Intrusive Rocks of the Holden and Lucerne Quadrangles, Washington— The Relation of Depth Zones, Composition, Textures, and Emplacement of Plutons

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1220

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By FRED W. CATER

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A study of intrusive rocks ranging in age from Triassic to Miocene and in depth zones from subvolcanic to catazone

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By FRED W. CATER

ABSTRACT

The core of the northern Cascade Range in Washington consists of Precambrian and upper Paleozoic metamorphic rocks cut by numerous plutons, ranging in age from early Triassic to Miocene. The older plutons have been eroded to catazonal depths, whereas subvolcanic rocks are exposed in the youngest plutons. The Holden and Lucerne quadrangles span a sizeable and representative part of this core. The oldest of the formations mapped in these quadrangles is the Swakane Biotite Gneiss, which was shown on the quadrangle maps as Cretaceous and older in age. The Swakane has yielded a middle Paleozoic metamorphic age, and also contains evidence of zircon inherited from some parent material more than 1,650 m.y. old. In this report, the Swakane is assigned an early Paleozoic or older age. It consists mostly of biotite gneiss, but interlayered with it are scattered layers and lenses of hornblende schist and gneiss, clinozoisite-epidote gneiss, and quartzite. Thickness of the Swakane is many thousands of meters, and the base is not exposed. The biotite gneiss is probably derived from a pile of siliceous volcanic rocks containing scattered sedimentary beds and basalt flows. Overlying the Swakane is a thick sequence of eugeosynclinal upper Paleozoic rocks metamorphosed to amphibolite grade. The sequence includes quartzite and thin layers of marble, hornblende schist and gneiss, graphitic schist, and smaller amounts of schist and gneiss of widely varying compositions. The layers have been tightly and complexly folded, and, in places, probably had been thrust over the overlying Swakane prior to metamorphism. Youngest of the supracrustal rocks in the area are shale, arkosic sandstone, and conglomerate of the Paleocene Swauk Formation. These rocks are preserved in the Chiwaukum graben, a major structural element of the region.

Of uncertain age, but possibly as old as any of the intrusive rocks in the area, are small masses of ultramafic rocks, now almost completely altered to serpentine. These occur either as included irregular masses in later intrusives or as tectonically emplaced lenses in metamorphic rocks. Also of uncertain age but probably much younger, perhaps as young as Eocene, are larger masses of hornblendite and hornblende periodotite that grade into hornblende gabbro. These are exposed on the surface and in the underground workings of the Holden mine.

Oldest of the granitoid intrusives are the narrow, nearly concordant Dumbell Mountain plutons, having a radiometric age of about 220 m.y. They consist of gneissic hornblende-quartz diorite and quartz diorite gneiss. Most contacts consist of lit-par-lit zones, but some are gradational or more rarely sharp. The plutons are typically catazonal. Closely resembling the Dumbell Mountain plutons in outcrop appearance, but differing considerably in composition, are the Bearcat Ridge plutons. These consist of gneissic quartz diorite and granodiorite. The Bearcat Ridge plutons are not in contact with older dated plutons, but because their textural and structural characteristics so closely resemble those of the Dumbell Mountain plutons, they are considered to be the same age. Their composition, however, is suggestive of a much younger age. Cutting the Dumbell Mountain plutons is the Leroy Creek pluton, consisting of gneissic biotite-quartz diorite and trondjhemite. The gneissic foliation in the Leroy Creek is characterized by a strong and pervasive swirling. Cutting both the Dumbell Mountain and Leroy Creek plutons are the almost dikelike Seven-fingered Jack plutons. These range in composition from gabbro to quartz diorite; associated with them are contact complexes of highly varied rocks characterized by gabbro and coarse-grained hornblendite. Most of the rocks are gneissic, but some are massive and structureless. Radiometric ages by various methods range from 100 to 193 m.y.

Dikes, sills, small stocks, and irregular clots of leucocratic quartz diorite and granodiorite are abundant in the Swakane Biotite Gneiss and are locally abundant in the Seven-fingered Jack and other plutons. Although the leucocratic rocks vary little in appearance or composition, some, particularly those in the Swakane, were formed by metamorphic segregation, whereas the others are probably felsic differentiates of intrusive rocks.

The Tenpeak and White Mountain plutons are closely similar and are probably connected at depth. Rocks of the Tenpeak are more varied and range in composition from gabbro to granodiorite; quartz diorite is not only most common in the Tenpeak, but also constitutes, by far, the greatest bulk of the White Mountain pluton. Much of the rock in both plutons is somewhat gneissic, but some is nongneissic. The north end of the White Mountain pluton is bordered by a contact complex similar to those associated with the Seven-fingered Jack and other plutons in the area. Maximum potassium/argon ages determined on hornblende from the Tenpeak are about 90 m.y. Probably somewhat younger than the Tenpeak and White Mountain plutons is the Sulphur Mountain pluton. Only a small part of the pluton extends into the Holden quadrangle, and here the rocks are gneissic granodiorite.

The High Pass and Buck Creek plutons are tabular, somewhat sill-like masses of granodioritic and quartz dioritic composition. Rocks in the Buck Creek pluton are entirely gneissic, whereas rocks only near the contacts or in the thinner parts of the High Pass are gneissic. In most places, the contacts of both plutons consist of lit-par-lit zones, but numerous dikes of the High Pass are present in the host rocks, especially the Sulphur Mountain pluton.

The Riddle Peaks pluton consists of layered and unlayered hornblende gabbro. Inasmuch as the pluton is cut on all sides by later intrusive rocks, its age relative to older plutons is not known, but it is almost certainly pre-Tertiary. Much of the gabbro is rhythmically layered, but some is unlayered or only vaguely layered. In places, thick sheets of unlayered gabbro alternate with equally thick sheets of rhythmically layered gabbro. The rock is mostly fresh and unaltered or

recrystallized. No pseudosedimentary structures other than the gravity-stratified rhythmic layers were seen.

The Cardinal Peak pluton has a core consisting largely of granodiorite and quartz diorite and a rim of contact complexes containing large amounts of gabbro and coarse-grained hornblendite. The northern part of the intrusive is highly protoclastic throughout and contains numerous spindle- and canoe-shaped masses a third of a meter to several meters across and a few meters to several tens of meters long that are either partly or completely enveloped by rinds of fine-grained protoclastic material. These masses seem to have behaved as roller bearings during intrusion of the partly crystalline magma.

Tertiary intrusive rocks range in age from early Eocene to Miocene. Overall compositions do not vary much from pluton to pluton, but the composition can range from gabbro to quartz monzonite within individual plutons. Most of the plutons are typically epizonal, but parts of some are mesozonal. Oldest of the Tertiary plutons are the rather small epizonal to mesozonal Clark Mountain stocks consisting of quartz diorite and granodiorite. Next oldest is the tadpole-shaped late Eocene Duncan Hill pluton. This intrusive has been eroded to mesozonal depths at its thin tail and to only subvolcanic levels at its much wider head. The composition grades from quartz diorite in its mesozonal northern part to miarolytic quartz monzonite porphyry at its southern, subvolcanic part. Only about a million or so years younger than the 45-m.y.-old Duncan Hill is the Railroad Creek pluton. Numerous dikes satellitic to the pluton and small, irregular related masses are widely scattered in the northern part of the Lucerne quadrangle. Rocks in the pluton vary in both composition and texture, but granodiorite predominates and quartz diorite and quartz monzonite occur in small quantities. Similar in age to the Railroad Creek are the Copper Peak and Holden Lake plutons of hornblende-quartz gabbro. These plutons are notable for spectacular contact complexes consisting of rocks ranging in composition from quartz diorite to hornblendite that contain innumerable inclusions in various states of assimilation. The Larch Lakes and Rampart Mountain Plutons are undated, but closely resemble other late Eocene intrusives, and are believed to be of that age. The Larch Lakes pluton consists of rocks ranging in composition from quartz diorite to quartz monzonite, whereas the Rampart Mountain consists only of granodiorite and quartz monzonite. Both are sharply bordered, typically epizonal masses.

Preserved in the Chiwaukum graben is the Old Gib volcanic neck in which is preserved a Peléan spine. The neck has a radiometric age of 44 m.y., consists largely of dacite porphyry, but contains some labradorite andesite and is cut by a few basaltic dikes. Other probably late Eocene rocks include a sizeable mass of intrusive breccia and dikes and irregular larger masses of generally fine-grained hornblende-biotite-quartz diorite, biotite-quartz monzonite, and granodiorite.

Youngest of the major intrusives in the area is the Miocene Cloudy Pass batholith, now in the process of being deroofed. It is characterized by numerous subvolcanic features, intrusive breccias, and chilled contact complexes. Most of the rock is labradorite granodiorite, but quartz diorite and leucocratic quartz monzonite also occur. The batholith is bordered on the east by a layered complex of chilled rocks, the complex of Hart Lake.

From late Paleozioc time until the present, probably no sizeable time spans devoid of either magmatic or tectonic activity occurred in the northern Cascades. As a result, plutons vary greatly in depths to which they have been eroded. The older plutons, such as the Dumbell Mountain, have been carved to catazonal depths; the youngest, such as the Miocene Cloudy Pass, only now are being unroofed, and consequently show numerous subvolcanic features. The long, narrow Duncan Hill pluton is particularly illuminating, for it has been strongly tilted and, hence, differentially eroded. The strongly uplifted northern part has been eroded to mesozonal depths and is typically synkinematic, but the moderately uplifted south part has been eroded only to subvolcanic and epizonal depths and is decidedly postkinematic. The terms "synkinematic" and "postkinematic" are probably meaningless when applied to these plutons as a whole, inasmuch as all are probably synkinematic at depth. Various other later Mesozoic and Tertiary plutons in the area more or less duplicate petrologic and structural features characteristic of given stretches along the length of the Duncan Hill.

All the major intrusives in the area reflect some degree of structural control, but such control is much more pronounced in the older plutons. The older plutons are decidely elongate and nearly concordant along strike but do crosscut host rocks downdip. Younger plutons are concordant only along parts of their contacts and tend to be much broader relative to their lengths, except for the conspicuously linear Duncan Hill mass. Furthermore, the younger intrusions tend to cut out large thicknesses of host rocks, at least to exposed levels. Because progressively younger plutons mostly are wide in proportion to their length, it seems likely that plutons in the area generally thin downward and become increasingly linear. The Dumbell Mountain plutons perhaps duplicate the appearance of the Cloudy Pass batholith at mesozonal depths. Again, the Duncan Hill pluton illustrates well the methods whereby an intrusion adjusts to its room problem at different depths, that is, by wedging host rocks apart at lower levels and lifting and cutting them out at upper levels.

Ages of the plutons have been determined by a variety of radiometric methods. Potassium/argon methods work well for Tertiary intrusions, but only lead/uranium ages on zircon have provided reliable or believable ages for pre-Tertiary intrusives. Ages range from about 220 m.y. for the Dumbell Mountain intrusions to about 22 m.y. for the Cloudy Pass batholith. The Cardinal Peak, Riddle Peaks, and Bearcat Ridge plutons have not been radiometrically dated but, on geologic evidence, are believed to be pre-Tertiary. At the time of intrusion of the Dumbell Mountain plutons, the upper Paleozoic sedimentary and volcanic rocks had already been metamorphosed to amphibolite grade. Although radiometric clocks have been reset by later plutonic events, the rocks have not been remetamorphosed, or only weakly so, since intrusion of Dumbell Mountain rocks.

Numerous samples of all the intrusive rocks have been modally analyzed, and one or more samples of all the major intrusions have been chemically analyzed. Compositions of the smaller intrusions are fairly uniform but, for most of the larger ones, variations are considerable. All the rocks are notably low in K_2O relative to average intrusive rocks of similar silica content; furthermore, the older the rock, the greater the deficiency of K_2O. Only the largest, mostly Tertiary, plutons are zoned. The Duncan Hill pluton progressively increases in SiO_2 and K_2O and decreases in calcium, magnesium, and iron along its length from north to south and, consequently, from deep to shallow levels within it. A similar, although more erratic, trend also occurs between plutons of increasingly younger age and, hence, between more deeply and less deeply eroded masses. Variations in content of silica and especially of K_2O in the Cloudy Pass batholith clearly seem to be the result of transfer of these constituents in supercritical aqueous solutions. The same processes probably also account for zoning in the Duncan Hill pluton and perhaps for compositional differences between more deeply and less deeply eroded plutons. Differentiation by crystal fractionation, although present, seems not to have been especially effective in presently exposed depths in the various plutons.

The textures of the older plutons have a crystalloblastic appearance, whereas the textures of younger plutons are typically igneous. It is unlikely, however, that the crystalloblastic-appearing textures are not the result of intense recrystallization in these rocks, but are the result of very slow cooling in catazonal regions of high temperatures and pressures. It seems extremely unlikely, for example, that recrystallization of the older plutons could have occurred and left unaffected the attitudes of gneissic foliation in disoriented inclusions. If these suppositions are true, then some of the metamorphic cycles and metamorphic suites detailed in the northern Cascades that have been based on the supposed metamorphism of various plutons are erroneous.

INTRODUCTION

Exposed in the core of the northern Cascade Range is a suite of plutons that is perhaps unrivaled in the country for the diversity of geology and ages of plutons and depths to which plutons are exposed. Within the confines of single 15-minute quadrangles are plutons ranging in age from Triassic to Miocene and in depth zones from catazonal to subvolcanic—marvelously revealed, furthermore, in a glacially scoured terrain of great relief. At one time most of these plutons were thought to be either part of or related to the so-called "Chelan batholith." Many of these plutons, however, are separated by time spans of tens of millions of years and by tectonic events so dramatic that an implied relationship indicated by the term "Chelan batholith" seems unwarranted.

This report presents the results of a study of these plutons carried out mostly during the geologic mapping of the Holden and Lucerne 15-minute quadrangles. These two quadrangles, together with the adjacent Glacier Peak quadrangle mapped by Crowder, Tabor, and Ford (1966), form a belt that crosses much of the plutonic core of the northern Cascades (fig. 1). This belt is representative of the core of the range, and statements and interpretations offered here probably apply with equal validity to the core as a whole. Inasmuch as some of the plutons in the Holden quadrangle extend into the Glacier Peak quadrangle, data concerning these plutons published by Crowder, Tabor, and Ford (1966) and Tabor and Crowder (1969) have been used freely. In addition, parts of some other plutons extending beyond the Holden and Lucerne quadrangles were investigated in reconnaissance. The Holden and Lucerne geologic quadrangle maps have been published previously (Cater and Crowder, 1967; Cater and Wright, 1967) and are not included in this report, although they should be considered an integral part of it and are referred to frequently. Figure 2 shows the location of various plutons described in this report. Field mapping was supplemented by examination of more than 900 thin sections of intrusive rocks and by 47 chemical analyses. Figure 3 shows the classification system for igneous rocks used in this report.

ACKNOWLEDGMENTS

I am indebted to the late Dwight F. Crowder and to C. A. Hopson, D. F. Kellum, R. W. Tabor, and T. L. Wright who helped map the Holden and (or) Lucerne quadrangles. To all of them I am also grateful for discussions that helped formulate some of the conclusions presented here. Crowder also examined many thin sections. I am particularly grateful to Hopson for unpublished data and mapping he contributed concerning the Duncan Hill pluton south of the Lucerne quadrangle.

PREVIOUS WORK

Prior to the mapping of the Holden and Lucerne quadrangles by the U.S. Geological Survey, work in the quadrangles was limited to descriptions of the rocks at Red Mountain by Richarz (1933), a discussion of geologic features at the Holden mine by Youngberg and Wilson (1952), and reports on two small areas mapped by Dubois (1954, 1956) and Morrison (1954).

TECTONIC SETTING

The northern Cascades were carved from an exotic block or minicontinent of continental crust that accreted to the North American continent during Mesozoic time (fig. 4). Many authors, including Davis, 1977; Davis, Monger, and Burchfiel, 1978; Dickinson, 1976; Hamilton, 1969, 1978; and Vance, 1978, have applied the concepts of plate tectonics to the region. They are not unanimous, however, on the origin of the minicontinent. Hamilton (1978, p. 42) considered it a far-travelled block that collided with the continental margin in middle Cretaceous time, whereas Davis, Monger, and Burchfiel (1978, p. 15) considered it a fragment of the Okanogan continental-margin terrain torn from the North American continent along a dextral transcurrent fault trending at a low angle to the continental margin. They called this fragment "Cascadia," and stated (p. 16), "Minimum right-slip of 160 km (100 miles) is represented by the length of unbroken Cascade crystalline terrain west of Jura-Cretaceous in the Methow trough. The distance is measured from the southern end of the trough, near Methow, where Cascade and Okanogan crystalline rocks are in fault contact, to the Hope area of British Columbia where Cascade core rocks are faulted

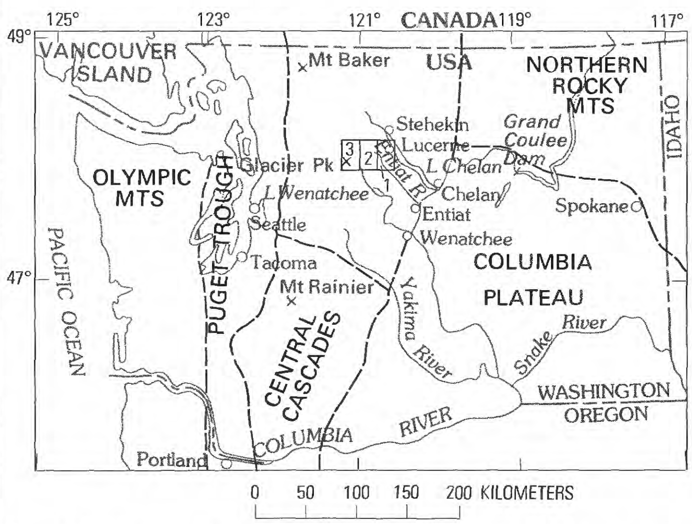

FIGURE 1.—Index map of Washington showing physiographic provinces and locations of Holden and Lucerne quadrangles.

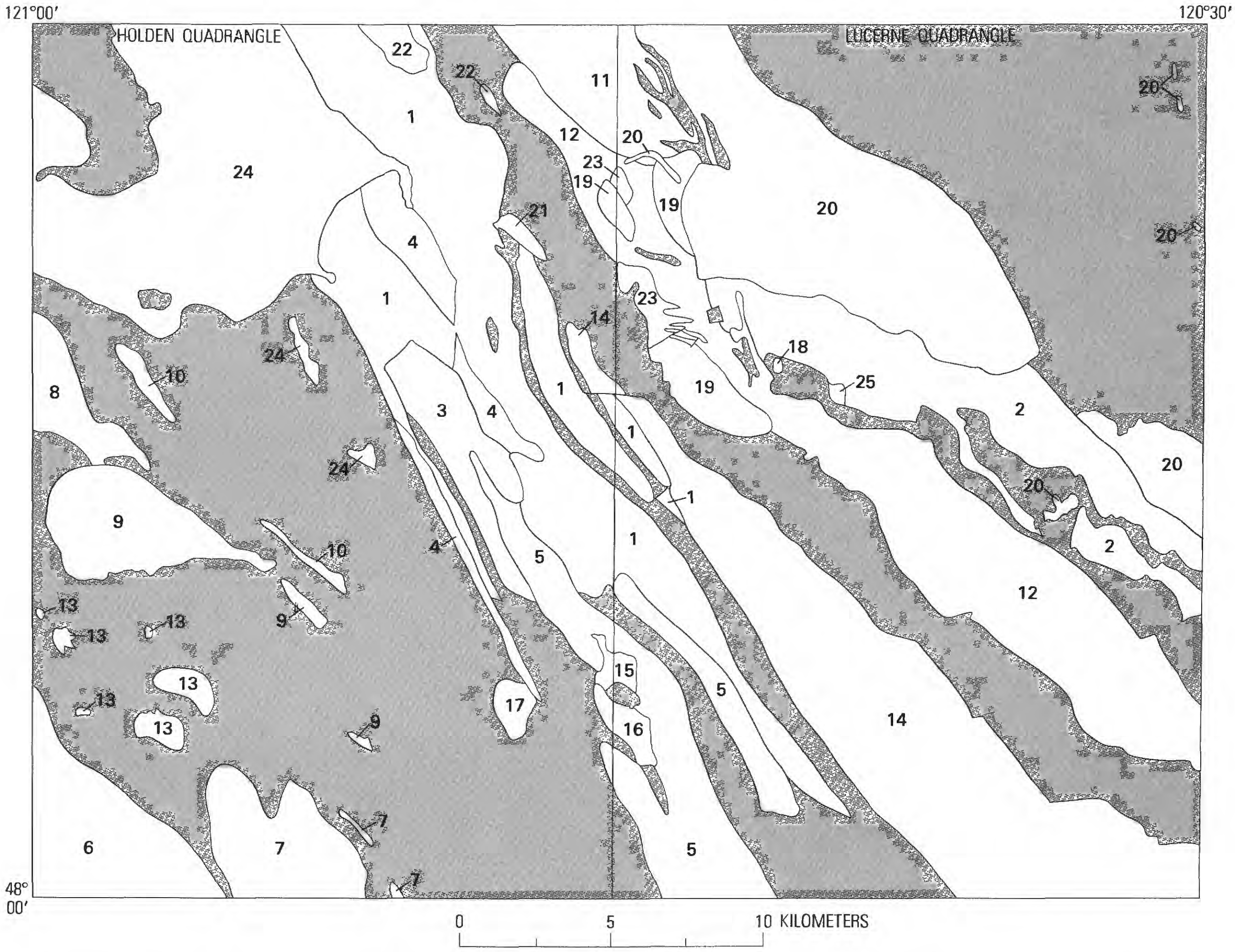

FIGURE 2.—Map showing locations of the plutons in the Holden and Lucerne quadrangles. Patterned areas are metamorphic rocks.

