkum stock, is mineralogically of the dark-colored phase (compare fig. 4*C* with fig. 4*A*); texturally, however, it is much like light-colored phases of the Sitkum stock, and it has the lowest color index of all the phases mapped as dark colored (fig. 4*D*).

In the Holden quadrangle, the light-colored rocks occur as small irregular patches scattered in the dark-colored phase near the roof of the batholith and on ridges (Cater and Crowder, 1967; Cater, 1969, p. 17; Grant, 1966, p. 221). In the Dome Peak area, they are sporadically distributed along the margin of the dark-colored batholith (Grant, 1966, p. 218).

DARK-COLORED PHASE

Rocks in the dark-colored phase are medium grained and hypidiomorphic granular granodiorite, tonalite, quartz gabbro, and gabbro (table 2, fig. 4). Large plagioclase crystals are euhedrally and oscillatorily zoned from cores of andesine or labradorite to narrow, commonly anhedral rims of oligoclase (average range about An_{50} to An_{22}). Cores of plagioclase in the White Chuck stock are as calcic as An_{78}. We estimate the average composition of plagioclase to be andesine. In the Holden quadrangle, however, Cater (1969, p. 19) considered that the average plagioclase composition of what he called the normal phase (our dark-colored phase or core phase, was labradorite; thus, he called the rock a labradorite granodiorite (granogabbro). Anhedral intergranular quartz forms a continuous network between plagioclase and mafic minerals; in places this network is an optically continuous single large crystal. Potassium feldspar is entirely intergranular.

In the Glacier Peak quadrangle, we found hypersthene and clinopyroxene in only the small intrusions—in the White Chuck and Cool stocks and in dark-colored rocks of the Sitkum stock, where they occur primarily as small resorbed inclusions in plagioclase or as relicts in uralite. Ford (1959, p. 210) found pyroxene near the contacts of the main pluton northeast of Image Lake and north of Dusty Creek, and Libby (1964, p. 122) found hypersthene to be a "typical constituent" near the pluton margin north of the Holden quadrangle. In the Holden quadrangle, hypersthene and augite are most abundant near the eastern margin of the batholith (Cater, 1969, written commun.). The pyroxene is thus preserved in border rocks or small stocks which may have undergone rapid cooling before hydrous minerals of Bowen's reaction series could form.

TABLE 2.—*Average modal composition of Cloudy Pass batholith and associated rocks*

[Volume percentages determined on thin sections stained for potassium feldspar by using the method of Chayes (1966). Five hundred points per section; numbers in parentheses indicate range. For additional modes see Ford (1959, p. 186–187, 243, 248)]

	Cloudy Pass batholith, dark-colored phases [1]	Sitkum and White Chuck stocks and Lost Creek bodies,[2] dark-colored phases [3]	All plutons, light-colored phases [4]
Quartz	28 (24–33)	16 (11–26)	28 (14–41)
Plagioclase	48 (44–52)	57 (52–61)	40 (32–51)
Potassium feldspar	13 (11–18)	6 (0–8)	23 (13–28)
Hornblende	3 (<1–6)	6 (1–15)	1½ (0–4)
Biotite	7 (4–8)	9 (7–11)	4 (0–9)
Clinopyroxene	0	4 (4–11)	0
Miscellaneous [5]	1 (1–3)	<2 (<1–2)	½

[1] Average of 6 specimens.
[2] Small unmapped bodies east of Lost Creek contain 35–40 percent potassium feldspar and are porphyritic.
[3] Average of 5 specimens.
[4] Average of 12 specimens.
[5] Includes apatite, sphene, opaque ore, and zircon. Secondary epidote, chlorite, sericite, and prehnite were counted as the minerals that they replace.

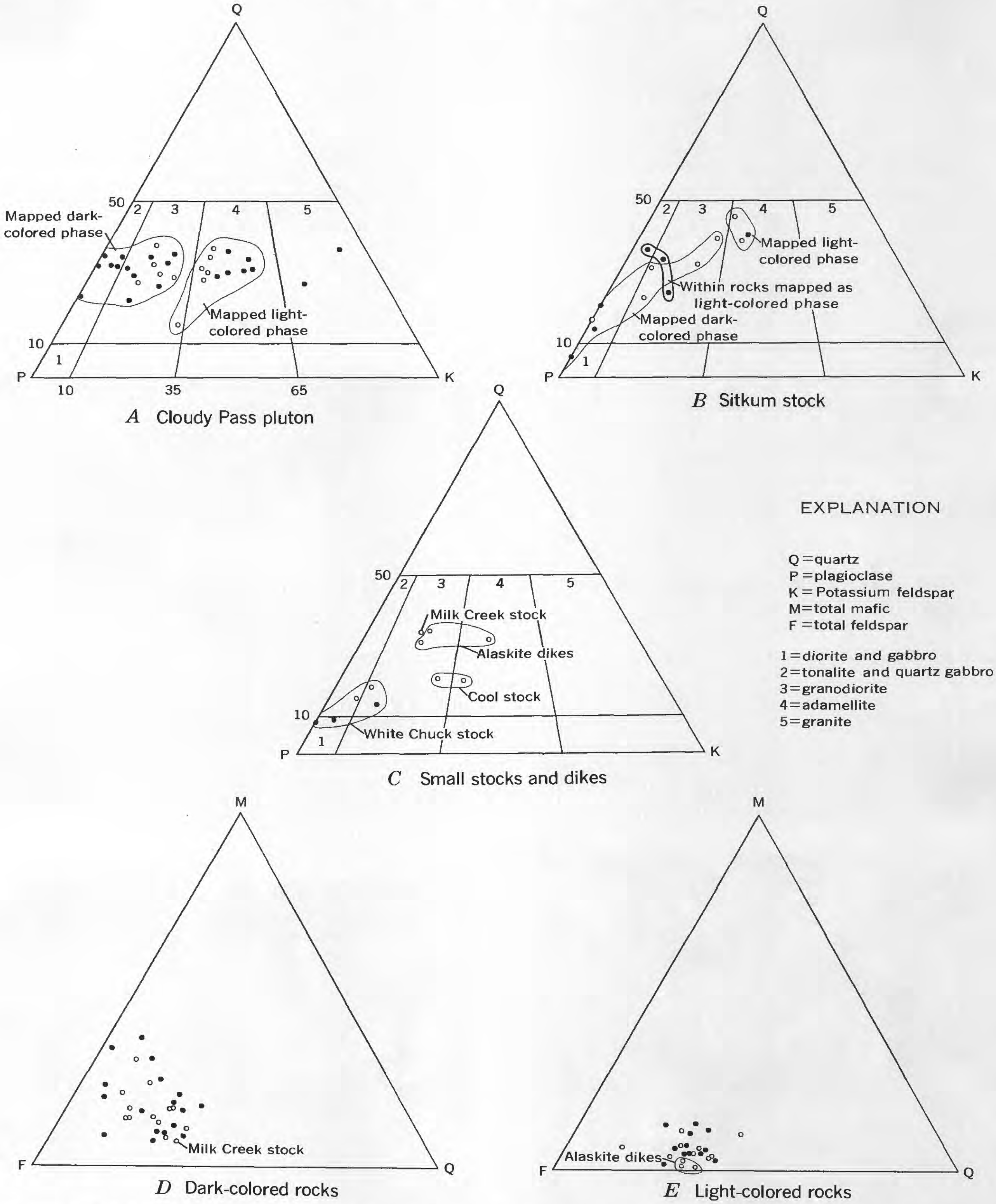


FIGURE 4.—Modal composition of the Cloudy Pass batholith and associated rocks. Dots, from Ford (1959, p. 186–187, 243, 248) ; circles, this report.

Plagioclase is in a transitional structural state in the small White Chuck stock, whereas it is in a mostly ordered and rarely transitional structural state in the larger Cool and Sitkum stocks—according to determinations made using methods and curves of Slemmons (1962)—and in the much larger main pluton of the batholith (Cater, 1969, p. 45). The transitional structural state suggests that the smaller masses cooled rapidly. Fuller (1925) ascribed the preservation of pyroxene in cupolas of the shallow Snoqualmie batholith to dehydration by degassing, and Cater ascribed the chilling of the eastern margin of the batholith to degassing, but we find no vesicles, vugs, or any other indication of degassing in the stocks.

LIGHT-COLORED PHASE

The predominant rock of the light-colored phase is adamellite; modal data is given in table 2 and figure 4. The light-colored phase is generally porphyritic with phenocrysts of euhedrally and oscillatorily zoned plagioclase and partly resorbed quartz. Plagioclase ranges from a maximum of An_{55} in euhedral cores to An_{20} in wide anhedral rims, but more commonly the crystals are normally zoned from andesine to oligoclase, the predominant composition being oligoclase. Inner zones of plagioclase crystals in two specimens have both ordered and transitional structural states.

The groundmass of the light-colored phase is of two types. One consists of fine-grained potassium feldspar, quartz, and subhedral to anhedral plagioclase in a xenomorphic aggregate (fig. 5). In the other type, the potassium feldspar and quartz are in micrographic or granophyric, commonly plumulose intergrowths (figs. 6, 7). Between plagioclase crystals, the quartz in either type locally forms continuous mesostasis of individual small grains or large optically continuous grains. Potassium feldspar is perthitic and most is orthoclase. Small optic axial angles (and crosshatch twinning observed by Ford, 1959, p. 198) indicate some potassium-sodium feldspar. In contrast to the light-colored rocks of the main pluton, micrographic or granophyric matrix is lacking in the light-colored phase of the Sitkum stock.

There is considerable evidence that the light-colored rocks contained abundant residual solutions which were particularly rich in potassium feldspar compo-

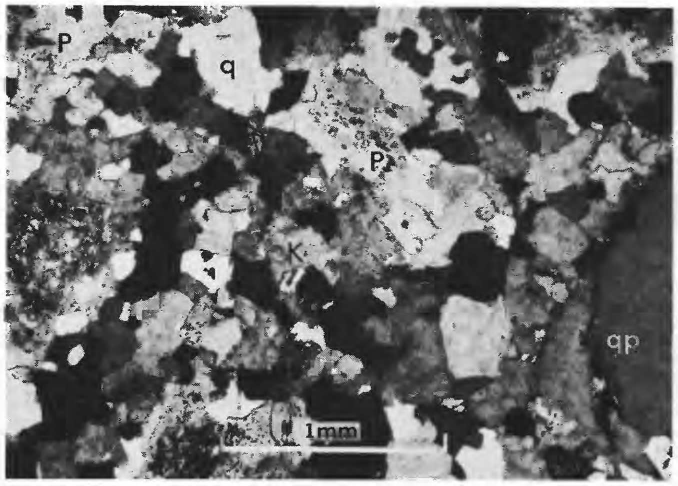


FIGURE 5.—Xenomorphic texture with potassium feldspar (K), quartz (q), and plagioclase (P) in light-colored phase of the Cloudy Pass pluton. Note quartz phenocryst (qp). Crossed nicols. Specimen RWT–297–61 from the northwest side of upper Vista Creek.

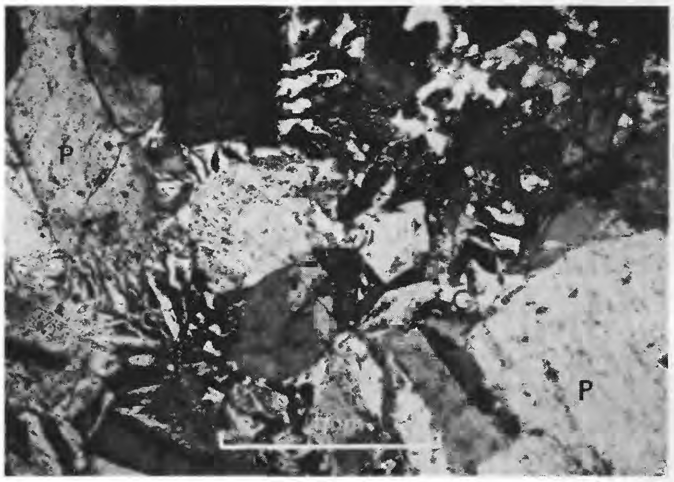


FIGURE 6.—Granophyric texture in light-colored phase of the Cloudy Pass pluton: granophyre (G), plagioclase (P). Crossed nicols. Specimen DFC–236–62 from the north side of Miners Ridge.

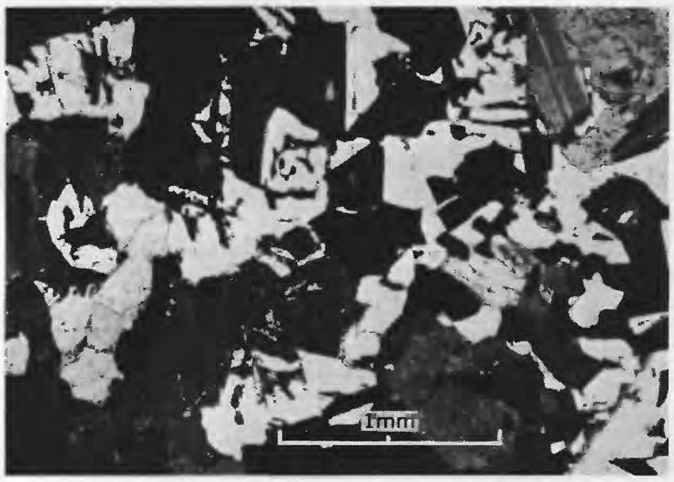


FIGURE 7.—Granophyric texture in light-colored phase of the Cloudy Pass pluton: quartz (white), potassium feldspar (black), and plagioclase (gray). Crossed nicols. Specimen RWT–40–62 from the south side of Dolly Creek.

nents (fig. 8). Potassium feldspar and micropegmatite rim and partially replace plagioclase in intricate comb-like intergrowths (fig. 9) and occur as irregular patches in calcic cores of plagioclase. Late sodic plagioclase also replaces potassium feldspar. In places, potassium feldspar appears to replace quartz of the groundmass (fig. 10). It has not been observed as phenocrysts. The light-colored phase is generally much altered; biotite is commonly replaced by chlorite, and plagioclase is clouded with epidote and white mica. Miarolitic cavities containing drusy quartz and sparse pyrite or iron oxides are common in the light-colored phases of the

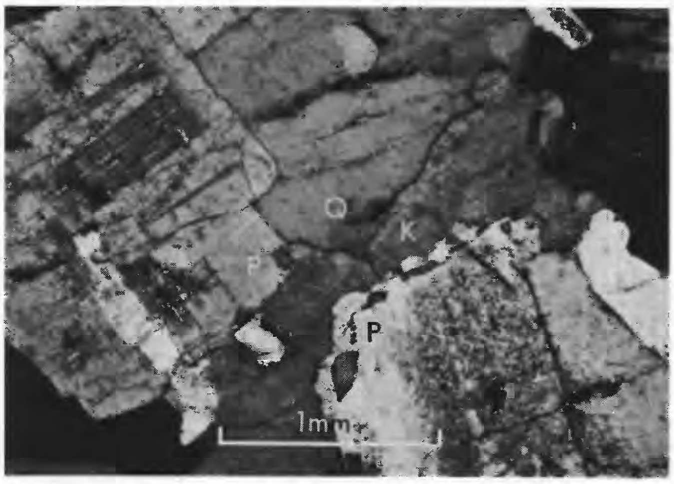


FIGURE 8.—Intergranular, late-formed potassium feldspar (K) intergrown with sodic plagioclase rims (P) in light-colored phase of the Sitkum stock. Replacement confined to rims of more calcic plagioclase. Quartz (Q). Crossed nicols. Specimen DFC–136–61 from upper Pumice Creek.

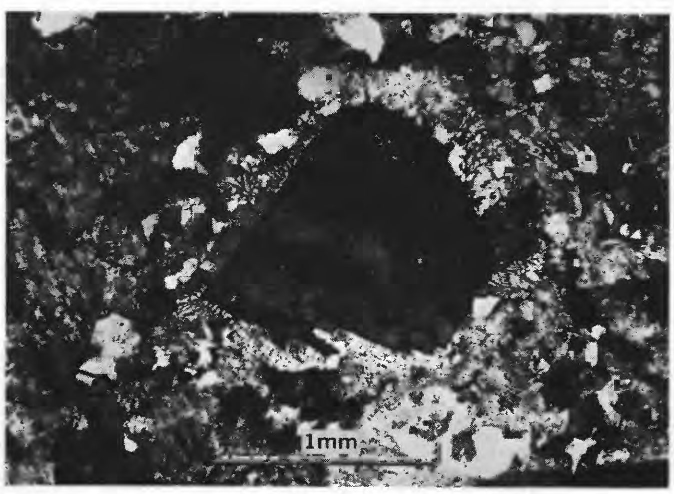


FIGURE 9.—Comblike granophyre intergrowth rimming and partially replacing twinned plagioclase crystal in Cloudy Pass pluton. Crossed nicols. Specimen DFC–236–62 from the north side of Miners Ridge.

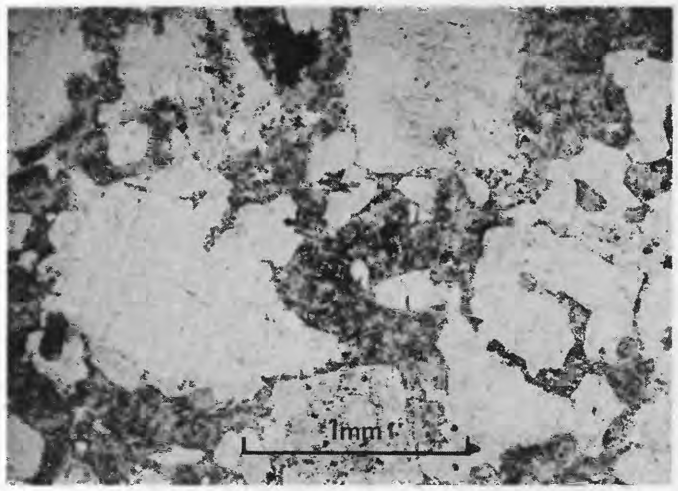


FIGURE 10.—Potassium feldspar (gray) partially replacing quartz (clear white) in light-colored phase of the Cloudy Pass pluton. Plane-polarized light. Specimen DFC–100–62 from the south side of Miners Ridge.

Stikum stock. Ford (1959, p. 208) reported quartz-lined cavities in light-colored rocks from Miners Ridge. The intergrowths, replacement features, and alterations of the light-colored phase indicate the prevalence of residual solutions; the cavities, an environment of low lithostatic pressure.

Ford (1959, p. 204–209) described and illustrated the micrographic textures of the batholith in detail. He stated (1959, p. 207–208) "there are all gradations from irregular micropegmatitic intergrowths in which the quartz feldspar ratio is highly variable to more regular intergrowths with a micrographic texture," and concluded, as did Grant (1966, p. 221 and 223) and Cater (1969, p. 20), that "these intergrowths in the Miners Ridge granitic rocks [part of our Cloudy Pass pluton] have a similar origin, namely, one of replacement [of crystals in earlier formed tonalite] rather than of primary magmatic crystallization." Grant (1966, p. 221) proposed that the replacement (on Fortress Mountain) caused mobilization of the early formed quartz diorite "resulting in small intrusive plugs of acid rock," our alaskite dikes (Grant, 1966, p. 221).

In the light-colored rock examined by us, quartz and the margins of plagioclase grains are replaced by potassium feldspar (figs. 8, 9, and 10), but prevalent textures (figs. 8 and 11) more strongly suggest that most of the quartz and potassium feldspar crystallized from residual melt between earlier formed plagioclase crystals. The similarity in the composition of light-colored rocks (and some of the alaskites discussed below) to the composition of rocks falling in the minimum melting trough of Tuttle and Bowen (1958,

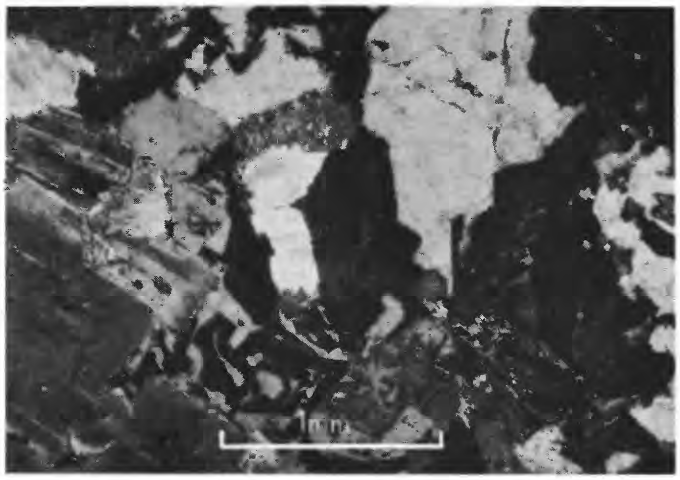


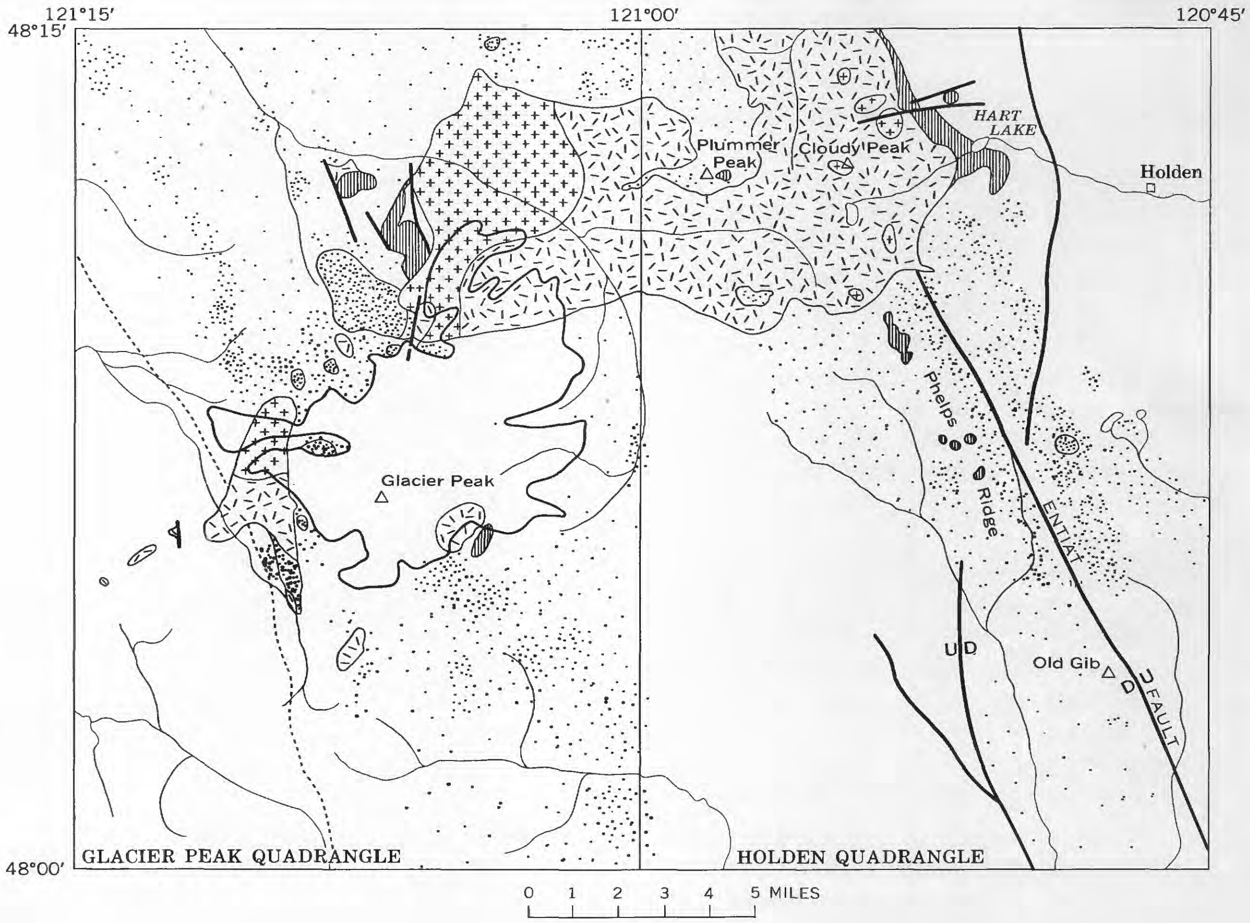
FIGURE 11.—Most prevalent texture of light-colored phase of the Cloudy Pass pluton. Micropegmatite fills in and around subhedral plagioclase crystals. Crossed nicols. Specimen DFC-40-62 from Suiattle River Trail west of Canyon Creek.

p. 55, and our fig. 20) supports the contention that these light-colored rocks formed by normal magmatic differentiation, not by replacement of an early formed phase by introduced residual solutions. These solutions, rich in alkalies, silica, and water should yield rocks of a diverse composition that would differ from the composition of rocks formed by separation of crystals and melt. A few rocks of diverse composition, testifying to the existence of residual siliceous solutions, do occur—for example, a quartz mass as on Miners Ridge (Grant, 1966, p. 223) and quartz veins with sulfides at the Glacier Peak Mines and near Crown Point in the Holden quadrangle (Cater, F. W., written commun., 1967). But the composition of the granitoid batholithic rocks is more limited, as would be unlikely if replacement by residual solution had been significant. We postulate that mafic minerals and plagioclase settled from a dark-colored phase of the magma essentially in place, so as to form an adamellite cap on the pluton. There is no evidence that the light- and dark-colored phase are separate intrusions where they are in contact in the main pluton and Sitkum stock, for the contacts are gradational. However, mixing of two magmas is suggested by banded and "marble cake" layers of light- and dark-colored phases in a few places in the Holden quadrangle (Cater, 1969, p. 19). On the east side of the pluton, a large satellitic dike of dacite porphyry at Hart Lake was later intruded by the core of the rising batholith (Cater, 1969, p. 47–48), and if the dark-colored core magma moved upward and intruded a still hot plastic cap of light-colored adamellite differentiate, the distribution of the adamellite along the north side of the batholith (pl. 1) could be explained. The lack of an intrusive contact between the dark-colored phase and the adamellite could be ascribed to the hot and plastic state of the adamellite.

ALASKITE DIKES

Small dikes, sills, and irregular masses of alaskite (light-colored granitoid rocks, composed predominantly of quartz and feldspar and generally with less than 5 percent mafic minerals) of diverse form and origin are widespread in the Glacier Peak area; for simplicity, we will use the term "dikes" to include them all. Crosscutting relationships between dikes indicate a wide range of relative and, in places, conflicting ages; but in general, dilation dikes and sharply bounded dikes cut schistose dikes and dikes with gradational contacts. In the Glacier Peak quadrangle, as elsewhere, the texture of the alaskites is highly varied and ranges from crystalloblastic and xenomorphic to, rarely, hypidimorphic granular. Grain size is mostly fine to medium, but a few coarse-grained, zoned pegmatities also occur. In some dikes quartz is intergranular. Biotite (commonly altered to chlorite), epidote, sphene, and opaque minerals are generally present in amounts of 3 percent or less. Small garnets are scattered through some specimens. Potassium feldspar is scarce; where it occurs, it is commonly intergranular and replaces quartz and plagioclase. Most of the potassium feldspar-rich alaskites are composed of poorly twinned oligoclase-andesine (50 percent), quartz (35 percent), and potassium feldspar (15 percent).

Crude estimates of the amount of alaskite in outcrops were made in the Glacier Peak, Holden, and Lucerne quadrangles (Crowder and others, 1966; Cater and Wright, 1967; Cater and Crowder, 1967). The data are not complete, because large areas are covered by younger volcanic rocks or by detritus and thick vegetation in valleys. For example, the linear concentration of dikes stretching to the northwest corner of the Glacier Peak quadrangle (fig. 12) could be mapped along a well-exposed ridge, but not in the valley bottom where bed-quartz and plagioclase. Most of the potassium feldspar-fined work would change the pattern depicted in figure 12. Although it is difficult to distinguish alaskite derived from the batholith from the abundant prebatholith alaskite, the older alaskite is definitely most abundant in biotite gneisses of the Glacier Peak-Lake Chelan area. In the Holden quadrangle, for example, replacement and secretion dikes of alaskite are particularly common in the Swakane Biotite Gneiss, of pre-Late Cretaceous age. They were formed from the gneiss by metamorphic differentiation (Crowder, 1959, p. 855–862). In contrast to their host rocks, the Cloudy



EXPLANATION

Outline of volcanic and volcaniclastic rocks of Gamma Ridge and lava flows of Glacier Peak

Cloudy Pass batholith and associated rocks
Crosses, light-colored phase; chicken tracks, dark-colored phase; ruled pattern, intrusive breccia and associated dacite and andesite porphyry

Alaskite
Dots represent relative concentration of alaskite dikes, sills, and irregular masses. In outlined areas, alaskite makes up 80 percent or more of rock volume. Southwest of dotted line in Glacier Peak quadrangle, light-colored material is ubiquitous and grades into gneiss on all scales; percentage of alaskite not estimated

Pre-Cloudy Pass rocks
Largely schist, gneiss, and granitoid gneiss

Contact

Fault U D

FIGURE 12.—Distribution of alaskite around the Cloudy Pass batholith. Data in Glacier Peak quadrangle from Crowder, Tabor, and Ford (1966); data in Holden quadrangle from Cater and Crowder (1967).

Pass batholith and nearby stocks are rarely cut by alaskite dikes. One alaskitic granophyre dike was found cutting the light-colored phase on Grassy Point, and irregular bodies of alaskite (points in the granite field in fig. 4A) were found within the light-colored phase of the batholith on Miners Ridge (A. B. Ford, oral commun., 1965; Grant, 1966, p. 222). A few alaskite dikes containing vugs and miarolitic cavities cut dark-colored phases of the pluton in the Holden quadrangle (Cater, 1969, p. 20). The dikes of alaskite that cut the batholith are apparently related to it, and so are clearly different from the replacement and secretion dikes in the gneissic host rocks.

Many alaskite dikes, however, are concentrated in country rocks near the Cloudy Pass batholith, especially north of Pumice Creek, between the forks of Milk Creek and along the Entiat fault (outlined areas in fig. 12). In these areas, irregular masses of alaskite grade locally into country rock intensely riddled by dikes. In upper Vista Creek, the amount of alaskite increases gradually away from the batholith contact through a zone a few hundred feet wide. Alaskite that appears to be the southern continuation of the Sitkum stock occurs above Baekos Creek and the White Chuck River (pl. 1), and south of Baekos Creek numerous sills of this alaskite penetrate the foliation of the host schist and are locally rich in unoriented inclusions of schist. Examples such as these suggest that some of the alaskite in the gneiss and schist of the host rock is genetically related to the batholith. The areas of alaskite, where particularly abundant in upper Milk and Pumice Creeks, are also thermally metamorphosed (compare fig. 3 with fig. 12). The alinement and concentration of stocks and dikes (satellitic bodies or cupolas) in those areas suggest that the batholith lies below.

Two generations of alaskite were seen along the eastern contact of the Sitkum stock east of the head of Chetwot Creek. Massive granodiorite of the stock grades within 2 feet into slightly gneissic alaskite with foliation parallel to the contact. The gneissic alaskite is cut by a dike of even-grained light-colored massive alaskite containing uralite with relicts of clinopyroxene. The alaskite dike is probably a satellite of the stock, but the affinity of the gneissic alaskite is uncertain.

Alaskite dikes that are definitely associated with the metamorphic rocks and (or) are at great distance from the pluton and its satellites are generally poor in potassium feldspar, as are the metamorphic rocks themselves (see Crowder and others, 1966; Crowder, 1959, p. 867). Alaskites with more than 10 percent potassium feldspar occur most commonly near the pluton and stocks (Crowder and others, 1966). Grant (1966, p. 239–246) described contact migmatites with introduced potassium feldspar adjacent to the pluton in the Ross Pass area (fig. 2). We therefore assume that most alaskite dikes with more than 10 percent potassium feldspar are related to the batholith.

In table 3, chemical analyses of four specimens (samples 13–16) of potassium feldspar-rich alaskite from the Glacier Peak area are given. Because two specimens (samples 15,16) have compositions near the variation curves and the ternary minimum of rocks of the Cloudy Pass batholith (figs. 19, 20), they may have differentiated from the batholith. The other two specimens (samples 13, 14) differ (fig. 20); if they are not of prebatholith rocks, they may be of rocks that have been altered by residual solutions emanating from the batholith.