1. Dumbell Mountain plutons
2. Bearcat Ridge plutons
3. Leroy Creek pluton
4. Seven-fingered Jack plutons
5. Entiat pluton
6. Tenpeak pluton
7. White Mountain pluton
8. Sulphur Mountain pluton
9. High Pass pluton
10. Buck Creek pluton
11. Riddle Peaks pluton
12. Cardinal Peak pluton
13. Clark Mountain stocks
14. Duncan Hill pluton
15. Larch Lakes pluton
16. Rampart Mountain pluton
17. Old Gib volcanic neck
18. Intrusive breccia
19. Hornblende-biotite-quartz diorite
20. Railroad Creek pluton
21. Copper Peak pluton
22. Holden Lake pluton
23. Biotite-quartz monzonite and granodiorite
24. Cloudy Pass batholith
25. Leucocratic quartz monzonite

out against the Hope–Straight Creek fault system. The northernmost extent of Cascade rocks west of the Straight Creek fault is not known because of the obliterative effects of the Coast Range Batholithic complex." They further postulated that the Ross Lake fault or a precursor of it was the most likely place where this shift occurred. The pull apart from the North American continent is assumed to lie beneath the Miocene basalts of the Columbia River plateau.

In any event the minicontinent is separated from the pre-Carboniferous continental shelf in northeastern Washington by some hundreds of kilometers, a gap now consisting of large masses of island-arc and oceanic assemblages intruded by very large amounts of granitic material.

PREINTRUSIVE ROCKS

The oldest plutons in the area intruded a terrain of metamorphic rocks of late Precambrian and late Paleozoic age. Younger plutons, of course, intruded not only the metamorphic rocks but also the older plutons. The oldest of the formations exposed in the area, and probably in the northern Cascades, is the Swakane

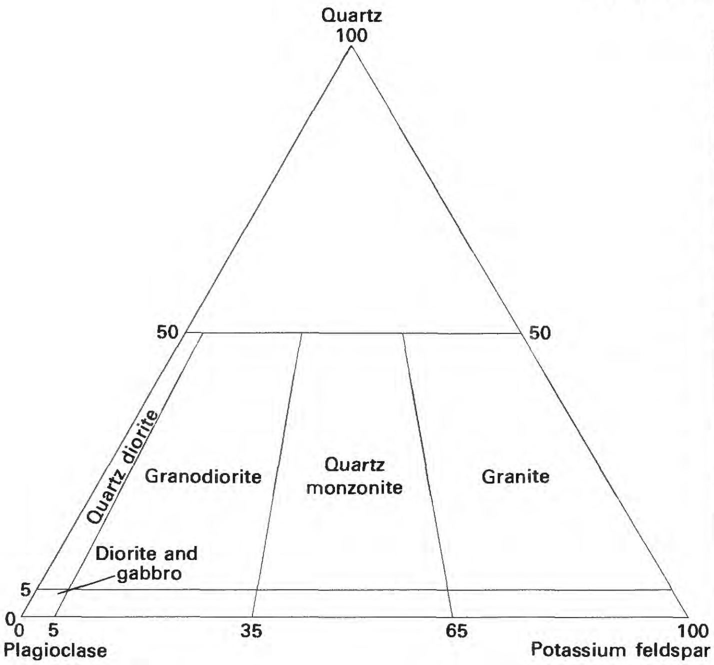

FIGURE 3.—Triangular diagram showing the modal rock classification system used in this report.

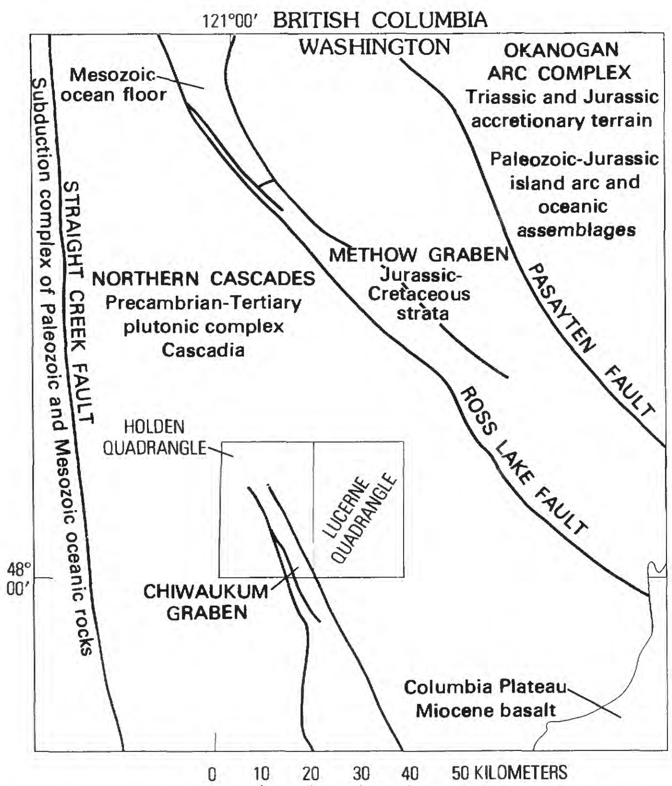

FIGURE 4.—Tectonic sketch map of north-central Washington showing the relation of the Holden and Lucerne quadrangles to the regional tectonic framework. Named faults separating major structural elements restored. Heavy lines are faults; lighter lines are contacts.

Biotite Gneiss. The Swakane is possibly equivalent to at least part of the Custer Gneiss of McTaggart and Thompson (1967), which was originally called the Custer Granite Gneiss by Daly (1912, p. 525-526). The formation has also been called the Skagit Gneiss by Misch (1952, p. 12-14) and others, but the name "Skagit" was preempted by Daly in 1912 for a sequence of volcanic rocks along the Canadian border west of Ross Lake. Overlying the Swakane is a sequence of metamorphosed eugeosynclinal, rather thinly laminated, complexly folded rocks of late Paleozoic age that is widely exposed in both quadrangles and elsewhere in the region. The unmetamorphosed Paleocene Swauk Formation outcrops in a few locations in the Chiwaukum graben (Willis, 1953) within the Holden quadrangle.

SWAKANE BIOTITE GNEISS

The Swakane Biotite Gneiss is predominantly a light-brown to brownish-gray, fine- to medium-grained, strongly foliated rock. Intercalated with the gneiss, locally, are rather thin layers of hornblende schist and gneiss, gneisses predominantly of clinozoisite-epidote, and more rarely, thin layers of quartzitic rock. Some of these layers can be traced for kilometers and represent an original compositional layering or bedding. Kyanite occurs sparsely on Phelps Ridge but is rare elsewhere, and garnet is common in many places. Streaks of biotite on the plane of foliation commonly define a marked lineation. Lenses and pods of quartz and irregular masses of leucocratic quartz diorite are notably abundant in some places and common elsewhere. Other than compositional layering, no original textural or structural features remain. Probably many thousands of meters of the formation are exposed in the northeast part of the Lucerne quadrangle, and equally great thicknesses are exposed elsewhere in the region; the base of the Swakane is not known to be exposed. The Swakane was assigned a Cretaceous and older age on the Lucerne and Holden quadrangle maps (Cater and Crowder, 1967; Cater and Wright, 1967). Mattinson (1972) obtained ages of more than 1,650 m.y. (age of parent material) from zircons in the rock along the Columbia River, but he also got Paleozoic ages of about 415 m.y. (metamorphic age) from zircons in the biotite gneiss along the Skagit River about 65 km northwest of the Lucerne quadrangle. On the basis of a minimum age of 415 m.y., the Swakane is considered early Paleozoic or older in this report. Staatz and others (1972, p. 3774, table 2) mapped these rocks as Custer Gneiss of McTaggart and Thompson (1967), and Misch (1952, 1966) mapped them as Skagit Gneiss. The Swakane on the Columbia River is directly traceable to the Swakane in the Holden quadrangle, which in turn is identical to rock mapped as Swakane in the Lucerne quadrangle. Misch (1966, p. 107, fig. 7-1) showed the Skagit Gneiss on the Skagit River as continuous with the Swakane of the Lucerne quadrangle. Possibly metamorphism of the rocks in the area between the two localities has obscured the relation of the Custer to the Swakane.

The nature of the material from which the Swakane Biotite Gneiss is derived is not known with certainty. Hornblende-rich layers may have been basaltic flows, and quartzitic and epidote-rich layers probably were sedimentary beds. Waters (1932, p. 616) considered it likely that the biotite gneiss was derived from mostly arkosic material, a possibility that still remains; but more recently Hopson (*in* Mattinson, 1972, p. 3773) considered a volcanic derivation more likely. The accumulation of a nearly uniform pile of arkose many thousands of meters thick of the wide areal extent of the Swakane and its equivalents seems unlikely. Arkosic piles such as the Permian Cutler Formation in southwest Colorado and Utah tend to be segregated by sedimentary differentiation into interlayered beds of sandstone, mudstone, and shale farther from source areas (Cater, 1970). The Swakane and its equivalents are remarkably uniform in composition throughout their outcrop area and show no tendency toward original segregation into contrasting beds. The chemical composition of the biotite gneiss approximates that of dacite; table 1 shows an analysis of a composite sample of representative specimens of biotite gneiss.

With the foregoing in mind, it seems more likely that the Swakane Biotite Gneiss was probably derived from a huge, fairly silicic volcanic pile. Scattered basaltic flows now form the hornblende gneiss and schist layers, and the quartzite and mica schist layers were probably thin sedimentary beds deposited in small, ephemeral basins in the volcanic terrain.

The Swakane Biotite Gneiss has been warped into steep-sided but generally open folds having steep to vertical axial planes. Waters (1932, p. 621) noted that the same type of folds characterize the Swakane farther to the south along the Columbia River. Generally, attitudes of the gneiss are uniform through considerable thicknesses, but locally attitudes of foliation are irregular, particularly where disturbed by various intrusives.

TABLE 1.—*Chemical and spectrographic analyses of Swakane Biotite Gneiss, central Washington*

[Na_2O and K_2O determined by flame photometer by Violet Merritt. Fe_2O_3, MgO, and CaO determined by atomic absorption by Violet Merritt. FeO determined volumetrically by H. H. Lipp. SiO_2 and Al_2O_3 determined colorimetrically by G. D. Shipley and G. T. Burrow. Spectrographic analysis by Harriet Neiman.]

Chemical analysis (percent)		Spectrographic analysis (percent)	
SiO_2	68.2	Ti	0.3
Al_2O_3	15.0	Mn	.07
Fe_2O_3	3.45	Ba	.05
FeO	2.8	Be	.0001
MgO	1.60	Co	.007
CaO	2.04	Cu	.0015
Na_2O	3.01	Ga	.002
K_2O	1.96	Ni	.002
Total	98.06	Pb	.0015
		Sc	.0007
		Sr	.03
		V	.015
		Y	.0015
		Yb	.0002
		Zr	.02

LATE PALEOZOIC METAMORPHIC ROCKS

Overlying the Swakane Biotite Gneiss is a highly diverse sequence of metamorphosed eugeosynclinal rocks consisting largely of rather thinly layered, highly and complexly folded hornblende and biotite-hornblende schist and gneiss, biotite schist, clinopyroxene-biotite schist, graphitic schist, quartzite, and lenses of marble (fig. 5). These rocks crop out on opposite sides of the Chiwaukum graben, which is mostly underlain by the Swakane. The rocks to the east of the graben were called "younger gneissic rocks of the Holden area" on the Holden and Lucerne geologic quadrangle maps, and the rock to the west, the "rocks of the Napeequa River area." The rocks in the two belts are almost surely parts of a single series or group, but attempts at stratigraphic correlations between the belts have been thwarted, in part, probably, by rapid facies changes combined with

FIGURE 5.—Interlayered upper Paleozoic quartzite, biotite schist, and hornblende gneiss, upper Klone Creek, Lucerne quadrangle.

depositional wedging, but more critically by metamorphic changes, extreme structural complexities, and mangling by the various intrusions. Sedimentary features are preserved well enough to determine tops of beds in a few places on the ridge north of Holden, although the rocks are metamorphosed to amphibolite grade. Search elsewhere, however, failed to find similar unequivocal evidence for tops, despite the little-modified aspect of the beds in some places. Isoclinal folding and other structural complexities render thickness determinations highly uncertain, but in the Holden quadrangle the exposed thickness cannot be less than about 1.5 km, and it may well be at least twice that much. If the "rocks of the central schist belt" of the Glacier Peak quadrangle (Crowder and others, 1966) are also part of the same sequence, as seems likely, then the thickness could be very much greater. Zircons from a layer of metamorphosed keratophyre tuff in the Holden quadrangle were dated by Mattinson (1972, p. 3773) as 265 ± 15 m.y. old; hence, the rocks are of late Paleozoic age.

The structure of the upper Paleozoic metamorphic rocks differs radically from that of the underlying Swakane Biotite Gneiss and is far more complex. The major folds in the Swakane are broad, open, and mostly fairly simple, whereas those in the upper Paleozoic rocks are tightly compressed and overturned or actually inverted. For example, sedimentary structures indicate that the antiform in these rocks that trends across the Lucerne quadrangle is an inverted syncline. East of the Chiwaukum graben, these rocks seem to have been thrust westward over the probably already metamorphosed Swakane before they became metamorphosed. West of the graben, great thicknesses of beds are missing from the northeast side of the synform of upper Paleozoic metamorphic rocks, where these upper Paleozoic rocks rest on the Swakane, or where the rocks are separated from the Swakane, by a sheet of intrusive rocks. As is detailed in the text that follows, the structure of both sequences of metamorphic rocks has had a profound influence on the form of the various plutons.

The metamorphic rocks are overlain by shale, arkosic sandstone, and conglomerate that were mapped as the Paleocene Swauk Formation. Later work (Whetten, 1976) indicated that the rocks are of late Eocene age; Whetten obtained a fission-track age of 44.1 ± 4.3 m.y. on zircons from a tuff near the base of the sequence. In the study area, the sedimentary rocks have been preserved only in the Chiwaukum graben in the Holden quadrangle, but they underlie large areas elsewhere in the northern Cascades. Within the Holden quadrangle, only a few dikes cut the formation, although farther south are a few small plugs and extensive dike swarms. Of particular interest are numerous cobbles in the conglomerates consisting of volcanic rocks. These volcanic rocks may be the extrusive equivalents of some of the late Cretaceous intrusive rocks described here.

PRE-TERTIARY INTRUSIVE ROCKS

ULTRAMAFIC ROCKS

A number of small masses of ultramafic rocks ranging from only a few meters to a few hundred meters across crop out in the area. The smaller ones consist of serpentine, and some of the serpentine has been extensively altered to talc or tremolite. The larger ones, on the other hand, are highly variable in composition and consist of gabbro, hornblendite, and peridotite. The serpentine masses mostly occur in a northwesterly trending zone extending through the southwest part of the Holden quadrangle to the northwestern part of the Glacier Peak quadrangle. The ultramafic masses of variable composition are confined to the Holden mine–Buckskin Mountain area and are probably considerably younger and unrelated to the serpentine bodies.

Serpentine occurs as scattered lenses apparently tectonically emplaced in gneiss and schist or in the interlayered zone in the Tenpeak pluton. Rare masses only a few meters across have been seen as inclusions in various quartz diorite plutons scattered about the study area. The largest masses are near the divide at the head of Boulder Creek in the Holden quadrangle. Contacts, where seen, are sharp and either sheared or unsheared. The serpentine is light green to black and either schistose and sheared or dense and structureless. Where altered to talc or tremolite, the rock is light green or nearly white; such masses are mostly confined to quartz diorite.

Thin-section examination revealed that the serpentine contains rare relics of olivine in a felted mat of antigorite; abundant magnetite occurs mostly as sagenitic webs of irregular grains. Most thin sections also contain talc and tremolite, and some consist almost entirely of talc. Scattered picotite grains are accessory.

Ultramafic rocks in the Holden mine and on Buckskin Mountain differ considerably from the serpentine bodies and from other ultramafic masses that have been described in the northern Cascades (for example, Ragan, 1963, and Southwick, 1974). Most ultramafic masses in the northern Cascades are of Alpine type and consist of little but saxonite or dunite or their serpentinized products, whereas the ultramafic rocks in the Holden area consist largely of hornblendite and hornblende peridotite that grade into hornblende gabbro. Saxonite and dunite are absent. Some of the peridotite in the Holden mine contains numerous coarse-grained gabbroic orbicules as much as 7 cm across (fig. 6). The rocks are dark green to black, coarse to very coarse grained, and some crystals are more than 2 cm across. The largest of

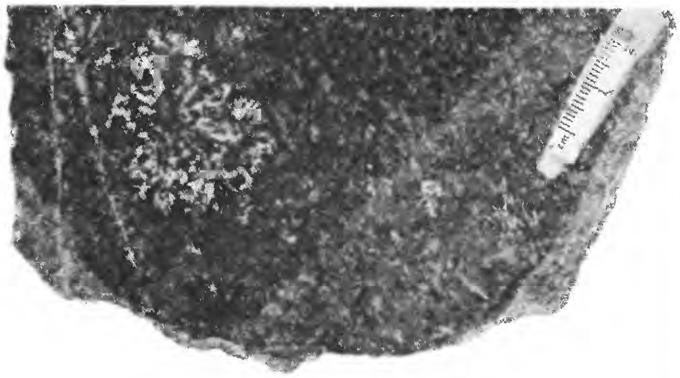

FIGURE 6.—Gabbroic orbicules in peridotite from the Holden mine, Holden quadrangle.

the masses cropping out on Buckskin Mountain is about 300 m across; the size of those in the Holden mine are not known, but some exceed several hundred meters. Contacts with older rocks are either sharp and intrusive or faulted. Contact effects on intruded rocks are minimal.

Microscopic examination of the ultramafic rocks confirms the heterogeneity evident in hand specimen. Hornblende is the only major constituent common to all the rocks, and it is optically similar in all facies of the rock regardless of other constituents. Hornblende crystals are commonly anhedral and pleochroic from nearly colorless to light brown. The intensity of pleochroism varies considerably within a single crystal, some parts of most crystals being nearly colorless in all orientations; in others, the brown shades into light green. Some grains are loaded with Schiller-like inclusions that may be spinel. In many of the rocks, hornblende has been either replaced or at least partly rimmed by tremolite containing magnetite dust. Pyroxene occurs only in peridotites, and in these it may be either clinopyroxene alone or both clino- and orthopyroxene. Most crystals are either euhedral or subhedral, but some rounded grains occur as poikilitic inclusions in hornblende. Small amounts of olivine are scattered through some of the hornblendite, and as much as 30 percent is in hornblende peridotite. Olivine is generally much altered to antigorite and magnetite. Light-colored biotite or phlogopite is common in most of the rocks and makes up 20 percent of some of them. It is pleochroic from colorless to light brown and is mostly shredlike. Plagioclase in amounts approaching 50 percent distinguishes the gabbros from the other rock types, although very small amounts of interstitial bytownite are found in some peridotite. Most of the plagioclase is bytownite, having an average composition of about An_{80}, but in some of the more felsic gabbro the plagioclase is sodic labradorite. Plagioclase in orbicular gabbro is bytownite, however. Regardless of composition, plagioclase is subhedral to euhedral and shows both oscillatory and patchy zoning. Magnetite, apatite, and ilmenite, which is commonly rimmed by sphene, are fairly abundant accessories. Mafic constituents in most of the rocks are variously altered to antigorite (replacing olivine and pyroxene), tremolite (replacing hornblende), and chlorite (replacing hornblende and phlogopite). In the Holden mine, various sulfides, including pentlandite, exsolved from pyrrhotite, locally replace both gabbro and ultramafic rocks.

Ages of the ultramafic rocks are not known with precision; the serpentine masses in the Holden and Glacier Peak quadrangles are, of course, older than the intrusive rocks in which they occur and may well be the oldest igneous rocks in the area. The hornblendic rocks in the Holden area are probably much younger and may be as young as late Eocene, inasmuch as they may be a facies of the mafic contact complex that envelops the north end of the Duncan Hill pluton.

DUMBELL MOUNTAIN PLUTONS

Rocks of the Dumbell Mountain plutons were described in detail by Crowder (1959). Since publication of Crowder's report, however, these rocks have been reexamined both in the light of what was learned from the intensive study of other intrusions in the area and from radiometric dating not then available. As a result, some of Crowder's earlier interpretations and conclusions seem untenable. He concluded that the Dumbell Mountain plutons, in addition to others now known to be much younger, were merely facies of a large granitized mass that has been locally mobilized. The present study indicates that these conclusions were probably invalid.

As Crowder (1959) showed, the Dumbell Mountain rocks within the mapped area consist of three separate but closely related units that I consider to be three distinct plutons. From the north border of the Holden quadrangle they extend south-southeastward into the Lucerne quadrangle where they either pinch out or are cut off by the late Eocene Duncan Hill pluton. They possibly correlate with Misch's (1966, fig. 7–1) "Marblemount Meta Quartz Diorite" to the northwest, which Mattinson (1972) showed to be of the same age. Misch (1966) considered the Marblemount a part of a pre-Middle Devonian "basement" consisting of regionally metamorphosed orthogneisses which he showed, citing theses maps of Tabor (1958) and Grant (1966), in thrust relation with the "Cascade River Schist," presumably equivalent to "younger gneissic rocks of the Holden area" of the Holden and Lucerne geologic quadrangle maps. Inasmuch as Misch's map (1966, fig. 7–1) is of an area extending well into the Holden quadrangle, he shows thereby quartz diorite of

Dumbell Mountain thrust over "younger gneisses of the Holden area." The Dumbell Mountain plutons are in fact neither older than nor thrust over the "Cascade River Schist" in the Holden quadrangle; rather, they are unrecrystallized or only incipiently recrystallized igneous rocks about 220 m.y. old (Mattinson, 1972) that are intrusive into, instead of thrust over, the metasediments in the Holden area. The evidence supporting these conclusions is presented, where appropriate, in the pages that follow. In any event, despite the resemblance of the "Cascade River Schist" to the "younger gneissic rocks of the Holden area," either the correlation is wrong or the "Marblemount Meta Quartz Diorite" is older than the Dumbell Mountain plutons.

Inasmuch as Crowder (1959) described the distribution, petrography, and contact relations of the Dumbell Mountain plutons in considerable detail, they are only summarized here.

The Dumbell Mountain plutons are narrow, nearly concordant masses of quartz diorite that trend north-northwest, more or less parallel to the attitudes of the metamorphic host rocks. Sheets or screens of schists and gneisses, some of them of mappable size, are common in the plutons. These are particularly abundant in the hornblende-quartz diorite augen gneiss between Railroad and Ice Creeks. In addition to these, a thin screen of hornblende gneiss and schist about 8 km long separates the quartz diorite augen gneiss from gneissic hornblende-quartz diorite between Big Creek and Ice Creek, and a similar screen of about the same size separates gneissic quartz diorite from the Leroy Creek pluton.

Contacts between the plutons and the metamorphic rocks are varied: sharp in some places, gradational in others, but more commonly characterized by lit-par-lit interlayering of quartz diorite and metamorphic rocks. Alternating layers in the lit-par-lit zones are several centimeters to tens of meters thick, and, indeed, some are almost the size of the mapped screens. Some layers of schist and gneiss have been wedged from the walls by quartz diorite and are inclined to the foliation of the quartz diorite. In general, contacts between layers are sharp, but layers of metamorphic rocks tend to fray out along strike and grade into and contaminate the intrusive material. Some hornblende schist and gneiss layers and inclusions have dark, more hornblende-rich margins from which felsic material has migrated (fig. 7); in fact, many thinner layers and inclusions consist almost entirely of hornblende.

Quartz diorite near contacts characterized by lit-par-lit injections tend to be crowded with inclusions of host rocks. As would be expected where host rocks are strongly foliated, inclusions of host rocks in the intrusive rock near contacts are mostly platy or discoidal, but many are more or less equidimensional and angular. As a rule, longer dimensions of inclusions—dimensions that usually accord with the planes of foliation in the inclusions—are parallel to the foliation of the quartz diorite, but some are inclined at high angles. Had foliation of the quartz diorite resulted from postintrusion recrystallization, as Crowder (1959) earlier thought and as Misch (1966) assumed by correlating these rocks with his ancient basement rocks, it seems unlikely that the angular relation between foliation of the quartz diorite and foliation of inclusions defined by elongate and platy minerals could have been preserved. Furthermore, the intricately swirled foliation, particularly characteristic of the hornblende-quartz diorite augen gneiss but occurring in the other Dumbell Mountain plutons, is not the type likely to result from regional metamorphism; the host rock schists and gneisses are devoid of this type of foliation. Swirled foliation, in fact, occurs locally in most of the plutons regardless of age and results from flowage during intrusion.

FIGURE 7.—Dumbell Mountain hornblende-quartz diorite augen gneiss containing inclusions with mafic margins, Holden quadrangle.

Locally contacts of plutons with metamorphic rocks are gradational, in most places through zones only a few tens of meters or less thick. In some places, however, as on the ridge south of the glacier on the east side of Copper Peak, the gradational contact zone is a few hundred meters thick. As contacts of plutons are approached, the grain size and proportion of felsic material in the hornblende schist and gneiss, of which the host rocks largely consist, increases, and thin seams of igneous material have been insinuated along foliation planes. Closer to the plutons, the amount of igneous material increases, and the metamorphic material becomes more thoroughly incorporated in the rock mass. Dikes and sills of quartz diorite cut these gradational contacts just as they do contacts marked by lit-par-lit zones where there is a marked difference between igneous and metamorphic material. Gradations are equally evident in thin sections, as is discussed later.

Although each of the Dumbell Mountain plutons is closely similar to the others in chemical and mineralogic composition, they differ significantly in outcrop appearance. These differences are mostly a function of gneissic foliation; its nature, its degree of segregation into light and dark laminae, and its persistence of attitude or prevalence of swirling. For each of the plutons there is a unity of gneissic characteristics that is more or less distinctive, although there is considerable overlap of these in the different plutons. Thus scattered masses of augen gneiss occur in both the gneissic hornblende-quartz diorite and the hornblende-quartz diorite gneiss plutons, but augen texture is the characteristic feature of the hornblende-quartz diorite augen gneiss pluton. Despite the similarities among the different plutons, contact relations point to a sequence of emplacement. Oldest is the hornblende-quartz diorite gneiss; this rock was intruded locally by gneissic hornblende-quartz diorite, but more commonly the contacts between the two appear to be completely gradational and nothing suggestive of an age difference is apparent. Hornblende-quartz diorite augen gneiss, on the other hand, clearly intrudes quartz diorite gneiss almost throughout their contact lengths, yet in the one area where the augen gneiss is in contact with gneissic quartz diorite, on the north side of Railroad Creek upstream from Holden Creek, the relations are equivocal.

The rocks in the Dumbell Mountain plutons differ little mineralogically; the principal difference is in the composition of the plagioclase, which ranges from about An_{38} to about An_{50} in the hornblende-quartz diorite gneiss and augen gneiss and from about An_{30} to An_{50} in the gneissic hornblende-quartz diorite. Most abundant in all the plutons are rocks containing plagioclase having a composition of about An_{38}; considerable but lesser amounts of rocks in all the plutons contain calcic andesine of about An_{47}, and in the gneissic quartz diorite pluton, about one-fourth of the thin sections examined contained andesine of about An_{32}. Rocks containing andesine of compositions intermediate between these peaks are rare. Megascopic appearance or texture give no clue to the composition of the plagioclase of any given rock, although biotite tends to occur more commonly in rocks containing less calcic andesine.

Since the Dumbell Mountain, Leroy Creek, Entiat, and Seven-fingered Jack plutons were described by Crowder (1959), the Dumbell Mountain pluton and rock of the Chelan Complex Entiat and Seven-fingered Jack plutons have been radiometrically dated by Mattinson (1972), and these rocks have been more thoroughly examined petrographically. The textures seen in many of the dated rocks where there is no question of recrystallization, particularly some of the older and deeper seated rocks, has made apparent the need for a reappraisal of what Crowder called "crystalloblastic" textures in the Dumbell Mountain and, for that matter, of the texture in the younger Seven-fingered Jack, Entiat, and Leroy Creek plutons. In my opinion, none of the rocks in any of these plutons are crystalloblastic; many, however, did crystallize under stress and most of the gneissic rocks show varying degrees of protoclasis.

Plagioclase is the mineral most notably affected by protoclasis because it was the first to crystallize and seems to have been the only crystalline component in the magma when protoclasis began—or at least these were the only grains of sufficient size to have effectively impinged on each other during the grinding process that accompanied intrusion. Locally, however, larger crystals of hornblende have been broken and distorted protoclastically and, in some places, protoclasis passed into cataclasis where stresses continued after the plutons had completely crystallized. Plagioclase grains in the protoclastic rock are rounded and abraded; many grains consist of a number of slightly rotated fragments (fig. 8). Fractures separating the fragments end at grain boundaries, and later hornblende, quartz, or biotite grains commonly have formed or replaced plagioclase along these fractures (fig. 8), but the later grains themselves are undeformed. Nearly every thin section of Dumbell Mountain rocks contains a few plagioclase grains where a few faint oscillatory and patchy zonings may be seen (fig. 9). Oscillatory zones in many grains are truncated, which indicates that such grains are but fragments broken from larger crystals during protoclasis. In some

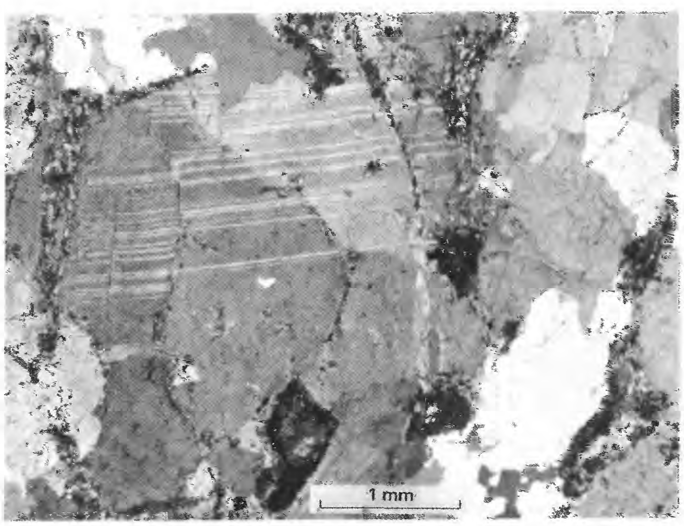

FIGURE 8.—Gneissic hornblende-quartz diorite from the Dumbell Mountain plutons, Holden quadrangle. Note fine-grained aggregates of quartz and sodic oligoclase filling fractures in andesine.

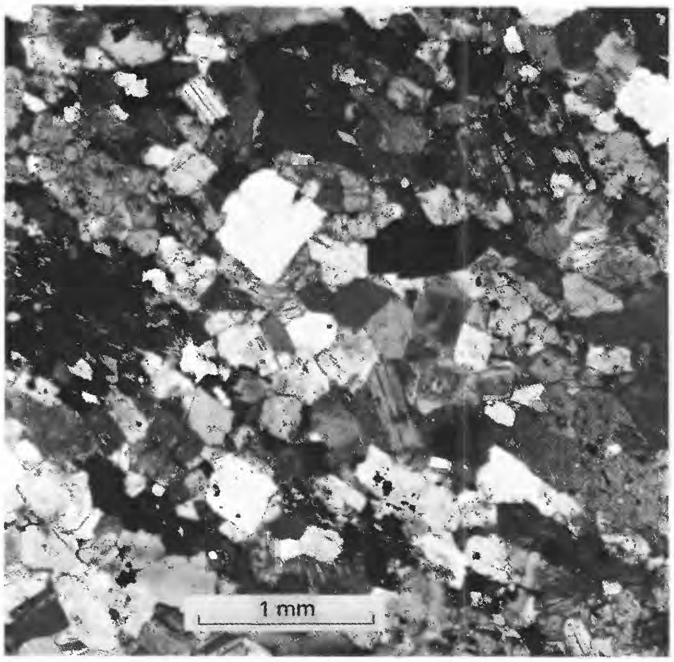

FIGURE 9.—Oscillatory- and patchy-zoned andesine in hornblende-quartz diorite gneiss from the Dumbell Mountain plutons, Holden quadrangle. See figure 14 for hand sample.

crystals, oscillatory and patchy zoning are preserved only in untwinned or only weakly twinned parts of crystals, suggesting thereby that the general lack of both types of zoning merely reflects destruction of them by twinning. A great many individual plagioclase crystals are twinned according to multiple laws, a feature many authors have detailed as suggestive of igneous origin (Gorai, 1951; Smith, 1958; Vance, 1961, 1962; Turner, 1951). The occurrence of patchy zoning in most thin sections of Dumbell Mountain rocks virtually precludes recrystallization following emplacement of the plutons and is strong presumptive evidence of magma transport from greater depths (Vance, 1965). Some sieve-textured hornblende crystals are clearly derived from partly assimilated metamorphic rocks, but some result from incomplete replacement of plagioclase by hornblende; such grains not uncommonly contain groups of simultaneously extinguishing inclusions apparently derived from a preexisting single crystal of plagioclase.

Partly for the sake of convenience and partly because significant differences do exist between them, the plutons are described separately. It should be emphasized, however, that although each pluton is a separate entity, they are closely related and are probably derived from a common magma in which differentiation had little effect—at least at the presently exposed level, which the evidence indicates is catazonal.

The location of modally analyzed specimens of the Dumbell Mountain plutons are shown on figure 10, the modal analyses are presented in table 2, and the chemical and spectrographic analyses are presented in table 3. The modes are also plotted on a quartz-potassium feldspar-plagioclase triangular diagram (fig. 11) and the norms are shown on figure 12. Compositions are plotted on a variation diagram (fig. 13).

HORNBLENDE-QUARTZ DIORITE GNEISS

Hornblende-quartz diorite gneiss crops out from the north edge of the Holden quadrangle on Bonanza Peak to Mount Fernow where it pinches out, a distance in the mapped area of 11 km. It lies between the younger quartz augen gneiss of Dumbell Mountain on the east and probably still younger gneissic quartz diorite to the west. As already noted, its contacts with these younger rocks range from sharp and intrusive to gradational.

The megascopic appearance of this rock is more uniform than that of the other Dumbell Mountain rocks, although the amounts of schlieren and incorporated material vary considerably from place to place. Nearly all of it is strongly and rather uniformly gneissic (fig. 14). The hornblende forms flat clusters or long black strings of needles that give much of the rock a well-defined lineation that plunges southeastward at low to moderate angles. Unlike the other Dumbell Mountain rocks, this gneiss is virtually but not entirely unswirled, and the foliation maintains rather constant attitudes through considerable distances.

Thin-section examination of the hornblende-quartz diorite gneiss showed it to consist largely of plagioclase, hornblende, and quartz, and in about half the sections a little biotite is present. Small quantities of magnetite, titanite, and apatite are accessory. In a few thin sections, very small amounts of potassium feldspar occur interstitially, or more commonly, as tiny veinlets. Chlorite, clinozoisite-epidote, and sericite, mostly in small quantities, are secondary. Plagioclase is mostly fresh and ranges in composition from andesine having an average composition of about An_{38} to sodic labradorite having an average composition of slightly more than An_{50}. Individual crystals range from subhedral to anhedral, and many are rounded and obviously abraded; a few grains in most sections show four or five oscillatory zones and equally faint patchy zoning. In a few sections showing hypidiomorphic textures, many crystals have well-defined oscillatory and patchy zoning, but the zones in any given crystal do not exceed four or five (fig. 9). Hornblende occurs as euhedral to anhedral grains; much of it forms aggregates resembling poikilitic hornblende, but such groups do not form single crystals, although this is commonly not apparent except under crossed nicols. The pleochroic formula for hornblende is X, straw yellow to light greenish yellow; Y, green; and Z, dark green or dark bluish green. The pleochroic formula for biotite is X, light yellow and Z, moderate to dark brown.

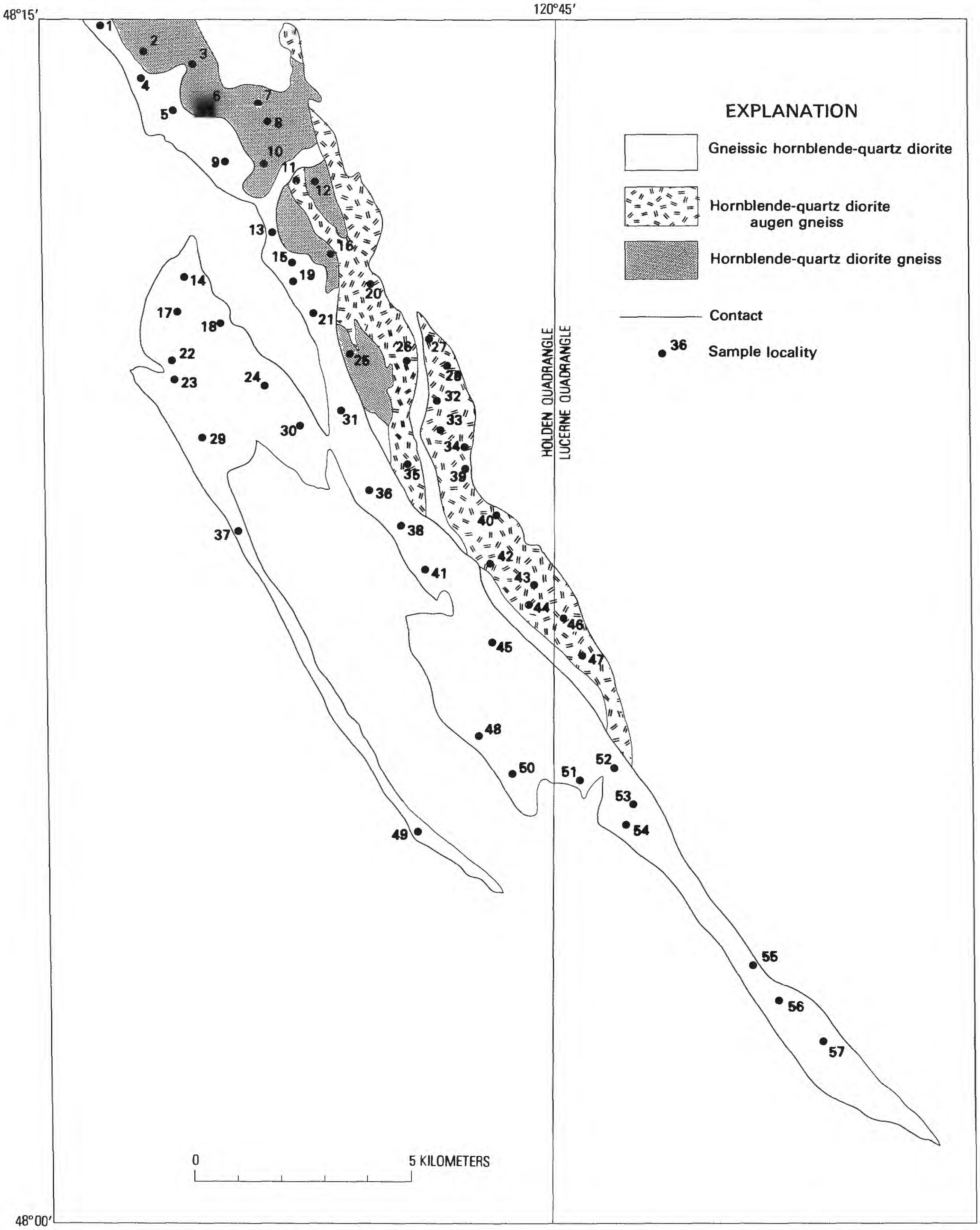

FIGURE 10.—Map showing location of modally analyzed samples from the Dumbell Mountain plutons, central Washington. Sample analyses are given in table 2.

TABLE 2.—*Modal analyses of samples of hornblende-quartz diorite and hornblende-quartz diorite gneiss from the Dumbell Mountain plutons*

[Values are in percent. Leaders (- - -), not present]

Sample No.	Plagioclase	Potassium feldspar	Quartz	Biotite	Hornblende	Accessory and secondary minerals	Total mafic minerals	Anorthite in plagioclase crystals (percent)			Remarks
								Average	Core	Rim	
					Gneissic hornblende-quartz diorite						
1	55.0	---	13.2	13.0	16.9	1.9	31.8	44	---	---	Hypidiomorphic.
4	41.4	---	4.5	---	52.3	1.8	54.1	40	---	---	Hornfelsed.
5	49.9	---	17.6	---	24.3	8.2	32.5	40	---	---	Protoclastic.
9	43.7	---	6.4	---	47.8	2.1	49.9	40	43	38	Xenomorphic.
13	55.6	---	5.4	---	38.5	.5	39.0	38	50	30	Hypidiomorphic.
14	61.7	---	14.1	.6	18.6	5.0	19.7	40	45	37	Do.
15	52.8	---	7.4	---	31.1	8.7	39.8	38	49	32	Do.
17	60.2	---	21.8	---	3.4	14.6	18.0	38	44	32	Do.
18	50.9	---	15.0	7.4	12.1	14.6	34.1	38	---	---	Do.
19	41.6	---	24.8	8.9	18.6	6.1	33.6	47	---	---	Xenomorphic
21	59.0	---	6.1	1.4	32.3	1.2	.9	42	48	36	Seriate; xenomorphic.
22	49.2	---	20.0	---	24.3	6.5	30.8	35	37	28	Xenomorphic; seriate.
23	62.5	---	4.1	---	32.6	.8	33.4	38	40	21	Hypidiomorphic.
24	43.5	---	15.0	14.9	26.1	.5	41.5	29	---	---	Protoclastic.
29	57.0	---	14.7	5.3	11.4	11.6	28.3	32	---	---	Xenomorphic.
30	45.0	---	12.3	---	35.9	6.8	42.7	48	---	---	Do.
31	52.6	---	8.4	---	32.1	6.9	39.0	32	---	---	Do.
36	47.8	---	11.6	---	38.7	1.9	40.6	44	45	36	Hypidomorphic.
38	58.8	---	7.3	---	32.6	1.3	33.9	47	51	41	Xenomorphic.
41	56.9	---	8.3	6.2	18.7	9.9	34.8	47	52	40	Do.
45	47.7	---	12.6	---	38.3	1.4	39.7	47	52	43	Protoclastic.
48	53.6	---	19.2	11.2	15.3	.6	27.1	32	---	---	Hypidiomorphic.
49	40.0	---	19.0	1.6	34.3	5.1	41.0	38	40	25	Hypidiomorphic-cataclastic.
50	48.5	---	20.1	.7	30.1	.6	31.4	33	36	24	Protoclastic.
51	47.9	---	4.1	2.5	35.6	9.9	39.0	38	41	24	Xenomorphic.
52	48.6	---	9.4	4.1	31.7	6.2	42.0	55	61	44	Hypidiomorphic.
53	49.0	---	8.2	2.1	38.4	2.3	44.8	31	32	29	Xenomorphic.
54	47.3	---	13.3	8.5	27.6	3.3	39.4	35	39	26	
55	47.4	---	27.9	4.1	16.7	2.2	23.0	48	51	41	Protoclastic.
56	50.6	---	30.7	10.1	7.5	1.1	18.7	32	---	---	Do.
57	46.4	---	36.8	5.5	10.6	.7	16.8	38	39	33	Do.
					Quartz diorite augen gneiss						
11	48.2	---	35.8	7.1	---	8.9	16.0	37	45	24	Protoclastic.
20	49.1	---	26.5	3.1	18.3	3.0	24.4	38	53	35	Hypidiomorphic-cataclastic.
26	48.8	---	21.8	4.0	23.3	2.1	29.4	38	49	36	Hypidiomorphic.
27	44.2	---	36.1	4.2	14.6	1.9	20.7	45	---	---	Xenomorphic-protoclastic.
28	30.8	---	48.3	7.1	11.9	1.9	20.9	31	35	28	Protoclastic.
32	36.8	---	36.7	---	25.9	.6	26.5	43	28	40	Reversed zoning of plagioclase; hypidiomorphic.
33	39.7	---	41.1	---	18.1	1.1	19.2	45	35	50	Reversed zoning of plagioclase; protoclastic.
34	40.5	---	40.1	.9	17.0	1.5	19.4	36	33	38	Protoclastic.
35	42.1	---	45.7	2.9	7.1	2.2	12.2	35	---	---	Do.
39	48.2	1.0	30.4	2.2	16.8	1.4	20.4	33	32	39	Reversed zoning of plagioclase; protoclastic.
40	45.5	.4	40.6	---	10.9	2.6	13.5	33	35	23	Protoclastic.
42	41.6	.9	34.5	4.2	16.1	2.7	23.0	32	29	49	Reversed zoning of plagioclase; seriate; xenomorphic.
43	34.6	.7	54.7	3.9	---	6.1	10.0	33	---	---	Protoclastic.
44	43.7	.2	45.1	---	7.9	3.1	11.0	36	38	34	Do.
46	52.4	.6	27.4	3.6	13.2	2.8	19.6	33	35	29	Porphyroclastic.
47	48.4	1.9	37.0	3.5	7.3	.2	11.0	42	44	38	Xenomorphic; protoclastic.
					Hornblende quartz diorite gneiss						
2	42.9	---	23.6	---	42.9	2.2	45.1	38	40	33	Xenomorphic.
3	44.3	---	27.1	---	21.8	6.8	28.6	42	46	29	Do.
6	33.5	---	19.5	6.9	26.9	13.2	47.0	55	---	---	Porphyroclastic.
7	47.5	---	6.4	2.4	42.2	1.5	46.1	46	51	36	Hypidiomorphic.
8	41.6	---	24.8	8.9	18.6	6.1	33.6	40	44	38	Protoclastic.
10	42.7	0.3	24.1	---	25.6	7.3	32.9	58	60	47	Xenomorphic.
12	37.4	.1	24.2	.8	26.0	5.5	32.3	40	45	33	Hypidiomorphic.
16	46.7	---	14.7	4.9	21.0	12.7	38.6	38	40	33	Xenomorphic.
25	48.5	---	9.0	---	36.8	5.7	42.5	49	65	35	Do.