INCLUSIONS AND DIKES OF HORNBLENDE TONALITE PORPHYRY

Hornblende tonalite porphyry inclusions and dikes are confined to the light-colored phase of the main pluton and are particularly prominent on Miners Ridge. The inclusions occur in swarms, which suggests that they were derived from disruption of discrete larger bodies. Many are cut by thin dikes of adamellite. Characteristically, the inclusions (fig. 13) contain decussate brown hornblends needles as much as 1 cm (centimeter) long in a fine-grained matrix. Partial digestion and reaction with the enclosing magma is suggested by some inclusions, where tonalite with hornblende needles grades into fine-grained tonalite without needles, and in other inclusions in which patches of medium-grained tonalite occur near the margins. The marginal patches contain coalescent grains of euhedrally zoned plagioclase similar to those in the dark-colored phase of the Cloudy Pass pluton.

The tonalite porphyry also occurs in a dike northeast of Grassy Point near the margin of the batholith. The dike is 20 to 40 feet wide, cuts adamellite, and has sharp contacts and aphanitic margins; clearly it was intruded when the adamellite was solid and relatively cool. Another dike of fine-grained microporphyritic hornblende tonalite also crops out on the lower slopes of Miners Ridge.

The dike on Grassy Point is less altered than the other tonalite porphyries, and its mode (volume percentages) may be considered representative: quartz, 10; plagioclase, 57; potassium feldspar, 6; hornblende, 20; biotite, 2; opaque minerals, 3; and apatite and white mica, 1. The conspicuous hornblende prisms are commonly poikilitic and have irregular borders (fig. 14).

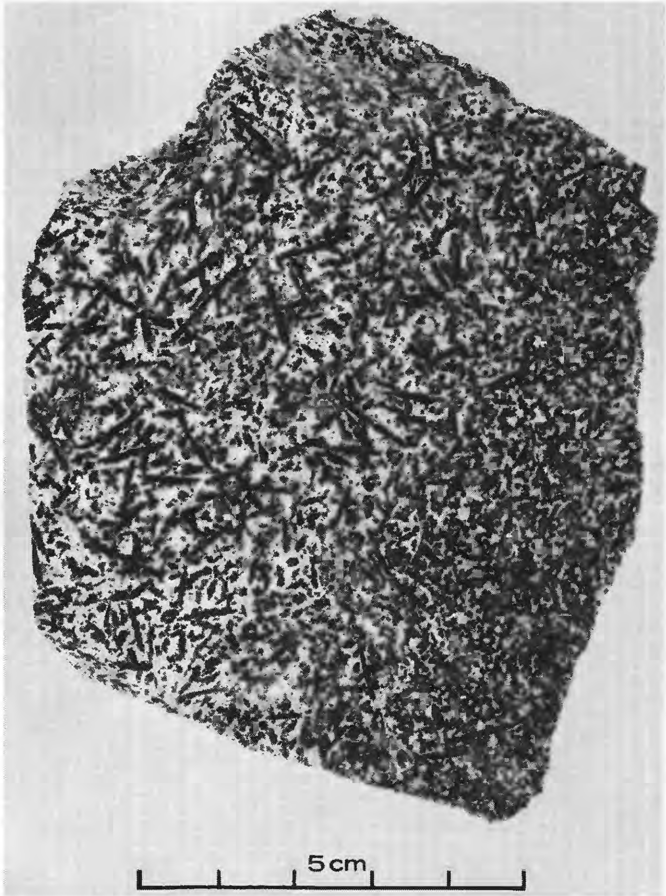


FIGURE 13.—Hornblende tonalite porphyry. Specimen DFC-99-61 from an inclusion on the south side of Miners Ridge. The hornblende tonalite porphyry dikes are identical. Note variable grain size.

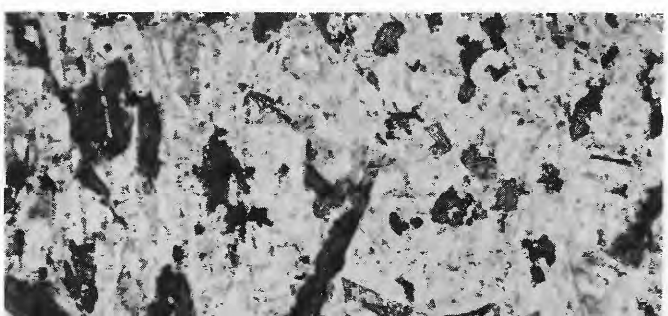


FIGURE 14.—Hornblende tonalite porphyry inclusion. Note ragged hornblende prisms, some with inclusions. Quartz and potassium feldspar (gray) fill spaces between tightly packed plagioclase laths (white). Plane-polarized light. Specimen RWT-58-62 from south side of Miners Ridge.

Crystals are zoned from cores in which Z equals greenish brown to rims in which Z equals pale green. In one specimen, brown hornblende crystals broken by stretching along the c axis are healed with green hornblende. Most hornblende is partly replaced by brown biotite, and in many inclusions chlorite and epidote replace mafic minerals; plagioclase is saussuritized. The matrix of the porphyry is a tightly packed mesh of oscillatorily zoned, subhedral to euhedral plagioclase laths surrounded by anhedral quartz, potassium feldspar, and fibrous green hornblende (figs. 14, 15). Opaque minerals and apatite are liberally sprinkled throughout some inclusions but are rare in others. The angular spaces between plagioclase laths are locally filled with clinozoisite (fig. 15).

In the Glacier Peak quadrangle, no inclusions or dikes of tonalite porphyry have been found outside the light-colored phase of the batholith, although similar porphyry forms a stock just south of Holden and forms dikes in the Entiat Mountains (Crowder, 1959, p. 864-865; Cater and Crowder, 1967). Grant (1966, p. 227-229) reported nonporphyritic(?) hornblende diorite inclusions in the main (dark-colored) phase of the batholith in the Dome Peak area; he considered them to be derived from hornblende gneiss country rocks.

In major-element and trace-element composition, the tonalite porphyry (sample 2, table 3 and fig. 19) is similar to the mafic phases of the Sitkum stock. The chemical composition and the occurrence of the tonalite porphyry in only the light-colored margin of the batholith in the Glacier Peak area strongly suggest that the porphyry is related not only to the batholith but to the light-colored phase.

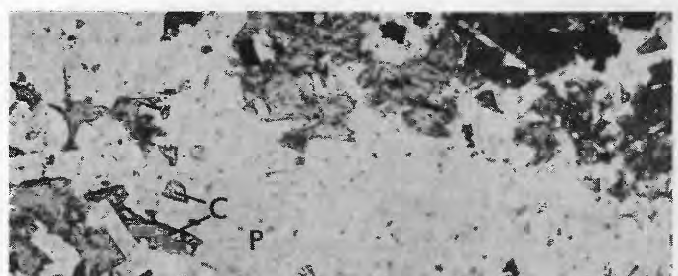


FIGURE 15.—Clinozoisite (C) filling space between plagioclase laths (P) in hornblende tonalite porphyry inclusion. Plane-polarized light. Specimen DFC-99-62 from the south side of Miners Ridge.

TABLE 3.—*Composition of the Cloudy Pass batholith and associated rocks*

[Samples, sawed from hand specimens; homogenous and fresh, except as noted, but not collected specifically for chemical analyses and (or) statistical studies of composition. Locations of samples are shown on plate 1, except for sample 18. Oxides: Samples analyzed by X-ray fluorescence supplemented by methods described in U.S. Geological Survey Bulletin 1144-A. Analysts: Paul L. D. Elmore, S. H. Botts, Gillison Chloe, Lowell Artis, and H. Smith]

	Dark-colored phase									Light-colored phase			Alaskite				Intrusive breccia	Average Dark-colored phase
Pluton	Sitkum stock	Hornblende tonalite porphyry dike	White Chuck stock	Sitkum stock	Cool stock	White Chuck stock	Cloudy Pass pluton	Sitkum stock	Cloudy Pass pluton	Cloudy Pass pluton		Sitkum stock	Sitkum stock			Alaskite mass	Mica Lake breccia	Cloudy Pass pluton, Holden quadrangle
Symbol on plate 1	Tcg	Tcp	Tcg	Tcg	Tcg	Tcg	Tcg	Tcg	Tcg	Tca	Tca	Tca	Tal	Not mapped		Tal	Tib	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Weight percentage of oxides																		
SiO_2	57.3	59.1	61.4	61.9	63.9	64.1	66.5	67.3	70.1	71.2	72.9	73.5	73.7	74.5	75.8	77.1	75.2	64.4
Al_2O_3	18.0	17.1	16.6	16.6	16.4	16.8	15.6	15.4	15.0	14.7	14.3	14.1	15.5	15.3	12.7	12.6	13.9	16.6
Fe_2O_3	.54	2.7	1.8	1.7	1.6	1.6	1.3	.75	1.3	.84	.90	.46	.00	.00	.00	.12	1.2	2.1
FeO	6.4	4.3	4.1	4.2	3.3	2.8	3.0	3.5	1.8	1.6	1.1	1.4	.68	.20	.34	.60	.48	2.8
MgO	4.3	3.1	3.4	2.9	2.3	2.2	1.9	1.3	1.0	.95	.26	.48	.57	.10	.2	.10	.2	2.1
CaO	7.6	5.9	5.8	5.6	4.4	4.0	4.2	4.1	2.2	1.9	1.8	2.0	1.5	1.8	.77	.21	1.1	5.0
Na_2O	3.0	3.4	3.7	3.1	4.4	4.6	3.2	3.2	4.6	4.6	4.2	3.5	4.9	5.5	2.9	3.5	3.5	3.1
K_2O	1.1	1.6	1.6	2.0	2.3	1.8	2.8	2.7	2.5	2.9	3.1	3.0	2.0	1.8	5.8	4.5	2.5	2.3
H_2O+	.11	.28	.27	.20	.31	.20	.17	.11	.26	.00	.28	.19	.10	.10	.91	.19	.93}	.77
H_2O-	.66	.84	.42	.90	.09	.85	.65	.63	.55	.68	.47	.65	.32	.41	.09	.28	.47}	
TiO_2	.75	1.3	.95	.58	.78	.67	.43	.44	.40	.37	.27	.19	.07	.00	.08	0.4	.08	.38
P_2O_5	.17	.27	.20	.10	.15	.17	.14	.06	.12	.06	.03	.02	.03	.00	.00	.01	.05	.24
MnO	.16	.13	.11	.12	.09	.07	.09	.09	.07	.07	.04	.04	.03	.00	.00	.04	.09	.10
CO_2	<.05	<.05	<.05	<.05	<.05	<.05	<.05	<.05	<.05	<.05	<.05	<.05	<.05	<.05	<.05	<.05	.10	.07
Total	100	100	100	100	100	100	100	100	100	100	100	100	99	100	100	99	100	100
Normative composition (CIPW)																		
Q	9.6	15.2	15.5	18.0	16.0	17.8	24.0	25.5	27.2	27.2	32.0	35.8	33.0	31.5	34.6	38.5	43.0	23.3
C						.4			1.0	.7	.8	1.5	2.6	1.0	.3	1.6	3.8	.7
Or	6.5	9.4	9.4	11.8	13.6	10.6	16.5	16.0	14.8	17.1	18.3	17.7	11.8	10.6	34.3	26.6	14.8	13.6
Ab	25.4	28.8	31.3	26.2	37.2	38.9	27.1	27.1	38.9	38.9	35.5	29.6	41.4	46.5	24.5	29.6	29.7	26.2
An	32.4	26.7	24.0	25.5	18.2	18.7	19.9	19.7	10.1	9.0	8.7	9.8	7.2	8.9	3.8	1.0	4.5	22.8
Wo	1.8	.3	1.4		1.1			.1										
En	10.7	7.7	8.5	.7	5.7	5.5	4.7	3.2	2.5	2.4	.6	1.2	1.4	.2	.5	.2	.5	5.2
Fs	10.4	3.8	4.7	5.6	3.6	2.8	3.9	5.2	1.7	1.8	.9	2.0	1.2	.4	.5	1.0		3.0
Mt	.8	3.9	2.6	2.5	2.3	2.3	1.9	1.1	1.9	1.2	1.3	.7				.2	1.6	3.1
Il	1.4	2.5	1.8	1.1	1.5	1.3	.8	.8	.8	.7	.5	.4	.1		.2	.1	.2	.7
Ap	.4	.6	.5	.2	.4	.4	.3	.1	.3	.1	.1		.1				.1	.6
Total	99.3	98.9	99.7	98.8	99.6	98.8	99.2	98.8	99.1	99.2	98.9	98.7	99.0	99.2	98.6	98.8	98.4	99.1
Salic	73.9	80.1	80.2	81.5	85.0	86.5	87.5	88.2	92.0	93.0	95.5	94.5	96.2	98.6	97.4	97.3	95.7	86.5
Femic	25.4	18.8	19.5	17.3	14.6	12.3	11.6	10.6	7.1	6.2	3.4	4.2	2.8	.6	1.1	1.5	2.7	12.5
Percent An in plagioclase	56.4	48.0	43.5	49.5	32.9	32.4	42.5	42.0	20.6	18.8	19.7	24.8	14.8	16.2	13.4	3.2	13.2	46.4
Trace element content [1]																		
B	0	0	0	0	0	0	0	0	0	0	0	15	5	10	10	20	50	0
Ba	500	500	500	1,000	700	700	1,000	1,000	700	700	700	1,000	1,500	1,500	1,500	200	700	100
Be	0	1.5	0	0	0	0	0	0	2	2	15	0	1	1.5	1.5	2	1	0
Co	20	20	15	15	15	15	15	15	7	7	3	0	0	0	0	0	0	10
Cr	50	50	70	30	70	30	50	30	20	50	30	50	50	50	3	100	3	10
Cu	20	7	10	20	20	20	5	30	15	15	10	10	3	2	30	3	7	30
Ga	20	20	20	20	20	20	20	20	20	20	20	15	20	20	10	20	10	30
Ni	15	20	20	10	15	15	10	15	10	15	15	15	10	15	0	30	2	0
Pb	0	0	0	15	30	0	20	30	20	15	20	0	15	20	30	20	0	10
Sc	50	30	20	30	15	15	20	20	7	7	5	7	0	0	0	0	0	10
Sr	1,000	1,000	1,000	1,000	1,000	1,000	700	700	700	500	500	300	1,000	1,000	70	50	150	300
V	200	300	150	200	150	150	150	150	50	50	30	30	0	0	0	0	0	10
Y	20	20	20	20	20	20	20	20	20	10	10	10	0	0	30	7	15	10
Yb	2	2	2	2	2	2	2	2	2	1	1.5	1	0	0	3	0.7	0	1
Zr	100	150	150	100	150	200	100	150	150	150	150	150	50	30	100	50	70	30

[1] Semiquantitative spectrographic analysis in parts per million. Results are reported in percent to the nearest number in the series 1, 0.7, 0.5, 0.3, 0.2, 0.15, and 0.1, which represent approximate midpoints of group data on a geometric scale. The assigned group for about 30 percent of semiquantitative results will include the quantitative value. Standard sensitivities in ppm are: Ag, 1; As, 500; Au, 30; B, 10; Ba, 10; Be, 1; Bi, 10; Cd, 50; Ce, 200; Co, 5; Cr, 1; Cu, 1; Ga, 10; Ge, 10; Hf, 300; Hg, 1,000; In, 10; La, 30; Li, 500; Mo, 5; Nb, 50; Ni, 5; Pb, 10; Pd, 3; Pt, 10; Re, 50; Sb, 100; Sc, 1; Sn, 20; Sr, 10; Ta, 400; Te, 1,000; Th, 500; Tl, 50; U, 500; V, 10; W, 500; Y, 10; Yb, 1; Zn, 200; and Zr, 10. Elements looked for and not found are: Ag, As, Au, Bi, Cd, Ce, Ge, Hf, Hg, In, La, Li, Mo, Nb, Pd, Pt, Re, Sb, Sn, Ta, Te, Th, Tl, U, W, and Zn. Analyst, Chris Heropoulos.

TABLE 3.—*Composition of the Cloudy Pass batholith and associated rocks*—Continued

1. Biotite-hornblende-quartz gabbro; head of Sitkum Creek; mafic minerals irregularly distributed.
2. Hornblende-quartz diorite porphyry dike; north side Grassy Point; mafic minerals irregularly distributed, slightly iron stained.
3. Pyroxene-biotite-quartz gabbro; west side White Chuck Glacier.
4. Hornblende-biotite granogabbro; north of Backos Creek; crumbly.
5. Clinopyroxene granodiorite; upper Suiattle River.
6. Hornblende-biotite granodiorite; west of White Chuck Glacier; mafic minerals irregularly distributed; dark inclusions but none showing in specimen; weathered.
7. Biotite granodiorite; head of Dolly Creek; mafic minerals irregularly distributed.
8. Biotite-hornblende granodiorite; west side White Chuck River; mafic minerals irregularly distributed.
9. Biotite granodiorite; south side lower Vista Creek; contains small mafic inclusions; slightly weathered.
10. Biotite adamellite; north side Grassy Point; slightly weathered.
11. Biotite (chlorite) adamellite; mouth of Canyon Creek; small inclusion, slightly weathered.
12. Biotite (chlorite) adamellite; upper Pumice Creek; mafic minerals irregularly distributed, crumbly, fresh.
13. Muscovite alaskite; north side of Beakos Creek, slightly gneissic, xenomorphic, small feldspathic vein.
14. Muscovite alaskite; below Ptarmigan Glacier; from xenomorphic granular core of a sharply bounded dike; pegmatite borders.
15. Myrolitic alaskite; upper Pumice Creek; spots of iron oxides and scattered sulphides.
16. Muscovite-biotite alaskite; west side upper Milk Creek; mafic minerals irregularly distributed, weathered.
17. Dacite porphyry associated with intrusive breccia; Mica Lake; stained by iron oxides.
18. Composite sample of labradorite granodiorite from Cloudy Pass pluton in Holden quadrangle from Cater (1969, table 1, p. 28).

The origin of the hornblende tonalite prophyry inclusions could have been as follows: The light-colored phase of the western border of the batholith was still hot and plastic, though sufficiently solidified to crack, when tonalitic magma of the still molten core intruded newly formed joints to form dikes; slightly later movement of the batholith then disrupted the dikes and formed inclusions. Ford (1959, p. 233) argued that, if the inclusions of hornblende tonalite porphyry were of early formed rock of the batholith, they should contain pyroxene or at least uralite. As has been shown, most of the pyroxene in the core rocks has been converted to hornblende; if the core magma containing pyroxene were injected to form the tonalite porphyry dikes, the pyroxene would have been similarly converted. The porphyry dike with chilled margins, which occurs on Grassy Point near the border of the pluton, may have been intruded either after the period of disruption or into the more solid light-colored border which was not disrupted (fig. 26). The hydrous residual solutions concentrated in the enveloping light-colored phase may have diffused into the drier tonalite and promoted the development of conspicuous hornblende prisms and variable grain size. The fibrous green hornblende, biotite, chlorite, saussurite, and epidote that the dikes and inclusions now contain may be the final reaction products of the hydrous milieu. Filter pressing of the light-colored cap or border by the intruding core of the pluton might well have occurred at this time with resultant separation of the interstitial melt from the adamellite to form alaskites.

INTRUSIVE BRECCIA, DIKES, AND SMALL MASSES

The country rock is pierced by tonalite dikes and intrusive breccia in and near the southwest-trending zone between the Suiattle River and Red Mountain thought to be underlain by the batholith. Associated with the breccia are small and poorly exposed masses composed predominantly of tonalite. Direct proof that the intrusive breccias, tonalite dikes, and small masses of tonalite are offshoots of the Cloudy Pass batholith is not found in the Glacier Peak area. Such intrusions do, however, cluster near the edge of the batholith or in the roof, and we know of no other pluton with which they might be associated.

The dikes on Sulphur and White Mountains are fine- to medium-grained hypidiomorphic granular tonalite. Some dikes contain clinopyroxene and resemble the dark-colored phases of the batholith and the Sitkum stock. The contacts of the small masses of tonalite (and some minor quartz gabbro) with intrusive breccia on Grassy Point and elsewhere were not observed. Some of the small tonalite masses also resemble dark-colored phases of the batholith, but many are finer grained. On Grassy Point and near the Cool stock, because the hornblende and biotite in the small masses of tonalite have been statically recrystallized, they may be akin to rocks with similar recrystallization textures that are described by Grant (1966, p. 211) as the early pyroxene diorite phase of the batholith. They also resemble the more granitoid phases of the "outer layer of the Hart Lake complex" and the "porphyry plugs" (Cater, 1969, p. 12 and 23) near Plummer Peak and on Phelps Ridge. Occurring with the small tonalite masses are porphyritic-aphanitic rocks, many of which are so highly altered to chlorite, calcite, epidote, and rare zeolites that their original character is obscure. Float from the nose of Vista Ridge, a location over a mile away from the lateral margin of the batholith but

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perhaps near its roof, is very similar to dacite capping the pluton at Cloudy Peak (Cater, 1969, p. 13).

The contacts of intrusive dacite breccia are sharp, and the wallrocks are locally shattered and altered. On Grassy Point, the intrusive breccia surrounds inclusions of shattered country rock as much as several hundred feet across and is capped by a jumble of tightly packed but partly rotated fragments of fresh hornblende schist having little or no matrix. The intrusive breccias consist of locally alined angular fragments of aphanitic rock and lesser amounts of schist, gneiss, and granitoid rock in a greenish matrix (fig. 16).

The matrix of the breccias ranges from porphyritic-aphanitic to protoclastic (fig. 18). In a monolithologic breccia near the Cool stock, the matrix consists entirely of ground-up and hydrothermally altered country rock (fig. 17). Phenocrysts and porphyroclasts are plagioclase and partly resorbed quartz that still show some crystal faces. The aphanitic parts of the matrix, and aphanitic clasts in it are dacite judging from the quartz

FIGURE 16.—Intrusive dacite breccia. RWT–352–61 from the north side of Grassy Point.

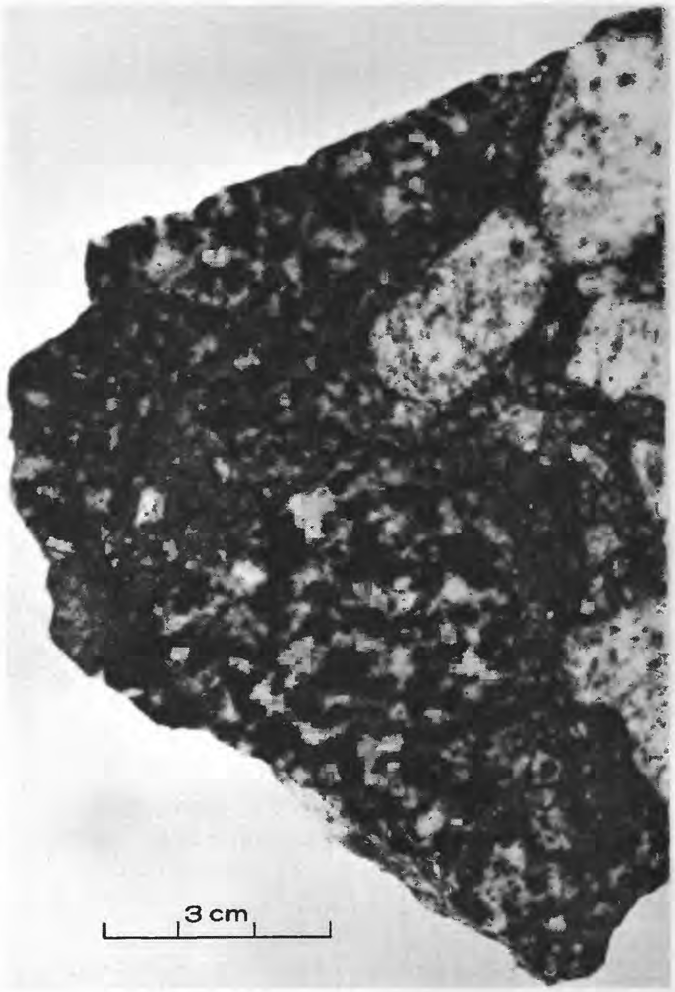

FIGURE 17.—Intrusive breccia near the Cool stock. Clasts or hornblende diorite and alaskite in protoclastic matrix. Specimen RWT–183–62 east of the Cool Glacier.

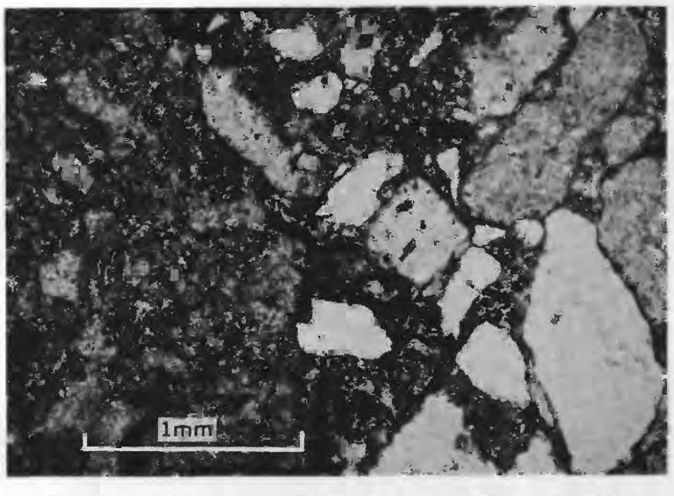

FIGURE 18.—Cataclastic, highly altered matrix of intrusive breccia. Plane-polarized light. Specimen RWT–313–61 west side of Dolly Creek.

phenocrysts and the andesine composition of plagioclase microlites. The numerous plagioclase microlites in both the matrix and the aphanitic clasts are commonly flow alined and occur in a mass of chlorite, opaque granules, low birefringent material (feldspar?), and a little glass.

Most of the intrusive breccias are intensely altered: the matrix is an indistinct mass of chlorite, epidote, and leucoxene; mafic minerals in the matrix or clasts are reduced to aggregates of chlorite and epidote; the plagioclase is saussuritized. In places, potassium feldspar forms an irregular mesostasis and embays the margins of plagioclase and lithic clasts and so appears to be a late addition to the rock.

Intrusive dacitic breccias in upper Milk Creek and near Mica Lake differ from the breccias just described. The Milk Creek breccia grades from a slightly protoclastic dacite to dacite charged with inclusions of country rock. The surrounding country rock is shattered and iron stained. The breccia near Mica Lake consists mostly of rotated blocks of country rock schist cut by thin dikes of pulverized schist and rhyodacite. Vuggy quartz veins and seams of pyrite cut the breccia at Milk Creek, and vuggy veins of quartz and calcite invade the breccia at Mica Lake. In the Milk Creek mass, crystal fragments and phenocrysts of quartz and plagioclase occur in a xenomorphic matrix of quartz, biotite, muscovite, and (or) scattered tiny euhedral hornblende crystals; there is no flow structure and the rock appears to have been statically recrystallized. The rhyodacite dikes which cut breccia at Mica Lake (sample 17, table 3) are similar to the Milk Creek mass, but they lack the protoclasis and bear abundant reticulated biotite instead of hornblende.

The intrusive breccias clearly originated under low lithostatic pressure when clasts of country rock, and earlier solidified magma, were explosively broken and transported by magma and gas in a diatreme. During the process, the breccia fragments were pulverized and altered. The intrusive breccias of the Glacier Peak area had an origin similar to that of some of the intrusive breccias to the east, particularly those on Phelps Ridge (Cater, 1969, p. 33). Many of the Phelps Ridge intrusive breccias were mobilized largely by gas rather than gas-magma mixtures, for matrices consist of highly pulverized and altered material and lack the abundant flow-alined plagioclase crystals and inclusions of aphanitic rocks common in most intrusive dacite breccias near Glacier Peak.

Although none of the intrusive breccias cut the batholith, they were probably emplaced after it cooled at the present erosional level. The breccias are not cut by alaskite dikes, which appear to be late derivatives of the main pluton. In the section on the early episode of volcanism, we discuss the possibility that the intrusive breccias of Glacier Peak area erupted onto the solidified and eroded batholith.

INTRUSION AND DIFFERENTIATION

The main plution probably did not emplace itself by stoping, for there is a conspicuous lack of engulfed roof rocks in it in both the Holden (Cater, 1969, p. 48) and the Glacier Peak quadrangles. The lack of marginal contamination, even where inclusions are abundant, and the presence of sharp chilled contacts as stressed by Cater (1969, p. 7–8) argue against assimilation. Furthermore, the discordant irregular shape of the batholith (fig. 2), together with the apparent lack of lateral shouldering aside of wallrock, suggests that room was made by lifting the roof, not by pushing the wall back—an appropriate hypothesis for a shallow pluton. The eastward bulge of the Cascade Crest over the batholith supports this lifting (see p. 55). The hypothesis of the rise of the batholith relative to its host rocks on the northeast flank (fig. 26) where the dislocation is marked by a zone of chilled rocks and breccias as proposed by Cater (1969, p. 47) clearly requires that the roof has been raised.

If the batholith raised its roof, the roof rocks should be more deeply eroded near and over the pluton than they are where not uplifted. Both Crowder (1959, p. 832, 834) and Cater (1969, p. 48) noted that well-segregated and swirled gneiss and associated leucocratic dikes (alaskites) and migmatites are more abundant above and near the pluton than they are to the southeast. Crowder, assuming that the greatest uplift and deepest erosion had been on the Cascade Crest, suggested that the migmatites and associated rocks are of relatively deep-seated origin. Cater, assuming the deep-seated origin of these rocks, infered that they had been uplifted by the batholith. Aside from the obviously circular nature of these arguments, there are two processes other than uplift that can account for the concentration of leucocratic rocks and associated features: (1) In the Glacier Peak area, we have shown that some of the leucocratic dike material (alaskite) is derived from the batholith and is not of deep-seated metamorphic origin; a concentration of such material may indicate only that the pluton lies buried nearby. (2) In the Holden quadrangle, leucocratic rocks are concentrated in or near biotite gneiss and biotite tonalite-gneiss not because the rocks were formed in a deeper environment but because these lithologies are particularly susceptible to metamorphic differentiation (Crowder, 1959, p. 861). Similar biotite gneisses characterized by abundant leucocratic material occur in the biotite gneiss belt in the southwest part of the Glacier Peak quadrangle (fig. 12) and in the biotite gneiss along Lake Chelan (Cater and Wright, 1967).

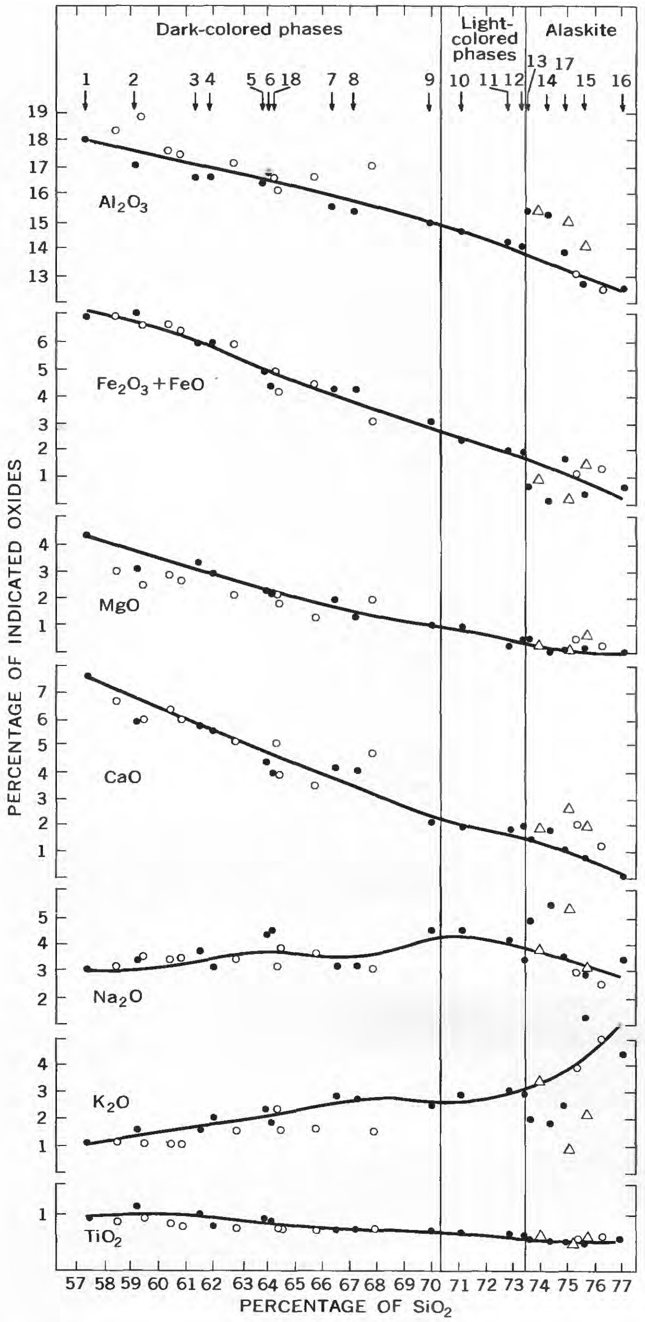

FIGURE 19.—Variation diagram of the Cloudy Pass batholith and associated rocks (dots). Circles are from Cloudy Pass rocks in the Holden quadrangle (Cater, 1969, table 1; Cater's unusual No. 6 has been omitted). Triangles are alaskite dikes and pods presumably of metamorphic origin and unrelated to the batholith (based on Crowder, 1959, table 5, p. 855–862, 868). Numbered arrows are samples from table 3.

Differentiation of the Cloudy Pass magma cannot be related to a conventional sequence of rock emplacement. Once the granodiorite or tonalite magma was in place at the level now exposed near Glacier Peak, an adamellite cap (the light-colored phase) formed by crystallization differentiation as early formed mafic minerals settled from the top of the chamber. The smooth curves in figure 19 do not prove crystallization differentiation occurred[1], but they do illustrate the changing composition. Furthermore, the composition of the adamellite approaches the composition of a magma in the minimum-melting trough (fig. 20) as derived by crystallization differentiation. Some of the light-colored rocks that occur sporadically within the batholith in the Holden quadrangle (Cater and Crowder, 1967) may be the roots of this adamellite cap, although most of them are thought by Grant (1966,

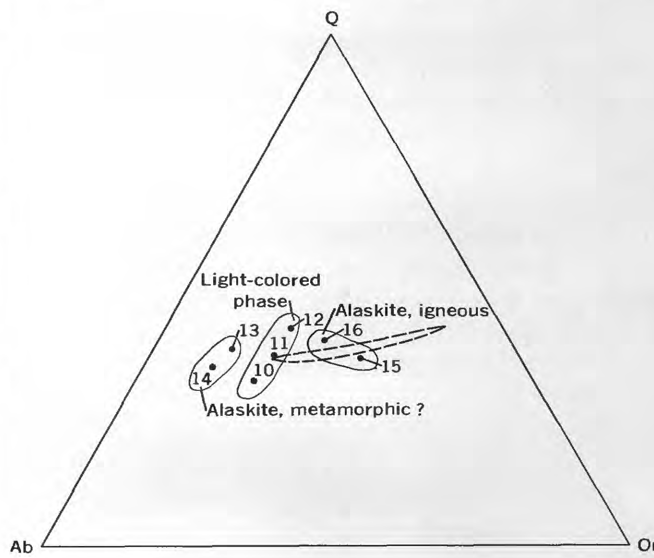

FIGURE 20.—Ternary diagram of orthoclase (Or), quartz (Q), and albite (Ab) showing normative position of alaskite and light-colored phases of the Cloudy Pass batholith in relation to minimum-melting trough of Tuttle and Bowen (1958, p. 55). The light-colored phases contain 9–10 percent anorthite as well as other components, which may account for their displacement to the left of the trough, which is that of a simple ternary system. Dashed line is 760° C isograd at pressure $P_{H_2O}=1000$ kg/cm² (kilograms per square centimeter). Numbers indicate samples listed in table 3.

p. 42) and Cater (1969) to have formed where potash-rich and silica-rich vapors rising from the crystallizing core replaced the early formed overlying tonalite.

The present position of the adamellite cap on the

[1] Chayes (1964) showed that a Harker variation diagram itself may be of little use in proving that crystallization differentiation has produced suites of igneous rocks. In such diagrams where components are summed to 100 percent, the major constituents other than silica are bound to decrease as the silica increases. A genetic relation between samples is implied only if points are very near the curves.

northwest side of the batholith is explained by assuming it was intruded by the core (fig. 26). This occurred when both the cap and the core were still largely molten, for their contacts are gradational. Dikes of hornblende tonalite porphyry presumably derived from the core were injected into more brittle parts of the cap, but were soon broken apart by movement of the still-plastic host. Interstitial melt in the cap (alaskite in composition and the likely residual product of crystallization differentiation) (figs. 19 and 20) may have been pressed out into the host rocks by the core intrusion. Locally, this alaskite was intruded into the more solid parts of the cap itself. With this event, the plutonic history of the Cloudy Pass batholith at the level now exposed came to an end.

EARLY EPISODE OF VOLCANISM: VOLCANIC AND VOLCANICLASTIC ROCKS OF GAMMA RIDGE

GENERAL CHARACTER AND AGE

The oldest eruptive rocks near the Cloudy Pass batholith are altered varicolored volcaniclastic rocks and a few lava flows that crop out on the eastern flanks of Glacier Peak; they underlie Gamma Ridge and occur in four small patches nearby (pl 1).

Included in this group are ridge-capping tuffaceous conglomerates containing many clasts of granitoid and metamorphic rocks (fig. 21). Mapped with these heterogeneous conglomerates near Gamma Peak, but not actually in contact with them, are conglomerates made up almost entirely of lava clasts of unknown affinity.

The thickness of the Gamma Ridge deposits as measured from the base in Dusty Creek or Gamma Creek to the crest of Gamma Ridge is about 2,000 feet. Bedding altitudes within this pile are poorly known. Rocks in Gamma Creek and Dusty Creek have moderate to steep easterly dips. Bedding in the ridge-capping conglomerate dips gently northeastward. However, bedding in a small block of similar heterogeneous conglomerate in Gamma Greek is parallel to the steep valley side; unless the block is a landslide, considerable downfolding or downfaulting is indicated.

The volcanic rocks of Gamma Ridge are between early Miocene and Pleistocene in age. On Gamma Creek, at 3,250 feet altitude, the volcanic rocks overlie the Cloudy Pass batholith and contain cobbles of it; they are thus younger than the batholith at the level now exposed, that is, younger than early Miocene (21 to 24 m.y.). Clearly it took some time, several million years, for erosion to deroof and expose the upper part of the batholith; the maximum age is therefore middle or even late Miocene. The lavas that overlie the Gamma Ridge rocks are the oldest of the Glacier Peak volcano, because they occur as small erosional remnants that cap ridges (unit Qdc, fig. 21); however, these lavas, as will be shown later, are not older than 0.7 m.y. If the Gamma Ridge rocks are derived from the batholith and in the manner considered in the following section, their age is middle or late Miocene or Pliocene.

PETROLOGY

Gamma Ridge is underlain by a wide variety of volcanic and volcaniclastic rocks; lithic wackes, tuffs, welded tuffs, and breccias; flows; and conglomerates. The composition of the extrusives ranges from andesite to dacite and possibly to rhyodacite.

The breccias can be broadly subdivided into volcanic breccias and nonvolcanic breccias, although intermediate types are common. Locally interbedded with them are dark-colored, medium-grained lithic wackes. Fragments in the breccias range in size from a few inches to 80 feet across and are composed both of nearby basement gneiss and schist and of volcanic rocks. Fragments of gneiss and schist are most common at the base of the volcaniclastic pile. In the volcanic breccias and volcanic tuff breccias, most fragments are composed of altered porphyritic-aphanitic rocks, many with flow-alined crystals. Most of the breccias are severely altered; unaltered mafic minerals are rare, and calcite, chlorite, and locally zeolites permeate the groundmass.

At the bottom of the Gamma Ridge pile in the gorge of Dusty Creek, greenish-gray volcanic tuff-breccias (figs. 22, 23) are interbedded with gray nonvolcanic breccias (fig. 24) and conglomerates, some of which closely resemble the monolithologic intrusive breccias (figs. 17, 18) on Grassy Point and near the Cool stock.

The tuffs are generally fine grained and, like the breccias, are highly altered. They contain a few clasts of granitoid rock, quartz, biotite, and rare volcanic rock, but in general consist of an indistinct mosaic of sodic plagioclase, quartz, rare potassium feldspar, clays, and calcite. Some tuffs are rich in pyrite cubes. Whole-rock X-ray diffraction patterns indicate the presence of considerable sericite and kaolinite. On the south slopes of Gamma Peak, large areas of tuff have been altered to a white siliceous kaolinite rock.

In lower Gamma Creek are two thin layers of alttered welded tuff in which shards and flattened pumice lapilli are still visible. Phenocrysts of quartz, biotite, and muscovite suggest that the welded tuffs are rhyodacitic.

The andesite and dacite flows interbedded in the tuffs and breccias are generally dark red brown or grayish green and look like andesites and basalts; indeed, a few of the less altered phenocrysts of plagioclase are andesine or labradorite. However, the rocks

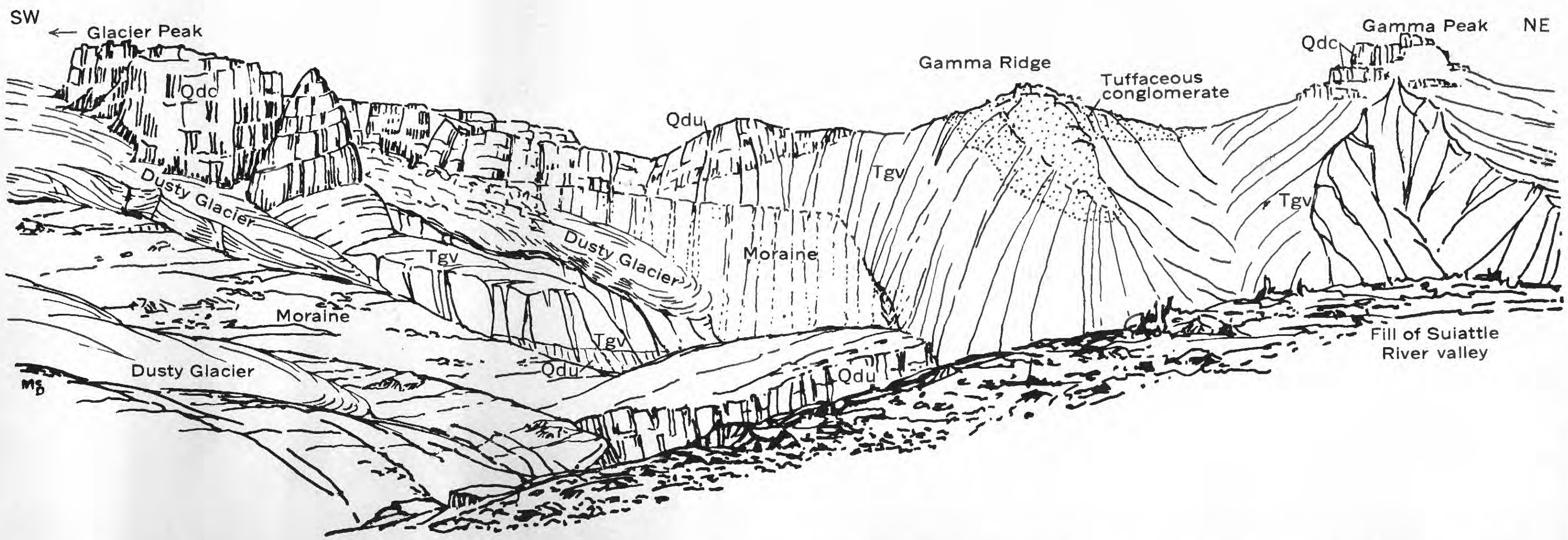

FIGURE 21.—View from the south across the head of Dusty Creek to Gamma Ridge. Sketched from several photographs. The cleaver of Glacier Peak ridge-capping lava (Qdc) on left rises about 200 feet above the tuff and breccia of Gamma Ridge. Undivided flows of the summit cone (Qdu). Volcaniclastic rocks of Gamma Ridge (Tgv).

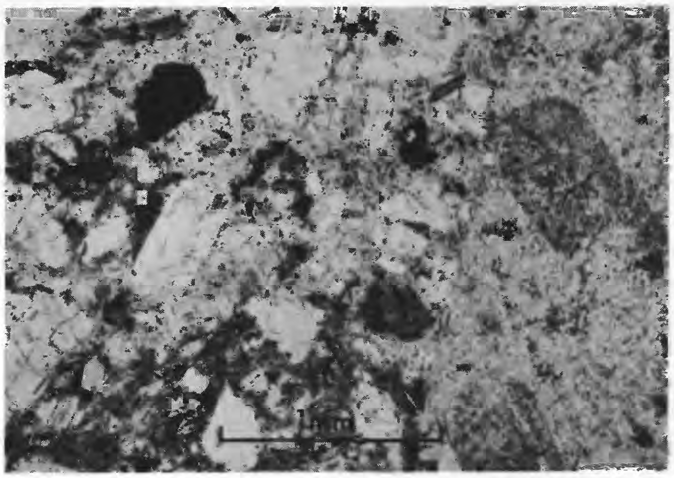

FIGURE 22.—Volcanic tuff-breccia from lower Dusty Creek Volcanic rock and mineral fragments in an indistinct altered matrix. Plane-polarized light. Specimen DFC–14–62.

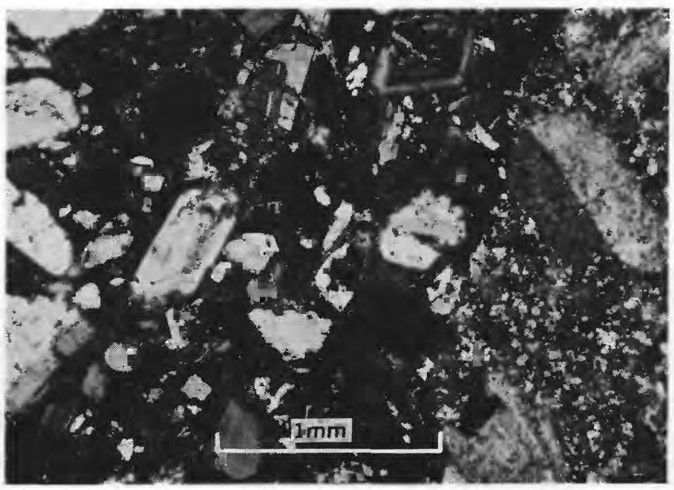

FIGURE 23.—Specimen shown in figure 22 under crossed nicols.

are altered and all that can be said about the composition (table 4 and fig. 55) of the lavas is that most range from andesite to dacite. The flows are strongly porphyritic and commonly holocrystalline; a few contain flow-alined microlites (fig. 25). The groundmass is typically a tight mesh of twinned feldspar, quartz, and a green to yellow-brown montmorillonite. Glassy rocks are commonly spherulitic. In the freshest rock, hypersthene, clinopyroxene, and hornblende occur as phenocrysts, but generally mafic minerals are entirely replaced by calcite and a green montmorillonite (fig. 25.) Small veinlets of quartz and zeolites crisscross some flows. Although the lavas of the Gamma Ridge unit look like lavas of Glacier Peak in the field, they can be distinguished in thin section by their higher degree of alteration. The possibility exists that some

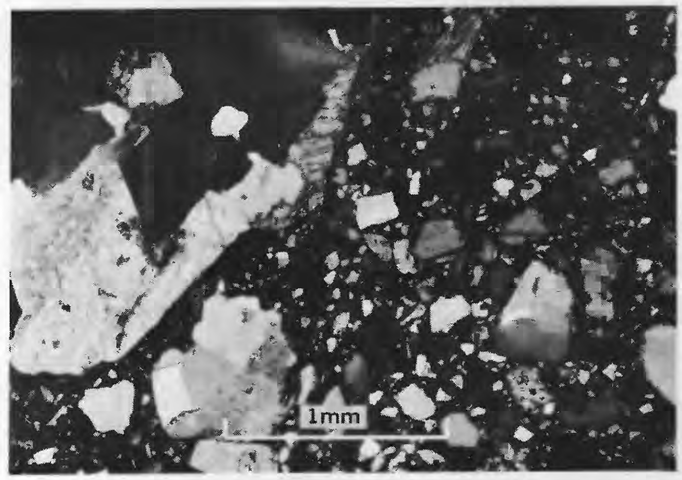

FIGURE 24.—Monolithologic (nonvolcanic) breccia composed of angular to rounded hornblende tonalite-gneiss fragments (upper left) in clastic matrix of quartz, plagioclase, and epidote. From lower Dusty Creek. Crossed nicols. Specimen DFC–13–63.

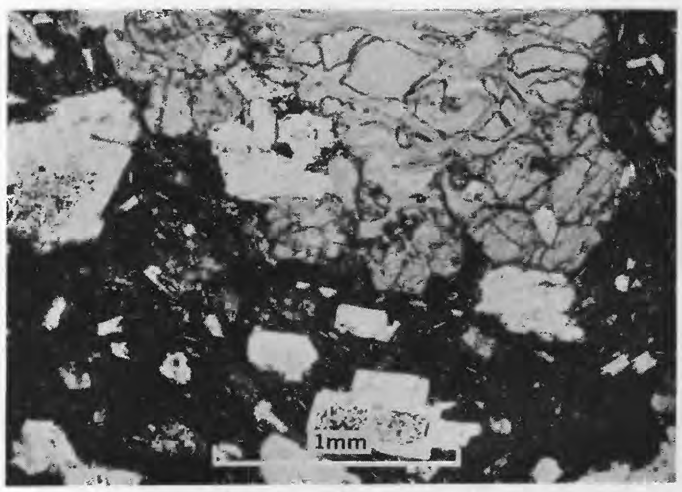

FIGURE 25.—Altered porphyritic dacite from Gamma Ridge, south tributary of Gamma Creek. Microlite-rich groundmass (black) surrounds phenocrysts of plagioclase and hypersthene (at top) that is altered to montmorillonite (grayveins). Plane-polarized light. Specimen DFC–115–62.

flows on the south side of Gamma Ridge and the ridge-capping dacite between the forks of Milk Creek might be remnants of Glacier Peak lava because they were not seen to be interstratified with altered tuffs and breccias.

The heterogeneous conglomerates that cap Gamma Ridge (fig. 21) are white to dirty gray and purple in color, are poorly bedded and tuffaceous, and are rich in well-rounded cobbles of schist, gneiss, and granitoid rocks of the basement terrain. Conglomerates composed entirely of lava clasts of unknown affinity are included in this unit; their relation to the heterogeneous conglomerates or ridge-capping Glacier Peak lavas is not known. The conglomerates as a whole clearly were derived from a mixed volcanic and basement terrain—a terrain which physiographic evidence suggests was ancestral Lime Ridge to the west.

THE WIDESPREAD ERUPTION OF GAMMA RIDGE TYPE ROCKS

Gamma Ridge eruptive rocks represent a general middle Tertiary episode of volcanism in the Washington Cascades; some of this volcanism appears to be fathered by batholiths. Eruption of Miocene and early Pliocene volcanic rocks from the magma of Snoqualmie batholith was first indicated by Fuller (1925). In the Mount Rainier area, the upper Miocene and lower Pliocene Ellensburg Formation is thought to contain extrusive equivalents of the explosively deroofed Tatoosh pluton and Snoqualmie batholith (reviewed by Fiske and others, 1963, p. 62–63). Hammond (1963, p. 203–205), however, questioned some of the evidence for a direct connection between cupolas of the batholith and effusive equivalents as first given by Smith and Calkins (1906, p. 9 and 13).

Lithologically similar volcanic rocks overlie the composite Chillwack batholith 66 miles northwest of Gamma Ridge near Hannagan Pass and were extruded between two pulses of batholith intrusion (Misch, 1966, p. 138; Tabor and Crowder, 1968, p. 21–23); they may be extrusive equivalents of the batholith.

Other extrusive rocks in the Washington Cascades that are lithologically similar to the post early Miocene rocks of Gamma Ridge are either of older or of unknown age and have not been closely linked to batholiths. Remarkably similar, but water deposited, is the Ohanapecosh Formation at Mount Rainier, and somewhat less similar is the Stevens Ridge Formation (Wolfe, 1968; Fiske and others, 1963, p. 3–17; Waters, 1961; Warren, 1941; Smith and Calkins, 1906). Of similar lithology but much less altered is the Fifes Peak Formation (Fiske and others, 1963, p. 27–30; Swanson, 1966, p. 1294).

Bedded volcanic rocks overlying the Cloudy Pass pluton on nearby Lyall Ridge (fig. 52; Libby, 1964, p. 118–119) may be of Gamma Ridge age. The Round Lake plug, a large breccia pipe and volcanic conduit of unknown age and affinity, lies a few miles west of Gamma Ridge (fig. 52; Vance, 1957, p. 288–291).

ORIGIN AND RELATION TO THE CLOUDY PASS BATHOLITH

The presence of welded tuffs and the lack of pillow lavas in the Gamma Ridge rocks points to subaerial eruption and deposition. High local relief along the basal contacts (see p. 55) indicates the terrain was mountainous.

The hypothesis that the magma from the Cloudy Pass chamber erupted as Gamma Ridge rocks (fig. 26) rests on establishing that the intrusive breccias stemmed from the batholith and that they were feeders for the Gamma Ridge rocks. The clustering of intrusive breccias near, over, and adjacent to the southern half of the Cloudy Pass batholith is the best evidence that the breccias stemmed from the batholith (fig. 12).

Two suites of chilled and (or) brecciated intrusive rocks related to the Cloudy Pass batholith in the adjacent Holden quadrangle have been described by Cater (1969). An early suite occurs as a border complex or stems from the presently exposed upper part of the batholith and a later one presumably stems from its not yet exposed core. The border complex is a broad zone of nonporphyritic to highly porphyritic andesite and dacite that occurs along the steep contact near Hart Lake. The chilled rock in this zone both grades into and is intruded by the main pluton. Cater explains most of the chilling in this broad zone not by conventional conduction but by the expansion of gases derived from the core; the gases used this zone as an escape route to the surface (Cater, 1969, p. 48). The "escape route" occurs at a steep dislocation zone between an early satellitic dike of dacite porphyry and the subsequently intruded granodiorite pluton. Of comparable age are dacite porphyry plugs near Plummer Peak that rise from the top of the granodiorite pluton and are considered possible vents. These plugs are locally replaced by sulfides, are chilled, and have a distinctive margin of *protoclastic* breccia.

The later suite of chilled rocks linked with the batholith according to Cater are lithologically and chemically similar dacite porphyry plugs that are intimately associated with highly *cataclastic* intrusive breccias. These plugs occur near the batholith in a line along Phelps Ridge and on Bonanza Peak near the aforementioned eastern border; some contain granodiorite inclusions of the Cloudy Pass batholith. The intrusive breccias on Phelps Ridge are altered and mineralized with sulfides, and some thin dikes consist entirely of pulverized material. Such rocks clearly represent a low lithostatic pressure and are considered by Cater as vents for late-stage explosive discharges of dacite magma and gas from the still partly molten core of the batholith.

Analogs of the early suite, that is, the dacite porphyry cupolas of Plummer Peak and the Hart Lake

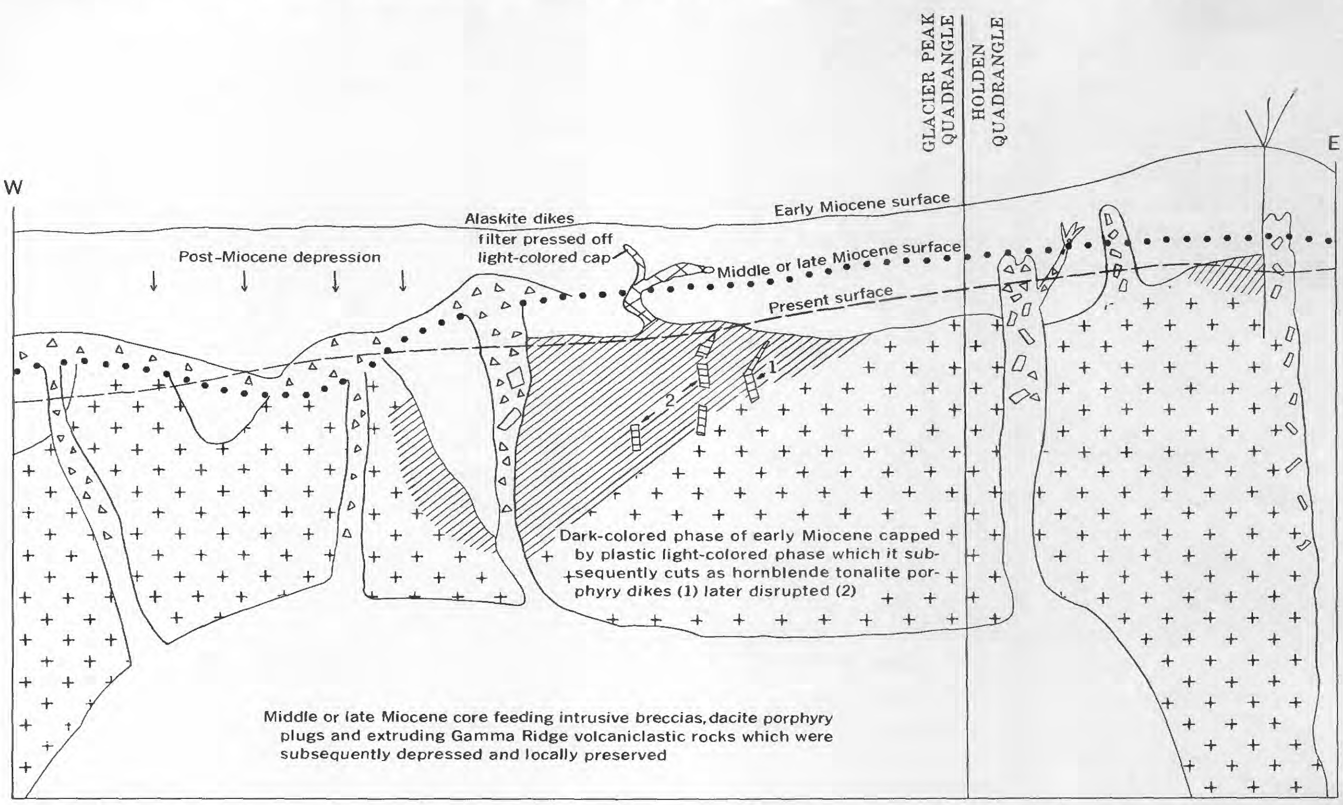

FIGURE 26.—Schematic cross section of the Cloudy Pass batholith showing its intrusive history. Holden quadrangle generalized from Cater (1969) and Cater and Crowder (1967). Illustrated is the hypothesis that middle or late Miocene Gamma Ridge rocks are fed from the batholith's core.

border zone in the Holden quadrangle, are the satellitic stocks (cupolas) in Glacier Peak quadrangle that are decidedly more plutonic; the top of the batholith apparently plunged westward and was thus emplaced under deeper cover. Analogs of the later suite of dacite porphyry plugs and associated intrusive breccias described by Cater are the intrusive breccias of the Glacier Peak quadrangle.

The largest masses of intrusive breccia in the Glacier Peak quadrangle and those which most resemble the basal parts of the Gamma Ridge pile occur on Grassy Point along the steep contacts of the batholith and near the Cool stock, one of its steep-walled cupolas. Magma and pent-up gas in the solidified core of the batholith might most easily escape along contacts of the batholith adjacent to its solid upper parts.

Gamma Ridge rocks lie on the batholith. If these eruptive rocks do stem from its lower core, the batholith must have been exposed by erosion before that core solidified (fig. 26). The time taken for the erosional deroofing can be estimated as 2 to 4 m.y. if the roof was thin, as the epizonal character of the batholith suggests. The core of the batholith could well have remained molten for this time, that is, into middle or late Miocene time.

The hypothesis that the Gamma Ridge rocks are middle or late Miocene eruptive rocks from the Cloudy Pass chamber is not, however, without its problems. Physiographic arguments to follow show that the present course of the Suiattle River was determined by diversion around the Gamma Ridge pile. Thus, if the Gamma Ridge rocks are Miocene, the river's course has been preserved in the face of continual erosion for a very long time (± 18 m.y.). The preservation of the rocks themselves, however, can be reconciled by presuming that the Gamma Ridge pile has been downwarped or downfaulted, although direct evidence for this depression is not available. If the Gamma Ridge rocks are significantly younger than Miocene (for example, late Pliocene), these physiographic difficulties are lessened, but a direct descent from the Cloudy Pass batholith would be possible only if the core of the batholith remained molten for an inordinantly long time. Without more definitive data the volcanic and volcaniclastic rocks of Gamma Ridge can only be assigned to the middle or late Miocene or Pliocene Epochs.

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LATE EPISODE OF VOLCANISM: GLACIER PEAK VOLCANO AND ASSOCIATED ROCKS

PREVIOUS WORK

Glacier Peak received little attention from geologists between the first ascent and exploratory reconnaissance at the end of the 19th century by I. C. Russell (1900, p. 134–135), who reported the mountain to be a cinder cone, and the geologic study in the fifties by A. B. Ford (1959, p. 250–331), who determined the basic history of the volcano and recognized it as a considerably eroded lava cone flanked by huge fans of volcaniclastic debris.

GENERAL FEATURES OF THE VOLCANO

Glacier Peak volcano rises magnificently above its basement of metamorphic rocks (frontispiece), and its dark-colored lava flows contrast strikingly with the lighter hues of the schist and gneiss. The volcano began to grow in a mountainous landscape considerably different from today's and continued growing into more recent time; hence its flows represent a variety of eroded forms, ranging from young, barely dissected flows in present valley bottoms to remnants of older flows carved into spurs and isolated ridge caps.

The aggregate thickness of the Glacier Peak lava flows nowhere exceeds 2,500 feet. The cone is perched on a high bedrock ridge. This is barely a third the thickness of flows standing as Mount Rainier (Fiske and others, 1963, pl. 1). The individual flows on Glacier Peak vary greatly in thickness. Columnar joints predominate in the thick flows, whereas platy or blocky joints are common in thin flows, especially those around the summit.

The predominant rock of Glacer Peak is pyroxene dacite. The dacites are dark gray to black, especially those which occur in thick flows that now cap ridges. Flows making up the summit area of the cone are commonly oxidized red or are gray with red splotches.

Little pyroclastic material is interbedded with the flows; this is somewhat surprising considering that the latest eruption(s) were predominantly pyroclastic. The most common interbeds between lava flows are coarse breccias which resemble the erosional debris and moraine that blanket many slopes of the volcano today. Such interflow breccias are best exposed along Kennedy Creek and southeast of Cool Glacier. Breccias are usually best exposed at the base of flows, and many are somewhat agglutinated, which suggests that they were derived from and overridden by the advancing front of the overlying flow. Some volcanic breccias and conglomerates which lie on the nonvolcanic basement rocks are rich in granitic and metamorphic debris and are overlain by lava. The volcano probably has been mantled by glaciers ever since it emerged, so that much of the breccia is certainly moraine. One graphic example of an interflow moraine crops out near the toe of the Kennedy Glacier (fig. 27).

THE CRATER

The crater, first recognized by Ford (1959, p. 313), lies just north of the summit; it is obscured by erosion and filled with snow and ice. The ice flows eastward out of the crater as the Chocolate Glacier (fig. 43). A considerable breach on the west rim of the crater forms the pass at the head of the Scimitar Glacier. Locally, the rocks on the north rim of the crater are highly oxidized, and some are stained a blotchy yellow, which suggests solfataric activity. The narrow pass between the north rim of the crater and the pinnacles of eroded lava known as the Rabbit Ears is also highly stained and brecciated.

DISAPPOINTMENT PEAK FLOW

On the south side of the main cone, Disappointment Peak (alt. 8,755 feet) interrupts the otherwise smooth declivity of the south slope. It is underlain by a single large and thick dacite flow (fig. 28). The hypersthene dacite flow of Disappointment Peak is uniform in appearance except for color, which ranges from light gray through hues of pink to deep red; joints break it into irregular blocks of varying size. Conspicuous red-black prisms of oxyhornblende and a higher vesicularity distinguish the Disappointment Peak dacite from most of the other dacites of Glacier Peak.

We found no flow lines in the lava of Disappointment Peak, but its uniform lithology suggests the peak is a dome that oozed down the side of the main cone. Its highly irregular jointing and its composition, characteristic of hornblende dacite domes of Lassen (Williams, 1932, p. 316; 1942, p. 155) and other Cascade volcanoes, support this contention.