TABLE 3.—*Chemical and spectrographic analyses and norms of rock samples from the Dumbell Mountain plutons, central Washington*

[For samples 1-5, 7, and 8, SiO_2, Al_2O_3, and TiO_2 determined colorimetrically; total Fe, MgO, CaO, and MnO determined by atomic absorption; FeO determined titremetrically; Na_2O and K_2O determined by flame photometer; analysts: G. T. Burrow, Wayne Mountjoy, H. H. Lipp, and Johnnie Gardner. For samples 6 and 9, rapid rock analyses by P. L. D. Elmore, K. E. White, and S. D. Botts. Spectrographic analyses by B. W. Lanthorn and K. E. Valentine. <, less than; N.d. not determined; leaders (- - -), below level of sensitivity]

Sample	1	2	3	4	5	6	7	8	9
				Chemical analyses (percent)					
SiO_2	61.0	62.4	63.8	70.8	73.7	68.9	52.5	65.7	56.9
Al_2O_3	17.8	17.5	17.1	15.4	15.0	14.3	20.9	16.2	17.9
Fe_2O_3	1.6	1.8	1.6	1.4	.9	2.1	2.0	1.2	2.7
FeO	4.46	4.20	3.14	2.46	2.79	2.6	6.45	3.87	4.2
MgO	3.10	3.04	2.48	1.46	1.23	1.7	3.67	2.63	3.7
CaO	7.2	6.5	5.7	5.2	4.1	4.7	11.1	7.1	7.3
Na_2O	3.43	3.85	4.06	3.88	3.52	3.5	2.74	3.59	3.4
K_2O	.57	.79	1.03	.11	.68	.42	.23	.24	.66
TiO_2	.67	.73	.56	.45	.41	.41	.93	.71	.59
P_2O_5	N.d.	N.d.	N.d.	N.d.	N.d.	.21	N.d.	N.d.	.24
MnO	.11	.10	.08	.09	.06	.11	.13	.10	.14
H_2O	N.d.	N.d.	N.d.	N.d.	N.d.	.76	N.d.	N.d.	1.5
CO_2	N.d.	N.d.	N.d.	N.d.	N.d.	< .05	N.d.	N.d.	< .05
Total	100	101	100	101	102	100	101	101	99
				Semiquantitative spectrographic analyses (parts per million)					
Ba	300	700	700	150	300	30	200	150	100
Be	---	---	---	---	---	---	---	---	30
Co	20	20	20	10	15	10	30	15	30
Cr	15	30	30	5	10	3	30	5	10
Cu	15	30	15	3	5	10	70	15	30
Ni	20	20	15	5	5	---	15	15	---
Pb	10	---	10	---	---	---	---	---	---
Sc	30	30	30	30	20	10	70	30	10
Sr	700	1,000	1,000	200	200	300	300	500	1,000
V	150	200	150	150	100	10	300	150	10
Y	30	30	30	30	30	10	30	30	10
Zr	50	100	70	150	200	10	30	30	10
Ga	30	30	30	20	30	10	30	15	30
Yb	3	3	3	7	5	1	3	5	1
				Norms					
q	17.05	16.91	19.40	33.16	37.40	34.25	4.75	23.83	12.98
or	3.37	4.63	6.11	.64	3.92	2.51	1.35	1.40	3.99
ab	29.02	32.26	34.49	32.40	29.07	29.89	23.02	29.96	29.40
an	31.52	27.88	25.51	23.99	19.86	21.84	43.76	27.02	32.35
di	3.46	3.32	2.35	1.22	6.72	6.87	9.03	6.34	2.23
hy	11.99	11.04	8.74	5.74	1.00	.17	13.45	8.40	13.22
mt	2.32	2.59	2.33	2.01	1.27	3.08	2.88	1.72	4.00
il	1.27	1.37	1.07	.84	.76	.79	1.76	1.33	1.15
ap						.60			.68
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
				Plagioclase composition					
an	52.1	46.4	42.5	42.5	40.6	42.2	65.5	47.4	52.4

TABLE 3.—*Chemical and spectrographic analyses and norms of rock samples from the Dumbell Mountain plutons, central Washington*—Continued

Sample descriptions
1. Composite sample of gneissic hornblende-quartz diorite; composition of plagioclase about An_{45} to An_{48}.
2. Composite sample of gneissic hornblende-quartz diorite; composition of plagioclase about An_{38}.
3. Composite sample of gneissic hornblende-quartz diorite; composition of plagioclase about An_{32}.
4. Composite sample of hornblende-quartz diorite augen gneiss; composition of plagioclase about An_{45}.
5. Composite sample of hornblende-quartz diorite augen gneiss; composition of plagioclase about An_{38}.
6. Composite sample of hornblende-quartz diorite augen gneiss; composition of plagioclase An_{39} to An_{44}.
7. Hornblende-quartz diorite gneiss; composition of plagioclase about An_{50}.
8. Hornblende-quartz diorite gneiss; composition of plagioclase about An_{38}.
9. Composite sample of hornblende-quartz diorite gneiss; plagioclase of various compositions.

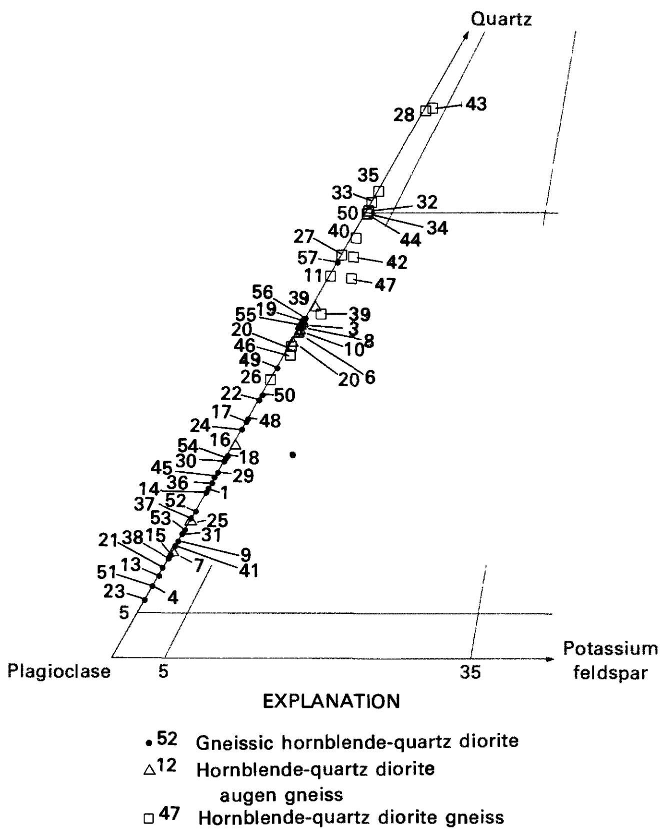

FIGURE 11.—Plot of modes of rock samples from the Dumbell Mountain plutons, central Washington, on a quartz-potassium feldspar-plagioclase diagram. Sample analyses are given in table 2.

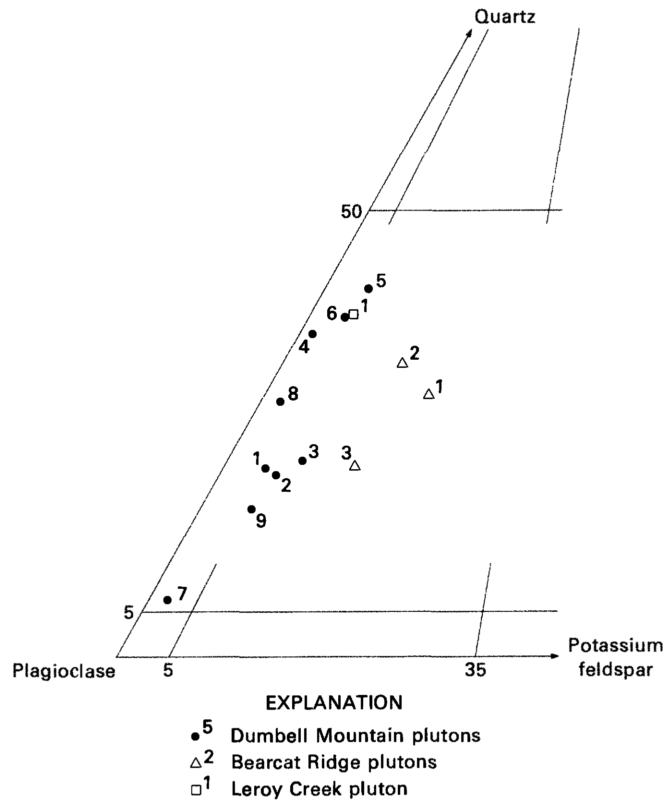

FIGURE 12.—Plot of norms of rock samples from the Dumbell Mountain, Bearcat Ridge and Leroy Creek plutons, central Washington, on a quartz-potassium feldspar-plagioclase diagram. Sample analyses are given in table 3 (Dumbell Mountain), table 5 (Bearcat Ridge), and table 7 (Leroy Creek).

The amount of mafic minerals, mostly hornblende, averages about 35 percent but ranges from 10 to 45 percent (table 2).

The microtexture ranges from hypidiomorphic to xenomorphic with varying degrees of protoclastic modifications. In general, however, the quartz diorite gneiss is the least protoclastic of the Dumbell Mountain rocks, and foliation seems to be largely a result of flowage and of crystallization under stress, but of generally insufficient stress to produce the extensive protoclasis so evident in the other Dumbell Mountain rocks.

The chemical composition of the hornblende-quartz diorite gneiss appears to be somewhat more variable than is true of the other Dumbell Mountain rocks, despite its generally more uniform appearance (table 3).

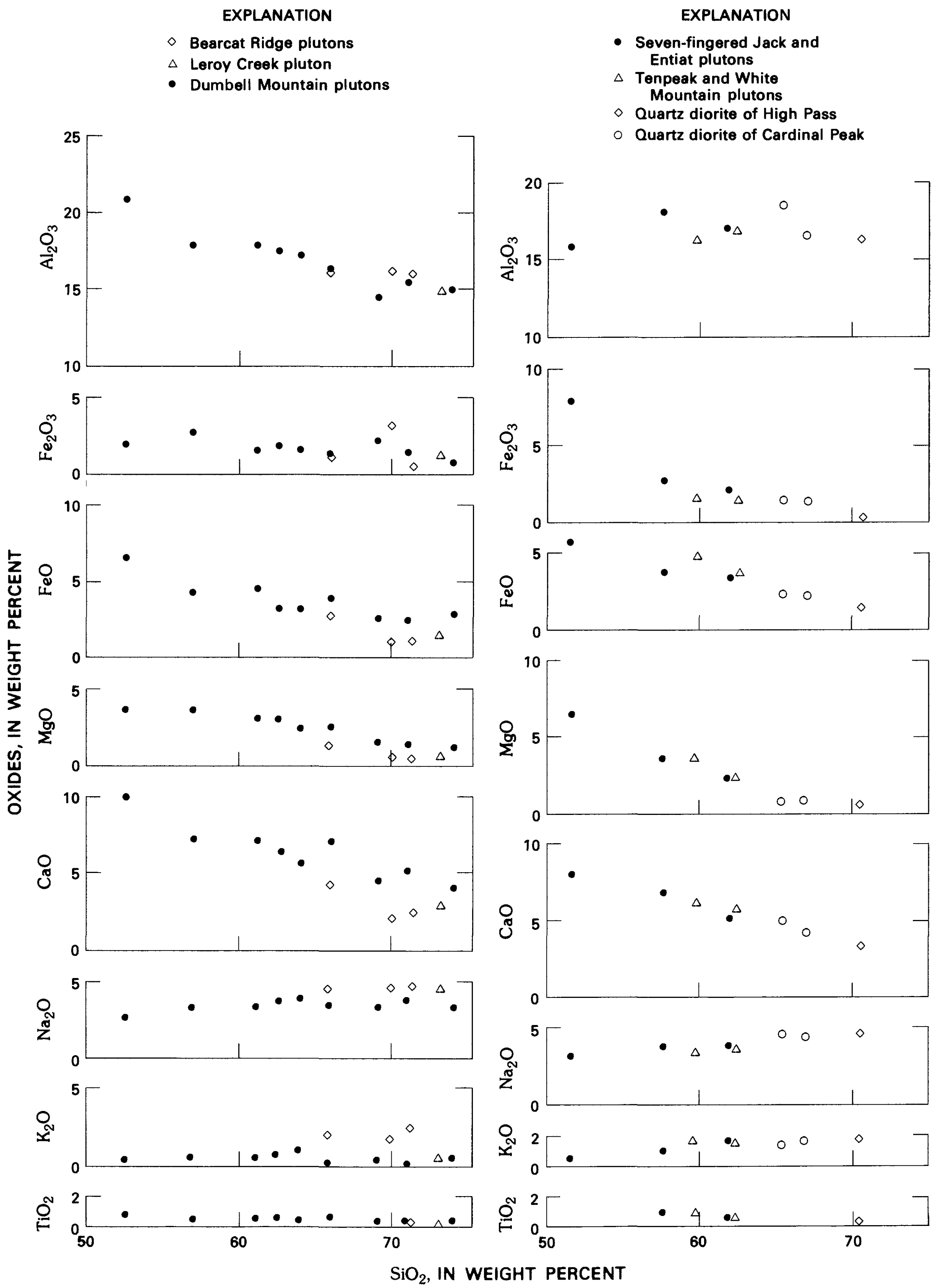

FIGURE 13.—Variation diagrams of major oxides in analyzed rock samples from pre-Tertiary plutons, central Washington.

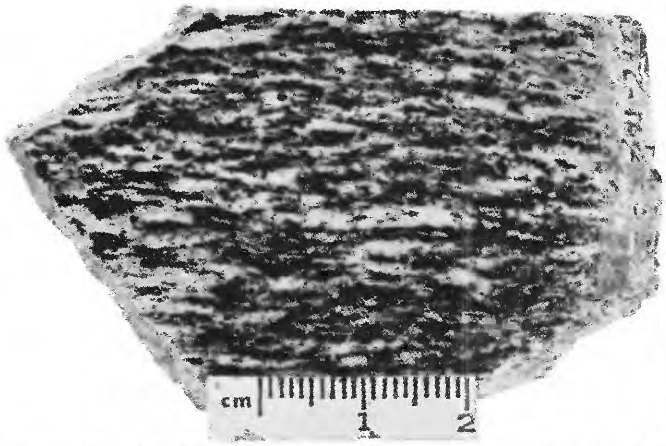

FIGURE 14.—Hornblende-quartz diorite gneiss from the Dumbell Mountain plutons, central Washington. Thin section shown in figure 9.

As is true of all the Dumbell Mountain rocks, the hornblende-quartz diorite gneiss is remarkably low in K_2O for a rock of otherwise unremarkable composition. A possible reason for the paucity of K_2O is discussed in the section on "Composition and differentiation."

HORNBLENDE-QUARTZ DIORITE AUGEN GNEISS

The pluton of hornblende-quartz diorite augen gneiss extends south-southeastward from near the outlet of Holden Creek to about the junction of Ice Creek and the Entiat River, a distance of about 15 km. Unlike the other Dumbell Mountain plutons, this one contains some screens of hornblende schist and gneiss a kilometer or two long, much larger than the small and unmapped sheets that occur in the others. Much of the eastern contact of this pluton has been intricately intruded by dikes satellitic to the late Eocene Duncan Hill pluton and these dikes furnished part of the material that forms the contact complex surrounding the northern end of the Duncan Hill pluton.

Most of the rock is characteristically an augen gneiss (fig. 7), the augen consisting of nearly pure aggregates of plagioclase and quartz or mixtures of both; more rarely an augen may consist of a single abraded grain of plagioclase. Unlike the hornblende-quartz diorite gneiss, the foliation of the augen gneiss is swirled in many places and attitudes vary greatly over short distances. Inclusions are numerous in the augen gneiss; many show little effect of immersion in the quartz diorite magma, but others have been almost completely assimilated and are barely distinguishable from the surrounding augen gneiss. Many are extremely flat and attenuated, particularly on Spectacle Buttes where we found one only 1 to 3 cm thick and 13 m long. Most of these consist almost entirely of hornblende. Great numbers of inclusions have dark, hornblende-rich margins from which felsic minerals have been almost completely removed (fig. 7). Long dimensions of most inclusions parallel foliation of the augen gneiss, but some are discordant.

Study of thin sections showed the augen gneiss to be mineralogically almost identical to the hornblende-quartz diorite gneiss, including the same range of compositions of the plagioclase. The texture, however, differs considerably in that the augen gneiss is everywhere protoclastic and in most places decidedly so, although the range of protoclasis is from extreme to mild. In gradational contact zones and where screens and inclusions of metamorphic rock are numerous, textures range from metamorphic in the inclusions to protoclastic in the intrusive material; in fact, because some of the augen gneiss closely resembles some varieties of the host metamorphic rocks, only by thin-section examination can distinctions be made, or, for that matter, can the augen gneiss and metamorphic rocks be distinguished from much of the contaminated or granitized rock of the gradational contacts. Plagioclase is most profoundly affected by protoclasis, and in many thin sections is the only mineral to show the effects of grinding. Quartz characteristically forms lentils consisting of a mosaic of interlocking grains, but small quantities are interstitial or replace earlier minerals, mostly plagioclase. Where present, biotite most commonly occurs with the quartz lentils. The relationship of quartz lentils and biotite to the rest of the rock suggests that these late constituents were squeezed or filter pressed when still fluid from the mass of crystals being milled during intrusion.

The hornblende-quartz diorite augen gneiss is the most siliceous of the Dumbell Mountain rocks (table 3) but shares with the other varieties an extraordinarily low content of K_2O.

GNEISSIC HORNBLENDE-QUARTZ DIORITE

Gneissic hornblende-quartz diorite forms the largest of the Dumbell Mountain plutons in the mapped area and has an outcrop area at least as large as the other Dumbell Mountain rocks combined. Younger Sevenfingered Jack intrusive rock nearly splits the pluton lengthwise; the western segment is cut off to the north by the Miocene Cloudy Pass pluton, but the eastern segment extends an unknown distance north of the Holden quadrangle. To the southeast, the pluton narrows and either pinches out or is cut off by the Duncan Hill pluton beneath the glacial debris and alluvium in the Entiat River valley near the Cottonwood Guard Station.

The quartz diorite is mostly medium grained and gray and ranges from massive and nearly nongneissic (fig. 15) to strongly gneissic. In many places, layers of highly foliated or gneissic rock a few centimeters to a few meters thick alternate with layers of nearly structureless rock. Swirled foliation is a common feature, probably even more so than in the hornblende-quartz diorite augen

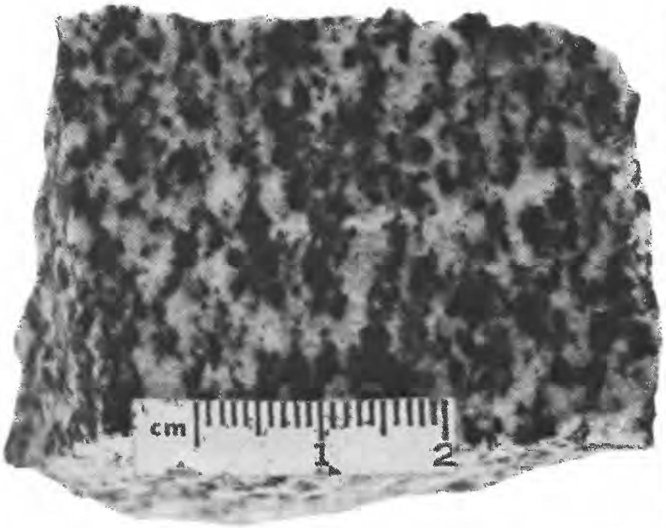

FIGURE 15.—Gneissic hornblende-quartz diorite, a less gneissic facies, from the Dumbell Mountain plutons, central Washington.

gneiss. Locally inclusions are common, but nowhere are they as attenuated as are some of those in the hornblende-quartz diorite augen gneiss.

In thin section, gneissic hornblende-quartz diorite is seen to be mineralogically identical to other Dumbell Mountain rock, except that considerable quantities of it contain sodic andesine averaging about An_{32}, but medium or calcic andesine still predominates. Textures range from hypidiomorphic through xenomorphic to protoclastic. Much is also cataclastic, especially near shear zones. The more gneissic varieties are more highly protoclastic, and in the interlayered gneissic and non-gneissic rocks, the gneissic layers are protoclastic.

The chemical composition of the gneissic hornblende-quartz diorite is apparently more uniform than is the composition of the other Dumbell Mountain rocks, but the content of K_2O is characteristically low (table 3).

BEARCAT RIDGE PLUTONS

The Bearcat Ridge plutons crop out in the Lucerne quadrangle between Lake Chelan and Railroad Creek. The larger of the two plutons has a length west of Lake Chelan of about 18.7 km and a maximum width of nearly 1.25 km. It is cut off to the north and northwest by the Railroad Creek and Cardinal Peak plutons. The smaller pluton has a length of about 4.8 km and a maximum width west of Lake Chelan of about 1.2 km. How far either pluton extends east of the lake, if at all, is unknown.

Both plutons are of granodiorite and quartz diorite and are roughly conformable to enclosing metamorphic rocks but locally crosscut them, particularly where they are isoclinally folded. None of the observed contacts, however, were discordant within the limits of the outcrops examined. The smaller pluton and the prong of the larger one that cuts across the headwaters of Bear Creek have wedged the host rocks apart and, in fact, may have been responsible for the tight and complex folding of the host rocks in the area. All contacts are either sharp or gradational through a zone only a few centimeters thick. In some places, however, most noticeably on the spur ridge between Klone and Tumble Creeks, the contact was difficult to locate precisely because the highly protoclastic, fissile border rocks of the pluton so closely resemble the sheared, highly fissile enclosing gneisses of similar composition.

Rocks of the Bearcat Ridge plutons are of variable appearance and composition, all are gneissic or foliated to some degree, and all are nearly white to dark gray, depending on the content of mafic minerals and the grain size. Most abundant are medium-grained, gray rocks verging on augengneiss (fig. 16). The plagioclase forms porphyroclastic eyes or thin lenses, around which are wrapped thin folia consisting of aggregates of biotite and hornblende crystals. Intermingled with these gray rocks are rather large quantities of light-colored gneiss that form conformable lenses and anastomosing dikes rarely more than several centimeters thick; the dikes intrude more or less aimlessly the darker rocks. Contacts between the normal and the light-colored facies are gradational, and attitudes of foliation cross the light facies without deviation. Foliation, however, is much less distinct in the lighter rocks. Dark facies also occur but are much rarer than the light facies and seem to be more common near contacts. Some of the darker rocks are actually more mafic, but most, particularly those near contacts, are merely finer grained and lack the

FIGURE 16.—Protoclastic biotite-hornblende-quartz diorite gneiss from the Bearcat Ridge plutons, Lucerne quadrangle. Dike is Tertiary granodiorite.

degree of segregation into felsic and mafic folia of rocks farther from contacts.

The larger pluton consists mostly of hornblende-bearing rocks that range in composition from biotite-hornblende granodiorite to quartz diorite, but some hornblende-free rocks also occur. Granodiorite shown in figure 17 is typical of the less gneissic rocks. The smaller pluton is almost, but not entirely, devoid of hornblendic rocks and consists of biotite granodiorite and quartz diorite. Figure 18 illustrates a nearly nongneissic facies of granodiorite. As a general rule, hornblendic rocks seem to be slightly older and are intruded by rocks containing only biotite, but contacts between the two types of rock are mostly gradational in places through many meters. The field relations suggest that both types were mobile simultaneously. Because of the similarity of appearance, the difficulty in recognizing rocks containing no hornblende (hornblende is commonly much subordinate to biotite in any case), and the erratic distribution of the two types, no effort was made to separately delineate them in either of the two plutons.

Thin-section examination of the rocks reveals many characteristics that are common to all rocks in the plutons, the most striking of which is the pervasive protoclasis that lends to the rocks their gneissic appearance, but there are also some significant differences between rock types. Hornblende-bearing rocks contain considerable ilmenite and coarse titanite, and plagioclase has an average composition of about An_{33}, whereas rocks lacking hornblende contain very little titanite, no ilmenite, and plagioclase has an average composition of about An_{20}. All the rocks contain varying quantities of quartz, biotite, and orthoclase, along with accessory magnetite and apatite. North of Graham Harbor Creek, near the southwest contact of the smaller pluton, the rock not only contains biotite but also considerable

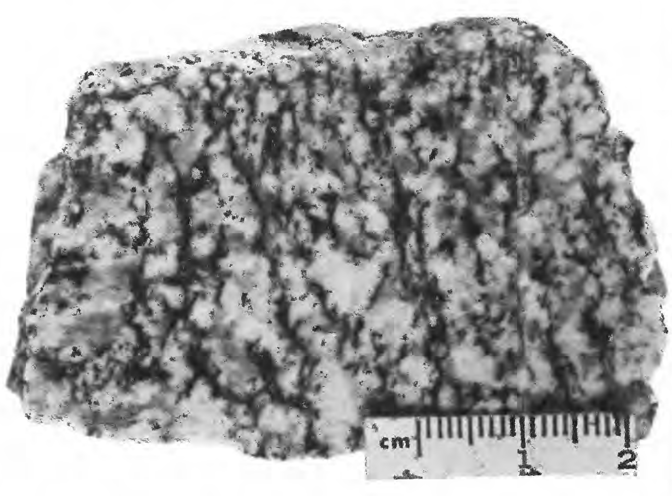

FIGURE 17.—Hornblende-biotite granodiorite gneiss from the Bearcat Ridge plutons, Lucerne quadrangle.

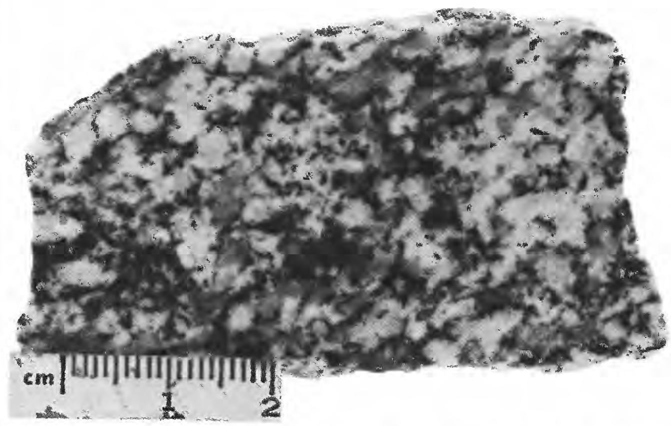

FIGURE 18.—Biotite granodiorite from the Bearcat Ridge plutons, Lucerne quadrangle.

muscovite. A little chlorite was seen in all sections as an alteration product of the mafic minerals, especially biotite, and some epidote occurs in a few thin sections. Andesine in the hornblende-bearing rocks and oligoclase in the hornblende-free rocks occur as abraded, rounded, and commonly fractured porphyroclasts. These porphyroclasts may have tails of abraded material streaming away from them, but most commonly, the abraded material forms a mortar surrounding the porphyroclasts. A few porphyroclasts, in most sections, show faint oscillatory and patchy zoning, attesting thereby to their igneous origin. Myrmekite showing a variety of forms is rather common. Quartz occurs as interstitial anhedral grains in the least deformed rocks, but by far the greatest amount occurs as thin, lenslike folia consisting of mosaics of interlocking crystals; these folia commonly occur in the zones of granulated plagioclase. Orthoclase, much of it perthitic, is commonly interstitial or is associated with the quartz folia, but some partly replaces both granulated and porphyroclastic plagioclase. Some of the larger grains of orthoclase are traversed by zones of perthite that follow lines of distortion in the grains. The amount of orthoclase ranges between rather wide limits; some of the biotite-hornblende quartz diorites contain less than 1 percent, whereas some of the leucocratic material may contain as much as 50 percent, but most rocks contain between 5 and 15 percent. Rocks containing sufficient orthoclase to be called granodiorite are at least twice as common as the quartz diorites low in orthoclase. The distribution of rocks containing more and less orthoclase, however, is haphazard, and in outcrop the rocks are indistinguishable. Microcline is rare; accessory amounts were seen in only one thin section. The major mafic mineral is biotite, and it occurs as folia of anhedral shreds that follow planes of granulation. Biotite in all the rocks is optically identical, the pleochroic colors ranging from straw yellow to dark olive brown. Hornblende, where present, usually occurs with biotite, and the longer dimensions of the grains are oriented in the plane of foliation; in this plane, however, the orientation is mostly random, but in a few places a vague lineation is apparent. Hornblende is anhedral and pleochroic from yellowish green to dark green. Biotite tends to replace hornblende, and hornblende adjacent to biotite is generally lighter colored. Titanite is a common accessory in the hornblendic rocks; much of it forms rhombs as long as 1 mm, but some forms irregular rims surrounding grains of ilmenite.

The most characteristic feature of the Bearcat Ridge rocks is their pervasive protoclastic texture. As a rule, all the minerals show some slight distortion, i.e., undulatory extinction in quartz and warping of scattered biotite and hornblende grains, but only plagioclase, the earliest formed mineral, has everywhere undergone intensive and extensive grinding. No grains have escaped abrasion entirely, and many porphyroclasts consist of slightly rotated fragments of an original crystal. The undistorted or only slightly distorted later minerals —hornblende, biotite, quartz, and potassium feldspar —that grew along planes of granulation, indicate that by the time they started crystallizing, the plutons had largely come to rest. The leucocratic lenses and dikes that are so common throughout the plutons and, indeed, cut the enclosing metamorphic host rocks are probably the results of this process of squeezing and grinding. The plagioclase in these lighter rocks is identical to the plagioclase of the surrounding granodiorites and quartz diorites and show the same abraded outlines, but they form a relatively small proportion of these lighter rocks, which consist largely of quartz and orthoclase. Thus, the still-fluid component that was to crystallize mostly as quartz and orthoclase seems to have been filter pressed from the crystal mush of the intruding plutons to form these leucocratic lenses and dikes. Directed stresses had not entirely ceased, however, by the time the leucocratic rocks crystallized. This is indicated by the rocks' vague foliated texture defined by the parallel orientation of the biotite, in places parallel to the walls of the dike but elsewhere parallel to the regional attitudes of enclosing rock regardless of orientation of dikes.

Modal analyses of the Bearcat Ridge plutons are given in table 4, and chemical analyses in table 5. Figure 19 shows the locations of modally analyzed specimens, and figure 20 is a plot on a triangular diagram of these modes. A plot of the norms is given in figure 12, and a variation diagram of major oxides in figure 13.

LEROY CREEK PLUTON

The Leroy Creek pluton, a mass of gneissic biotite-quartz diorite about 10 km long and 2 km wide, extends along the west side of the Entiat Mountains from upper Rock Creek to upper Phelps Creek. The pluton intrudes Dumbell Mountain gneissic hornblende-quartz diorite and is in turn intruded by quartz diorites of the Seven-fingered Jack plutons; hence, the ages of 45 and 54 m.y., determined on mica (Engels and others, 1976) are much too young and indicate heating by later intrusions.

The Leroy Creek pluton consists of fine- to medium-grained gneissic biotite-quartz diorite (fig. 21). The rock

TABLE 4.—*Modal analyses of samples of quartz diorite and granodiorite gneiss from the Bearcat Ridge plutons, Lucerne quadrangle*

[Leaders (- - -), not measured or not present]

Sample No.	Plagioclase	Potassium feldspar	Quartz	Biotite	Hornblende	Accessory and secondary minerals	Total mafic minerals	Anorthite in plagioclase crystals (percent): Average	Core	Rim	Remarks
1	54.5	0.4	18.0	11.2	14.5	1.4	27.1	40	---	---	Protoclastic.
2	46.4	10.6	12.8	2.8	23.0	4.4	30.2	33	35	31	Do.
3	53.9	9.1	14.2	9.7	10.8	2.3	13.1	33	40	26	Xenomorphic.
4	41.8	11.8	3.2	11.0	3.1	1.1	15.2	29	---	---	Protoclastic.
5	47.1	8.5	18.7	13.7	10.7	1.3	25.7	32	33	28	Do.
6	55.7	7.8	19.4	6.7	8.2	2.5	17.4	32	33	29	Xenomorphic; sphene rimmed with ilmenite.
7	67.6	1.7	13.8	6.8	5.5	4.6	16.9	35	---	---	Xenomorphic.
8	54.5	3.4	23.4	16.6	1.3	.8	18.7	32	---	---	Do.
9	55.2	6.8	18.2	9.4	9.7	.7	19.8	28	32	25	Protoclastic.
10	56.8	4.1	19.2	6.2	12.6	1.1	19.9	27	29	25	Xenomorphic; slightly protoclastic.
11	55.0	6.2	30.4	7.9	---	.5	8.4	25	26	23	Protoclastic.
12	55.9	13.2	21.0	9.0	---	.9	9.9	23	27	15	Xenomorphic.
13	44.2	15.7	30.2	7.6	---	2.3	9.9	23	27	16	Some muscovite; hypidiomorphic- protoclastic.
14	36.4	33.3	25.1	4.5	---	.7	5.2	22	23	18	Xenomorphic-protoclastic.
15	50.1	12.3	30.8	6.3	---	.5	6.8	24	---	---	Protoclastic.

TABLE 5.—*Chemical and spectrographic analyses and norms of rock samples from the Bearcat Ridge plutons, Lucerne quadrangles*

[For samples 1 and 3, standard rock analysis by E. E. Engleman. For sample 2, SiO_2 and Al_2O_3 determined colorimetrically; FeO determined volumetrically; Fe_2O_3, MgO, CaO, and Mn determined by atomic absorption; Na_2O and K_2O determined by flame photometer; analysts: Violet Merritt, Wayne Mountjoy, J. D. Mensick, Claude Huffman, H. H. Lipp, G. T. Burrow, and G. D. Shipley. Spectrographic analysts: Barbara Tobin, H. G. Neiman, and B. W. Lanthorn. N.d., not determined; leaders (- - -), below sensitivity limit; N.p., not present]

Sample	1	2	3
Chemical analyses (percent)			
SiO_2	71.25	69.8	65.7
Al_2O_3	15.99	16.2	17.1
Fe_2O_3	.45	3.14	1.12
FeO	1.06	1.00	2.68
MgO	.52	.48	1.3
CaO	2.44	2.12	4.3
Na_2O	4.79	4.77	4.53
K_2O	2.55	1.83	1.96
H_2O+	.29	N.d.	N.d.
H_2O-	.02	N.d.	N.d.
TiO_2	.23	N.d.	N.d.
P_2O_5	.07	N.d.	N.d.
MnO	.04	.04	.076
CO_2	.00	N.d.	N.d.
Cl	.00	N.d.	N.d.
F	.04	N.d.	N.d.
Subtotal	99.74		
Less H_2O	.02		
Total	99.72	99	99
Semiquantitative spectrographic analyses (parts per million)			
B	20	---	---
Ba	1,000	500	1,000
Be	1	---	---
Co	---	---	15
Cr	5	1	50
Cu	3	5	5
Ga	30	30	20
Nb	10	---	---
Ni	---	---	20
Pb	70	15	---
Sc	5	15	15
Sr	1,000	500	1,000
V	30	20	100
Y	---	10	10
Yb	1	1	1
Zr	100	70	50
Norms			
q	27.51	30.00	19.24
or	15.13	10.88	11.72
ab	40.68	40.59	38.79
an	11.40	10.58	20.80
hy	2.57	1.20	.66
c	.120	2.34	7.14
mt	.65	3.38	1.65
il	.44	.83	N.p.
ap	.17	N.p.	N.p.
Total	100.00	100.00	100.00

TABLE 5.—*Chemical and spectrographic analyses and norms of rock samples from the Bearcat Ridge plutons, Lucerne quadrangles*—Continued

Sample	1	2	3
Plagioclase composition			
an	21.9	20.7	34.9

Sample descriptions

1. Composite sample of biotite granodiorite gneiss.
2. Composite sample of hornblende-biotite-quartz diorite gneiss.
3. Composite sample of biotite-hornblende-quartz diorite gneiss.

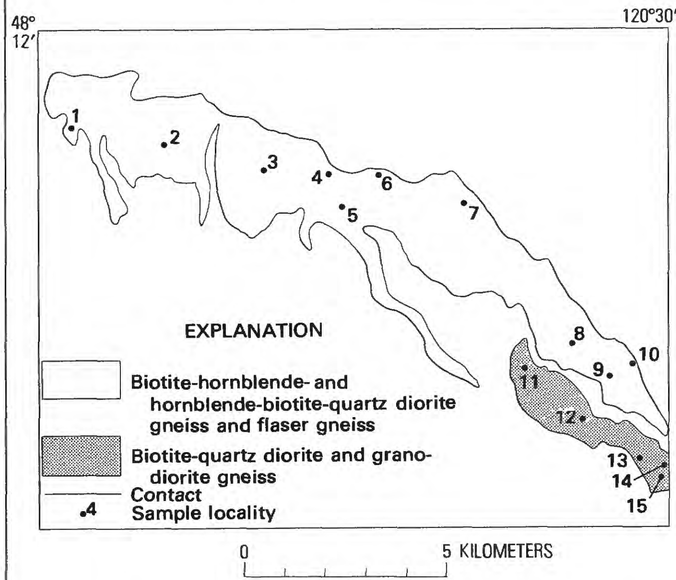

FIGURE 19.—Map showing location of modally analyzed samples from the Bearcat Ridge plutons, Lucerne quadrangle. Sample analyses are given in table 4.

varies considerably in appearance from place to place; most of it is rather light colored, but where contaminated with considerable mafic material derived from host rocks of hornblende and biotite gneiss and schist, it is dark. Some of it is nearly nonfoliated and medium grained, whereas at the other extreme rocks are so finely foliated as to appear almost schistose. Probably the most characteristic feature of the rock is the pervasive swirled foliation. This foliation, defined mostly by planar parallelism of biotite flakes, trends generally northwest, but at the north end of the pluton, trends are northeast more or less parallel to the contact. Everywhere, however, are local changes in trends—swirls—on scales ranging from a few meters to many tens of meters. As with other gneissic intrusive rocks in the area, the foliation is the result of pervasive protoclasis, but here the foliation is generally far more highly swirled

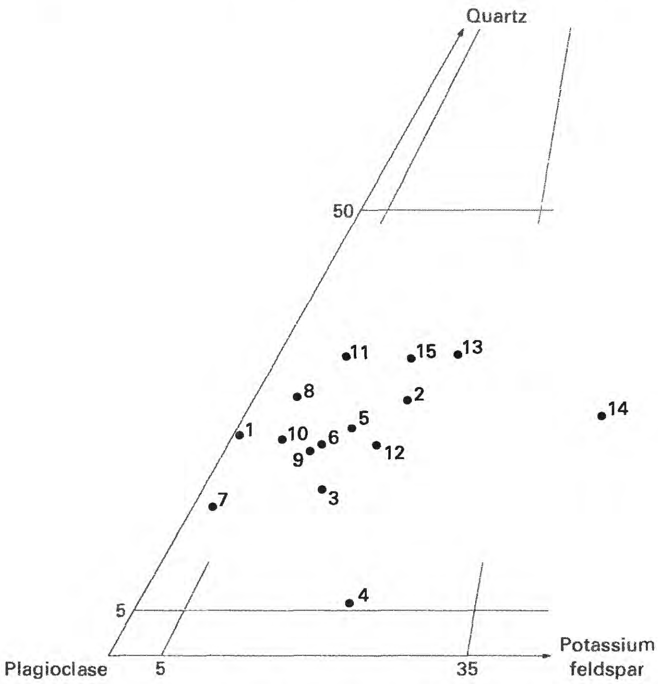

FIGURE 20.—Plot of modes of rock samples from the Bearcat Ridge plutons, Lucerne quadrangle, on a quartz-potassium feldspar-plagioclase diagram. Sample analyses are given in table 4.

FIGURE 21.—Gneissic biotite-quartz diorite from the Leroy Creek pluton, Holden quadrangle.

than in other plutons, indicative, perhaps, of more irregular movement of the crystal-packed magma during intrusion than seems to have been true in other plutons.

Despite the variability of appearance, the composition of the Leroy Creek pluton is rather uniform except for the hornblende-bearing rocks at the north end. The hornblende-free rocks consist of 48 to 58 percent oligoclase, 33 to 37 percent quartz, and 5 to 11 percent biotite as essential minerals, and epidote, sericite, and chlorite in generally small but variable quantities as secondary minerals (table 6). Potassium feldspar, opaque minerals, titanite, muscovite, and apatite are accessory. In the northern part of the pluton, garnet crystals as much as 1 cm across are fairly common.