On the west side of Glacier Peak, the contact between the Disappointment Peak dome and Glacier Peak flows trends directly upslope, and the dome appears to overlie and truncate the flows (fig. 28). The lowest outcrop of the Disappointment Peak dome is at 7,200 feet, 400 feet below the highest exposures of bedrock on the southwest side of the cone and well below projections of the bedrock surface from beneath the cone (see p. 59). If the lava of Disappointment Peak dome were older than most of the summit cone lavas, it could not have flowed to such a low altitude, for presumably the entire erosional level was higher prior to formation and degradation of the cone. Hence, the

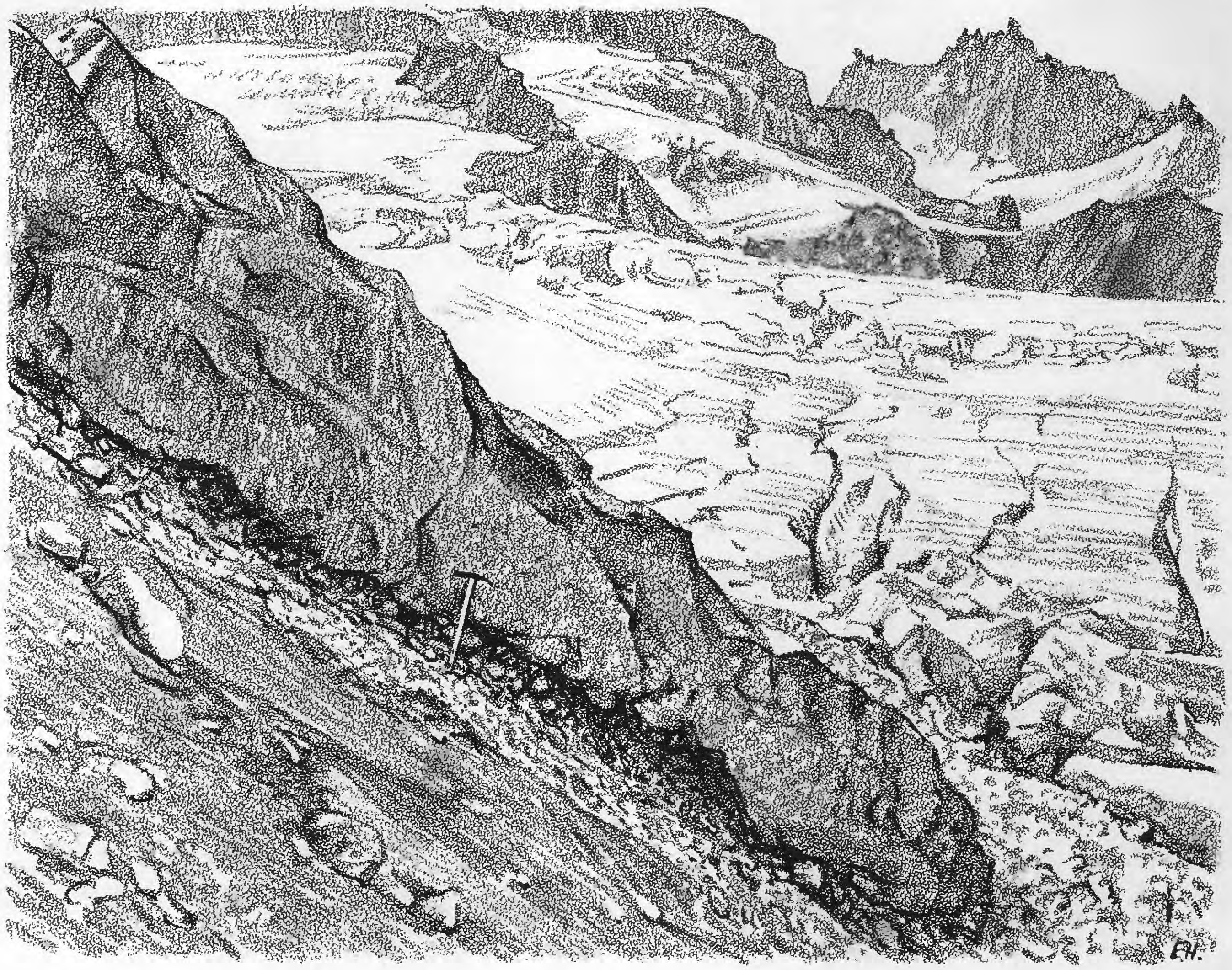


FIGURE 27.—Moraine underlying dacite flow of Glacier Peak on north side of Kennedy Glacier. More recent moraine lies immediately adjacent to the ice. Ice ax for scale. Sketched from a photograph by Ed Hanson.

dome is probably younger than most of the Glacier Peak lava flows.

STRATIGRAPHY OF THE LAVAS

"The scoffers said it couldn't be done,
The odds were so great who wouldn't.
But we tackled the job that couldn't be done,
And what do you think? It couldn't!"

—*Anonymous*

The lavas of the northernmost Cascade volcanoes have been described by several generations of workers as monotonous in lithology, mineralogy, and chemistry. Indeed, we have found no sure criteria by which the lavas of Glacier Peak can be distinguished from one another, nor could we determine a stratigraphic sequence which could be integrated over the entire volcano. Marker beds of pyroclastics are conspicuously lacking, and attempts at correlation on a lithologic basis have failed, except locally. It has been necessary to rely largely on physiography and certain assumptions set forth below to achieve the tentative sequence depicted on the map. A concise description of these same principles has been presented by Fiske, Hopson, and Waters (1963, p. 68).

The oldest flows are those that cap ridgetops or form ridges (fig. 29). Some of these are 100 to 400 feet thick; such a thickness indicates that they must have ponded in flat-floored valleys. Several of these flows have been isolated by erosion from the peak itself and the valleys beside them have been deeply carved by glaciers. The best example of the oldest is the flow(s?) forming Vista Ridge.

The next oldest flows are those that cling to the sides of present valleys but have been considerably dissected by modern streams and perhaps by Pleistocene

FIGURE 28.—Southwest side of Glacier Peak, view showing thin flows of the summit cone truncated by dark-colored dacite of the Disappointment Peak dome. Outcrops at lower right (A) are basement schists. Possible dike (B) visible against snow at base of summit snowfield. Photograph by Austin Post.

FIGURE 29.—Ridge-capping flow of Gamma Ridge at end of ridge (left) unconformably overlain by younger Glacier Peak ridge-capping flows (middle and right). View looking northeast across head of Milk Creek. Glaciated outcrops of bedrock gneiss below Ptarmigan Glacier on right, altered dacite intrusive breccia on left. Sketched by Ed Hanson from a photograph.

glaciers as well. Their bottom contacts lie close to the present drainage level, and their upper surfaces still show some of their original flow form.

Clearly the youngest flows are those that bottom present-day stream valleys and, in general, show little dissection. Ford (1959, p. 321) thought that the Vista Creek flow overlies uneroded moraines in the Vista Creek valley. The flow in the bottom of Vista Creek is the best example; but others included in this age group are flows in Kennedy Creek—more highly eroded than the flow in Vista Creek—and flows interbedded in the stratified fill in the Suiattle valley, a deposit laid down in a Pleistocene valley.

The timespan for any one of these age categories may be great, and assignment of a particular flow to a particular age is commonly questionable. The distinction between valley-clinging and valley-bottom flows is especially difficult to make.

Flows making up the cone may be younger than all the ridge-capping flows except for the very thick and subhorizontal flows that rest on Gamma Ridge volcanic rocks and form a striking cleaver at the head of Dusty Creek (see fig. 21). The risks of assigning other flows of the summit cone to the age categories outlined above are obvious, and we have treated them as undifferentiated.

The Disappointment Peak dome apparently truncates many of the thin flows of the summit cone and may be one of the youngest eruptive features, yet there is no sure way to place the dome in the sequence of age groups. Its age lies between that of the valley-clinging flows and final pumice eruptions. There are a few (young?) flows of similar lithology scattered about the summit cone.

The stratified fill of the Suiattle River valley is clearly the result of a recent event. Its age and origin are discussed in detail in a later section, but the conclusions can be stated here: It is roughly of the same age as the Disappointment Peak dome and the valley-bottom flows, but older than the overlying blanket of pumice lapilli and the fill of the White Chuck River valley, which contains these lapilli.

AGE OF THE VOLCANO

There are little data on the age of Glacier Peak. Of great interest would be studies of datable Pleistocene and Recent deposits west of the volcano that may be interbedded with its debris. These studies have not been made except in a limited way by Vance (1957, p. 292–294). We can, however, bracket the age of Glacier Peak between 700,000 and 12,000 years B.P. (before present). The maximum age was determined by measuring, with a flux-gate magnetometer, the polarity of two oriented specimens from each of five flows that range from the oldest recognized ridge-capping flow to the Disappointment Peak dome. We did not check for viscous magnetization, which in special circumstances can mask reversed polarization (Cox and Doell, 1960, p. 650). All specimens but one have normal polarity, and the magnetic poles of this one are so scattered that we suspect it was struck by lightning—an event that produces anomalous magnetization (Cox, 1961). The Matuyama reversed polarity epoch extends from 0.7 to 2.5 m.y. B.P. and includes one very short normal event (the Jaramillo) at about 0.9 m.y. B.P. (Cox and Doell, 1960, p. 650; Doell and Dalrymple, 1966, p. 1061). If activity of Glacier Peak began before the reversed epoch (before 2.5. m.y. B.P.) and extended to recent postglacial time, some flows should show reverse polarization, but they do not. Thus all the flows were probably extruded during the present period of normal polarization, that is, within the past 700,000 years. Our sampling might have missed the short reversal prior to the Jaramillo event; if so, the age could be extended to about 900,000 years. The minimum age of 12,000 years is a carbon-14 date on shells occurring with pellets of the youngest Glacier Peak pumice in lake deposits of eastern Washington (Fryxell, 1965; see also p. 41).

Some flows are older than 15,000 to 13,500 years, which is indicated by the work of Vance (1957, p. 292), who found till containing Glacier Peak dacite fragments underlying lake deposits. The lake formed in the White Chuck valley because it was dammed by an ice lobe (Vance, 1957) which last occupied the Puget Sound area between 15,000 and 13,500 years ago (Rigg and Gould, 1957, p. 357–358; Crandell and others, 1965, p. B134). The oldest flows, that is, the ridge-capping flows and the valley-clinging flows, were erupted before the main valleys were last glaciated, as was recognized by Ford (1959, p. 321). The last major advance of Cascade glaciers took place 18,000 to 21,000 years ago (Armstrong and others, 1965, p. 324); hence, the first eruptions of Glacier Peak began prior to about 18,000 years B.P. Carithers (1946, p. 31) did not recognize the older flows and stated that the cone of the volcano was built "since Pleistocene time."

The flows lying in glaciated valleys were erupted after the last major glacial advance in the Cascades in late Pleistocene time, 17,000 to 21,000 B.P., but before the pumice eruption at 12,000 years B.P. The deposition of the stratified fill in the glaciated Suiattle valley apparently took place in this same interval. Glaciers may well have occupied valleys near the high-standing volcano longer than in most other places; thus, flows in these nearby valleys may be considerably younger than 17,000 years.

There is no evidence of eruptions of Glacier Peak more recent than 12,000 years B.P. The only indication of lingering heat are three hot springs at the base of the cone.

PETROLOGY OF THE GLACIER PEAK LAVAS

In outcrop, the flow rock ranges generally from black to light gray or, rarely, brownish or greenish gray. Red varieties are not uncommon and reflect pervasive oxidation of magnetite to hematite. Plagioclase phenocrysts are conspicuous in almost all the flows; smaller phenocrysts of hornblende or pyroxene are less obvious. In the field and under the microscope, the rocks resemble those of Mount Rainier and Mount Baker.

Although the lavas of Glacier Peak display textures more typical of andesites, chemically they are dacites (table 4; fig. 30). Many flows contain quartz in very rare, partially resorbed phenocrysts and in the groundmass. As studies of the Cascade volcanoes continue, it becomes apparent that some of them are composed principally of dacite. In fact, the normative composition of the volcanic rocks around the Pacific rim in general is dacite (Chayes, 1966, p. 155). But the name andesite, based chiefly on field classifications, has lingered on (see Williams, 1932, p. 376, 1942, p. 153; Verhoogen, 1937, p. 289; Coombs, 1939, p. 1506; Fiske and others, 1963, p. 86; Crowder and others, 1966).

TEXTURAL VARIATIONS

Textures in the flows vary considerably. Flow margins and some entire flows are vitrophyric to hyalopilitic (figs. 31, 32). The majority of flows are intersertal to pilotaxitic or trachytic (figs. 33, 34). The lavas of the Disappointment Peak dome are uniformly porphyritic and hyalopilitic. Commonly the brown glass is crowded with crystallites, but intermediate-sized plagioclase phenocrysts are rare. The thin, mostly steeply dipping flows of the summit cone encompass all textural types.

Most of the thick flows now exposed as ridge cappings or as remnants on valley sides are pilotaxitic, but many are holocrystalline. Irregular patches of a

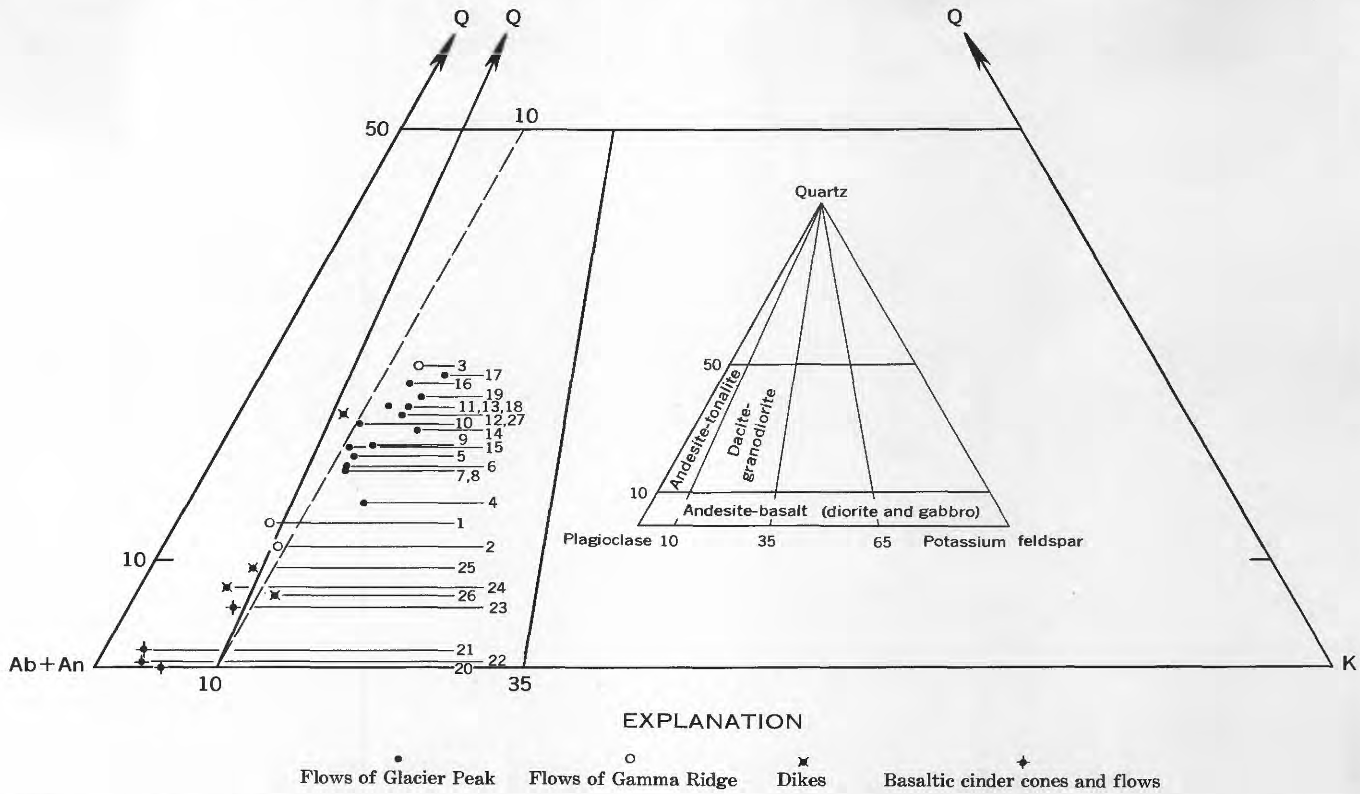


FIGURE 30.—Ternary diagram showing predominant dacite composition of Glacier Peak lavas. Numbers refer to samples listed in table 4.

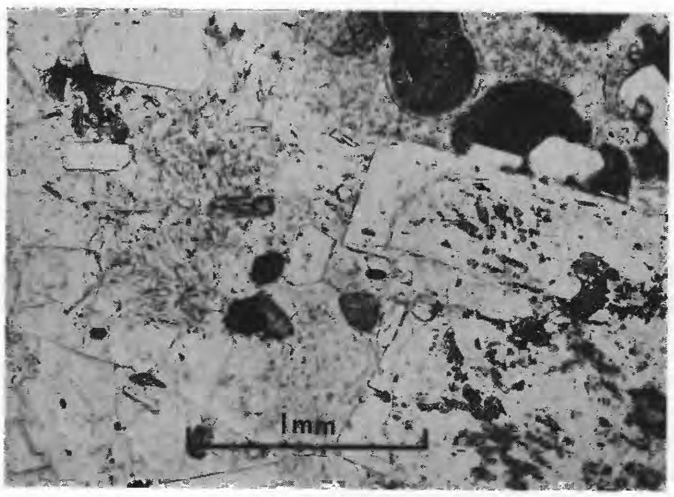


FIGURE 31.—Vitrophyric texture in dacite on ridge south of Chocolate Creek. Note spherulites. Plane-polarized light. Specimen DFC–184–62.

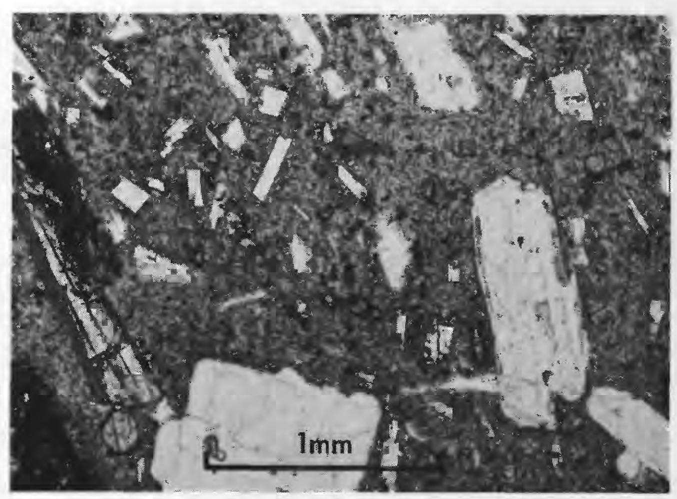


FIGURE 32.—Hyalopilitic texture in dacite from north rim of crater. Plane-polarize light. Specimen 721569AF.

TABLE 4.—*Composition of eruptive rocks*

[Samples, sawed from hand specimens (except pyroclastic rocks); small, homogeneous, and fresh, except as noted. Locations of samples are shown on plate 1, except for Samuel Botts, Gillison Chloe,

	Gamma Ridge lavas			Glacier Peak lava flows								
				Principal flows								
	1	2	3	4	5	6	7	8	9	10	11	12
Symbol on plate 1	Tgf	Tgf	Tgf	Qdc	Qdu	Qdu	Qdc	Qdc	Qds	Qdc	Qdc	Qdb
												Weight percent
SiO_2	55.4	57.0	64.2	60.3	62.1	62.3	62.3	62.4	63.4	63.9	65.0	65.3
Al_2O_3	17.5	18.0	16.1	16.6	17.3	17.6	17.6	17.6	16.7	16.5	16.5	16.5
Fe_2O_3	3.0	1.9	3.2	2.3	2.0	1.6	1.6	1.6	1.6	1.7	2.0	1.2
FeO	2.1	4.2	.84	3.0	3.0	3.2	3.3	3.4	3.2	2.4	1.9	2.9
MgO	4.9	4.9	2.3	4.1	3.0	3.0	2.8	2.9	2.9	3.4	2.4	2.4
CaO	6.5	7.0	4.0	5.7	5.1	5.3	4.8	5.2	4.9	5.0	4.4	4.2
Na_2O	3.7	3.6	3.8	4.0	4.0	4.0	4.4	4.0	4.0	3.9	4.1	4.1
K_2O	1.0	1.2	1.8	1.9	1.6	1.6	1.6	1.6	1.8	1.6	1.8	2.0
H_2O+	1.5	1.1	1.1	.85	.72	.71	.40	.58	.76	.73	.79	.81
H_2O-	3.0	.25	1.7	.27	.27	.15	.20	.14	.18	.18	.52	.01
TiO_2	.91	.78	.57	.80	.67	.67	.68	.65	.66	.67	.59	.58
P_2O_5	.22	.23	.15	.35	.17	.15	.16	.15	.15	.19	.17	.13
MnO	.12	.3	.07	.11	.11	.11	.12	.11	.11	.09	.09	.10
CO_2	.11	<.05	.06	<.05	<.05	<.05	<.05	<.05	<.05	<.05	<.05	<.05
Total	100.00	100.3	99.9	100.3	100.1	100.4	99.9	100.4	100.4	100.3	100.3	100.4
												Normative
Q	10.1	8.3	23.8	12.2	16.4	15.8	14.8	16.1	17.4	19.1	21.3	20.0
C			1.1		.1		.3	.2			.2	.3
Or	5.9	7.1	10.6	11.2	9.5	9.5	9.5	9.5	10.6	9.5	10.6	11.8
Ab	31.3	30.5	32.2	33.9	33.9	33.9	37.2	33.9	33.9	33.0	34.7	34.7
An	28.2	29.4	18.5	21.7	24.2	25.3	22.8	24.8	22.3	22.8	20.7	20.0
Wo	.8	1.6		1.8					.4	.3		
En	12.2	12.2	5.7	10.2	7.5	7.5	7.0	7.2	7.2	8.5	6.0	6.0
Fo												
Fa												
Fs	.1	5.1		2.5	3.0	3.7	3.8	4.1	3.7	2.1	1.0	3.6
Mt	4.4	2.8	1.3	3.3	2.9	2.3	2.3	2.3	2.3	2.5	2.9	1.7
Hm			2.3									
Il	1.7	1.5	1.1	1.5	1.3	1.3	1.3	1.2	1.3	1.3	1.1	1.1
Ap	.5	.5	.4	.8	.4	.4	.4	.4	.4	.5	.4	.3
Cc	.3		.1									
Total	95.2	99.0	94.7	99.2	99.1	99.5	99.4	99.6	99.4	99.4	99.0	99.4
Salic	75.5	75.3	86.2	79.0	84.1	84.5	84.6	84.4	84.2	84.3	87.5	86.7
Femic	20.0	23.7	10.9	20.2	15.0	15.1	14.8	15.2	15.3	15.0	11.4	12.7
Total plag	59.5	59.9	50.7	55.6	58.1	59.2	60.0	58.7	56.2	55.8	55.4	54.7
Percent An in plagioclase	48.6	49.1	36.7	39.0	41.7	42.8	37.9	42.3	39.8	40.8	37.4	36.7
												Trace element
Ba	500	500	700	1,000	500	700	500	500	700	700	700	500
Be	0	<1	<1	<1	<1	<1	1.5	<1	<1	<1	<1	<1
Ce	0	100	0	150	100	100	0	0	0	100	0	0
Co	30	30	15	20	15	20	20	15	15	15	15	15
Cr	200	150	70	150	70	70	50	50	50	100	50	30
Cu	70	30	15	70	30	70	15	20	30	20	30	10
Ga	15	15	15	15	20	20	15	15	15	15	15	7
La	0	0	0	50	0	0	0	0	0	30	0	0
Mo	0	<3	0	3	3	3	0	3	3	<3	<3	3
Nb	0	3	0	5	3	3	0	3	5	3	5	3
Ni	100	150	50	100	50	30	50	100	50	70	30	20
Pb	0	15	0	200	20	100	0	150	30	30	15	10
Sc	30	20	20	20	15	15	20	15	15	10	10	15
Sn	0	0	0	7	0	7	0	7	0	0	0	7
Sr	1,000	1,500	700	200	1,000	1,000	700	1,500	1,000	1,500	1,500	700
V	300	150	150	150	150	150	200	150	150	100	100	100
Y	20	15	20	20	20	20	20	15	15	10	10	15
Yb	2	15	2	15	2	3	2	1	1.5	1	1	1.5
Zr	150	200	150	200	200	200	150	200	200	200	150	200

[1] Semiquantitative spectrographic analysis in parts per million. Results are reported in percent to the nearset number in the series 1, 0, 7, 0.5, 0.3, 0.2, 0.15, and 0.1, which represent approximate midpoints of group data on a geometric scale. The assigned group for about 30 percent of semiquantitative results will include the quantitative value. Standard sensitivities in ppm are: Ag, 1; As, 500; Au, 30; B, 10; Ba, 10; Be, 1; Bi, 10; Cd, 50; Ce, 200; Co, 5; Cr, 1; Cu, 1; Ga, 10; Ge, 10; Hf, 300; Hg, 1,000; In, 10; La, 30; Li,

1. Andesite, altered, amygdaloidal; north side lower Dusty Creek.
2. Olivine andesitic dacite; upper Milk Creek.
3. Dacite, altered; north side lower Dusty Creek.
4. Olivine pyroxene dacite; Backos Creek; medium-sized sample.
5. Pyroxene dacite; upper Sitkum Creek; phenocrysts irregularly distributed.
6. Pyroxene dacite; north side Kennedy Creek; phenocrysts irregularly distributed.
7. Pyroxene dacite; northwest Ptarmigan Glacier.
8. Replicate of sample 7.
9. Pyroxene dacite; nose of Glacier Ridge; phenocrysts irregularly distributed.
10. Pyroxene dacite; Vista Ridge; phenocrysts irregularly distributed, cut by weathered fractures.
11. Pyroxene dacite; east fork Milk Creek; phenocrysts irregularly distributed.
12. Pyroxene dacite vitrophyre; south side Vista Creek; phenocrysts irregularly distributed.
13. Oxyhornblende-hypersthene dacite; Disappointment Peak, oxidized red.
14. Oxyhornblende-hypersthene dacite; Disappointment Peak; medium-sized sample; some diktytaxitic inclusions.
15. Vitric tuff; mouth of Glacier Creek; large sample; may contain dacite inclusions.

and dikes in the Glacier Peak area

sample 17. Oxides: Weight percentages by X-ray fluorescence supplemented by methods described in U.S. Geological Survey Bulletin 1144-A Analysts: Paul L. D. Elmore, Lowell Artis, and H. Smith]

Glacier Peak lava flow—Continued		Glacier Peak pyroclastic and clastic rocks					Cinder cones and flows							
Disappointment Peak dome		Vitric tuff	Pumice		Other tuff	Suiattle fill(?)	Indian Pass cinder cone	White Chuck Cinder Cone		Lightning Creek flow	Dikes and flows			
13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Qdd	Qdd	Qvt	Overprint		--------	--------	--------	Qcb	Qcl	Qbl	Not shown on plate 1			
of oxides														
64.7	65.9	63.5	65.1	65.5	65.7	66.3	49.9	50.8	51.0	55.3	52.7	54.7	56.8	62.7
16.7	16.5	17.2	16.7	16.0	16.3	16.4	17.1	18.2	18.2	16.5	17.8	17.4	18.0	17.2
3.4	1.7	2.0	1.4	1.2	1.5	1.4	2.1	2.6	2.7	1.3	7.4	1.9	2.6	3.1
.95	2.3	2.3	2.2	1.9	2.4	2.4	5.4	5.5	5.4	5.2	.60	4.8	4.2	1.0
2.6	2.2	2.2	2.1	1.7	1.7	2.0	9.4	7.1	7.3	7.5	6.2	5.8	3.3	2.3
4.3	4.3	4.8	2.2	3.6	3.9	4.0	8.1	9.5	9.3	7.6	9.1	8.0	6.6	4.8
4.0	4.1	4.4	4.8	3.9	4.5	4.1	4.0	3.0	3.2	3.5	3.3	3.2	4.7	4.2
2.0	2.0	1.7	1.8	2.2	2.3	2.1	.60	.39	.41	.59	.85	1.0	1.5	1.3
.55	.46	.69	1.8	2.69	.38	.78	.89	.48	.63	.49	.51	.83	.51	1.1
.12	.08	.21	.43	.79	.23	.07	.61	.27	.22	.06	.14	.77	.14	1.4
.57	.54	.61	.53	.43	.61	.51	1.20	1.1	1.1	1.1	.78	.92	1.2	.51
.12	.12	.16	.13	.12	.15	.12	.39	.18	.18	.26	.29	.23	.25	.13
.11	.10	.14	.12	.07	.10	.10	.14	.14	.16	.12	.17	.12	.12	.12
<.05	<0.5	.08	<.05	--------	.09	<.05	.08	<.05	.15	<.05	.08	.16	.05	.05
100.2	100.4	100.0	99.4	99.9	100.0	100.3	100.0	99.3	100.0	100.0	100.0	100.8	100.0	100.0
composition (CIPW)														
21.0	21.3	17.7	21.8	23.7	19.5	22.0	--------	0.9	0.3	3.5	5.0	6.4	5.3	20.0
.4	.1	--------	3.2	.9	--------	.4	--------	--------	--------	--------	--------	--------	--------	.5
11.8	11.8	10.0	10.6	13.0	13.6	12.4	3.6	2.3	2.4	5.6	5.0	5.9	8.9	7.7
33.9	34.7	37.2	40.6	32.7	38.1	34.7	33.9	25.4	27.1	29.6	27.9	27.1	39.8	35.5
20.6	20.6	22.2	10.1	17.3	17.5	19.1	26.9	35.0	34.1	26.5	31.3	30.2	23.6	23.0
--------	--------	--------	--------	--------	.1	--------	4.3	4.6	4.1	4.0	4.8	2.9	3.1	--------
6.5	5.5	5.5	5.2	4.2	4.2	5.0	5.6	17.7	18.2	18.7	15.4	14.4	8.2	5.7
--------	--------	--------	--------	--------	--------	--------	12.5	--------	--------	--------	--------	--------	--------	--------
--------	--------	--------	--------	--------	--------	--------	3.9	--------	--------	--------	--------	--------	--------	--------
--------	2.1	1.8	2.2	1.9	2.4	2.6	1.5	6.4	6.2	6.9	--------	6.0	3.8	--------
1.8	2.5	2.9	2.0	1.7	2.2	2.0	3.1	3.8	3.9	1.9	.2	2.8	3.8	2.1
2.2	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	7.2	--------	--------	1.6
1.1	1.0	1.2	1.0	.8	1.2	1.0	2.3	2.1	2.1	2.1	1.5	1.8	2.3	1.0
.3	.3	.4	.3	.3	.4	.3	.9	.4	.4	.6	.7	.6	.6	.3
--------	--------	.2	--------	--------	.2	--------	.2	--------	.3	--------	.2	.4	--------	--------
97.3	99.8	98.9	97.1	96.5	99.1	99.4	82.0	98.5	98.8	99.4	91.9	97.9	99.3	95.8
87.7	88.4	87.1	86.3	87.7	88.7	88.6	64.3	63.6	63.9	65.2	69.2	69.5	77.5	86.6
11.8	11.4	12.0	10.8	8.9	10.6	10.9	34.1	34.9	35.3	34.1	30.1	28.7	21.8	10.8
54.4	55.3	59.4	50.7	50.0	55.6	53.8	60.8	60.4	61.2	56.1	59.2	57.3	63.4	58.5
37.7	36.4	37.3	20.8	34.6	31.5	35.4	43.4	58.1	55.8	47.2	52.8	52.8	37.3	39.3
content [1]														
700	700	700	700	--------	700	700	500	150	200	700	500	500	700	500
<1	<1	0	0	--------	0	<1	0	0	0	0	0	0	<1	0
0	100	0	0	--------	0	0	0	0	0	0	0	0	0	0
20	15	15	15	--------	15	15	70	50	50	50	50	50	10	30
50	50	30	20	--------	30	20	700	500	300	700	150	300	300	150
20	20	15	7	--------	10	15	50	50	50	50	100	50	15	50
15	15	15	15	--------	10	15	15	10	15	15	15	15	15	15
0	0	0	0	--------	0	0	0	0	0	0	0	0	0	0
3	3	0	0	--------	0	3	0	0	0	0	0	0	0	0
3	3	0	0	--------	0	7	0	0	0	0	0	0	0	0
30	30	30	20	--------	30	30	700	150	150	500	50	70	15	50
15	200	0	0	--------	0	15	0	0	0	0	0	0	0	0
15	15	20	15	--------	15	10	30	50	50	30	70	30	15	30
0	7	0	0	--------	0	0	0	0	0	0	0	0	0	0
1,000	1,000	700	700	--------	500	1,000	1,500	700	700	1,000	1,500	1,000	1,000	1,000
150	150	150	7	--------	150	100	500	200	700	500	700	500	300	150
15	15	20	20	--------	20	15	30	30	30	30	20	20	15	30
1.5	1.5	2	2	--------	2	2	3	3	3	3	3	2	1.5	3
200	200	100	150	--------	200	200	150	100	100	200	150	100	100	200

500; Mo, 5; Nb, 50; Ni, 5; Pb, 10; Pd, 3; Pt, 10; Re, 50; Sb, 100; Sc, 1; Sn, 20; Sr, 10; Ta, 400; Te, 1,000; Th, 500; Tl, 50; U, 500; V, 10; W, 500; Y, 10; Yb, 1; Zn, 200; and Zr, 10. Elements looked for and not found are: Ag, As, Au, Bi, Cd, Ge, Hf, Hg, In, Li, Pd, Pt, Re, Sb, Ta, Te, Th, Tl, U. W, and Zn. Analysts, I. H. Barlow and Chris Heropoulos.