As with other quartz diorite plutons in the study area, the Leroy Creek pluton also contains many inclusions of hornblende gneiss and schist and Swakane Biotite Gneiss. Relicts of Swakane are less obvious than hornblendic inclusions because of the similarity of the Leroy Creek gneissic quartz diorite to the Swakane. Inclusions of Swakane tend to form ghostlike wisps and streaks and larger irregular masses that grade into quartz diorite, whereas inclusions of hornblende gneiss and schist mostly form long, thin layers having sharp contacts with the enclosing quartz diorite. Scattered dark, angular, unoriented inclusions do occur, however, and are largely restricted to the swirled facies of the rock.

Contacts of the Leroy Creek pluton are mostly rather abrupt, the lateral contacts commonly consisting of thin zones of lit-par-lit injections. The northwest end is marked by a zone of migmatite a few meters thick, and here gneissic quartz diorite contains considerable hornblende in contrast to the rock elsewhere in the pluton. The pluton has had little megascopically discernible effect on the enclosing wall rocks.

Plagioclase is medium oligoclase in the hornblende-free rocks but ranges up to sodic andesine in the hornblendic rocks at the north end of the pluton. Plagioclase is mostly anhedral and unzoned, but some grains are progressively zoned and a few show pronounced oscillatory and patchy zoning. Quartz forms anhedral interstitial grains, irregular lenses of interlocking grains, and matrices consisting of mosaics of irregular grains in which plagioclase and other minerals occur as partly resorbed islands. Nearly all the quartz is strained. Biotite occurs as shreds or aggregates of irregular grains; in some thin sections, biotite is mostly confined to zones of granulation. The biotite is characteristically olive brown and has been analyzed previously (Crowder, 1959, table 2). Hornblende forms anhedral blades or aggregates of small blades pleochroic in shades of light yellowish brown to green. Most clinozoisite-epidote is secondary, but in thin sections showing the best hypidiomorphic textures, large subhedral crystals, apparently of primary origin, occur separately or with biotite. Such clinozoisite-epidote is also characteristic of some other plutons in the study area.

Textures of rocks in the Leroy Creek pluton range from typically hypidiomorhpic to xenomorphic and protoclastic. Some of the rock is slightly recrystallized. Most characteristic are xenomorphic textures with subdued protoclastic modifications. Plagioclase grains show con-

TABLE 6.—*Modal analyses of samples of biotite-quartz diorite gneiss from the Leroy Creek pluton, Holden quadrangle*

[Leaders (- - -), not measured or not present]

Sample No.	Plagioclase	Potassium feldspar	Quartz	Biotite	Hornblende	Accessory and secondary minerals	Total mafic minerals	Anorthite in plagioclase crystals (percent) Average	Core	Rim	Remarks
1	40.3	0.2	48.3	2.9	5.4	3.9	12.2	28	38	16	Xenomorphic.
2	47.4	---	33.0	2.2	13.2	4.2	19.6	30	31	26	Do.
3	48.7	---	36.7	1.3	---	13.3	14.6	20	27	16	Do.
4	50.8	---	43.8	---	.7	4.7	5.4	20	21	17	Do.
5	48.5	---	38.4	9.8	---	3.3	13.1	23	26	21	Protoclastic.
6	57.2	.2	33.0	7.1	---	2.5	9.6	22	27	19	Xenomorphic.
7	53.4	---	28.4	3.8	10.9	3.5	18.2	23	30	18	Do.
8	54.3	---	38.9	3.6	---	3.2	6.8	20	23	12	Protoclastic.
9	49.7	---	36.6	4.3	---	9.4	13.7	22	23	15	Do.
10	41.2	---	39.6	1.0	13.2	5.0	19.2	26	31	21	Xenomorphic-protoclastic.

siderable rounding and some have been broken, and the individual fragments have been differentially rotated with respect to other fragments. Nevertheless, fine-grained comminuted material is mostly rather rare and seems to have been resorbed before complete crystallization.

Some of the textures suggest mild recrystallization has occurred, but if so, it has been insufficient to destroy the swirled foliation indicative of irregular intrusive movements or even to obliterate oscillatory and patchy zoning. Furthermore, there seems little reason to believe that granitization was particularly effective in forming the pluton, as Crowder (1959) once thought. Repeated episodes of large-scale granitization or ultrametamorphism, explaining each successive gneissic pluton that otherwise had little effect on the surrounding terrane, seem far less likely than magmas rising periodically from the lower crust.

Chemical and spectrographic analyses and norms are shown in table 7; locations of modally analyzed specimens are shown in figure 22, and a plot of the modes in figure 23. A plot of the norms is in figure 12 and a variation diagram of major oxides in figure 13.

SEVEN-FINGERED JACK AND ENTIAT PLUTONS

The Seven-fingered Jack and Entiat plutons make up a group of intrusions cropping out from the vicinity of Hart Lake south-southeastward across the Holden and Lucerne quadrangles. The Seven-fingered Jack pluton, consisting largely of biotite-hornblende-quartz diorite, is the northernmost of these plutons and extends into Ice Creek in the Holden quadrangle. The Entiat plutons, composing the rest of the plutons, are more variable in composition and are directly traceable into the Chelan Complex of Hopson (cited in Mattinson, 1972, p. 3772), and hence they are correlative with that complex. Within the two quadrangles, the plutons are closely associated spacially with the Dumbell Mountain and Leroy Creek plutons and were considered by Crowder (1959) to be genetically related. Mattinson (1972, p. 3771–3772) also correlated them with these older plutons and considered them part of Misch's (1966) "Marblemount belt," although he did not rule out emplacement during the Jurassic or Early Cretaceous (Mattinson, 1972, p. 3378). Although the Seven-fingered Jack and Entiat plutons do resemble the Dumbell Mountain plutons in many respects, they are compositionally far more diverse, and they not only intrude the Dumbell Mountain rocks but contain considerably more K_2O (tables 3, 8). Ages as determined by Mattinson (1972) are tens of millions of years younger for rocks collected from the Chelan Complex. These ages

TABLE 7.—*Chemical and spectrographic analyses and norms of a composite sample of biotite-quartz diorite from the Leroy Creek pluton, central Washington*

[SiO_2 and Al_2O_3 determined by X-ray fluorescence; total Fe, MgO, and CaO determined by atomic absorption; FeO determined volumetrically; Na_2O and K_2O determined by flame photometer; TiO_2 determined colorimetrically; analysts: P.L.D. Elmore, K. E. White, and S. D. Botts. Spectrographic analyses by H. G. Neiman]

Chemical analyses (percent)		Semiquantitative spectrographic analysis (parts per million)		Norms	
SiO_2	73.0	Ba	500	q	36.07
Al_2O_3	14.0	Cr	1.5	or	3.83
Fe_2O_3	1.24	Cu	3	ab	39.74
FeO	1.39	Mo	3	an	14.82
MgO	.72	Sc	10	hy	3.11
CaO	2.95	Sr	500	c	.32
Na_2O	4.64	V	30	mt	1.82
K_2O	.64	Y	15	il	.29
TiO_2	.15	Zr	70	Total	100.00
Total	98.73	Ga	15	Plagioclase composition	
		Yb	1.5	an	27.2

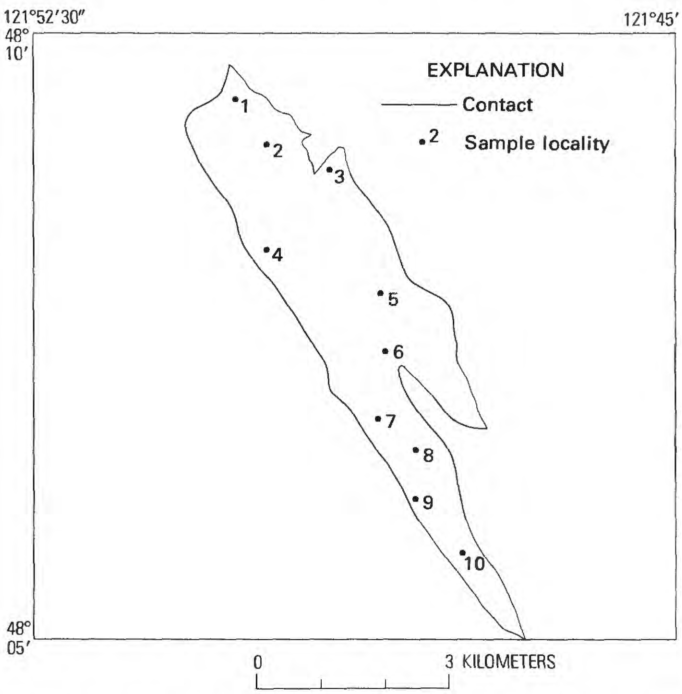

FIGURE 22.—Map showing location of modally analyzed samples of biotite-quartz diorite gneiss from the Leroy Creek pluton, Holden quadrangle. Sample analyses are given in table 6.

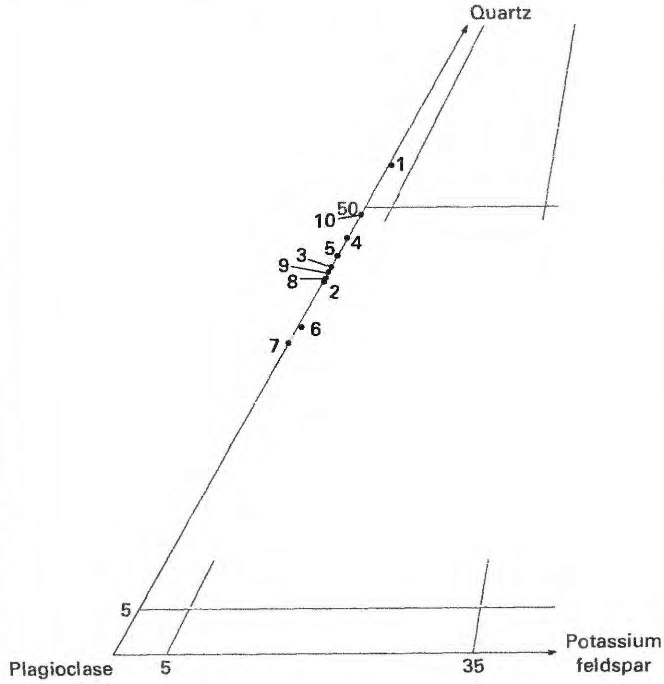

FIGURE 23.—Plot of modes of biotite-quartz diorite gneiss samples from the Leroy Creek pluton, Holden quadrangle, on a quartz-potassium feldspar-plagioclase diagram. Sample analyses are given in table 6.

range from about 100 to 193 m.y. for zircons from samples of these rocks to only 71 to 87 m.y. for sphene from the same samples (table 38). Although only one age, a Pb^{207}/Pb^{206} age of 183 m.y. for a medium-grained fraction of zircon, was clearly discordant, the Pb^{207}/Pb^{206} ages ranging from 100 to 132 m.y. for other samples were either concordant or but moderately discordant "within the limits of the lead-lead ages" (Mattinson, 1972, p. 3778). He considered it likely that these rocks were "remobilized" from rocks of the "Marblemount belt," a possibility for which little evidence exists. Engels (Engels and others, 1976) obtained potassium/argon ages of about 60 and 64 m.y. from biotite and hornblende from the Entiat pluton, figures that are probably much too low because of argon loss. For these reasons, correlations of the Seven-fingered Jack and Entiat plutons with the Dumbell Mountain or Leroy Creek plutons are considered erroneous.

The plutons are elongate, narrow masses injected into fault zones or zones of structural weakness. None of the masses within the mapped area exceeds a thickness of about 1.5 km. The largest is the Entiat pluton, consisting of hornblende-biotite- and biotite-hornblende-quartz diorite; its length within the mapped area is about 16 km, but its total length is not known. The Seven-fingered Jack plutons are smaller but more diverse in composition, consisting of hornblende-quartz diorite and quartz diorite gneiss, hornblende-biotite- and biotite-hornblende-quartz diorite, quartz gabbro, diorite, and gabbro. Some of the smaller masses, which are merely dikes as little as 30 m or so thick, consist of a single rock type. Others, particularly the larger plutons, consist of a variety of types, although a single type is commonly dominant.

Unfaulted contacts of Seven-fingered Jack plutons are mostly sharp where not obscured by later dikes and irregular masses of leucocratic quartz diorite, but locally they are gradational through a zone a few meters thick. The Entiat pluton, on the other hand, is characterized by wild contact complexes, particularly where it cuts metamorphic rocks, but the contact is generally sharp where intrusive into other plutons. Similar complexes characterize the contacts of other quartz diorite plutons of different ages in the area; all consist of spectacular melanges of various intrusive rocks, inclusions, and coarse-grained hornblendite (figs. 24 and 25). In more gneissic parts of the complex, foliation laminae wrap around inclusions in a manner suggestive of rotation by the inclusion because of differential flowage.

BIOTITE-HORNBLENDE-QUARTZ DIORITE

Biotite-hornblende-quartz diorite of the Seven-fingered Jack pluton is mostly a gray, medium-grained rock ranging from massive to gneissic (figs. 26, 27). Gneissic varieties are erratic in distribution but are

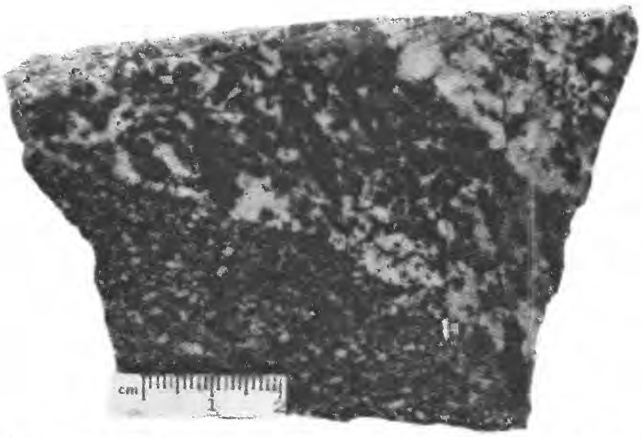

FIGURE 24.—Coarse- and medium-grained hornblende gabbro from contact complex of Entiat pluton, Lucerne quadrangle.

FIGURE 25.—Contact complex of Entiat pluton showing pegmatitic hornblende gabbro (Hgb), schist (sch), and hornblendite (hdld).

generally more common near contacts; the westernmost dikelike mass paralleling the Entiat fault is gneissic nearly everywhere. Locally, the large mass between Hart Lake and Ice Lakes consists of layers of gneissic quartz diorite 0.3 m or more thick that alternate with nongneissic rock. Probably the most noteworthy feature of this mass, however, is a conspicuous lineation defined by closely spaced pencillike mafic streaks and schlieren having parallel orientation (fig. 27). In places, the rock has a gneissic appearance because of mafic xenoliths smeared out in the plane of foliation; angular inclusions are common locally.

In thin section, the rock is seen to consist of andesine, quartz, and hornblende, and in most specimens, small amounts of biotite as essential minerals. Titanite, opaque minerals, apatite, and rare zircon are accessory; generally small amounts of clinozoisite-epidote, chlorite, and sericite occur as secondary products. Andesine ranges in average composition from about An_{38} to nearly An_{50}, but most of it falls between An_{38} and An_{45}. Crystals are subhedral to euhedral and, except where destroyed by twinning, show conspicuous oscillatory and patchy zoning. In contrast to plagioclase in the Dumbell Mountain plutons, no crystals of which show more than four or five oscillations, plagioclase in this quartz diorite commonly shows a dozen or more oscillatory zones. This characteristic helps to distinguish rocks of these plutons from those of the very similar Dumbell Mountain plutons. Quartz is interstitial or replaces andesine and hornblende. Hornblende is anhedral to subhedral and much of it is zoned, the rims being deeper green than the cores. The pleochroic scheme of most of it is X, pale yellow; Y, greenish brown; and Z, dark green or bluish green. Cores of some grains contain poikilitic inclusions of quartz and smaller amounts of plagioclase. Biotite occurs as irregular flakes or is secondary after hornblende. In a few thin sections, clinozoisite-epidote is coarse and euhedral and seems to have formed in equilibrium with hornblende.

Textures, which in some of the gneissic varieties show slight protoclastic modifications, are characteristically hypidiomorphic; cracks in crystals of abraded andesine are filled with biotite (fig. 28), although most of the rock in the westernmost mass is decidedly cataclastic and sheared. This mass seems to have been intruded along the zone of dislocation marked by the Entiat fault.

HORNBLENDE-BIOTITE-QUARTZ DIORITE

Hornblende-biotite-quartz diorite of the Entiat pluton is also a gray rock but is rather more variable in grain size than biotite-hornblende-quartz diorite and ranges from medium to fairly coarse grained (fig. 29). Locally it is gneissic, in places because of protoclasis, elsewhere because of alined crystals resulting from flowage. Mafic streaks and lenses are common, particularly near contacts. Hornblende-biotite-quartz diorite is microscopically similar to biotite-hornblende-quartz diorite, the principal differences being the preponderance of biotite over hornblende, generally more sodic

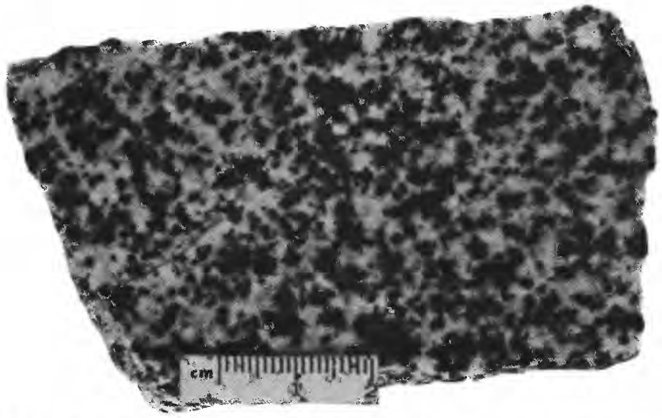

FIGURE 26.—Biotite-hornblende-quartz diorite from Seven-fingered Jack pluton, Holden quadrangle.

plagioclase, and the common occurrence of small amounts of interstitial potassium feldspar, and in a section or two, enough to classify the rock as granodiorite. Characteristic also is considerable titanite as rhombs as much as 4 mm long. The textures are hypidiomorphic granular with local protoclastic and cataclastic modifications.

HORNBLENDE-QUARTZ DIORITE GNEISS

Hornblende-quartz diorite gneiss of the Entiat pluton that cuts the southwestern part of the Lucerne quadrangle and adjacent parts of the Holden quadrangle is a light- to dark-greenish-gray, medium-grained rock having a pervasive and highly swirled but not strongly accentuated foliation (fig. 30). Light-colored segregation dikes and pods are common. Lenticular segregations consisting largely of biotite, and other mafic streaks and lenses are fairly common and, in places, particularly near contacts, angular blocks of amphibolite are numerous. Inclusions, except for the angular ones that are commonly rotated (fig. 31), are elongated along planes of foliation. The rock varies considerably in both composition and texture. It consists of calcic oligoclase or sodic andesine, quartz, hornblende, and biotite in various proportions. Biotite occurs in only accessory amounts in most of the rock, but in places it is more abundant than hornblende. In lighter colored rocks, muscovite is also common. Accessory minerals are magnetite, titanite, and apatite. Chlorite and epidote-clinozoisite are secondary. Textures range from hypidiomorphic to xenomorphic, variously modified by protoclasis and cataclasis (fig. 32).

HORNBLENDE DIORITE AND GABBRO

Hornblende diorite and gabbro of the Seven-fingered Jack pluton are confined to the Lucerne quadrangle, although small masses of these rocks do occur locally in plutons consisting dominantly of the other rock types.

FIGURE 27.—Biotite-hornblende-quartz diorite from the Seven-fingered Jack pluton, showing strong lineation defined by pencils of mafic-rich material, Holden quadrangle.

The contact complexes do, indeed, consist perhaps dominantly of hornblende diorite and gabbro, and along the western margin of this diorite-gabbro pluton, the contact between the pluton and the complex is gradational. The rocks are of varied appearance and range from gray to nearly black with a greenish cast and from medium to coarse grained, and some are slightly pegmatitic. The hornblende diorite is generally of more uniform appearance, is gray, medium grained, and mostly massive, but some has a slight foliation. Gabbro is darker and some is greenish black; grain size, arrangement, and shapes of crystals differ greatly from place to place. Some gabbro is rather coarse grained and has a panidiomorphic texture; much is medium grained and granitoid, but fair quantities are relatively fine grained and, in outcrop, are very similar to the pawdite of various dikes in the area. The various rock types, including the diorite, are intergradational and locally stirred together in mixtures that look like marble cake.

FIGURE 28.—Protoclastic hornblende-biotite-quartz diorite from Seven-fingered Jack pluton, showing cracks in fractured crystal of andesine (A) filled with biotite (B), orthoclase (O), and quartz (Q), Holden quadrangle.

Inclusions of various kinds are abundant; among the more numerous are knots of hornblendite and clots of coarse-grained plagioclase-hornblende rock. Hornblende and plagioclase are the only major constituent minerals common to all the rocks, but some contain considerable biotite and even a few percent of quartz. Plagioclase in diorite is calcic andesine and in gabbro is sodic labradorite; both oscillating and patchy zoning are common. Orthoclase occurs as a sparse interstitial mineral locally, and titanite, apatite, muscovite, and magnetite are accessory. Epidote, chlorite, and sericite are secondary. Textures range from xenomorphic to panidiomorphic; both protoclasis and cataclasis are prevalent.