16. Hornblende dacite pumice; upper Suiattle River; large sample; slightly weathered.
17. Hornblende dacite pumice; mouth of Phelps Creek, Holden quadrangle. From Czamanske and Porter (1965).
18. Pyroxene pumaceous tuff; upper Suiattle River; crumbly; layered; large-sized sample.
19. Pyroxene dacite breadcrust bomb; north of Disappointment Peak.
20. Olivine basalt; Indian Pass cinder cone; feeder dike.
21. Olivine basalt; White Chuck Cinder Cone; flow; medium-sized sample; slightly weathered; phenocrysts irregularly distributed.
22. Olivine basalt; White Chuck Cinder Cone; cinders.
23. Olivine andesite; mouth of Lightning Creek.
24. Pyroxene andesite; north of Reflection Pond on Cascade Crest; medium-sized sample; oxidized red.
25. Pyroxene andesite; on Cascade Crest at head of Lightning Creek; some small inclusions.
26. Andesite; upper Napeequa River, Northeast of Tenpeak; medium-sized sample; slightly weathered.
27. Hornblende dacite; 2 miles south of Mackinaw Shelter on ridge crest west of north fork of Sauk; medium-sized sample; slightly weathered.

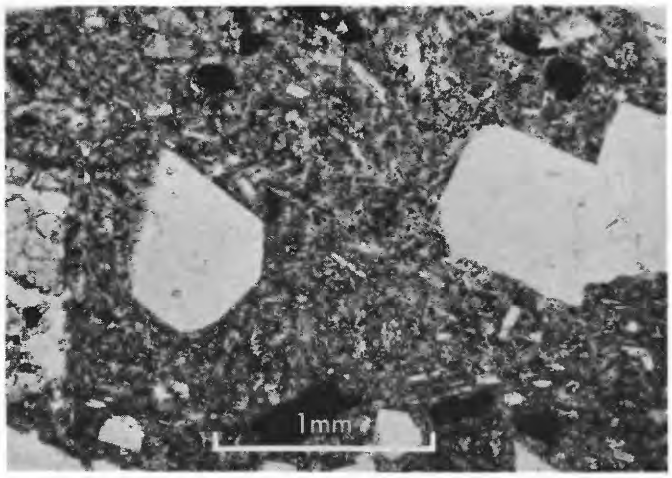


FIGURE 33.—Intersertal texture in dacite from south of upper Suiattle River. Plane-polarized light. Specimen RWT–188–62.

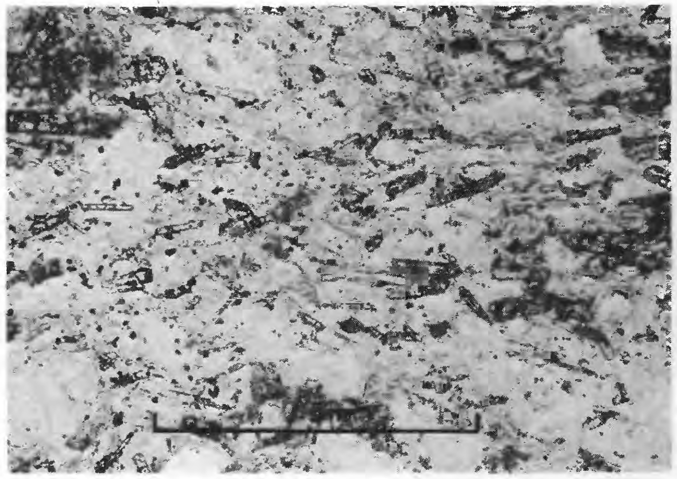


FIGURE 34.—Flow-banded pilotaxitic texture in dacite from flow capping Vista Rige. Plane-polarized light. Specimen DFC–220–61.

holocrystalline mesostasis of sodic feldspar and (or) alkalic feldspar, quartz, and scattered flakes of pale-brown biotite are characteristic of these flows (figs. 35, 36). These patches appear devitrified, but as similar patches occur in flows of all ages, they may not be time dependent. Perhaps they are related to conditions during cooling, such as local accumulations of volatiles. Similar holocrystalline patches are common in the flows of Mount Rainier (C. A. Hopson, oral commun., 1965).

MINERALOGY

QUARTZ

The ubiquitous occurrence of partially resorbed quartz crystals (fig. 37) makes a xenocrystic origin unlikely. In the lavas bearing the holocrystalline groundmass patches, resorbed quartz phenocrysts are commonly surrounded by a halo of holocrystalline material similar to the patches, which suggests that the quartz was reacting with the melt in situ. In a few flows, partially resorbed quartz is surrounded by reaction rims of small crystals of pyroxene. X-ray diffraction studies indicate cristobalite is present in the groundmass of the lavas, but it was not identified in thin section except in inclusions.

PLAGIOCLASE

Considerable attention has been given to plagioclase in the flows of Mount Rainier by Coombs (1936, p. 175–180). He described three habits of plagioclase, and his classification can be applied to the plagioclase in Glacier Peak lavas: (1) Large glomeroporphyritic clots, commonly welded together by a common rim zone, (2) smaller intermediate-sized phenocrysts composed of single crystals, and (3) tiny groundmass crystals down to microlite size.

The conspicuous plagioclase phenocrysts in individuals and clusters (fig. 38) generally range in length from 0.5 to 2.0 mm (millimeters). Intermediate-sized plagioclase phenocrysts in pilotaxitic rocks are from 0.1 to 0.25 mm long. Larger glomeroporphyritic clots, particularly prominent in gray lavas, are 3 to 5 mm across. In most flows, the plagioclase phenocrysts are polysynthetically twinned and show oscillatory zoning, but the overall compositional differences between adjacent zones is small. Cores contain as much as 20 percent more anorthite than rims, although in a few lavas, especially those of Disappointment Peak, reverse zoning has produced rims nearly as calcic as the core. Most of the plagioclase [2] in Glacier Peak flows is An_{35-48}.

[2] Extinction angles in plagioclase were measured in crystals cut perpendicular to (001) and (010), and the compositions were inferred from curves for high-temperature optics constructed from data by Slemmons (1962). In pracitce, the extinction angle of a zoned crystal was measured when the whole crystal was at its darkest position of rotation, which gave a rough average composition. Structural state was found to be disordered (high-temperature) by universal-stage study of two specimens, according to the method of Slemmons (1962).

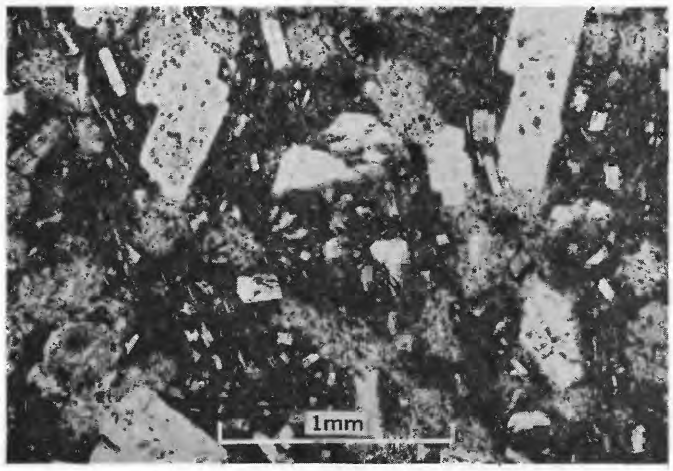


FIGURE 35.—Patches of fine-grained holocrystalline groundmass in flow of dacite from side of Glacier Ridge. Plane-polarized light. Specimen DFC–116–61.

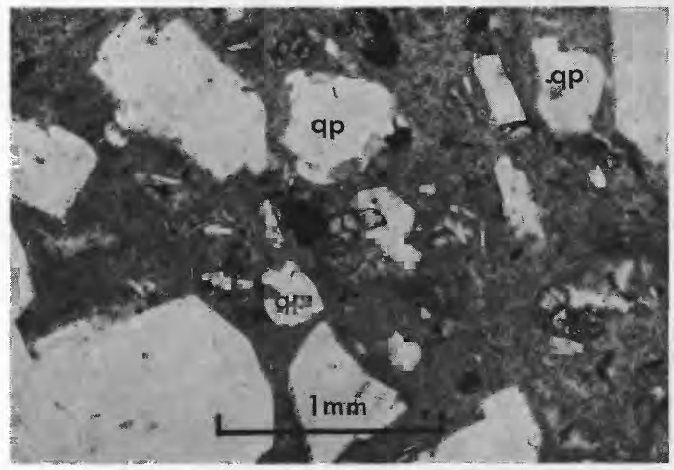


FIGURE 37.—Unusually abundant resorbed quartz phenocrysts (qp) in dacite from west side of Glacier Peak. Plane-polarized light. Specimen DFC–96–61.

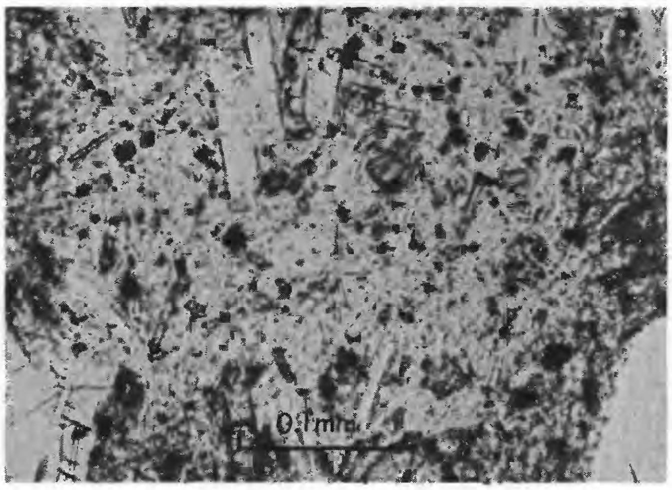


FIGURE 36.—Specimen DFC–220–61 (dacite in fig. 34) showing holocrystalline mesostasis of sodic feldspar and quartz with small biotite flakes (circular black spots with indistinct margins). Plane-polarized light.

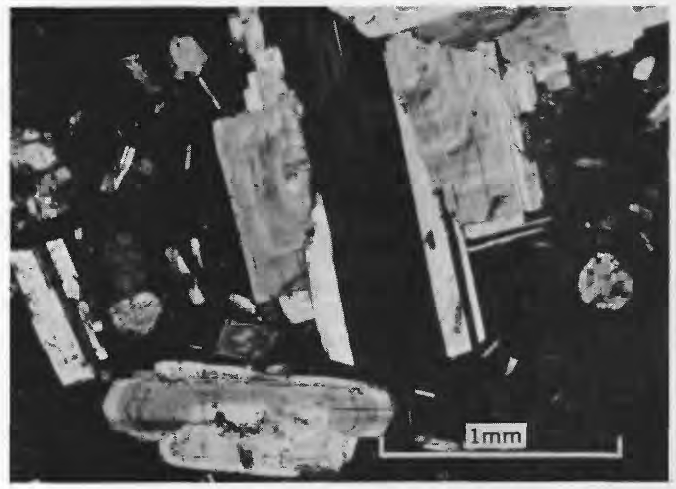


FIGURE 38.—Oscillatorily normally zoned plagioclase phenocrysts, both individuals and glomeroporphyritic clots in dacite. Crossed nicols. Same specimen as shown in figure 37.

PYROXENE

The predominant mafic silicate in most of the flows is hypersthene. It occurs as sparse euhedral phenocrysts as much as 2 mm long and as common but scattered crystals 0.1 to 0.3 mm long. More rarely it occurs as tiny prisms in the groundmass. Larger phenocrysts are here and there rimmed with clinopyroxene grains, and one crystal of hypersthene was observed with a clinopyroxene overgrowth. Measured $2V_x$ indicates the hypersthene has a composition of about En50–70 (total range of $2V_x$: 50°–90°; $n_z<1.73$), using a curve of Deer, Howie, and Zussman (1963, v. 2, fig. 10, p. 28).

In strongly oxidized rocks, normal hypersthene, with Z parallel to the c axis or to the elongation of the grain, is irregularly zoned on edges and in cracks to a hypersthene with Y parallel to c. This oxidized(?) hypersthene has a higher birefringence, slightly stronger absorption, and a somewhat smaller $2V_x$ (40°–50°) than the normal hypersthene. Lacroix (1910, p. 765) described a similar hypersthene which he named B-hypersthene. Oxidized hypersthene with an unusually small $2V$ has also been reported by Lewis (1960).

Monoclinic hypersthene is absent in Glacier Peak lavas, although it has been reported from rocks of several other Cascade volcanoes (Mount St. Helens, Verhoogen, 1937, p. 284; Mount Rainier, Fiske and others, 1963, p. 88; and Mount Baker, Coombs, 1939, p. 1503). The lack of clinohypersthene in the rocks from Glacier Peak was first noted by Ford (1959, p. 272).

Clinopyroxene is most abundant as small phenocrysts 0.1 to 0.3 mm long, and small prisms in the groundmass of pilotaxitic and trachytic rocks. Aggregates of clinopyroxene, and more rarely hypersthene, which pseudomorph amphibole are common. In some rocks the pyroxene of these pseudomorphs occurs as large discontinuous skeletal crystals set in a matrix of plagioclase—a combination which looks deceptively like a small plutonic xenolith. Optic axial angles of the clinopyroxene generally lie between 54° and 58° (range 45°–64°), which indicates a calcic variety (Deer, Howie, and Zussman, 1963, v. 2, p. 132). Ford (1959, p. 258–271) indicated that most of the clinopyroxene in the Glacier Peak lavas is augite, and this is consistent with optical properties observed by us.

HORNBLENDE

Deep red-brown or dark-brown oxyhornblende phenocrysts (or opaque pseudomorphs after them) are conspicuously abundant in the dacite of the Disappointment Peak dome and in similar-appearing dacite flows which, for the most part, are scattered about the summit cone. In other flows, oxyhornblende, although present, is sparse. Oxyhornblende is commonly pseudomorphed by aggregates of clinopyroxene, hypersthene, magnetite (fig. 39), and rarely, actinolite.

Small amounts of brown hornblende ($\parallel Z$=strongest absorption; $Z \wedge c > 10°$) rimmed with opaque granules occur in flows of all ages, whereas greenish-brown to olive-brown (Z) hornblende phenocrysts are relatively abundant in younger glassy flows. An exception to this is the cliff-forming flow which is shown as a valleyside clinging flow in the upper reaches of the Suiattle River, and which contains olive-green hornblende. No greenish hornblende has been found in the oldest ridge-capping flows.

Out of nine samples of dacite containing green hornblende, seven have a silica content of more than 64.0 percent, in contrast to the predominant range for silica of 62.0 to 65.5 percent in all the flows. The green hornblende is also abundant in some of the youngest pyroclastic rocks (for example, the tuff of the White Chuck River valley and the yellow pumice discussed later), which also have a silica content of more than 65.0 percent.

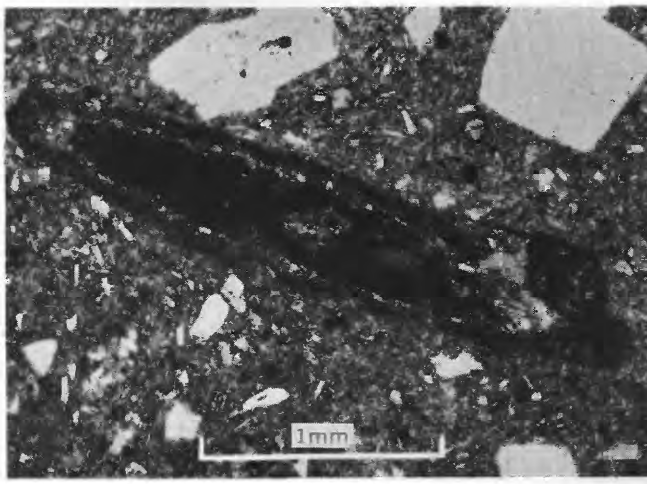


FIGURE 39.—Magnetite pseudomorph of hornblende rimmed by pyroxene. Dacite from upper Vista Creek. Plane-polarized light. Specimen RWT–343–61.

The crystallization of intratelluric hornblende in lavas of Mount Rainier has been ascribed to higher-than-normal water-vapor pressure (Fiske and others, 1963, p. 89). The higher pressure can occur if the water is trapped by rapid chilling. Williams (1942, p. 155) also found hornblende in rapidly chilled rocks at Crater Lake:

> Hornblende andesite lavas are rare throughout the High Cascades. In the Crater Lake region, only two examples are known. Between Mount Mazama and Mount Shasta, only one occurrence is known, namely in the dome on the summit of Rustler Peak. On Mount Shasta, hornblende andesite is developed in the dome of Black Butte. On Mount St. Helens, the plugs (domes) invariably carry hornblende. In brief, hornblende andesite lava is almost confined to quickly chilled viscous domes erupted from parasitic vents.
>
> On the other hand, hornblende is extremely abundant in the basic scoria flows of Mount Mazama. It is also common in the dacite pumice and almost ubiquitous, though in small amount, among the glassy dacite domes and flows erupted from the Northern Arc of Vents. Yet among the holocrystalline, pilotaxitic dacites of Mazama, the mineral is scarcely ever present. Hence, rapid cooling appears to be necessary to prevent complete resorption of the mineral in magmas of shallow origin.

In general, these remarks apply also to the occurrence of hornblende at Glacier Peak; we find that hornblende is most abundant in the Disappointment Peak dome, in the younger glassy flows, and in rocks with a silica content greater than 64.0 percent. The higher silica content, by making the lavas more viscous, may also have hindered replacement of the hornblendes by opaque ore minerals.

OLIVINE

Olivine is sparsely present in most of the flows. Crystals are commonly euhedral and fresh appearing, but many are rimmed by an extremely fine-grained aggregate of pyroxene and opaques. Not uncommonly there is a concentration of plagioclase laths or a holocrystalline mesostasis of plagioclase around olivine crystals. More rarely the olivine is partially replaced by plagioclase and phlogopite and, in a few lavas, by a moderately birefringent green montmorillonoid. Optic axial angles ($2V_Z$) for the olivine generally range from 88° to 94° (total range 82°–101°), which indicates a composition of Fo_{76-88}. Partially resorbed quartz and olivine occur together in some rocks.

BIOTITE

One flow contains brown biotite of possible phenocrystic origin. The small crystals are partially resorbed and rimmed with an opaque mineral, green biotite, and chlorite. Biotite is relatively common as tiny pale-brown flakes in holocrystalline groundmasses and in the "devitrified" patches. It is associated with opaque minerals in pseudomorphous aggregates of pyroxene after amphibole. In a few flows it also fills tiny fractures along with quartz.

OTHER MINERALS

Opaque minerals, mostly magnetite, are abundant in the groundmass of all lavas and occur as inclusions in the mafic phenocrysts. In the red flows, the magnetite is oxidized to hematite. Small amounts of apatite (rarely manganoapatite) and zircon also occur.

INCLUSIONS

The most common inclusions are medium-grained gabbroic rocks a few millimeters across that are thought to be glomeroporphyritic clots. These inclusions are generally more mafic than the host. They consist of subhedral to euhedral zoned plagioclase, clinopyroxene and (or) orthopyroxene and rare olivine, all of which are generally about the size of the largest phenocrysts in the host rock. Some of the larger inclusions are locally subophitic (fig. 40). These gabbroic inclusions are not plutonic equivalents of their volcanic host, because small angular patches of glass or a mesostasis of sodic plagioclase and cristobalite (?) are common between the larger crystals; the glass and mesostasis represent interstitial melt trapped between the larger crystals, which indicates that the inclusions are accumulates.

The most distinctive inclusions are porphyritic, hyalo-ophitic, and diktytaxitic (fig. 41); they are thought to be cognate crystal accumulates torn from the walls of feeder conduits. They occur in rounded fragments as much as 6 inches across (much larger than the gabbroic inclusions) and are generally light gray. The inclusions are most abundant in the hornblende dacite of the Disappointment Peak dome. Though mineralogically like their host, these inclusions are commonly richer in mafic minerals but nevertheless contain considerable intergranular cristobalite. The plagioclase laths are about the same size as intermediate-sized phenocrysts in the enveloping lava, although this size range is rare in lavas of the Disappointment Peak dome, which contains the greatest

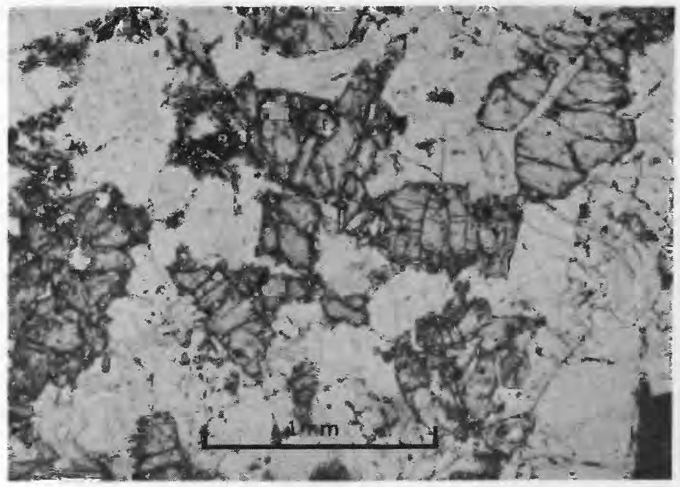


FIGURE 40.—Medium-grained inclusion with subophitic texture in dacite on ridge north of Gamma Creek. Note small areas of intersertal texture between larger crystals at upper left, which indicate a volcanic affinity. Plane-polarized light. Specimen RWT–12–63.

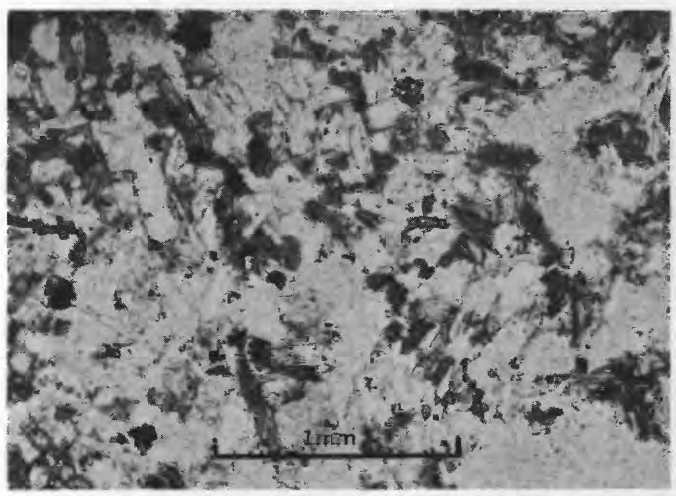


FIGURE 41.—Diktytaxitic inclusion from dacite of Disappointment Peak dome. Plagioclase is considerably finer grained than that shown in figure 40. Plane-polarized light. Specimen RWT–130–61.

abundance of diktytaxitic inclusions. Inclusions of similar appearance and origin are common in the lavas of Crater Lake (Williams, 1942, p. 134–135). The medium-grained gabbroic inclusions and glomeroporphyritic clots of plagioclase containing the largest phenocrysts (fig. 40) probably crystallized in a deep magma chamber. The porphyritic and diktytaxitic inclusions containing intermediate-sized phenocrysts may have been torn from the walls of a near-surface chamber or vent. The inclusions derived from near-surface chambers are larger than those from chambers at greater depth, perhaps because of less trituration. The larger inclusions may have been drained of interstitial liquid during times of magma withdrawal from the higher chambers; thus, they acquired a diktytaxitic texture.

Rare small inclusions of volcanic rock that are distinct from the host probably are fragments of earlier lavas. Certain pre-Glacier Peak inclusions have been identified in only one flow, an obsidian just below the Cool Glacier which contains numerous fragments of the underlying quartz diorite and of nearby Gamma Ridge volcanic rocks.

ALTERATION

Considering the volcano as a whole, the alteration is spotty and probably resulted from fumarolic activity. Around the summit crater, lavas are stained red and yellow. Carbonate partly replaces the groundmass of a few rocks, and very fine grained green to brown montmorillonoid mineral partly replaces the groundmass and mafic phenocrysts in others. The montmorillonoid alteration is particularly prominent at an altitude of 5,300 feet in Vista Creek, where the rocks are covered with yellow and red-brown blotches and are somewhat brecciated. Similar alteration is detectable in thin sections from scattered places in lower Vista Creek, from near the Cool Glacier, and from the west side of Glacier Peak (north of Sitkum Glacier), where an interflow breccia is green.

PYROCLASTIC DEPOSITS AND VALLEY FILLS

The most recent eruptions of Glacier Peak volcano have been characterized by violence that may signify the expulsion of gas-rich magmas for the first time. The rise and nearly coincident crumbling of a gassy, vesicular plug is the probable source of a giant debris fan that fills the Suiattle valley, (pl. 1; fig. 42). Pumice and ash subsequently erupted lie in a widespread blanket (overprint on pl. 1; fig. 43) and are major components of a debris fan in the White Chuck valley that was built by streams and numerous mudflows. On this White Chuck fill is a cliff-forming, columnar-jointed layer of ash-flow tuff overlain by reworked pumice deposits.

All these clastic rock are obviously young; the debris fans and ash-flow tuff fill the previously glaciated canyons of the Suiattle and White Chuck Rivers, and the pumice mantles the sides and tops of present ridges. A few flows are intercalated with Suiattle fill in upper Dusty (fig. 44) and Chocolate (fig. 43) Creeks. Some of the youngest lava flows that cover the bottom of glaciated canyons or occur on the summit cone may be younger than the clastic deposits, but the volume of such young lava is small compared to the amount of the volcaniclastic debris.

FILL OF THE SUIATTLE RIVER VALLEY

A debris fan on the east side of Glacier Peak (pl. 1) extends from an apex high on the volcano (7,000 feet, fig. 42) down the Suiattle River to half a mile below the mouth of Canyon Creek (fig. 45). This great fan of unconsolidated volcanic debris has surrounded the ridge spur crossed by Chocolate Creek, filled the Suiattle River valley, and pushed the river against bedrock slopes on the east (fig. 58). The volume of the debris fan is about one cubic mile. Dusty Creek, Chocolate Creek, and to a lesser extent the Suiattle River have cut awesome canyons in the fill, mostly along its sides. In Dusty Creek strong winds sweeping past the steep cuts (fig. 42) produce dust clouds visible for miles.

The bulk of the fill debris is sand, with lesser grit and gravel; silt is not abundant. Lava clasts, a few of which are as much as several yards across, are conspicuous and fairly numerous. Bedding is discontinuous, and well-sorted or crossbedded lenses of sand a few inches or feet thick, as well as gravel-filled or sand-filled channels, attest to deposition by streams or slurries (fig. 46). Most of the unsorted and ungraded beds, many of which are 20 feet thick, are probably the products of mudflows, although a few could be moraines. The scattered large blocks of lava also indicate transport by mudflows or glaciers (Ford, 1959, p. 282).

The alternation of stream and mudflow deposits indicates that the Suiattle fill grew sporadically over a long period of time, not in a few days or weeks as envisioned by Ford (1959, p. 297). A long halt in the growth of the fill is suggested by an interfill unconformity (figs. 43, 44), which truncates lava flows and interbedded clastic debris. Ford (1959, p. 276) interpreted the unconformity in Chocolate Creek (and other similar surfaces downstream) as the "surface of a [younger] valley fill" that lies within the canyon of Chocolate Creek. In upper Dusty Creek, the volcaniclastic materials below the unconformity are stained red. Farther down Dusty Creek (near an altitude of

FIGURE 42.—Glacier Peak from the east; view shows apex of Suiattle fill (A) between Chocolate Glacier (middle left) and Dusty Creek (right foreground). The escarpment (B) shows large lava blocks and the irregular beds which dip away from the volcano at the bottom of the photograph. Interbeds (C) of lava in the fill (as shown best in fig. 44) make cliffs just to the right of the escarpment. Also visible at lower right are the white kaolinitic tuffs and breccias (D) of the Gamma Ridge unit. The Gamma Ridge rocks extend around the head of Dusty Creek and underlie the prominent dacite cleaver (E) that rises between tongues of Dusty Glacier (see fig. 21). Photograph by Austin Post.

FIGURE 43.—Glacier Peak from the east; view shows Suiattle fill between Chocolate Creek, Dusty Creek, and Suiattle River at center left. The break in slope in the fill escarpment on Chocolate Creek (A) marks the possible unconformity discussed in the text. Note the same surface occurring on the small patch of fill (B) to the left of the lower Chocolate Glacier. The light-gray slopes on the broad ridge left of the glacier are underlain by the pumice blanket which also underlies vegetated slopes on the Suiattle fill at lower right. Small remnants of this blanket (C) cling to the foreground ridge above High Pass. The breached crater of Glacier Peak lies between the highest summit on the south and the broader, lower summit on the north (right). The black lava cleaver (D) at the head of the Suiattle River lies above the Sitkum stock, which is exposed as white slabs. The gullied slopes above and to the right of the cleaver are Gamma Ridge breccias. Photograph by Austin Post.

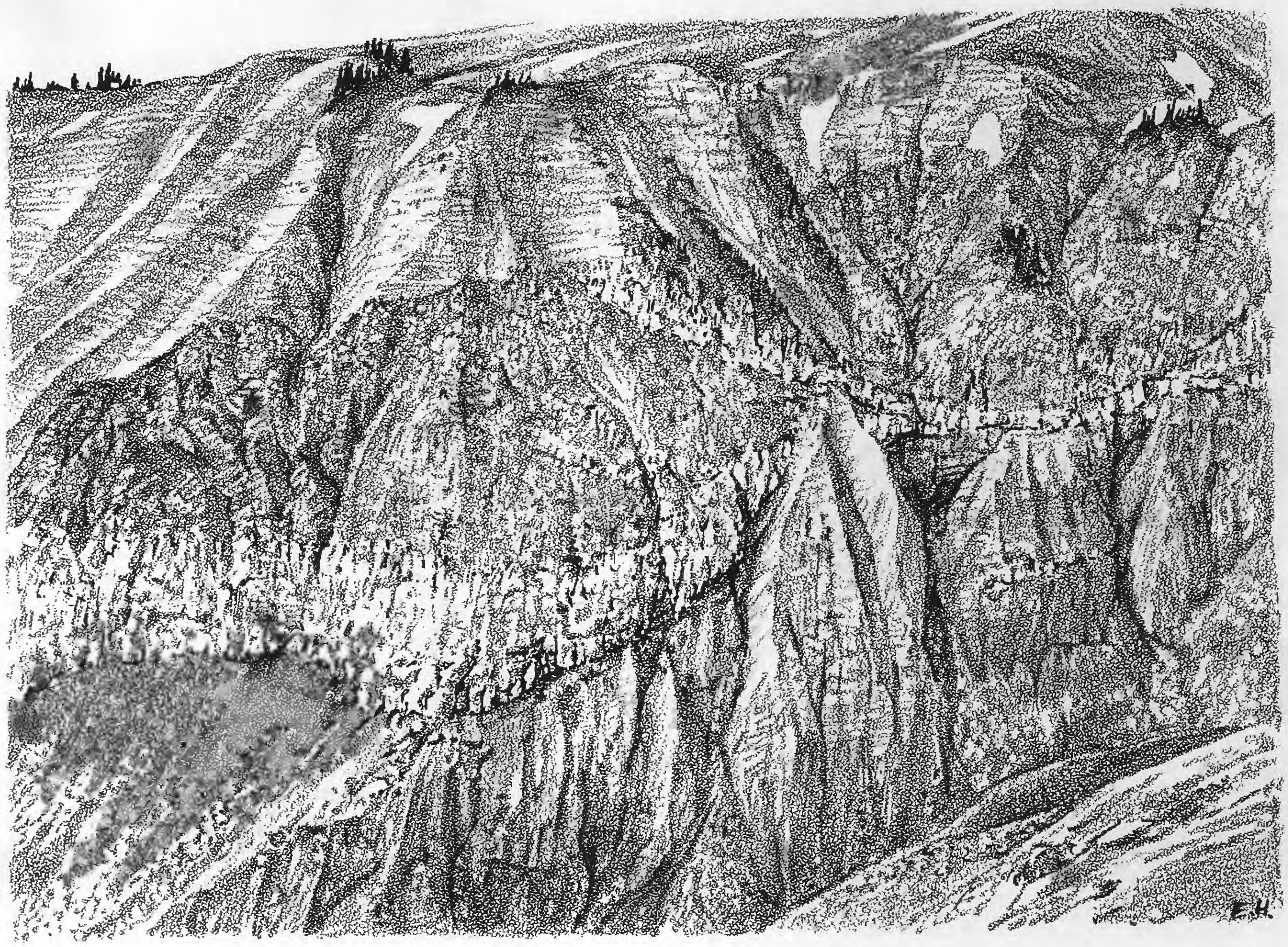


FIGURE 44.—Interbeds of lava in the Suiattle fill above upper Dusty Creek as barely visible in deep shadows on figure 42. Note the lava-filled valleys that show a complex history of erosion, eruption, and deposition. Flows in lower well-consolidated fill end abruptly at a major unconformity. Sketched from a photograph by Ed Hanson.

4,000 ft), a well-defined color change from buff or variegated in the lower part of the fill to purplish white or pink in the upper part may represent this (or another) unconformity. The establishment of the Chocolate Creek drainage on the fill and the ensuing history of erosion and renewed deposition of fill (fig. 58) also indicate a fairly long history of growth. Lack of organic debris in the fill indicates the area was barren during deposition. We believe this barrenness was due to a rigorous climate, but Ford (1959, p. 282, 293) proposed that it is evidence of rapid growth.

Most of the coarse angular clasts of the Suiattle fill are diktytaxitic dacite that contains hornblende or hypersthene and hornblende. This lava is unlike most of the lavas of the volcano. The sand of the fill consists of crystal fragments of hornblende, plagioclase, a little olivine, and glass charged with microlites. Almost all the glass occurs as angular pieces, not as shards.

Near the saddle north of Disappointment Peak above 9,500 feet, small bread-crust bombs (sample 19, table 4) are scattered through a deposit of coarse white crystal ash that may be the near-vent facies of the Suiattle fill. The ash is composed of crystal sand and angular lumps of vesicular glass very similar to the sand and rock fragments composing the bulk of the Suiattle fill. However, the refractive indices of the glass in the ash and the glass in the fill are not the same (fig. 47).

The source of the debris comprising the Suiattle fill is poorly defined. The material seems to have issued from a small area above the apex of the fan, presumably under the upper Chocolate Glacier. Such a high local source and the preponderance of a rock type unusual elsewhere in the volcano rule out the possibility that the fill is moraine, outwash, or the product of normal stream erosion of lavas exposed in

FIGURE 45.—Radar image of Glacier Peak that emphasizes the smooth constructional surface of the Suiattle fill (A). The map (B) at Chocolate Creek across the spur ridge is particularly apparent (see fig. 58). Note the smooth constructional surface of the valley-bottom flow (C) in Vista Creek.

FIGURE 46.—Bedding in Suiattle fill near mouth of Dusty Creek. Sorted beds of variable thickness are indicative of stream or thin-slurry flood deposition; lower thick unsorted bed with vague layering may be a mudflow.

the cone, even though much of the debris is indistinguishable from such sediments. That the Suiattle fill was fed by the rise and periodic crumbling of a vesicular hornblende dacite plug or spire is suggested by the vesicular character of the angular dacite clasts, the prevalence of hornblende associated with viscous extrusions elsewhere (Williams, 1942, p. 155), the evidence that the source area was small, and the fact that numerous mudflows issued repeatedly from the source area. Wise (1967, p. 347) has described a more obvious example of plug-dome collapse and resultant fan on Mount Hood, where the hornblende andesite fragments in the fill match a remnant of the dome in the crater.

Ford (1959, p. 273) considered the Suiattle fill to be a pyroclastic deposit. One thin layer of ash and pumice lapilli was found in a young part of the fill near the apex of the deposit, and Carithers (1946, p. 34) reported finding pumice overlain by gravel and sand near the mouth of Chocolate Creek. These occurrences probably represent reworked parts of the fill and the younger pumice blanket. This interpretation is supported by the fact that glass in the pumice and in the ash overlain by fill has the same refractive index as the glass in the pumice deposit overlying the fill elsewhere (fig. 47). Much buoyant pumice could have been winnowed out of the stream-sorted layers in the Suiattle fill as it was being deposited, but absence of pumice and the scarcity of shards in virtually all the deposit are not to be expected if the fill had been produced largely by pyroclastic eruptions.

A deposit of dazzling white, fairly well sorted sand clings to the north side of Dusty Creek and is tentatively classed as a remnant of the Suiattle fill. Thin cross bedded layers rich in small pumice lapilli are common. The largest clasts are pumice and some gray and brown aphanite fragments as much as 1 cm across. The bulk of fine- to medium-grained sand is composed largely of crystals of plagioclase, hypersthene, and green hornblende, and a few fragments of dirty brown and clear glass ($n=1.503\pm0.001$). These sands appear to underlie an outlier of Glacier Peak lava (Crowder and others, 1965). Yet they are too unconsolidated and unaltered to belong to the Gamma Ridge suite. Their fair sorting, bedding, and crossbedding suggest a fluviatile origin, and their rock fragments are more like the later pyroclastic eruptive rocks of Glacier Peak than its earlier lava flows. Perhaps they are plastered on the side of the canyon and are related to the Suiattle fill. The overall homogeneity which distinguishes these sands from the fill with which they are correlated might be explained if the sands were deposited in a lake formed between the fill and the side of Gamma Ridge.

PUMICE DEPOSITS

The most recent eruptions of Glacier Peak sowed pumice and ash over a large area. The extent and age of the ash has been the subject of much study because of its great usefulness for dating and correlating postglacial events over much of the Northwest (see summary by Fryxell, 1965, p. 1288). During or immediately after the eruptions of pumice and ash, a great deal of pumice was flushed down Kennedy Creek and partly filled the White Chuck valley. A thick bed of tuff was deposited by a nuée ardente on top of this fill and was quickly overlain by more pumice washed from the highlands. Except for this occurrence in the White Chuck valley, most of the pumice deposits are concentrated near the summit or east of Glacier Peak (pl. 1) and thin markedly eastward. Thickness of the deposits ranges from inches to many feet; the thickest are on the Suiattle fill and on the broad ridge south of Chocolate Creek (pl. 1). Average diameter of lapilli decreases eastward and is half an inch (some as much as 3 or 4 inches) in the Chiwawa Valley bottom, a third of an inch along the Entiat, less than a quarter of an inch in the Columbia River area, and less than a tenth of an inch on the Columbia Plateau (Carithers, 1946, p. 33).

Distinguishing primary airfall pumice from slightly reworked pumice is difficult. Indeed, the original airfall blanket on the snowclad volcano and on the crags and steep slopes of the North Cascades must have been dissected almost immediately. The remnants of pumice in saddles atop precipitous ridges (fig. 43) or on broad ridges near the volcano (pl. 1) are probably little reworked. In most lower places, however, lenticular layers of pumice which show sorting and crossbedding indicate water deposition. As discussed by Carithers (1946, p. 32–47), such fluviatile features are conspicuous in the deposits which lie in the valley bottoms of the Chiwawa and Entiat Rivers. The pumice layer overlying the vitric tuff in the White Chuck valley was examined in a 35-foot section just north of Glacier Creek. Here the fluviatile nature is shown by thin layers and lenses of pumice sand, crossbedding, and a basal layer of poorly sorted pumice sand containing rounded lava cobbles.

In the Chiwawa valley (at Trinity in roadcuts above the mill site) and in the Entiat valley near Cottonwood (Cater, 1967, written commun.), layers that are a few inches thick and are thought to represent soil were observed, but these may well represent breaks in deposition of reworked material rather than separate eruptions. In the Chiwawa and Entiat deposits, buff pumice commonly overlies gray or gray and buff pumice, and the two are separated in many places by a thin layer of pumice sand (Carithers, 1946, p. 35–37, 39–47; Wilcox, written commun., 1965). The upper buff layer contains rounded lapilli and pebbles of granitic rock, gneiss, and schist, whereas the gray lower layer contains angular lapilli only; the lower layer is air laid, the upper, reworked (Carithers, 1946, p. 32). These observations are in agreement with ours on the flanks of Glacier Peak, where weathered lapilli are buff and fresh lapilli are white to gray. Except for a few very local deposits, we have found no evidence of more than one Glacier Peak pumice eruption. The vitric tuff on the White Chuck fill (see p. 43) is the deposit of another local pyroclastic eruption, but one which was only a little younger than, or contemporaneous with, the large pumice eruption.

The pumice lapilli (samples 16 and 17, table 4) consists of highly vesicular, clear brown glass surrounding a few small crystals and crystal fragments of euhedrally zoned andesine and small prisms of greenish-brown hornblende plus less abundant hypersthene, magnetite, quartz, and cristobalite(?). No clinopyroxene occurs, even in specific gravity fractions heavier than 3.3 (R. E. Wilcox, written commun., 1965). The hypersthene (En_{63-70}) and plagioclase (An_{33-53}) (see fig. 47) are essentially similar in composition to the plagioclase and hypersthene in the Glacier Peak lavas. The abundance of greenish-brown hornblende and the lack of clinopyroxene in the pumice distinguish it mineralogically from most of the older lavas. The abundance of hornblende may be due to high water-vapor pressure that built up in the magma just before eruption of the pumice (Fiske and others, 1963, p. 89). The glass making up the pumice lapilli has a refractive index of about 1,500. This index is a little higher than the index of the glass in the Suiattle fill and lower than that in the vitric tuff of the White Chuck valley (fig. 47).

FILL OF THE WHITE CHUCK RIVER VALLEY

The debris fan that fills the White Chuck valley appears to have debouched from Kennedy Creek, and it may have dammed the White Chuck River (Ford, 1959, p. 285). The fill is overlain by a cliff-forming layer of vitric tuff which supports a conspicuous terrace mantled with pumice lapilli. Westward, the fill and overlying tuff underlie a terrace that extends downstream to the mouth of Camp Creek. Beyond this, numerous low terraces containing fragments of the tuff extend for several miles down the White Chuck valley (Vance, 1957, p. 296). The volume of the White Chuck fill to the point of reworking at Camp Creek is roughly a third of a cubic mile.

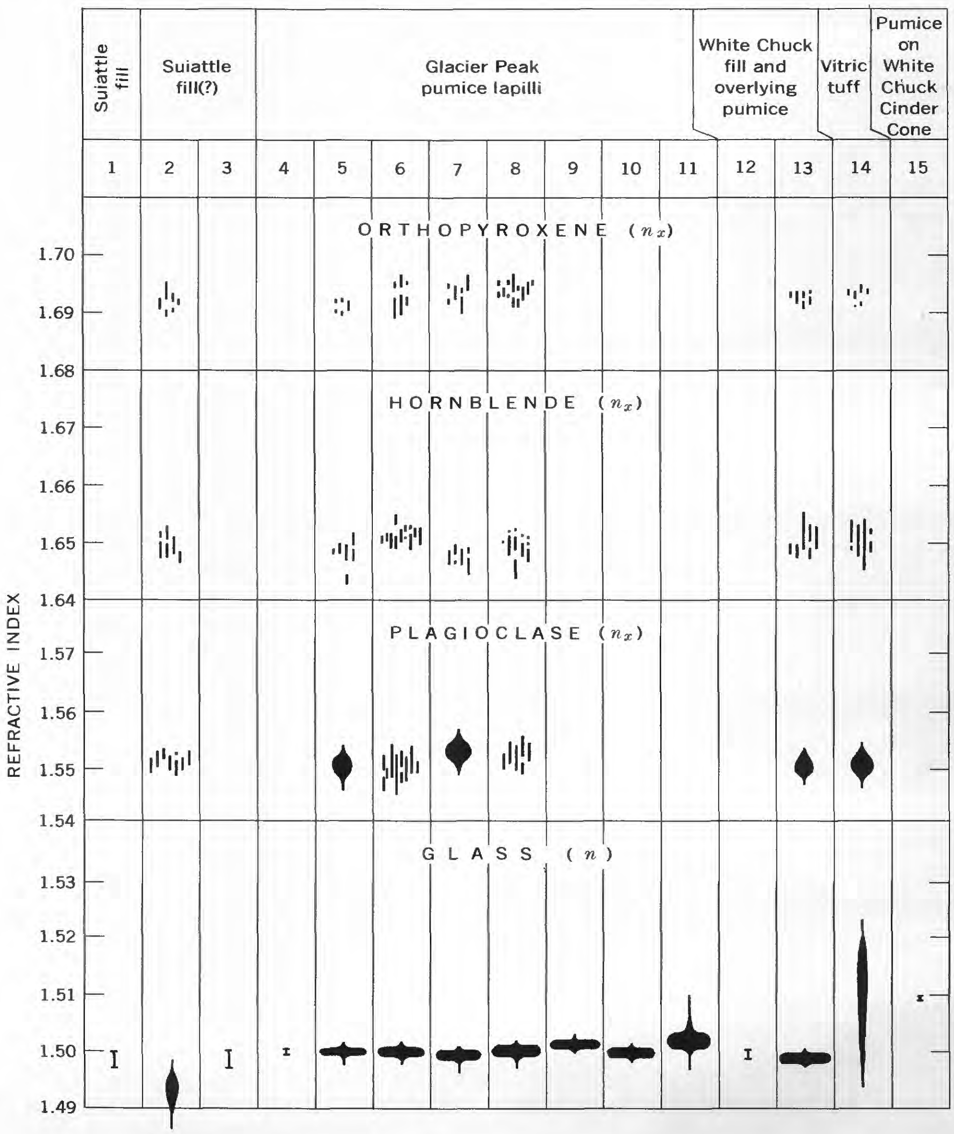


FIGURE 47.—Optical properties of minerals and glass that occur in pyroclastic ejecta and in clasts and that comprise the Suiattle and White Chuck fills, Glacier Peak volcano. Indices of refraction $n \pm 0.002$ of Nos. 1, 3, 4, 12, and 15 were determined by conventional oil immersion techniques; properties of No. 11 were summarized from Steen and Fryxell (1965, p. 880). All other data were by R. E. Wilcox (written commun., 1965), who used the focal plane masking technique (Wilcox, 1960) and the spindle stage (Wilcox, 1959); solid figures represent the estimated range and predominant refractive index as determined in random mounts of crushed fragments; each short vertical line represents index and range of a single crystal fragment.

1. Vesicular vitrophyre from Suiattle fill, Glacier Peak quadrangle, specimens RWT–127–62, RWT–126b–62, DFC–136–62.
2. Vesicular vetrophyre from 9,600-foot altitude just south of summit of Glacier Peak, Glacier Peak quadrangle; occurs with bread-crust bomb (sample 18, table 4). Specimen RWT–135–61.
3. Bedded white ash on north side of Dusty Creek, Glacier Peak quadrangle. Specimen DFC–119–62.
4. Ash and pumice lapilli on or near surface of Suiattle fill, Glacier Peak quadrangle. Specimen DFC–84–62.
5. From 4¼ miles southeast of summit of Glacier Peak, on ridge crest near summit of Tenpeak Mountain, Glacier Peak quadrangle. Specimen DFC–24–60.
6. From a recent mudflow at mouth of White Chuck River, about 17 miles northwest of Glacier Peak summit. Specimen 61P4.
7. Gray lapilli from lower part of young alluvium, Chiwawa River at mouth of Phelps Creek, Holden quadrangle 19.2 miles east of Glacier Peak summit. The glass fraction has been analyzed (Powers and Wilcox, 1964, p. 1334, table 1, column III). Specimen 56P24.
8. Yellow lapilli from upper part of young alluvium. Specimen 56P25 from same locality as specimen 56P24.
9. An upper layer of alluvium about 2 feet thick on north fork Entiat River, 5.0 miles southeast of Duncan Hill Lookout. Specimen 63W73.
10. A lower layer of alluvium about 2 feet thick, below layer of specimen 63W73 and separated from it by about 6 inches of "soil"(?). Specimen 63W74.
11. Five specimens on a line extending east from Glacier Peak, as given by Steen and Fryxell (1965, p. 879).
12. Pumice lapilli from the White Chuck fill, Glacier Peak quadrangle; specimens RWT–174–62, RWT–125–62, DFC–263, DFC–363.

Ford (1959, p. 290) found little stratification in the White Chuck fill and suggested that much of it was direct airfall material of a single eruption. However, several layers of unbedded sands as much as 20 feet thick occur in excellent exposures of the White Chuck fill, just above Kennedy Hot Spring (fig. 48). Some layers show a vague vertical-size grading which coarsens upward, and some contain abundant dacite clasts about 1 inch across and rare ones as much as 6 inches across. The poorly sorted and thick beds probably are mudflow deposits, although we observed little muddy matrix. They are interbedded with lenses of sand, silt, and conglomerate which are locally crossbedded (fig. 49) and probably were deposited by streams. No organic debris was found. The White Chuck fill thus seems to have been deposited on barren land by mudflows and streams in much the same fashion as the Suiattle fill. Its clasts, however, differ from those of the Suiattle fill; the principal clasts in the White Chuck fill are pumice lapilli (n=1.498–1.500±0.002, fig. 47), not the vesicular and much denser lava clasts constituting most of the Suiattle fill. Lenses of ash and a few cobbles of alaskite and granitoid rock were also found in several places throughout the White Chuck fill. The rare volcanic rock clasts present include vesicular dacite like that in the Suiattle fill and denser lavas of various textures (see also Ford, 1959, p. 285). Orthopyroxene, as well as hornblende and plagioclase, are conspicuous as crystal fragments in the White Chuck fill.

The high percentage of pumice (and some ash) in the White Chuck fill suggests that the ultimate source of much of the material in the fill was from pyroclastic eruptions. On the basis of refractive index and mineralogy, the pumice appears identical to that of the widespread pumice blanket described in the preceding section. Thus, the White Chuck fill may have been built by some of the first mudflows and streams which attacked the pumice that had fallen high on the cone. On the east side of the volcano, similar pumice-laden mudflows and streams added their loads to the pumice falling directly onto the already existing Suiattle fill.

FIGURE 47.—Continued

13. Yellow lapilli overlying vitric tuff (RWT–191–61), east side of White Chuck River, 4½ miles west-northwest of summit of Glacier Peak, Glacier Peak quadrangle. Specimen RWT–193–61.
14. Vitric tuff from east side of White Chuck River, 4½ miles west-northwest of summit of Glacier Peak. Specimen RWT–191–61.
15. Weathered yellow pumice from top of White Chuck Cinder Cone. Specimen DFC–80–61.

FIGURE 48.—Mudflow deposits in White Chuck fill just above river at Kennedy Hot Spring. Unsorted bed in center of photograph is about 20 feet thick.

VITRIC TUFF IN THE WHITE CHUCK RIVER VALLEY

Overlying the White Chuck fill is a layer of cliff-forming vitric tuff (pl. 1). How far below Camp Creek the layer originally extended is unknown, but large blocks of the tuff occur farther downstream in reworked parts of the White Chuck fill. Small remnants of the tuff and underlying fill that cling to the west side of the incised White Chuck River indicate that the fill must have been continuous across the valley when the tuff was deposited. As the river had not yet had time to begin incising the fill appreciably, the fill and overlying tuff are very close in age. The continued deposition of reworked pumice on top of the tuff supports this supposition.

The tuff forms well-exposed cliffs 15 to 50 feet high along the White Chuck River and its tributaries. Pumice Creek has cut a precipitous scenic gorge through it. Irregular vertical columnar joints are evident in most cliffs. The lowermost few feet is friable and poorly jointed and locally weathers back to form a recess. The tuff has weathered brown and gray in most outcrops, but near the mouth of Fire Creek, trail cuts reveal the fresh white interior. Scattered throughout the tuff are numerous pumice lapilli, a few blocks of

FIGURE 49.—Crossbedded, locally well-sorted sands and gravels in the White Chuck fill deposited by streams. Note gravel-filled channel at upper right (arrow).

dacite, and cognate fragments of tuff (Ford, 1959, p. 294). No horizontal variations in the tuff have been noted by us or by Ford (1959, p. 292), and clasts show no sign of sorting, layering, or flattening. The matrix that makes up most of the tuff consists mainly of cloudy brown glass with no hint of shards ($n \approx 1.495$–1.520; compare with other pyroclastics, fig. 47); the glass envelops crystals and crystal fragments of oscillatorily zoned plagioclase (n_x about 1.547–1.553, An_{37-48}), greenish-brown hornblende (n_x about 1.644–1.653), hypersthene (n_x about 1.690–1.694, En_{64-67}), and minor accessories including some biotite (identifications and optical properties by R. E. Wilcox, written commun., 1965). The matrix shards show no flattening or streaking. A chemical analysis (sample 15, table 4) shows that the composition is dacitic and quite similar to that of the younger dacite lavas of the peak.

Ford (1959, p. 294–295) recognized the vitric tuff as the product of an avalanche of hot pyroclastic debris such as a nuée ardente. Though warm enough to be lithified and to form columnar joints, the sheet was either too cool or too thin to weld. More rapid cooling at the base is shown by the more friable character of the lowermost few feet. The lack of any organic debris in the pumice beds above and below the tuff suggests that the terrane was barren.

The most likely vent from which the nuée ardente poured was the summit area above Kennedy Creek, yet the tuff sheet is found only on gentle slopes at the base of the cone. Either the tuff has been eroded from the steeper upper slopes, and this seems unlikely, or the glowing avalanche did not settle until it reached flats at the base of the mountain. The presence of cognate(?) tuff fragments in the tuff cannot be readily explained.

OTHER PYROCLASTIC DEPOSITS

Most of the pumice and ash deposits near Glacier Peak which have already been described have a characteristic mineralogy and refractive index of glass, and they stem from two eruptive phases in one period of relatively short duration. However, three other deposits of pyroclastic debris in the Glacier Peak area are apparently unrelated to this eruptive period, and one of these may not even come from the Glacier Peak volcano.

In the upper Suiattle valley are poor exposures of a well-consolidated but irregularly layered tuff (sample 18, table 4). Crystal fragments of plagioclase and clinopyroxene are in a brown matrix of devitrified glass. Flattened pumice lapilli are still recognizable. The layering, the lack of hornblende, and the presence of clinopyroxene serve to distinguish this rock from any other pyroclastic material at Glacier Peak. Gamma Ridge rocks occur nearby, but are all more highly altered than the tuff.

A thin layer as much as 2½ inches thick of highly weathered hornblende pumice and ash overlies basaltic cinders near the center of the eroded White Chuck Cinder Cone southwest of the volcano. This pumice resembles the Glacier Peak pumice in all respects except its glass, which has a considerably higher refractive index (No. 15, fig. 47). Judging from the refractive index, this pumice does not belong to the main Glacier Peak pumice, and its silicic composition makes it unlikely that it came from the cinder cone.

Overlying this pumice and ash at the White Chuck

Cinder Cone is a layer of white ash which may be equivalent to a widespread ash described by Carithers (1946, p. 32). He found this ash at grass roots and assumed it was the product of the youngest Glacier Peak eruption. We did not find this ash anywhere but at the White Chuck Cinder Cone (nor did Ford, 1959, p. 250–307). Perhaps it is the widespread Mount Mazama ash, reported by Fryxell (1965, p. 1288) as 6,600 years old (see p. 47).

AGE AND HISTORY

The age of the pumice deposits has been determined by a carbon-14 date of 12,000±310 years B.P. obtained on a shell fragment found "within a deposit of interbedded fine sand, silt, and small pellets of Glacier Peak ash" (Fryxell, 1965, p. 1289) which occurs on the Columbia Plateau. The date is a minimum and agrees with stratigraphic relations of ash and glacial deposits in western Washington (Fryxell, 1965). Previously reported carbon-14 dates of about 6,700 years B.P. for Glacier Peak ash have turned out to be dates of the culminating Mount Mazama eruption (Fryxell, 1965). Distinguishing the Mount Mazama ash from the Glacier Peak ash is generally facilitated by differences in the refractive index of the glass, the heavy mineral assemblage, refractive indices of the heavy minerals, and the titanium dioxide content of pumice from the two eruptions (Powers and Wilcox, 1964; Steen and Fryxell, 1965; Wilcox, 1965; Czamanske and Porter, 1965).

Glacier Peak must have had its largest pumice eruption after the peripheral canyons of the Suiattle and White Chuck were free of ice, for the pumice is incorporated in the debris fan which fills the glaciated White Chuck valley and blankets the debris fan which fills the glaciated Suiattle valley. Neither fill has been appreciably eroded by glaciers (pl. 1). These peripheral valleys certainly had ice in them during the last maximum advance of Cascade glaciers, an advance that lasted until at least 17,000 years B.P. in the North Cascades (Evans Creek Stade of the Fraser Glaciation, Armstrong and others, 1965, p. 324, 326). Close to the Cascade Crest and the heavily glaciated volcano, the upper parts of the valleys may well have retained glaciers even into the subsequent Vashon Stade, which marked considerable waning of most alpine glaciers and lasted until sometime before 13,500 years B.P.[3]

Ford (1959, p. 297–298) interpreted the vitric tuff of nuée ardente origin, the widespread pumice deposits, and both the valley fills as products of a single eruptive phase, the deposits being laid down in "rather rapid succession." We distinguish several eruptive phases which took place close together in time. They are summarized thus: Shortly after about 13,500 years B.P., a vesicular dacite dome or plug rose on the east side of the volcano. The cone crumbled as it rose, and melt waters helped spread the debris into the great fan that filled the ice-free but still barren Suiattle valley. About 12,000 years B.P. and still before vegetation established, a violent summit eruption ejected large volumes of pumice and ash. Most of the debris was spread eastward by prevailing winds, but on the west side of the cone, pumice was washed from the volcano by melt-water floods and streams and was deposited as a debris fan in the ice-free White Chuck valley. On the Suiattle River side of Glacier Peak, streams likewise spread pumice onto the Suiattle fan. Shortly thereafter, before the White Chuck River had entrenched itself into its debris fan, hot pyroclastic debris descended Kennedy Creek as a nuée ardente and settled onto the White Chuck fill to form the columnar-jointed vitric tuff. Tributary streams near the volcano continued aggrading until eruptions stopped or until most of the pumice was swept off the steep flanks of the cone. Then the rivers and streams began incising the valley fills.

OTHER VOLCANIC ROCKS NEAR GLACIER PEAK

WHITE CHUCK CINDER CONE

The White Chuck Cinder Cone, discovered by Everett Houghland in 1934 at the head of the White Chuck River (fig. 50), was first noted in print by Carithers (1946, p. 31). Ford (1959, p. 299–306) was the first to describe it in detail. It is composed primarily of red, black, and brown basalt lapilli and a sprinkling of scoriaceous and ropy bombs. Stream gullies near the center of the cone reveal a rude stratification of the pyroclastc rocks—alternating fine ash and coarser scoriaceous basalt lapilli in layers from 2 to 18 inches thick. Two basalt lava flows, locally separated by as much as 100 feet of cinders, crop out around two-thirds of the cone's base in cliffs 10 to 30 feet high. The flows have crude columnar joints and grade upward into highly vesicular aa tops.

Ford (1959, p. 300) thought that the main cinder cone was little eroded and that the small central hill

[3] During the Vashon Stade, when continental ice of the Puget lobe dammed the White Chuck valley, the White Chuck glacier had retreated from the lower valley, and left a lake in which silts and clays were deposited (Vance, 1957, p. 293). Indeed, the continental ice carried rocks foreign to the valley at least 7 miles up the valley (Vance, 1957, p. 293). Analogous conditions prevailed in the Carbon River valley northwest of Mount Rainier (Armstrong and others, 1965, p. 326) when a general warming ensued in the early part of the Everson interstade, which followed the Vashon Stade (Armstrong and others, 1965, p. 324).

FIGURE 50.—View of the eroded White Chuck Cinder Cone from the northwest. Central part of cone is in lower left of view. Note the thin lava flows cropping out interbedded with cinders (A) and the fresh moraine overlying the upper edge (B) of the cone. Photograph by Austin Post.

was a younger spatter cone. Our findings suggest that the cinder cone has been much dissected and that the central hill is an erosional remnant of one side of the cone. The flanks of the cone have been cut back, especially on the side overlooking the White Chuck River. The steep-sided pile of bare cinders locally known as The Cinder Cone is also an erosional remnant on the ridgelike rim of the breached cone; there is no evidence here of a subsidiary vent. The location of the actual crater of the White Chuck Cinder Cone is unknown, but it may well lie toward the center of the erosional remnants and may be filled with rubble.

The cone lies at the edge of a glacier-carved cirque and interrupts the smooth concavity of the cirque; it therefore was built after the latest Pleistocene alpine glaciation during which this cirque was formed—the Evans Creek Stade (Crandell, 1965, p. 344), about 17,000 to 21,000 years B.P. However, a small fresh moraine lies on the cinders on the western edge of the cone. Clearly this moraine was deposited by a more recent glacier, presumably one that occupied the cirque 2,000 to 3,500 years ago during the so-called Little Ice Age of the Cascades (Matthes, 1942; Crandell and Miller, 1964, p. D110), or possibly by a still younger glacier. The considerable erosion of the cinder cone suggests that it is much older than 2,000 years B.P.

Ford (1959, p. 307) found no Glacier Peak pumice on the cone. As we previously described (p. 45), we found one location where a highly weathered yellow pumice overlies basaltic cinders and is overlain by a thin white ash. The source of the weathered yellow pumice is unknown, because its high refractive index (fig. 47, No. 15) differs significantly from that of the Glacier Peak pumice, but the overlying white ash may be the Mount Mazama ash of 6,600 years B.P. We conclude that the White Chuck Cinder Cone is certainly younger than 17,000 years B.P. and older than 2,000 years B.P., and it is possibly younger than 12,000 years B.P. and older than 6,600 years B.P.

In the high-alumina olivine basalt flows of the White Chuck Cinder Cone (sample 21, table 4), small (0.1–0.3 mm) rare phenocrysts of olivine (forsterite-rich) and plagioclase (andesine-labradorite) swim in a felty mat of small plagioclase laths. The spaces between plagioclase microlites are filled with very small crystals of olivine, pyroxene(?), an opaque mineral, and minor glass. In contrast, the basalt scoria (sample 22, table 4) is mostly black glass with rare microphenocrysts of olivine and plagioclase.

INDIAN PASS CINDER CONE

The Indian Pass cinder cone is less well exposed than the White Chuck Cinder Cone. Erosion has reduced it to a circular mound on the south slopes of Indian Head Peak and to reworked(?) rubble underlying Indian Pass about one-fourth mile south of the southern limit of the map area (plate 1). The sides of gullies reveal a rude stratification of the pyroclastic rocks—alternating fine ash and coarser scoriaceous basalt lapilli—in layers 2 to 18 inches thick. Well-stratified beds of tuff and breccia are fairly well consolidated; they dip steeply southward approximately parallel to the slope (fig. 51), which suggests that the crater of the cone was upslope to the north on the side of Indian Head Peak (Ford, 1959, p. 304). The degree of lithification of the cinders suggests that the cone was large. The ejecta consist mostly of light-brown to black, scoriaceous basalt lapilli, ½ to 2 inches in diameter, which differ little from those of the White Chuck Cinder Cone.

The Indian Pass cinder cone appears to be younger than the last major glaciation. Ford (1959) suggested that it is older than the White Chuck Cinder Cone because of its greater erosion, but its location on a steep hillside could account for this.

An olivine basalt dike found in one place in the compacted cinders was probably one of the feeders (sample 20, table 4). It is much like the flows of the White Chuck Cinder Cone, though it contains more and larger phenocrysts of plagioclase. It is more alkalic than most high-alumina basalt (Kuno, 1960). Granules of opaque grains and pyroxene occur in the groundmass.

DISHPAN GAP CINDER CONE

Just south of Indian Pass at Dishpan Gap (fig. 52), Rosenberg (1961, p. 94–96) reported another basaltic cinder cone. Areal photographs reveal a lava flow along upper Pass Creek that was probably derived from it. The obvious constructional form of the flow supports Rosenberg's contention that the cinder cone is relatively young.

FLOW OF LIGHTNING CREEK

At the mouth of Lightning Creek, a flow of olivine andesite underlies a bench that slopes gently valleyward about 150 to 200 feet above the White River. The flow has been breached by Lightning Creek, and the two remnants face the White River with an erosion scarp which prominently displays vertical columns, ½- to 2-feet thick. Fracture zones, probably related to cooling, cut the columns and parallel the bottom contact of the flow, which also dips valleyward.