CONTACT COMPLEXES

The Seven-fingered Jack and Entiat plutons have the largest volume of highly varied contact complexes of any intrusive masses in the area. These complexes have the same general appearance and contain the same varieties of rock types as do the other complexes. Hornblende gneiss and schist, inclusions of all orientations, very

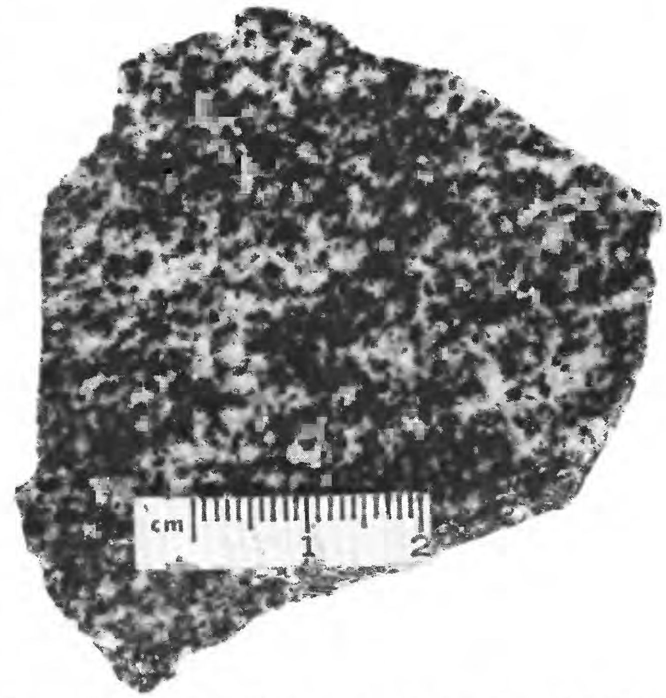

FIGURE 29.—Hornblende-biotite-quartz diorite from the Entiat pluton, Lucerne quadrangle.

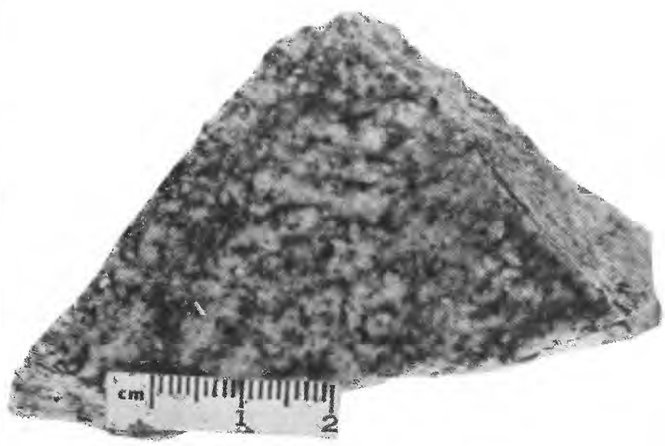

FIGURE 30.—Hornblende-biotite-quartz diorite gneiss from the Entiat pluton, Holden quadrangle.

coarse grained hornblendite in crystals as much as 15 cm long, swarms of dikes and irregular masses of fine-grained to pegmatitic hornblende-quartz diorite, diorite, and gabbro are mixed together in spectacular melanges. The zone extending from Shetipo Creek to Pomas Creek is sheared and intruded by swarms of porphyry dikes. Mostly, core rocks of the plutons intrude the contact complexes, but in scattered outcrops, elements of the complex, largely hornblende-quartz diorite and diorite but locally gabbro, cut core rocks. In a few places, as for example, 1 km south of Larch Lakes, gabbro is chilled

FIGURE 31. —Rotated inclusions of late Paleozoic gneiss in hornblende-quartz diorite gneiss from the Entiat pluton, Lucerne quadrangle.

against quartz diorite (fig. 33). In any case, field relations indicate that the rocks of the complexes were certainly at least partly molten when the main masses of the plutons were injected. Microscopic examination of rocks making up the complexes, particularly the finer grained ones, shows that the quartz diorite in them differs little from core rocks of the associated plutons. The relation of these contact complexes to the plutons is discussed in a later section entitled "Contact complexes" where the general problem of these and contact complexes of other plutons or groups of plutons are considered. It should be stressed, however, that these complexes are devoid of any indication of regional metamorphism.

Locations of modally analyzed samples are shown in figure 34, modal analyses in table 8, and chemical analyses in table 9. A plot of modes is shown in figure 35 and norms in figure 36. The content of major oxides is shown in the variation diagram (fig. 13).

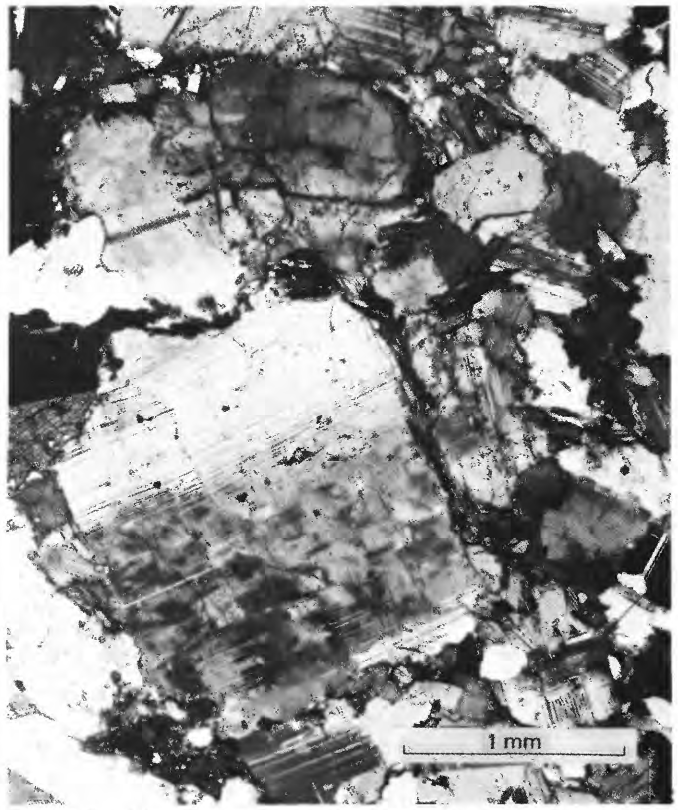

FIGURE 32.—Hypidiomorphic and protoclastic hornblende-quartz diorite gneiss from the Entiat pluton, Lucerne quadrangle. Note slightly rotated fragments of zoned andesine crystal.

LEUCOCRATIC QUARTZ DIORITE AND GRANODIORITE

Leucocratic quartz diorite (trondjemite) and granodiorite are the most widespread of the intrusive or intrusive-related rocks in the region. Crowder (1959, p. 855–862) has described these rocks and their mode of occurrence in detail, and the reader is referred to that paper for a more comprehensive treatment of these rocks. The interpretation of the genesis and significance of these rocks here presented, however, differ in some respects to those elucidated by Crowder who believed, at that time, that most of the various older intrusive rocks formed by granitization and local fusion of the host metamorphic rock.

The leucocratic rocks form an extraordinarily complex assemblage of dikes, sills, irregular clots, pods, and small stocks or plutons in the Swakane Biotite Gneiss and in the Seven-fingered Jack and older granitoid intrusives. The shape of individual masses is rather strongly dependent on the fabric of the host rock; thus, in foliated rocks, lenses and sills parallel to foliation are characteristic, whereas irregular dikes and masses form in more massive rocks. In many places, bodies of leucocratic material are numerous enough to form migmatites (fig. 37). In the Swakane, the amount of

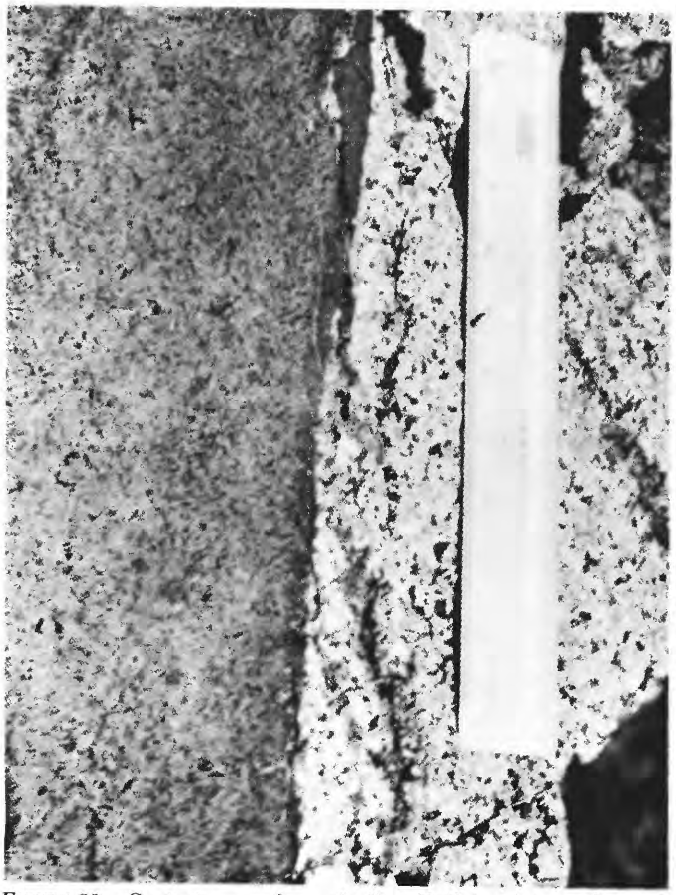

FIGURE 33.—Contact complex of the Entiat pluton, Lucerne quadrangle, showing gabbro chilled against quartz diorite.

leucocratic material increases from the southeast to the northwest. Inasmuch as the rocks are more deeply eroded to the northwest, it may be that the abundance of leucocratic rocks in the Swakane is at least partly depth dependent. The largest masses of leucocratic rock occur east of Pomas Creek in the Lucerne quadrangle. Most of the leucocratic quartz diorite and granodiorite is nearly white and massive (fig. 38) but in places it is obscurely gneissic because of parallelism of mica flakes, mostly biotite. Fine-grained and medium-grained rocks are most abundant, but pegmatitic varieties are common, and all textural varieties are intergradational within single masses. The leucocratic rocks consist mostly of oligoclase and quartz; the main accessory mineral is biotite. Potassium feldspar is almost absent, except locally, as in a few dikes on the east side of Rock Creek and in pods and pegmatitic masses on the south side of Chiwawa Mountain where microcline is sufficiently abundant for the rock to be classed as granodiorite. Minor accessory minerals are apatite, titanite, opaque minerals, and muscovite. Chlorite and epidote replace biotite, and sericite replaces oligoclase. Most of the oligoclase has a composition of about An_{20}, but some is

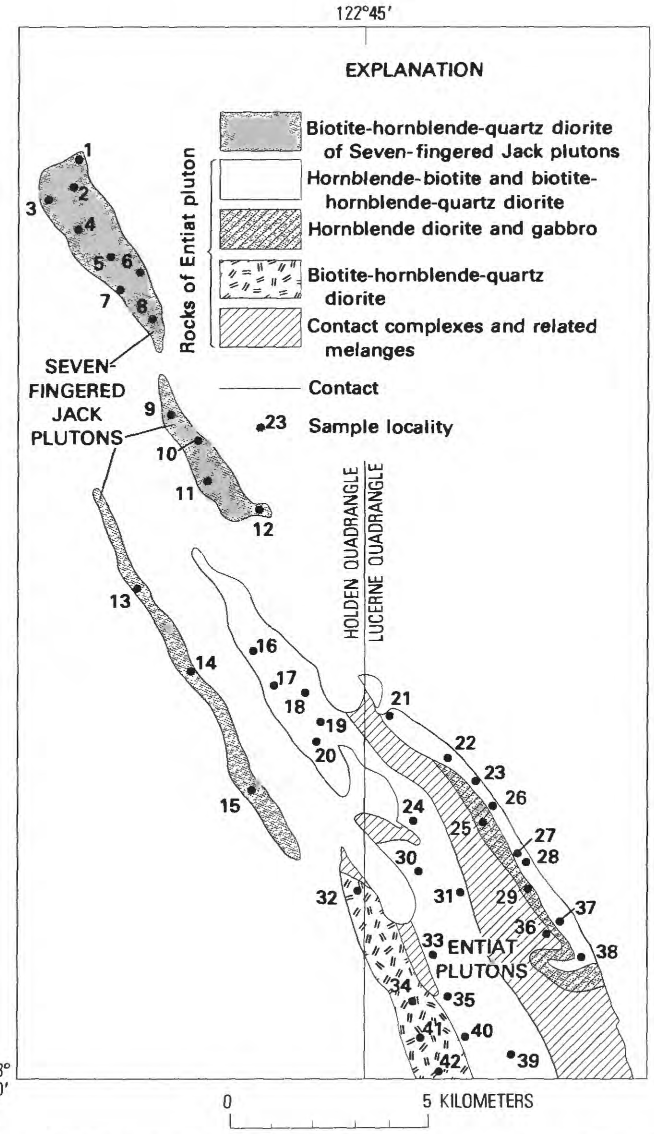

FIGURE 34.—Map showing location of modally analyzed samples from the Seven-fingered Jack and Entiat plutons, Holden and Lucerne quadrangles.

as calcic as An_{30}. No discernible difference in texture or mode of occurrence was apparent between rocks containing medium oligoclase and those containing calcic oligoclase. Much of the oligoclase is anhedral or forms rounded grains, and is largely unzoned, but some thin sections have subhedral crystals of oligoclase that are oscillatorily zoned. Rounded blebs of quartz as inclusions are common in oligoclase. Quartz mostly occurs as irregular lenses and folia of interlocking grains that wrap around the larger plagioclase grains. Biotite occurs as orange-red shreds. Textures are xenomorphic and have crystalloblastic appearance generally, but some specimens approach a hypidiomorphic texture. Protoclasis is fairly common.

TABLE 8.—*Modal analyses of samples of diorite, gabbro, quartz diorite, and quartz diorite gneiss from the Seven-fingered Jack and Entiat plutons, central Washington*

Sample No.	Plagioclase	Potassium feldspar	Quartz	Biotite	Hornblende	Accessory and secondary minerals	Total mafic minerals	Anorthite in plagioclase crystals (percent)			Remarks
								Average	Core	Rim	
1	54.4	0	19.4	2.8	8.6	14.8	26.2	46	51	33	Hypidiomorphic.
2	53.6	0	17.8	10.6	16.5	1.5	27.6	46	49	33	Do.
3	46.3	0	13.6	7.9	21.5	.7	30.1	38	43	31	Do.
4	32.0	0	14.5	2.5	28.5	22.5	53.5	38	41	15	Do.
5	58.4	0	16.5	0	12.2	12.9	25.1	41	44	38	Do.
6	51.8	0	11.6	.2	22.3	14.1	36.6	38	44	31	Do.
7	51.0	0	21.9	14.0	9.2	3.9	27.1	38	40	35	Do.
8	53.6	0	19.1	4.4	20.0	2.9	27.3	42	47	38	Do.
9	50.1	0	8.9	3.3	31.8	5.9	41.0	47	0	0	Do.
10	54.7	0	11.2	6.1	27.0	1.0	34.1	47	0	0	Hypidiomorphic-protoclastic.
11	54.7	0	11.7	6.6	24.0	3.0	33.6	40	48	33	Xenomorphic.
12	42.2	0.2	15.9	.3	31.0	10.4	41.7	38	50	34	Protoclastic.
13	59.0	0	10.2	3.5	13.9	13.4	30.8	44	0	0	Do.
14	52.7	.5	7.5	0	27.8	11.5	39.3	43	0	0	Hypidiomorphic.
15	50.7	0	5.8	.5	38.4	4.6	43.5	38	55	28	Do.
16	50.2	0	31.2	3.9	13.0	1.7	18.6	33	37	31	Do.
17	49.5	.6	22.9	11.6	4.8	10.6	27.0	34	36	27	Hypidiomorphic-cataclastic.
18	39.2	5.5	28.7	13.7	2.1	12.8	28.6	35	39	27	Do.
20	56.7	0	21.9	10.4	9.3	1.7	21.4	39	47	35	Hypidiomorphic.
21	57.6	0	18.7	7.9	13.3	2.5	23.7	35	0	0	Do.
22	49.1	0	26.5	3.1	18.3	3.0	24.4	37	42	33	Cataclastic.
23	57.2	1.4	14.9	9.5	14.9	5.5	29.9	40	45	33	Hypidiomorphic-protoclastic.
24	55.6	1.0	20.3	11.0	6.8	5.3	23.1	39	45	31	Hypidiomorphic.
25	49.8	0	1.9	.4	43.0	4.9	48.3	48	64	32	Do.
26	44.0	4.2	19.0	20.3	7.9	4.6	32.8	34	0	0	Do.
27	58.7	0	9.2	.5	22.1	9.5	32.1	36	43	31	Do.
28	43.3	3.4	19.9	20.7	11.1	1.6	33.4	38	41	14	Protoclastic.
29	51.9	0	.4	.6	35.8	11.3	47.7	48	0	0	Xenomorphic-cataclastic.
30	53.3	.7	18.3	19.2	3.2	5.3	27.7	40	44	19	Hypidiomorphic.
31	56.0	3.5	15.6	11.4	1.7	11.8	24.9	47	0	0	Xenomorphic-cataclastic.
32	50.8	0	38.7	3.3	4.1	3.1	10.5	27	0	0	Do.
33	47.6	.7	22.0	20.7	6.4	2.6	39	39	42	36	Do.
34	65.2	0	17.8	5.7	0	11.3	17	26	38	11	Hypidiomorphic; 6 percent muscovite
35	45.1	3.1	21.9	15.2	8.8	5.9	29.9	58	60	55	Hypidiomorphic-cataclastic.
36	43.2	4.0	25.6	12.5	13.3	1.4	27.2	38	0	0	Protoclastic.
37	41.2	0	22.1	18.3	12.4	6.0	13.7	35	0	0	Do.
38	58.5	3.1	20.6	11.7	4.2	1.9	17.8	38	0	0	Do.
39	45.0	0	18.4	25.5	5.2	5.9	36.6	39	41	35	Hypidiomorphic.
40	43.6	11.3	17.3	9.4	14.8	3.6	27.8	37	47	31	Do.
41	42.0	0	27.1	12.8	16.9	1.2	30.9	27	40	18	Do.
42	48.1	0	25.1	.4	25.2	1.2	25.8	30	0	0	Xenomorphic.

Chemical and spectrographic analyses and norms of leucocratic quartz diorite and granodiorite are given in table 10, and a plot of the norms is shown in figure 36.

The origin of these enigmatic rocks is not altogether clear: some are obviously intrusive, disrupt the enclosing host rocks, and contain disoriented inclusions of them. Others, particularly the leucocratic rocks in the Swakane, seem mostly to have sweated out of the gneiss passively by a process of metamorphic segregation. In places, dikes of leucocratic quartz diorite or granodiorite cut masses of similar material that seem to be metamorphic segregations. Contacts of leucocratic rock with enclosing gneisses or intrusive rocks are commonly sharp, but in the gneissic rocks, particularly the Swakane, the adjacent gneiss in most places is enriched in mafic constituents as though the felsic constituents had migrated from the Swakane Biotite Gneiss. In other places, leucocratic material, apparently derived by metamorphic segregation, became mobile and formed crosscutting dikes; a good example is illustrated by Crowder (1959, pl. 6, fig. 7). Available evidence suggests that although the leucocratic rocks vary little in composition or appearance, some formed by metamorphic segregation and others are probably felsic differentiates of intrusive rocks. Certainly in many places the two processes are so blurred that it seems they were essentially contemporaneous, but the abundance of these rocks in the Swakane everywhere and their localized occurrence in the Seven-fingered Jack and older plutons strongly suggests a wide difference in age for some of these rocks. Mattinson (1972, p. 3778–3779), for example, obtained ages that ranged from 60 to 90 m.y. for zircons from pegmatitic material collected from the Swakane along the Columbia River, from Misch's "Skagit" gneiss, and from a Dumbell Mountain pluton. These ages probably are from igneous-derived material.

TABLE 9.—*Chemical and spectrographic analyses and norms of rock samples from the Seven-fingered Jack and Entiat plutons, Holden and Lucerne quadrangles*

[For samples 1 and 2 rapid rock analyses by P.L.D. Elmore, K. D. White, and S. D. Botts. For sample 3, SiO_2 and Al_2O_3 determined colorimetrically; Fe_2O_3, MgO, CaO, and Mn determined by atomic absorption; FeO determined volumetrically; Na_2O and K_2O determined by flame photometer; analysts: Violet Merritt, H. H. Lipp, G. D. Shipley, and G. T. Burrow. Spectrographic analyses by K. E. Valentine and Harriet Neiman. Leaders (- - -), below sensitivity limit]

Sample	1	2	3
Chemical analyses (percent)			
SiO_2	57.5	61.8	51.5
Al_2O_3	18.0	17.0	15.7
Fe_2O_3	2.7	2.1	7.80
FeO	3.9	3.5	5.9
MgO	3.6	2.4	6.6
CaO	6.9	5.2	8.00
Na_2O	3.8	3.8	3.14
K_2O	1.0	1.7	.39
TiO_2	.98	.71	0
P_2O_5	.32	.33	0
MnO	.12	.11	.14
H_2O	1.0	1.2	0
CO_2	.07	.05	0
Total	100	100	99
Semiquantitative spectrographic analyses (parts per million)			
Ba	100	100	70
Co	10	10	20
Cr	30	30	300
Cu	10	10	30
Ga	30	30	15
Ni	---	---	50
Sc	10	10	20
Sr	300	300	300
V	10	10	300
Y	10	10	20
Yb	1	1	3
Zr	30	100	50
Norms			
q	11.61	18.07	5.33
or	5.97	10.18	2.32
ab	32.49	32.55	26.77
an	29.44	23.69	27.83
di	2.10	.00	9.73
hy	11.63	9.83	16.62
c	0	.35	0
mt	3.96	3.09	11.40
il	1.88	1.37	.00
ap	.76	.76	.00
cc	.16	.11	.00
Total	100.00	100.00	100.00
Plagioclase composition			
an	47.5	42.1	51.0

TABLE 9.—*Chemical and spectrographic analyses and norms of rock samples from the Seven-fingered Jack and Entiat plutons, Holden and Lucerne quadrangles*—Continued

Sample descriptions

1. Composite sample of biotite-hornblende-quartz diorite.
2. Composite sample of hornblende-biotite-quartz diorite.
3. Hornblende gabbro of contact complex.