The lava apparently flowed into the glacial-carved White River valley, although subsequently the White Chuck Glacier may have advanced enough to erode

FIGURE 51.—Stratified basaltic cinder deposits of the Indian Pass cinder cone just north of Indian Pass. Cascade Crest just to right.

the flow. Thus, the age of the flow might be somewhat close to that of the valleyside-clinging flows of Glacier Peak that also lie in glaciated valleys, but it could be considerably younger.

The rock of the flow is black and dense and its texture is intergranular to intersertal. It is rich in phenocrysts of olivine (forsterite-rich), oscillatorily zoned labradorite, and smaller clinopyroxene crystals. Plagioclase laths, clinopyroxene, opaque granules, and rare brown glass make up the groundmass. Chemically, it is more like an andesite than a basalt (sample 23, table 4; fig. 30).

The source of the andesite flow is unknown. Its presence at the mouth of Lightning Creek suggests it came down the creek. A probable feeder on the west rim of the Lightning Creek cirque is a prominent spine of andesite (sample 25, table 5), the erosional remnant of a large dike. The flow and the dike have similar chemical composition. Another possible source is a basalt dike at the head of the White River (sample 24, table 5) though it is chemically dissimilar to the flow. If either dike was the feeder, it is remarkable that no remnants are found between them and the flow remnant on Lightning Creek.

DIKES

We have not identified with certainty any dikes cutting the lavas of the Glacier Peak volcano. This is surprising, considering that other workers have found feeder dikes on the flanks of many Cascade volcanoes and one would not expect the eruptions at Glacier Peak to have been confined entirely to the central vent. However, there are numerous medium-grained, fine-grained, and aphanitic dikes exposed in the metamorphic and granitic rocks around the volcano. These dikes include basalt, microdiorite, dacite and rhyodacite porphyries, and fine- to medium-grained hornblende and biotite-hornblende diorites. Various highly altered dikes contain calcite, sericite, chlorite, and epidote minerals and locally have relict volcanic textures; some of these altered dikes could be related to Gamma Ridge volcanic rocks.

Of special interest are the fresh basaltic and andesitic dikes concentrated in a northeast-trending belt that includes the three basaltic cinder cones already discussed; this belt trends under the Glacier Peak volcano (fig. 52). The basaltic and andesitic dikes in this belt (samples 24–26, table 4) are conspicuously fresh, and many are tens of feet thick and form prominent ribs or spires. They generally trend northeast-

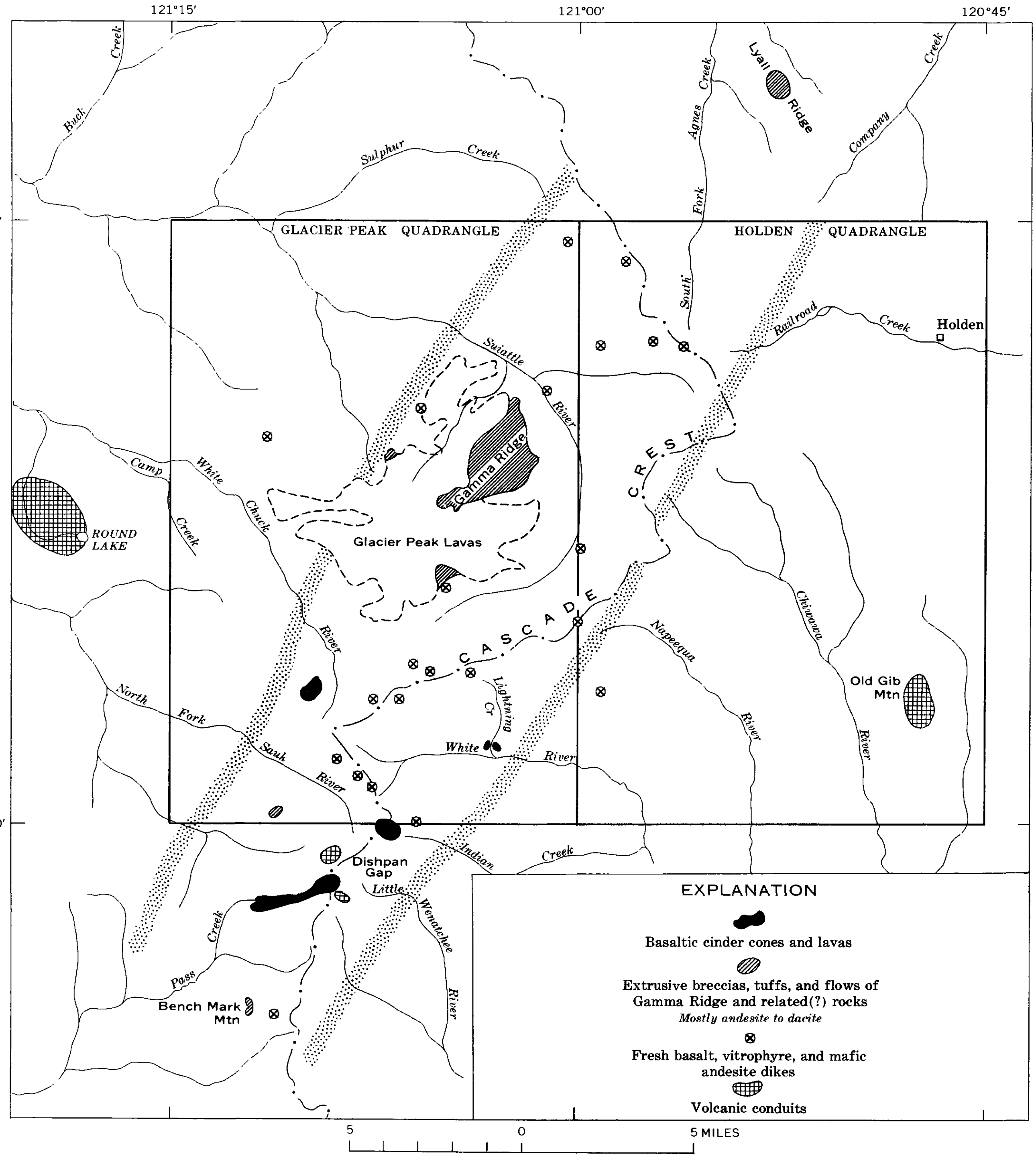


FIGURE 52.—Sketch map showing distribution of volcanic rocks, fresh andesitic and basaltic dikes, and probable volcanic conduits. Basaltic eruptive rocks and dikes are concentrated in a northeast-trending zone between the stippled lines. Data south of the Glacier Peak quadrangle, from Rosenberg (1961, p. 83–96, pl. 11) and Oles (1957, p. 183–188, pl. B); west of the Glacier Peak quadrangle, from Vance (1957, p. 288–289, pl. 1); and north of the Holden quadrangle from Libby (1964, p. 118–119, pl. 27).

ward (see Crowder and others, 1966). Nothing is known of the possible existence of dikes or extrusive rocks southwest of Bench Mark Mountain (fig. 52), but Grant (1966, p. 250) mentioned the occurrence of numerous fresh aphanitic dikes along the northeast strike of the belt. Workers elsewhere in the region surrounding the Glacier Peak area (Vance, 1957; Bryant, 1955; Libby, 1964; Adams, 1961; Tabor, 1961) reported no basaltic extrusive rocks or dikes other than those shown in figure 52.

OTHER CENTERS OF VOLCANISM

Several workers have described centers of volcanic activity near Glacier Peak (fig. 52). The conduit at Round Lake described by Vance (1957, p. 288–289) has been mentioned in the section on Gamma Ridge eruptive rocks. The Old Gib, a volcanic neck of probable Eocene age at Old Gib Mountain, has been described by Cater and Crowder (1967).

We found another probable volcanic neck and other evidence of an ancient volcano just north of the Dishpan Gap cinder cone, at the head of the North Fork of the Sauk River. A prominent rotten spine exposed here consists of an inner core of altered porphyritic hornblende-pyroxene dacite separated from its glassy margin by a concentric zone of highly altered rock containing much montmorillonite. Drainages (fig. 52) radiate from the area of this spire, presumably because they are superposed from a volcano once located here. Other indications of an ancient volcano are: (1) The numerous hypabyssal bodies to the south of Dish Pan Gap mapped by Rosenberg (1961, p. 83–96), (2) a columnar-jointed mass south of the Dishpan Gap cinder cone, which Rosenberg considered to be another volcanic orifice, perhaps the feeder for the flow on Bench Mark Mountain described by Oles (1957, p. 183–188), and (3) a mass of volcanic rock about 2 miles to the northwest that might also be a lava-flow remnant. On the basis of its outcrop shape this lava-flow remnant was first interpreted as a thick dike (Crowder and others, 1966), but the facts that its columnar joints are nearly vertical and that it is permeated by montmorillonite as is the rock of the suspected conduit now suggest to us that it is a flow. Chemically (sample 27, table 4, and fig. 30) the flow remnant is more like the earlier lava flows of Glacier Peak or the analyzed Gamma Ridge rocks than the other analyzed dikes.

HOT SPRINGS

There are three springs on the flanks of Glacier Peak (see table 5). Gamma Hot Springs on Gamma Creek and Kennedy Hot Spring on the White Chuck River are shown on plate 1; Sulphur Hot Springs on

TABLE 5.—*Chemical analyses of hot springs in the Glacier Peak area*

[Sulphur Hot Springs water analyzed by R. Schoen; others by G. F. Roberson. Nd, not determined. Also not determined are Al, Fe, Mn, Pb, PO_4, H_2S. Analyses in parts per million unless otherwise specified]

Name of springs	Sulphur Hot Springs	Kennedy Hot Spring	Gamma Hot Springs
Bedrock	Quartz-mica schist with layers of hornblende schist.	Biotite gneiss cut by dikes and sills of leucocratic tonalite.	Dacite to rhyodacite tuffs, highly altered near the springs.
Date of collection	July 7, 1962.	July 30, 1961.	August 28, 1962.
SiO_2	75	136	150
As	Nd	.02	Nd
Ca	1.0	37	47
Mg	.3	48	2.6
Sr	Nd	2.1	Nd
Na	103	655	491
K	1.7	64	77
Li	.2	3.3	2.6
NH_4	Nd	.02	Nd
HCO_3	99	1,190	269
CO_3	Nd	0	Nd
SO_4	66	3	43
Cl	54	643	728
F	Nd	.9	Nd
Br	Nd	1.2±0.2	Nd
I	Nd	0.1±0.1	Nd
NO_2	Nd	0.00	Nd
NO_3	Nd	2.2	Nd
B	0.67	8.9	9.9
Specific conductance, at 25°C—microohms	495	3,350	2,810
pH	7.78	7.7	7.87
Dissolved solids:			
Calculated		2,190	----------
Residue	352	2,170	1,660
Hardness, as $CaCO_3$	316	291	128
Estimated temperature °C	30	30	60
Estimated discharge gpm	1 or 2	3 to 5	3 to 4
Ratios by weight:			
Ca:Na	0.0097	0.057	0.0096
Mg:Ca	.3	1.3	.056
K:Na	.0165	.097	.157
Li:Na	.00194	.005	.0053
HCO_3:Cl	1.81	1.85	.371
SO_4:Cl	1.22	.00467	.0059
B:Cl	.012	.0138	.0136

Sulphur Creek, three-fourth of a mile from the Suiattle River road, can be located on the Downey Mountain topographic 7½-minute quadrangle map.

The Sulphur Hot Springs are highly odiferous and bubble forth in a shallow murky pool. Gamma Hot Springs, the hottest of the three (table 5), issue from several cracks in the bedrock of the streambed. Kennedy Hot Spring (1963) has been developed as a wilderness spa and now flows into a log tub coated with tufa, iron oxides, and slime. Several cold but odiferous seeps frequented by game are scattered on the slopes behind Kennedy Hot Spring, and one a few yards upstream has covered a few square yards of bedrock with tufa.

As a group the waters of the springs (table 5) are similar to those of other thermal springs associated with volcanic rocks, and they are classified as sodium chloride bicarbonate waters (White and others, 1963, table 18, p. F42). Assuming they have the same magmatic source, their differences in composition could be ascribed to ground-water dilution, especially in the case of Sulphur Hot Springs.

COMPOSITION OF GLACIER PEAK LAVAS AND HOW IT VARIES IN TIME

Many students of Quaternary Cascade volcanoes have sought evidence that the erupted magmas changed in composition with time, and some workers have commented on the great variety of rock types associated with the Quaternary volcanoes in Oregon and California, in contrast with the uniform composition of eruptives from the companions of Glacier Peak in Washington (Hague and Iddings, 1883, p. 225; Coombs, 1939, p. 1506; Williams, 1935, p. 300, 1942, p. 155; Fiske and others, 1963, p. 90). Though Glacier Peak lavas are quite uniform chemically, there is a suggestion that their composition varied with time. Furthermore, in the Glacier Peak area as a whole, the Quaternary eruptives include contemporaneous basalt, dacite, and rocks of intermediate composition. Similarly, in the Mount Garibaldi area of southern British Columba, Mathews (1957) has described Quaternary eruptive rocks ranging from basalt to dacite and possibly rhyodacite. Thus, there is a hint that the latest Cenozoic eruptives of northern Washington and British Columbia are not as monotonous as they first appear.

The refractive indices of glass beads fused from specimens of analyzed rocks were determined, and the relation between the refractive indices and the analyzed silica contents was thereby established for the Glacier Peak area (fig. 53). The indices of fused beads made from unanalyzed flows and ejecta were then measured, and their silica content was estimated by consulting the established curve. The methods used are those outlined in Mathews (1951) and Huber and Rinehart (1966, p. 103). The chemical analyses include water and the beads do not; but since the curve is empirical, it is not necessary to subtract water from the analyses. Refractive indices were determined for at least two and generally four or more beads from each specimen. The maximum deviation between beads of the same specimen for all the rocks, including the standards (analyzed specimens), is ±1.8 percent silica; 70 percent of the samples deviated no more than ±0.5 percent silica, the average deviation.

The silica contents have been plotted as histograms (fig. 54). Silica content of the volcanic rocks of Gamma Ridge ranges from 55.4 to 78.2 percent, but this gives only a rough approximation of the original composition because the rocks are much altered. The silica content of undoubtedly comagmatic Glacier Peak lava flows and ejecta is remarkably uniform. Over 80 percent of the specimens, which were collected throughout the volcanic pile and are probably representative

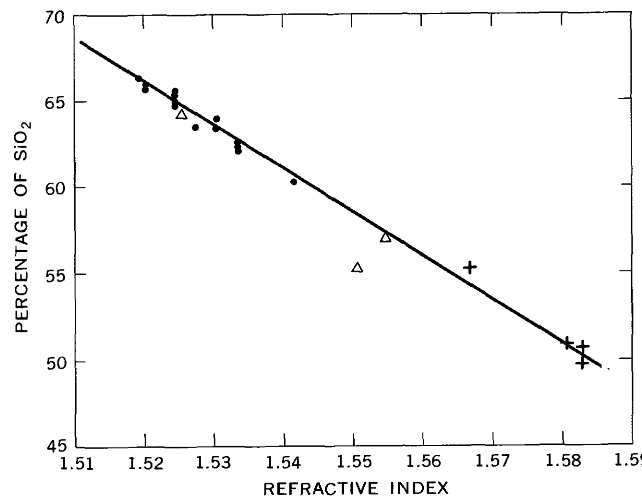


FIGURE 53.—Relationship between silica content and refractive index of glass beads fused from analyzed Cenozoic volcanic rocks in the Glacier Peak area. Dots are Glacier Peak dacites, and crosses are basaltic cinder cones and the Lightning Creek andesite. The triangles are altered flows from the Gamma Ridge unit that were not used to establish the curve. Maximum and average deviation of points from the curves are 1.0 and 0.36 percent silica, respectively.

of about 80 percent of the rocks extruded from Glacier Peak, have a silica content between 62.0 and 65.5 percent. The lavas varied a maximum of only 8.0 percent silica over a period of at least 10,000 years, but more likely on the order of 500,000–700,000 years. Although silicic rocks were erupted early in the volcano's history, the most mafic compositions are lacking in its most recent activity.

The variation of composition of Glacier Peak lavas with time is shown in a differentiation index diagram (fig. 55). The White Chuck vitric tuff contains clasts of older lava and is thus not plotted; the pumice (No. 6 in fig. 55) from the widespread airfall blanket is plotted to represent the latest eruptions. If we exclude the mafic cinder cones and Lightning Creek flow, there is a suggestion that the magma composition became slightly more felsic with time (increasing differentiation index). Perhaps differentiation was slight because the volcano's life was short and the magma was viscous—a possibility suggested by the fact that even thick flows of Glacier Peak and Mount Rainier (Fiske and others, 1963, p. 90) show no obvious evidence that crystals settled.

The eruption of basalt in cinder cones and flows during eruption of dacite at Glacier Peak suggests a persisting source of basalt magma during Quaternary time. The absence of basalts near Mount Rainier has been used as evidence that lavas there were not derived from primary basalts high in alumina (Fiske and others, 1963, p. 91). At other volcanic centers basaltic

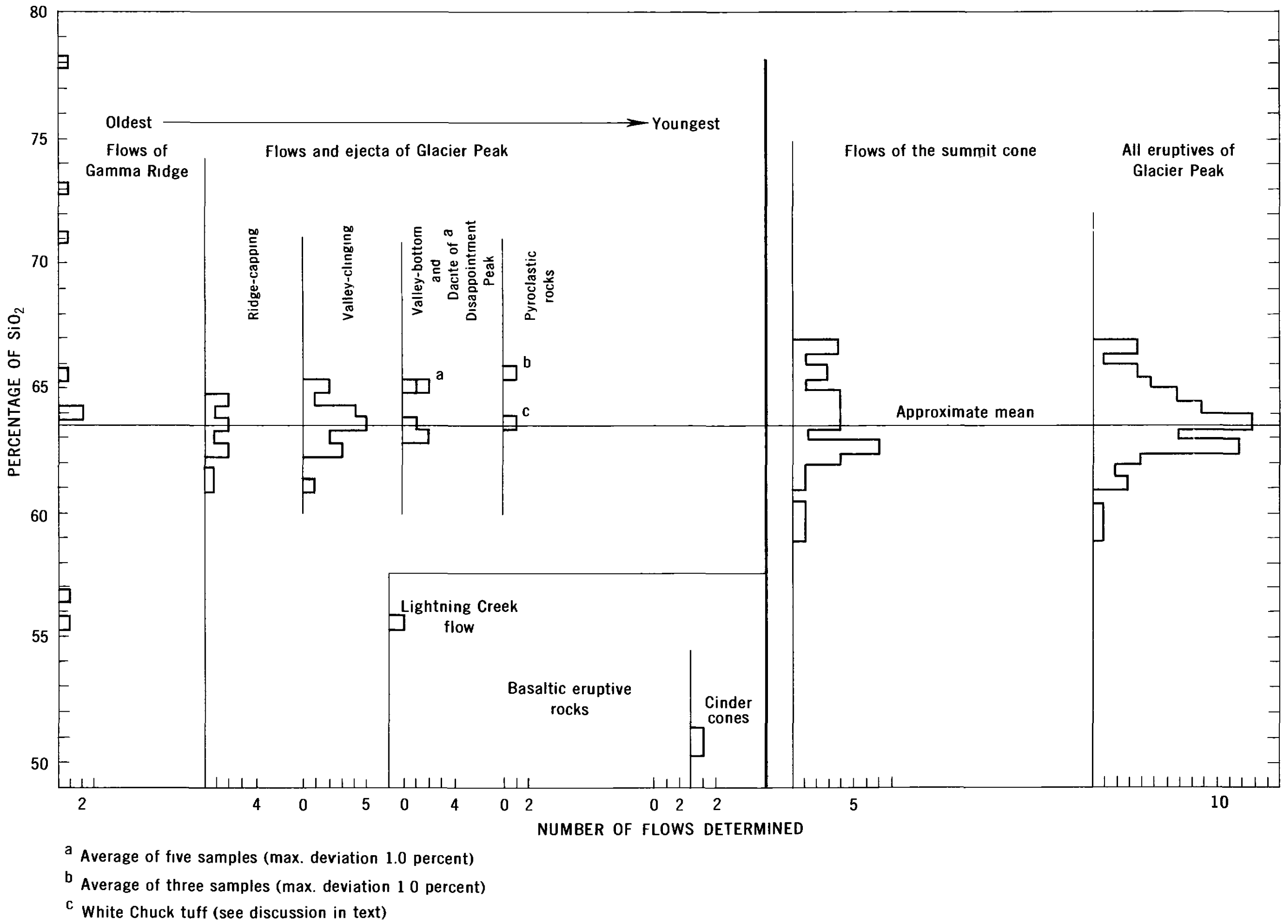


FIGURE 54.—Silica content of extrusive rocks in the Glacier Peak area.

rocks have been included in the discussion of magma differentiation (for example, Williams, 1942, p. 154), and the composition of the basaltic eruptives near Glacier Peak is in line with differentiation trends shown by the dacites (see fig. 55). Thus the basalt might be considered the parent magma of all the rocks. But if the chamber that fed Glacier Peak and Gamma Ridge was filled with differentiating basalt magma like that which fed the basalt cinder cones and flows, why is there no basalt and little andesite interlayered with the dacite flows of Glacier Peak and Gamma Ridge, and why did the basalt issue from entirely separate vents? Conversely, if the basalt is the mafic residuum drained from the chamber at the end of the Glacier Peak dacitic eruptions, why do not the basaltic rocks contain many clots of crystal accumulates? As is true at other Cascade volcanic centers (for example, Wiliams, 1935, p. 301; Macdonald and Katsura, 1965, p. 480), both basaltic and the dacitic magmas appear to have been present at the same time and to have had separate plumbing systems. Perhaps they had separate ultimate sources; the basaltic magma near Glacier Peak rose along a hypothetical deep-seated northeast-trending fracture zone defined by basaltic eruptive rocks and dikes (fig. 52), while the more silicic magmas of the volcano and Gamma Ridge came from another shallower source.

The similarity between the chemical composition of most of the Glacier Peak flows and that of the Cloudy Pass batholith suggests that these rocks are comagmatic (tables 3 and 4, fig. 56; Hopson and others, 1966), but the similarity is not unique; most other "hypersthene andesites" of the western Cordillera and nearby granodiorite plutons are also similar. The similarity in bulk chemical composition could reflect a common magma for all these rocks, not just a common magma for a single pluton and a nearby volcano. Or, more likely, it may indicate that all were derived from magmas formed through similar processes from diverse materials, for example, through crystallization differentiation or anatexis. If the kinship of a volcano and a batholith cannot be demonstrated by field evidence or

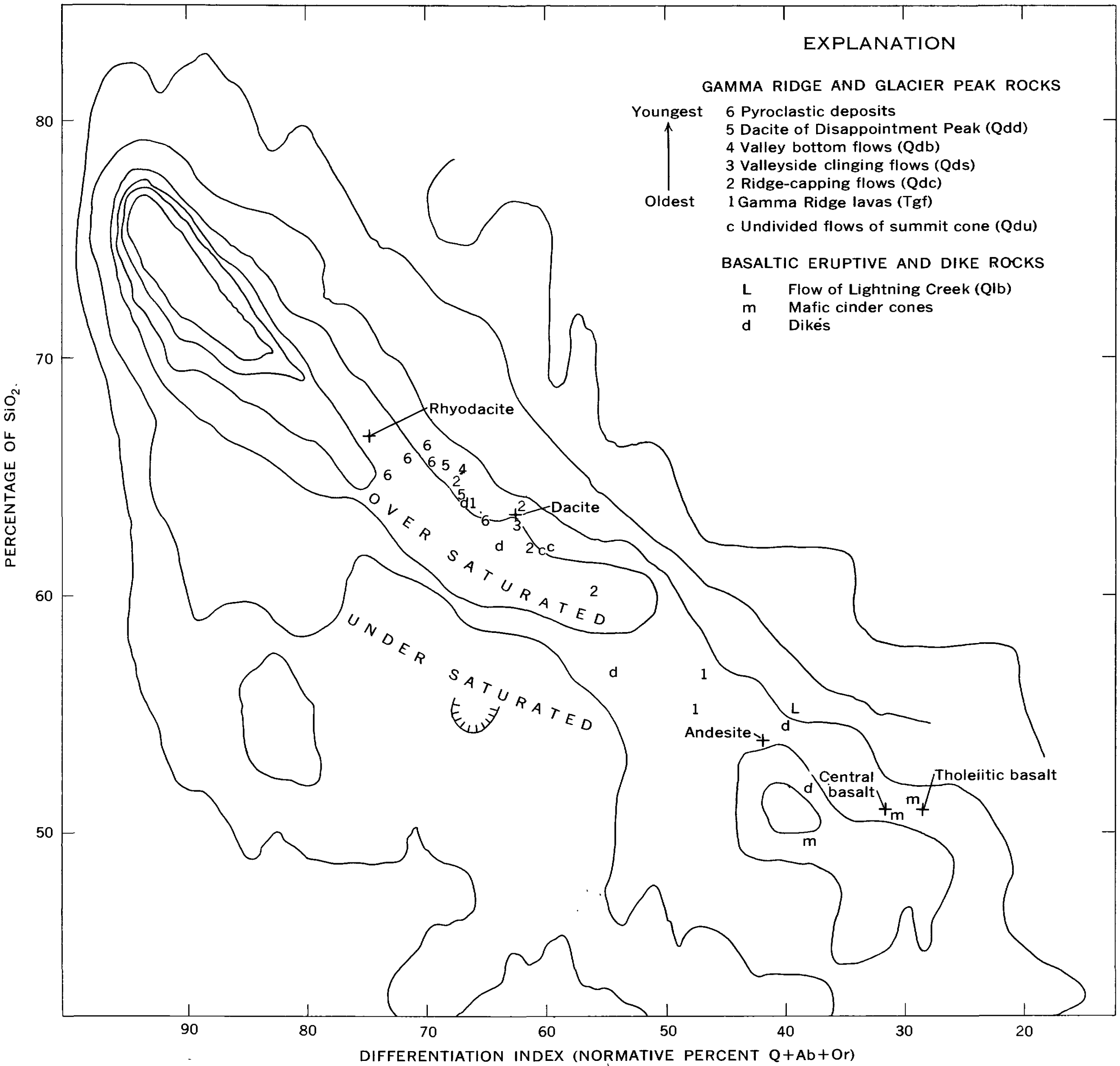


FIGURE 55.—Differentiation index diagram. Named points in silica field are average extrusive rocks from Nockolds (1954). Note that the younger Glacier Peak eruptives follow a trend to a higher index. The contours show the abundances of 5,000 igneous rocks plotted from Washington's tables, from Thornton and Tuttle (1960, p. 674).

by comparing their bulk chemical compositions, it may perhaps be determined by comparing isotopic compositions.

The strontium isotopes in volcanic rocks marginal to the Pacific Ocean are like those in oceanic basalt magmas, which presumably have been derived by anatexis of the mantle (Hedge, 1966). Indeed, the strontium-87: strontium-86 content of Glacier Peak dacite (one sample of a valleyside clinging flow from Glacier Ridge; $\delta Sr^{87}:Sr^{86}=-4.1$) is the same as that of most oceanic basalts (C. E. Hedge, written commun., 1967). No strontium-isotope data are available for the Cloudy Pass batholith, but such data on the post-Jurassic granitic rocks of southern British Columbia indicate that the magma forming these granitic rocks was derived from the deep crust or the mantle and that this magma, during its rise, assimilated geosynclinal material and became slightly enriched in strontium-87 (Fairbairn and others, 1964).

The lead isotopes of several Cascade volcanoes and

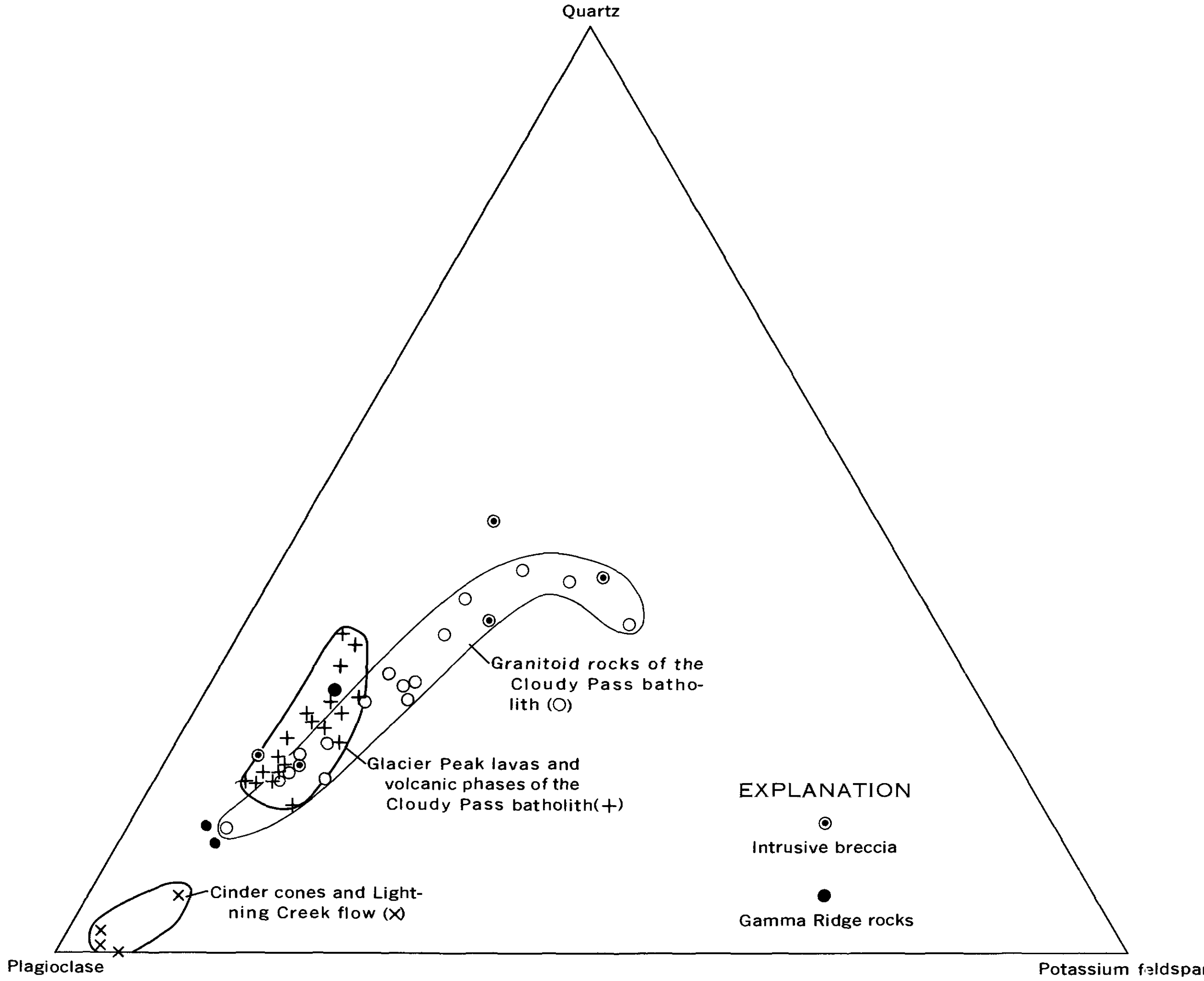


FIGURE 56.—*Ternary diagram of normative compositions of Cenozoic igneous rocks of the Glacier Peak area.*

TABLE 6.—*Preliminary isotopic composition of lead from rocks of Glacier Peak volcano and Cloudy Pass batholith*

[From G. R. Tilton, written commun., 1967. Standard error of ratios: Pb^{206}/Pb^{204}, 0.3 percent; Pb^{206}/Pb^{207}, 0.15 percent; Pb^{206}/Pb^{208}, 0.2 percent. Uncorrected for decay of uranium in sample since crystallization]

	Pb^{206}/Pb^{204}	Pb^{206}/Pb^{207}	Pb^{206}/Pb^{208}	Pb^{207}/Pb^{204}	Pb^{208}/Pb^{204}
Granodiorite of Cloudy Pass batholith					
CR-21	19.025	1.2237	0.4933	15.55	38.57
CR-20	19.084	1.2247	.4911	15.58	38.86
RWT-212-62 (Sitkum stock)	19.023	1.2189	.4915	15.61	38.70
Dacite of Glacier Peak					
GP-1	18.915	1.2092	0.4886	15.64	38.71
RWT-26b-62	18.882	1.2060	.4876	15.66	38.72

CR-21, Cloudy Pass, Holden quadrangle.
CR-20, altitude, 5200 feet on Railroad Creek trail, north of Crown Point Falls, Holden quadrangle.
RWT-212-62, altitude, 5700 feet, 2.1 miles west of summit of Glacier Peak, Glacier Peak quadrangle.
GP-1, Summit of Glacier Peak, Glacier Peak quadrangle.
RWT-26b-62, altitude, 6300 feet on east side of cirque at head of the east Fork Milk Creek.

nearby plutons, for example, Mount Rainier volcano and the Tatoosh pluton, are similar and may indicate that the volcanoes and the batholiths are comagmatic (Davis and others, 1966). However, Glacier Peak volcano and the Cloudy Pass batholith appear to contain distinctly different lead isotopes (G. R. Tilton, written commun., 1967; table 6). The explanation for this difference, when understood, may have general petrogenetic significance.

DEVELOPMENT OF THE GLACIER PEAK SCENE

POSITION OF THE CASCADE CREST

The physiographic history of the Glacier Peak area is depicted in figure 57. The North Cascades were certainly high prior to Gamma Ridge time, because the Columbia River, which was forced against the Cascade foothills by floods of late Miocene to early Pliocene plateau basalt, had to flow far to the south before it could again turn westward to the sea (Mackin and Cary, 1965). Today the Cascade Crest trends nearly due north for 80 miles and swings eastward only in the Glacier Peak area (fig. 60). This eastward loop at first glance appears to be the result of a divide migration caused by the growth of the Glacier Peak-Gamma Ridge eruptive piles. However, there is no evidence that the headwaters of the east-flowing streams have been captured or that their profiles are truncated at headwaters; barbed tributaries are absent on west-flowing streams like Triad and Small Creeks (see pl. 1 and Cater and Crowder, 1967). Although the Suiattle River was pushed eastward by the growing Gamma Ridge eruptive pile (see below), the eastward loop of the crest appears to have already existed before Gamma Ridge time. The eastward migration of the crest from a straight northerly course across an eastern upland may have been caused by doming over the Cloudy Pass batholith in early Miocene time.

THE GAMMA RIDGE ERUPTIONS AND RESULTANT DRAINAGE CHANGES

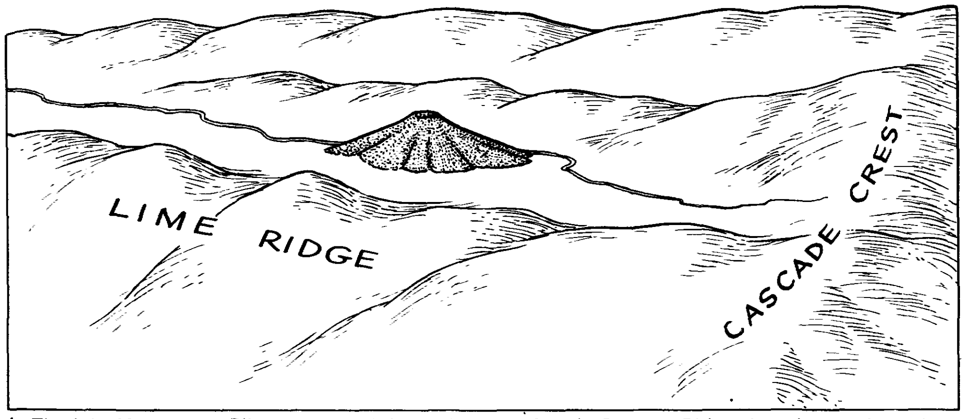
Gamma Ridge rocks were erupted west of the Cascade Crest onto a mountainous terrain (fig. 57*A*), as shown by the high relief preserved under them. Total buried relief is nearly 4,000 feet, but part of this could be due to post-Gamma Ridge deformation, or concurrent valley cutting and eruption. At Cool Glacier, the local relief under the Gamma Ridge volcanic rocks is 600 feet within half a mile, and in places north of Gamma Creek the local relief is 300 and 500 feet. It is unlikely that post-Gamma Ridge deformation would affect estimates of relief that are based on points so close together; thus, we assume that the buried terrain had a local relief of at least 600 feet and that many local slopes were as steep as those of the mountains today. The pre-Gamma Ridge landscape was dominated by northwest-trending valleys and ridges parallel to the grain of the bedrock, a trend well established in the Washington Cascades as early as the Oligocene (Mackin and Cary, 1965, p. 12–13).

We have not been able to reconstruct the details of the topography onto which the Gamma Ridge volcanic rocks poured nor to determine their overall extent and continuity. However, the original overall extent of the volcanic field in the Glacier Peak quadrangle might have been as much as 40 square miles (pl. 1), as suggested by the distribution of intrusive breccias that may be the feeders (for example, as on Grassy Point and near the Cool stock) and by the distribution of the five erosional remnants of the field itself.

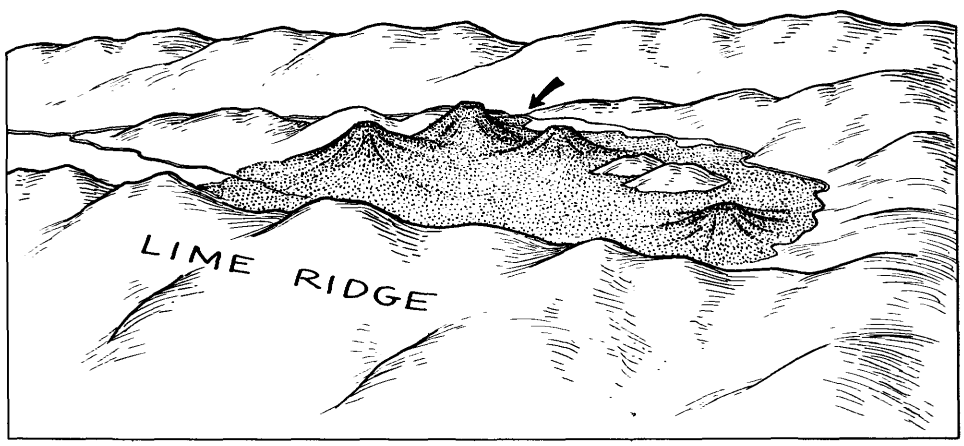
The conspicuous loop of the Suiattle River around the apron of extrusive rocks of Glacier Peak and Gamma Ridge is manifestly due to stream diversion around the eruptive center (fig. 57*B*). Below the mouth of Milk Creek, the Suiattle River flows in a northwesterly course parallel to the crest of Lime Ridge and the trend of bedrock structures, as do most master streams. Above Milk Creek, the river begins the loop where it abruptly enters a gorge north of Grassy Point (pl. 1). The oldest Glacier Peak lavas (for example, those capping Vista Ridge and Gamma Ridge) extend radially from the summit region of Glacier Peak northeastward nearly to the present course of the Suiattle River, which indicates that the river was near its present position at the beginning of Glacier Peak time. Thus, the major diversion of the Suiattle River must be due almost entirely to the eruption of the Gamma Ridge rocks.

Gamma Ridge rocks occur on basement rocks along the Suiattle River at Lyman Camp (and not far above it on Gamma Creek) and nearly 4,000 feet above the river at the Cool Glacier and in upper Milk Creek. This altitude difference may be attributed to downcutting by the river as it was diverted eastward around the growing Gamma Ridge pile. The earliest Glacier Peak flows apparently ponded in valleys tributary to the river's present position, for they now hang high above it (1,200 feet above on Vista Ridge). These tributary valleys formed at this higher level because the Suiattle River was overwhelmed by Gamma Ridge volcanic eruptions and the Suiattle River valley was partly filled with volcanic rocks. After Glacier Peak lavas flowed into tributaries, the fill was removed and the oldest Glacier Peak lavas were left hanging.

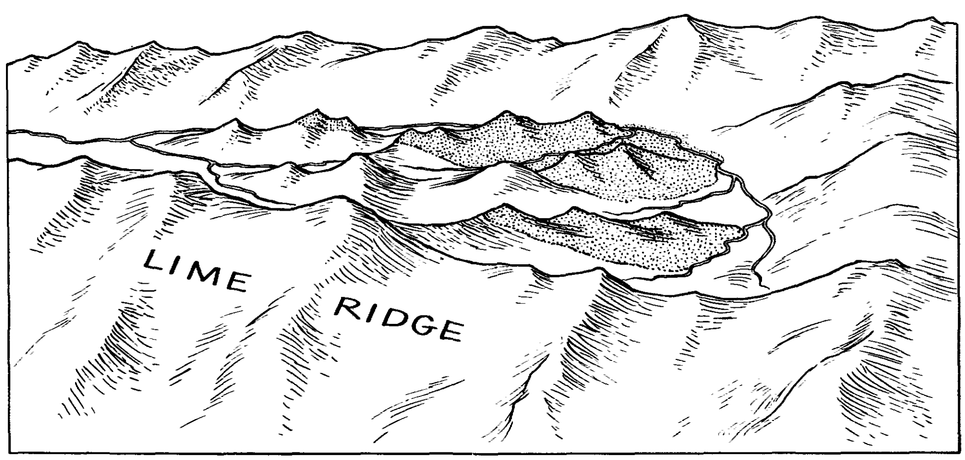
An alternate hypothesis, more compatible with the supposition that Gamma Ridge rocks are much older Miocene extrusives from the Cloudy Pass chamber (fig. 26), is that the Gamma Ridge rocks occur at their present low level and are preserved because they were downwarped or downfaulted relative to older rocks on the high ridges to the east and west. As the details of the structure of Gamma Ridge rocks are unknown, except for a few steep dips observed locally, there is little direct evidence for folding or depression. However, folding along northwest-trending axes has been a dominant and continuous process in western Washington since early Tertiary time (Mackin and Cary, 1965), and post-Miocene folding along these trends has occurred to the southeast, on strike with the rocks of the upper Suiattle River area (Waters, 19?2, p. 623). Furthermore, the easternmost of the many faults that border the Chiwaukum graben in the Holden quadrangle (Cater and Crowder, 1967; fig. 60) project through the westernmost edge of the Gamma Ridge pile. There are no faults recognized here, and there is no direct evidence of movement as late as late Miocene or Pliocene along mapped faults.



A, The late Miocene or Pliocene mountainous terrain of early Gamma Ridge time is dominated by northwest-trending ancestral Lime Ridge. The Cascade Crest loops eastward over an old highland above the Cloudy Pass batholith. Gamma Ridge eruptions are just beginning in the ancestral Suiattle River valley.

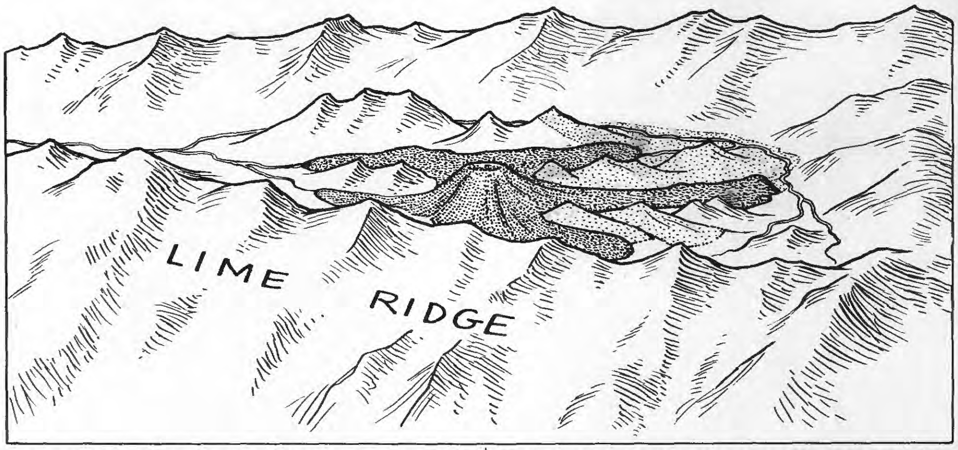


B, Gamma Ridge volcanic rocks have flooded the ancestral Suiattle River valley. The river has been forced north and east by a series of diversions (arrow).

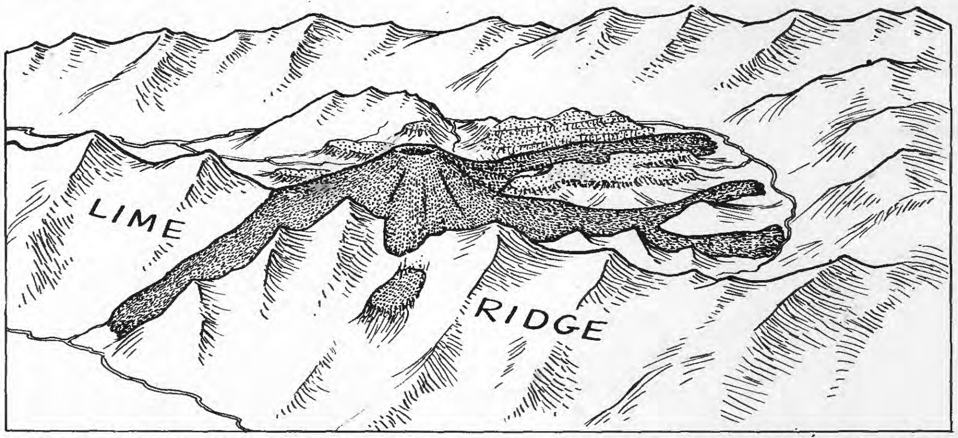


C, Erosion has removed much of the Gamma Ridge pile; gneiss and schist have been exhumed. Glacier Peak time is approaching.

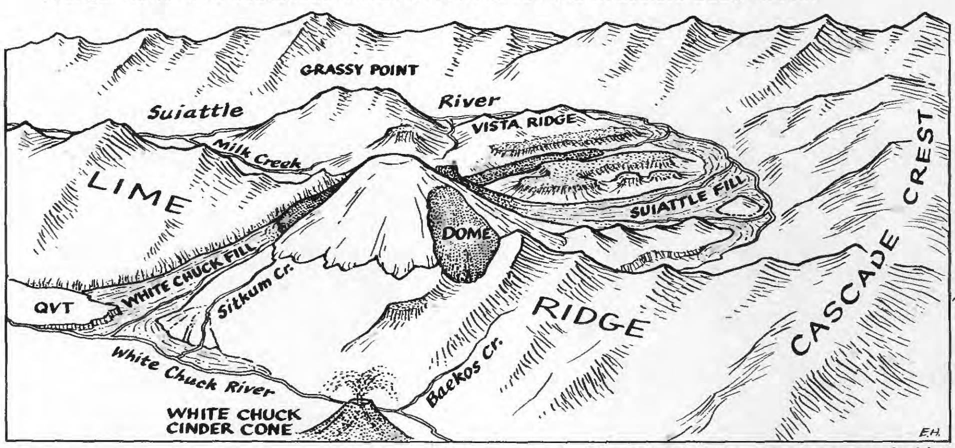
FIGURE 57.—Historical development of the Glacier Peak scene.



D, In Pleistocene time, the earliest Glacier Peak lavas have been erupted east of the crest of Lime Ridge and have descended valleys tributary to the Suiattle River.

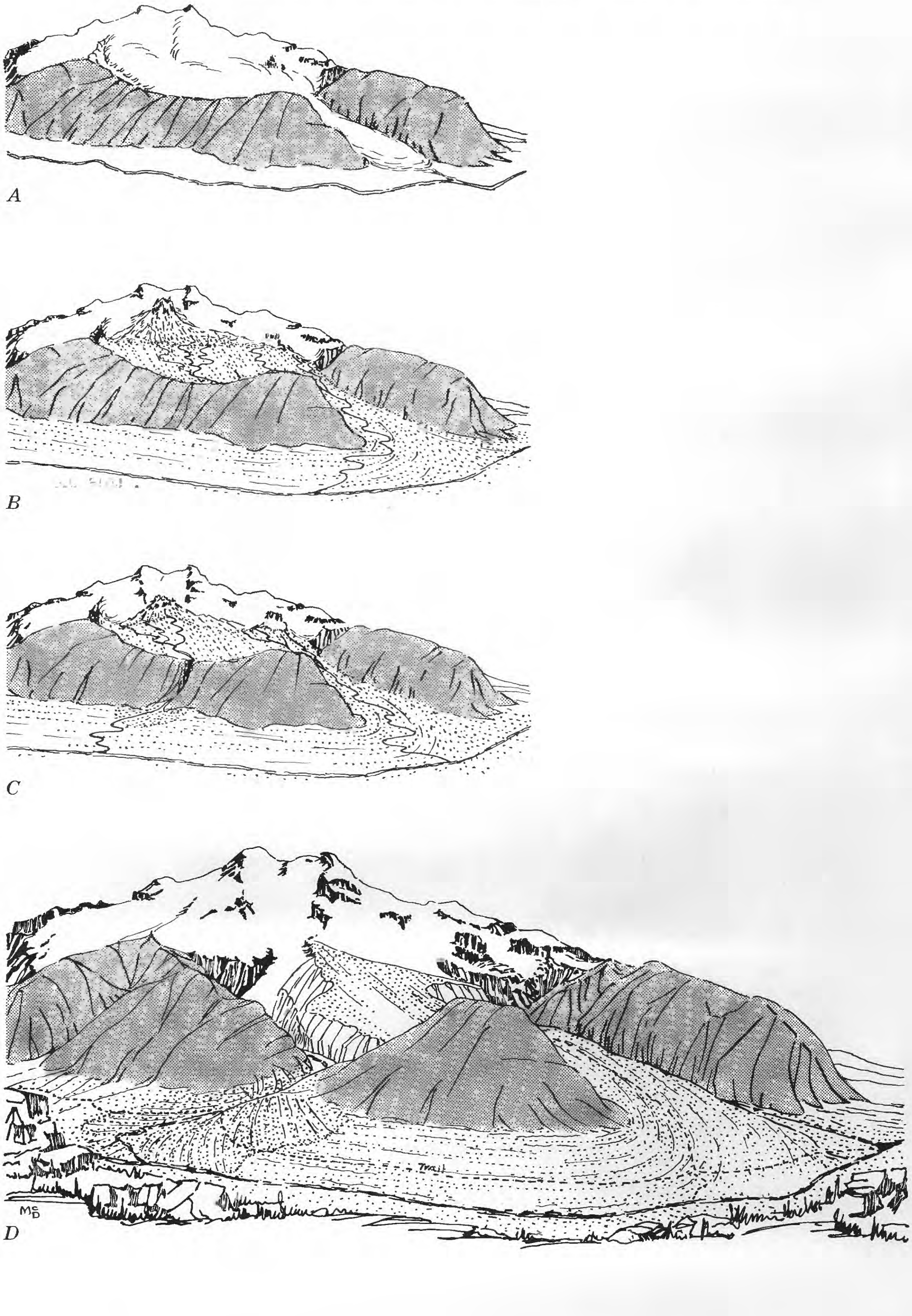


E, The Glacier Peak volcano has grown to overtop Lime Ridge and sent flows of lava westward into tributaries of the White Chuck valley; some of these flows are already dissected. On the east, erosional remnants of the oldest flows, which once filled valleys, are perched on top of ridges, and younger flows have descended ancestral Vista Creek and Chocolate-Dusty Creek.



F, In Recent time, the present valleys have been glaciated. The oldest flows have been eroded into isolated ridge caps, and the younger ones into remnants clinging to valley sides. Valley-bottom flows have descended Vista Creek and Kennedy Creek. Disappointment Peak dome has welled out of the south side of the Glacier Peak volcano, and the Suiattle fill has been discharged from a dome on the east side (see also fig. 58). An eruption has blanketed the area with pumice; on the west, the pumice has washed down to form the White Chuck fill, which was capped shortly thereafter by a thin layer of vitric tuff (Qvt) of nuée ardente origin. The basaltic White Chuck Cinder Cone has begun to erupt to the south.

FIGURE 57.—Continued.


A
B
C
Trail
D

THE GLACIER PEAK ERUPTIONS AND RESULTANT DRAINAGE CHANGES

Initial eruptions of Glacier Peak lavas also took place in rugged mountains 2,000 to 3,000 feet below adjacent ridgetops (fig. 57*D*). The amount of relief is estimated from the difference in altitude between the base of Vista Ridge flows at 3,550 feet and the highest nearby remnants of older rocks such as Grassy Point at 6,505 feet. When eruptions began, the relief must have been greater still, for the lava-covered terrain has been protected from ensuing erosion while high ridges of basement rock without protective cover have been eroded an unknown amount. The volcano is perched on Lime Ridge (Carithers, 1946, p. 31), and Ford (1959, p. 312) estimated the maximum relief of the original terrain by noting the present relief of Lime Ridge, 4,500 feet. Except for a fault in Gamma Creek, we have found no evidence of deformation since the beginning of Glacier Peak eruptions; the estimated relief is therefore erosional, not structural.

The basement rocks of Lime Ridge disappear under lava flows high on the volcano at altitudes near 8,000 feet, about 1,000 feet above the average height of Lime Ridge where flows are not present; doubtless the overlying volcanic rocks have protected the ridge from erosion. The oldest flows of the volcano, the ridge-capping flows, are no older than 700,000 years. Those protecting the high rise of Lime Ridge are somewhat younger, for, as shown below, the volcano did not begin to erupt on the ridge crest. The minimum rate of ridge-top erosion is thus 1,400 feet per million years. A comparable minimum rate of stream valley lowering calculated from the perched flows above the Suiattle River valley (as at the end of Vista Ridge and Gamma Ridge) is 1,700 feet per million years.

We find little evidence that the area covered by flows from the volcano was ever significantly larger than that covered today, although other workers (Carithers, 1946, p. 31; Ford, 1959, p. 266, 317) have inferred it to have been considerably larger. The broad glacier-blanketed area south of the volcano is anomalously high and might be considered to have been once protected by a lava apron. But since there are no lava outliers here, this area probably represents a highland near the Cascade Crest that prevented flows from traveling far southward. Ford (1959, p. 317) implied that this highland area was covered with lavas, because he considered a small mass of dacite on it to be a remnant of a flow. We think the same mass to be a dike because of its steep contacts. The many projections of lava that extend from the summit cap (for example, north of Gamma Creek and around the head of Milk Creek) are not remnants of a significantly larger cone, but instead are remnants of narrow valley-filling flows (fig. 57*D* and *E*). The long, flat spurs, one of which is capped by a dacite outlier, border the East Fork of Milk Creek and probably exist because they once had a protective cover of lava.

The Glacier Peak eruptive pile, as a whole, is clearly on the east side of Lime Ridge; this means that the earliest flows moved eastward toward the ancestral Suiattle River (fig. 57*D*). Thus, the ridge-capping flows on the east (for example, the ridge-capping flow on Gamma Ridge) are older than the ridge-capping flows on the west (for example, the ridge-capping flow in upper Baekos Creek). Those on the west had to await the growth of the volcano before they could flow down the west side of Lime Ridge (fig. 57*E*). The local master streams (for example, the Suiattle River), being near the sea and being well supplied with water during moist and glacial periods (Crandell, 1965, p. 342), were probably never far from grade. The continual erosion, as indicated by the successively older flows occurring at successively higher altitudes, must be due to a continual uplift during Glacier Peak time. Flows in valleys forced the streams aside; here they cut down, eventually leaving the flow perched on the valley wall (fig. 57*E* and *F*). The growth of the Suiattle fill forced the Suiattle River farther east and created Chocolate Creek (fig. 58). The construction of the White Chuck fill after the pumice eruption 12,000 years ago forced the White Chuck River to its western bank.

Today's streams have cut into the youngest valley flows. Erosion is rapidly removing the cone, which is high standing and heavily glaciated. The fractured lavas and unconsolidated valley fills are more easily eroded than the surrounding ridges of metamorphic and granitoid rocks. Cleavers of lava stand several hundred feet above the glaciers. Continuing floods of debris from Chocolate and Dusty Creeks (fig. 59) keep the Suiattle River pinned to its eastern bank.

FIGURE 58.—Development of the fill of the Suiattle River valley. *A*, Chocolate-Dusty Glacier in an ancient valley. *B*, Glacier retreat; volcanic debris, washed down from a rising dome, builds up fill. *C*, Ancestral Chocolate Creek spills in falls over saddle in confining ridge. Streams begin eroding fill when volcanic activity wanes. Some lavas extruded on fill. *D*, Renewed volcanic activity builds up more fill and chokes gorge cut by Chocolate Creek. Today, Chocolate Creek has cut a gorge again. Dusty Creek, hugging Gamma Ridge, also has cut deeply into the fill. Recently Dusty and Chocolate glaciers entered these valleys.

FIGURE 59.—Forest buried in recent flood deposits along the Suiattle River near the mouth of Dusty Creek. Adamellite of the Cloudy Pass pluton exposed on timbered hillside in middle distance.

STRUCTURES THAT GUIDED THE LATE CENOZOIC MAGMAS

The ascending magma of the presently exposed part of the Cloudy Pass batholith appears to have been guided along three structural features (fig. 60): (1) Northwest-trending foliation, compositional layering, and fold axes of metamorphic rocks, (2) northwest-trending high-angle faults associated with the Chiwaukum graben (Cater, 1969, p. 5–6), and (3) a northeast-trending local structure defined by the alinement of steep-walled satellitic dikes and stocks (cupolas) west of the White Chuck River and the westward projection of the Sitkum stock. A large dike at Cascade Pass (Tabor, 1963, p. 1205) and many late Cenozoic dikes in the Glacier Peak-Lake Chelan area have a similar northeasterly trend (Cater and Crowder, 1967; Cater and Wright, 1967; Crowder and others, 1966). This northeasterly trend may be caused by joints perpendicular to regional fold axes (*ac* joints).

The Glacier Peak volcano and the volcanic rocks of Gamma Ridge lie on the intersection of the northwesterly foliation and layering and the northeasterly *ac* joints. In addition, two other lineaments intersect beneath the volcanic center (fig. 60): (1) A north-

FIGURE 60.—North Cascades showing major intersecting structures in the area of the Cloudy Pass batholith and Glacier Peak volcano. In the Glacier Peak area, data is from "Geologic Map of Washington" by Huntting (1961) and is modified according to figures 2 and 52; east of Holden, according to Cater and Wright (1967); north and northwest of the Cloudy Pass batholith, according to Tabor (1961), and Libby (1964) and Grant (1966) (see fig. 2); in the Methow graben, according to unpublished U.S. Geological Survey data; and in the area north of the Skagit River, according to Misch (1966). Data for the mafic cinder cone and dike belt from figure 52. Small ultramafic pods north of the Suiattle River from Bryant (1955, p. 49) and along the White River from Van Diver (1964, pl. 2).

westward-trending zone of small pods of serpentinized ultramafic rock, and (2) the zone of basaltic dikes and cinder cones that trends north-northeast (fig. 52). The zone of ultramafic pods also appears to be of regional extent and may, as elsewhere (for example, Irwin, 1964, p. C7; Misch, 1966, p. 120), mark a major dislocation. There is no other evidence of a major rupture under Glacier Peak, though the ultramafic pods near Leavenworth are along a Chiwaukum graben fault (fig. 60)—a fault active in late Cenozoic time (Willis, 1953, p. 795; Cater, 1969, p. 5–6)—and older faults near the White River (Van Diver, 1964, p. 124; 1967, p. 135). More data are needed to establish the regional extent of the zone of basaltic eruptive rocks, but it appears to include other Tertiary batholiths, such as the Golden Horn and Snoqualmie plutons and the volcanic centers of Island Mountain to the northeast and Mount Rainier and Mount St. Helens to the southwest. Perhaps the zone is a surface expression of a deep fracture zone which has led basalt magma to the surface. The same zone could have influenced the emplacement of the magmas of both batholith and volcano, no matter what their ultimate source.

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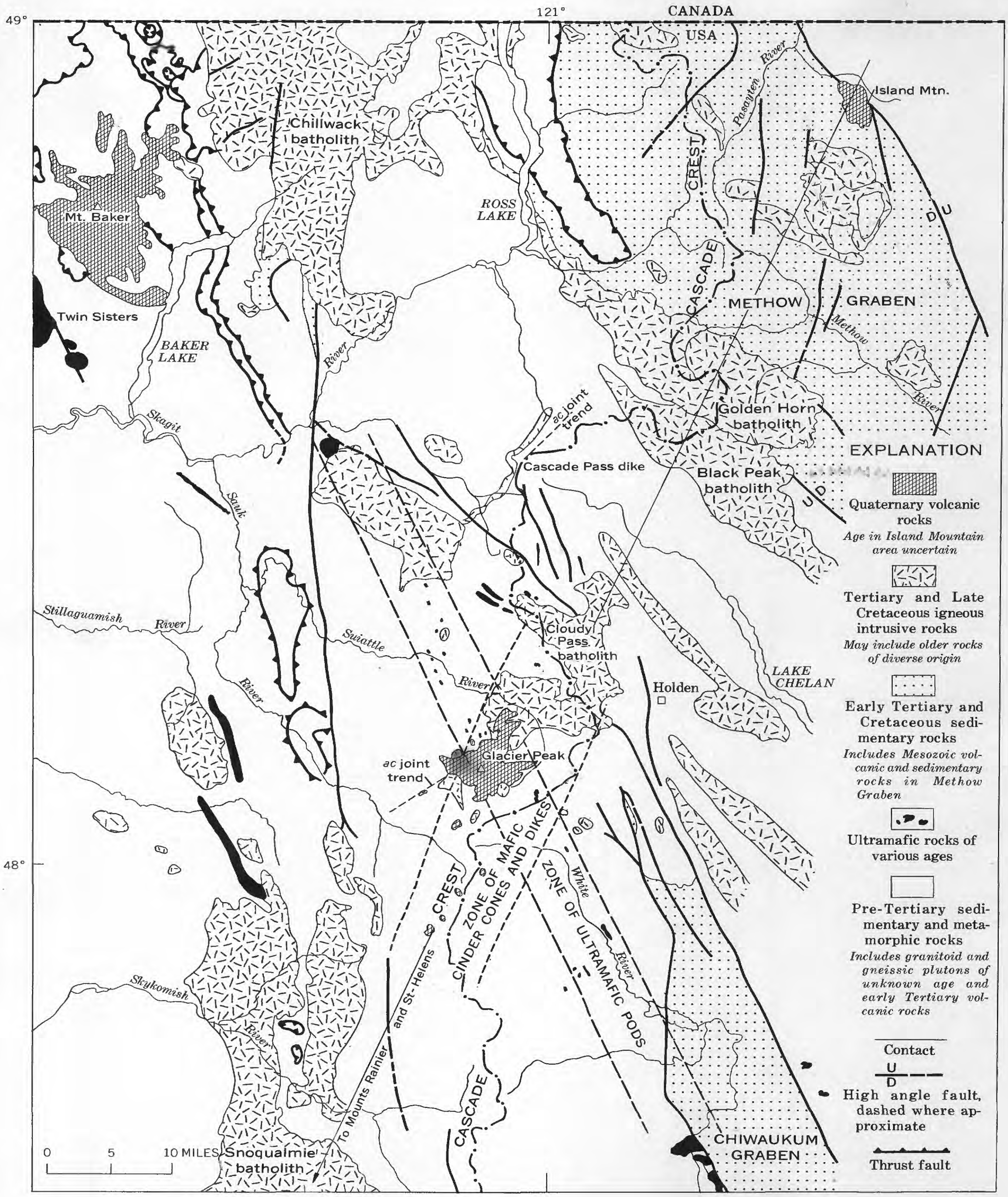
49°
121°
CANADA
USA
48°
Island Mtn.
Chillwack batholith
Mt. Baker
Twin Sisters
ROSS LAKE
BAKER LAKE
CASCADE CREST
METHOW GRABEN
Methow River
Pasayten River
Skagit
River
Sauk
ac joint trend
Cascade Pass dike
Golden Horn batholith
Black Peak batholith
Stillaguamish River
Suiattle River
Cloudy Pass batholith
Holden
LAKE CHELAN
Glacier Peak
ac joint trend
ZONE OF MAFIC CINDER CONES AND DIKES
ZONE OF ULTRAMAFIC PODS
White River
CREST
CASCADE
To Mounts Rainier and St-Helens
Skykomish River
Snoqualmie batholith
CHIWAUKUM GRABEN
0 5 10 MILES
U
D
EXPLANATION
Quaternary volcanic rocks
Age in Island Mountain area uncertain
Tertiary and Late Cretaceous igneous intrusive rocks
May include older rocks of diverse origin
Early Tertiary and Cretaceous sedimentary rocks
Includes Mesozoic volcanic and sedimentary rocks in Methow Graben
Ultramafic rocks of various ages
Pre-Tertiary sedimentary and metamorphic rocks
Includes granitoid and gneissic plutons of unknown age and early Tertiary volcanic rocks
Contact
High angle fault, dashed where approximate
Thrust fault

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