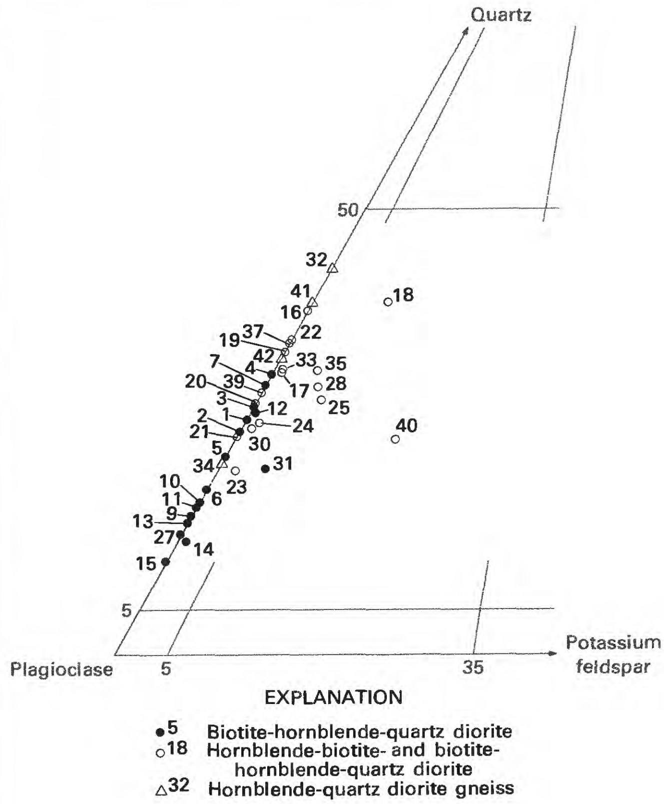

FIGURE 35.—Plot of modes of rock samples from the Seven-fingered Jack and Entiat plutons, Holden and Lucerne quadrangles, on a quartz-potassium feldspar-plagioclase diagram. Sample analyses are given in table 8.

TENPEAK AND WHITE MOUNTAIN PLUTONS

The Tenpeak and White Mountain plutons consist of closely similar rocks and are probably connected at depth. From north of Glacier Peak volcano, near the center of the Glacier Peak quadrangle, the Tenpeak pluton extends south-southeast across the southwest corner of the Holden quadrangle and beyond. Along the southern border of the mapped area, the pluton has a width of about 8 km. The White Mountain pluton forms a thick sill-like mass extending from the south-central part of the Holden quadrangle southward roughly 8 km, about 3 km of which are south of the quadrangle. The width is about 4 km. South of the mapped area, both plutons have been studied and described by Van Diver

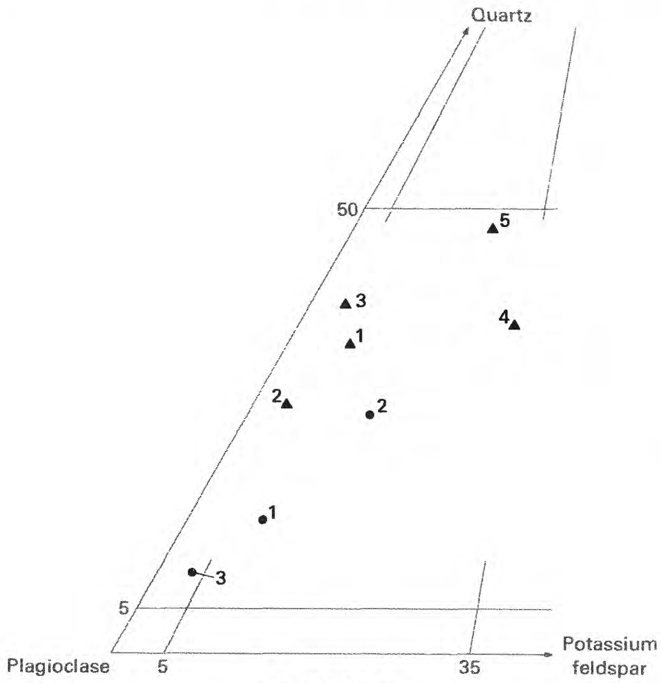

FIGURE 36.—Plot of norms of leucocratic quartz diorite and granodiorite samples and rock samples from the Seven-fingered Jack and Entiat plutons, Holden and Lucerne quadrangles. Sample analyses are given in tables 9 and 10.

FIGURE 37.—Migmatite of leucocratic quartz diorite in biotite-hornblende-quartz diorite of the Seven-fingered Jack pluton, Holden quadrangle.

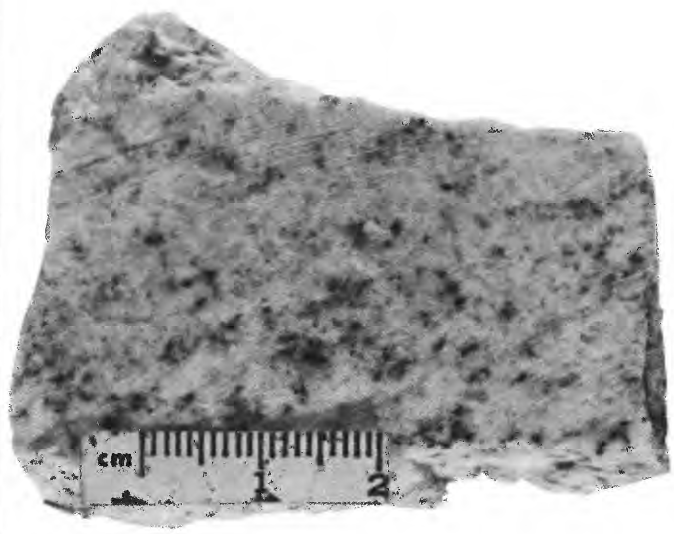

FIGURE 38.—Leucocratic quartz diorite, Holden quadrangle.

(1967) as orthogneiss. He stated (p. 146) that, "It is not known whether the igneous parent rock of the White River Orthogneiss represents a premetamorphic intrusive later than the deposition of the supracrustal sequence, or whether it is part of the basement on which the sequence was laid down." He thought that the weight of evidence probably supported a "fault emplacement" of the pluton (p. 133), but that at any event, the plutons were metamorphosed concomitant with the enclosing gneisses. However, the plutons, which are about 90 m.y. old (Engels and others, 1976) contain fairly numerous inclusions of the host metamorphic rocks, and these rocks probably correlate with part of the upper Paleozoic metamorphic rocks of the Holden area. Van Diver apparently considered the protoclastic margins of the plutons to be recrystallized shears related to probable tectonic emplacement of the plutons.

The plutons consist of a variety of rocks ranging from granodiorite to gabbro and hornblendite, but by far the most abundant rock type is quartz diorite. The Tenpeak is the more complex of the two plutons and consists of a number of separately mapped units that differ somewhat in composition and appearance. The largest of these units, consisting of the same rock type that makes up most of the White Mountain pluton, is mostly light-colored, medium-grained hornblende-biotite-quartz diorite. Also common to both plutons are spectacular-appearing contact complexes consisting of an extraordinary variety of rocks. The second unit of the Tenpeak pluton is a layer nearly 1 km thick that borders the northeast side of the pluton. It consists of hornblende- and (or) biotite-quartz diorite flaser gneiss. Separating this unit from the main mass of the pluton, the light-colored hornblende-biotite-quartz diorite, is a unit of in-

TABLE 10.—*Chemical and spectrographic analyses and norms of samples of leucocratic quartz diorite and granodiorite, central Washington*

[For samples 1-3, SiO_2 and Al_2O_3 determined by X-ray fluorescence; total Fe, MgO, and CaO determined by atomic absorption; FeO determined volumetrically; Na_2O and K_2O determined by flame photometer; TiO_2 determined colorimetrically; analysts: J. S. Wahlberg, Wayne Mountjoy, and G. T. Burrow. For samples 4 and 5, rapid rock analyses by P.L.D. Elmore, K. E. White, and S. D. Botts. Spectrographic analyses by Harry Bartron and Harriet Neiman. N.d., not determined; leaders (- - -), below limit of detection]

Sample	1	2	3	4	5
Chemical analyses (percent)					
SiO_2	74.0	70.00	75.0	74.2	75.9
Al_2O_3	14.6	16.8	14.0	15.5	14.1
Fe_2O_3	.44	.64	.47	.48	.6
FeO	1.15	1.19	.86	.33	.90
MgO	.44	.46	.48	.32	.64
CaO	2.59	3.34	3.00	1.8	2.0
Na_2O	5.20	5.76	4.78	3.8	3.2
K_2O	.99	.58	.57	3.4	2.1
TiO_2	.09	.14	.10	.08	.16
P_2O_5	N.d.	N.d.	N.d.	.04	.06
MnO	N.d.	N.d.	N.d.	.01	.03
HO	N.d.	N.d.	N.d.	.64	.96
CO_2	N.d.	N.d.	N.d.	.05	.05
Total	100	99	99	101	101
Semiquantitative spectrographic analyses (parts per million)					
B	---	---	---	10	10
Ba	500	500	700	3,000	3,000
Be	---	---	---	1	1
Co	---	---	---	---	5
Cr	1	3	2	---	20
Cu	3	5	3	10	20
Mo	---	3	3	---	---
Ni	---	---	---	5	5
Pb	---	10	10	30	20
Sc	---	3	---	---	---
Sr	1,000	1,500	1,000	400	700
V	30	30	20	20	40
Zr	70	70	50	40	30
Ga	15	15	15	10	10
Norms					
q	33.22	26.10	37.67	34.98	44.02
or	5.88	3.46	3.39	20.09	12.44
ab	44.20	49.24	40.68	32.13	27.13
an	12.91	16.75	14.98	8.35	9.24
hy	2.71	2.60	2.24	.89	2.55
c	.27	.64	.17	2.51	3.20
mt	.64	.94	.68	.70	.87
il	.17	.27	.19	.15	.30
ap	0	0	0	.09	.14
cc	0	0	0	.11	.11
Total	100.00	100.00	100.00	100.00	100.00

TABLE 10.—*Chemical and spectrographic analyses and norms of samples of leucocratic quartz diorite and granodiorite, central Washington*—Continued

Sample	1	2	3	4	5
Plagioclase composition					
an	22.6	25.4	26.9	20.6	25.4

Sample descriptions

1. Sample of irregular trondjhemite mass.
2. Sample of trondjhemite dike.
3. Sample of leucocratic, veinlike segregations in hornblende gneiss.
4. Composite sample of leucocratic granodiorite pods in biotite gneiss.
5. Composite sample of leucocratic granodiorite pegmatite dikes.

terlayered light- and dark biotite-hornblende diorite, quartz diorite, quartz diorite gneiss, and flaser gneiss. The unit is about half a kilometer thick. Confined to the northwestern end of the Tenpeak pluton, in the Glacier Peak quadrangle, is a third unit consisting of dark biotite-hornblende diorite.

HORNBLENDE-BIOTITE-QUARTZ DIORITE AND QUARTZ DIORITE GNEISS

The hornblende-biotite-quartz diorite and quartz diorite gneiss composing the bulk of both plutons is mostly a light-colored, medium-grained rock in which crystals of hornblende as much as 1 cm long and flakes of biotite are conspicuous (fig. 39). In the White Mountain pluton, small amounts of granodiorite indistinguishable in outcrop from quartz diorite also occur. Reddish-amber crystals of garnet nearly 1 cm across are locally common in the Tenpeak pluton, and rhombs of sphene as much as 0.6 cm long are characteristic of both plutons. Much of the rock is slightly foliated, and most also has a distinct lineation defined by the parallel orientation of hornblende and scattered elongate xenoliths. In places, particularly near contacts, inclusions are plentiful; they range from angular, undigested fragments of host rocks to vague rounded schlieren that differ little from quartz diorite. Contacts of the granodiorite in the Tenpeak pluton with the interlayered zone unit are gradational, but elsewhere the quartz diorite becomes increasingly streaky near most contacts, particularly those that are more or less conformable, and here the rock is commonly highly gneissic.

FLASER GNEISS

The flaser gneiss borders the entire northeast side of the Tenpeak pluton. The rock is fine to medium grained and contains porphyroclasts of sodic andesine enveloped

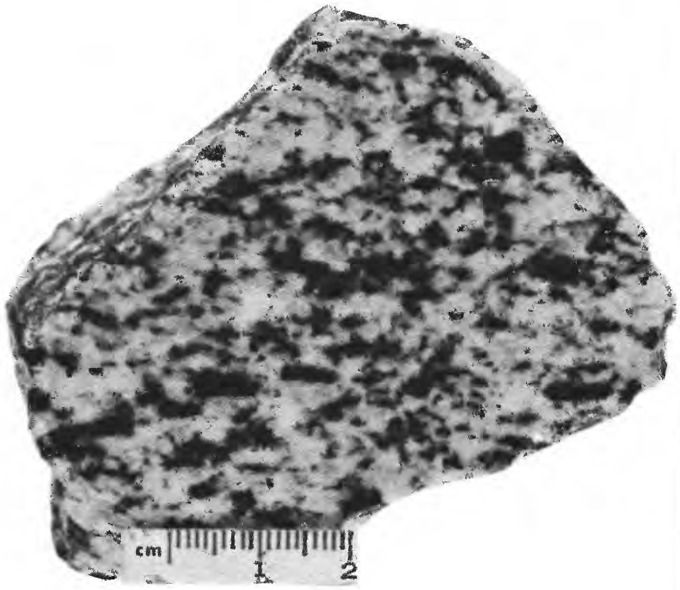

FIGURE 39.—Hornblende-biotite-quartz diorite from the Tenpeak pluton, Holden quadrangle.

by warped folia of biotite. Locally, hornblende crystals and mafic streaks define a lineation. Coarse crystals of sphene are common, but garnet is rare. The contacts of this unit with metamorphic rocks to the northeast are almost strictly conformable and range from sharp to gradational, but where gradational, the gradational zone is fairly narrow and consists in part of lit-par-lit injections. The southwest contact with the interlayered zone unit is gradational.

INTERLAYERED ZONE UNIT

The interlayered zone unit consists mostly of alternating lenses and layers of light- and dark-colored biotite-hornblende diorite and quartz diorite gneiss, and flaser gneiss (fig. 40). Even the lighter colored lenses and layers of light-colored gneiss, however, are generally darker than the rocks that form the interior of the pluton. The lenses and layers of gneiss and flaser gneiss range in thickness from a few centimeters to many meters; mixed with these are thinner sheets and thin wisps of hornblende schist, quartzite, and rare hornblendite. Schist inclusions are locally spotted with porphyroblasts of plagioclase. Gneisses are fine to medium grained and contain augen of plagioclase surrounded by anastomosing mats of finer grained hornblende. Contacts between layers and lenses or different rock types may be either sharp or gradational.

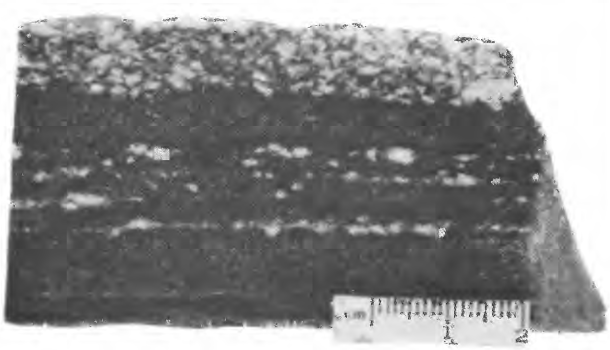

FIGURE 40.—Interlayered biotite-hornblende-quartz diorite gneiss and hornblende schist of the interlayered unit of the Tenpeak pluton, Holden quadrangle.

CONTACT COMPLEXES

Contact complexes of the White Mountain pluton are very largely confined to the northwest end where it trangresses the enclosing metamorphic rocks; those of the Tenpeak pluton are confined to the southwest side. These complexes are identical, in most respects, to those associated with other pre-Tertiary intrusive masses in the mapped area and consist of spectacular melanges of gabbro, diorite, hornblendite, quartz diorite, pegmatitic diorite, and inclusions of metamorphic rocks. Crystals in some of the hornblendite and pegmatitic rocks are as much as 5 cm long. The main body of quartz diorite sharply cuts the contact complex in some places, but elsewhere the contact has a stirred appearance that strongly suggests that the complex was plastic or molten when the quartz diorite was intruded. Locally, drawn-out, highly irregular masses of the complex are enclosed in quartz diorite.

PETROGRAPHY

Under the microscope, rocks of the various units are seen to be rather similar in composition, the principal difference between the light and dark colored quartz diorites being in the abundance of biotite and hornblende. Uncontaminated rocks consist of 45 to 55 percent sodic andesine, 11 to 25 percent quartz, 8 to 15 percent biotite, and 0 to 25 percent hornblende as primary minerals, and muscovite, apatite, opaque minerals, potassium feldspar, and as much as 2 percent titanite as accessory minerals. Granodiorites, however, contain as much as 15 percent potassium feldspar, mostly microcline. Primary, coarse-grained, euhedral clinozoisite-epidote is notably abundant and occurs in amounts of as much as 7.5 percent.

Plagioclase ranges in composition from An_{18} on the rims of some crystals to An_{53} in the most calcic cores; the average composition of plagioclase in most thin sections is about An_{35}. Oscillatory and patchy zoning is fairly common, but twinning has destroyed zoning in many crystals. Adjacent twin lamellae can differ in composition by as much as 3 or 4 percent of anorthite.

Myrmekite is common along granulated zones and adjacent to potassium feldspar. Hornblende is pleochroic in various shades of green, and much of it contains inclusions of quartz and less commonly of plagioclase. Probably some of the quartz grains are replacements rather than inclusions. Hornblende has also been extensively replaced by biotite, in many places, with a separation of fine-grained titanite. Quartz occurs as replacements of earlier formed minerals and as irregular seams of interlocking grains; lines of liquid inclusions are notably abundant. Much of the coarse-grained, euhedral clinozoisite-epidote contains blebs of simultaneously extinguishing quartz in intergrowths identical in appearance to myrmekite (fig. 41). This clinozoisite-epidote, in fact, appears to be a primary mineral growing in equilibrium with plagioclase and hornblende. Some scattered grains of clinozoisite-epidote have cores of allanite. Primary epidote in the Ellicott City Granodiorite, Maryland, has been described by Hopson (1964). Dietrich (1961, p. 42–45) indicated that high pressure and (or) high content of hydroxyl in magma favors development of primary epidote. Small amounts of chlorite replace biotite, and sericite sparingly replaces plagioclase, commonly as flakes along cleavage planes. Garnet and calcite occur in small amounts in a few sections.

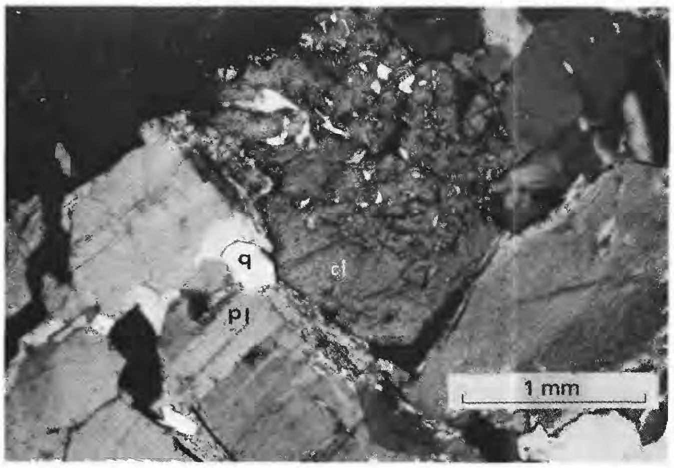

FIGURE 41.—Intergrowth of clinozoisite-epidote and quartz resembling myrmekite, quartz diorite from the Tenpeak pluton, Holden quadrangle. cl, clinozoisite-epidote; pl, plagioclase; q, quartz.

The textures of the quartz diorite range from hypidiomorphic to xenomorphic with barely perceptible to extensive protoclastic modifications. Rocks of the main body of the two plutons are mostly hypidiomorphic and show only minor protoclasis, whereas rocks of the interlayered and particularly the flaser-gneiss units are highly protoclastic, and it is protoclasis that lends the gneissic appearance to so much of the rocks.

Modal analyses of Tenpeak and White Mountain rocks are shown in table 11, and chemical and spectrographic analyses and norms in table 12. Locations of modally analyzed specimens are shown in figure 42, the modes are plotted in figure 43, and the norms are shown in figure 44. A plot of the major oxides is shown in the variation diagram (fig. 13).

SULPHUR MOUNTAIN PLUTON

Only a small, poorly exposed lobe of the Sulphur Mountain pluton extends into the western edge of the

TABLE 11.—*Modal analyses of samples of quartz diorite gneiss from the Tenpeak and White Mountain plutons, Holden quadrangle*

Sample No.	Plagioclase	Potassium feldspar	Quartz	Biotite	Hornblende	Accessory and secondary minerals	Total mafic minerals	Anorthite in plagioclase crystals (percent): Average	Core	Rim	Remarks
1	53.0	0	25.3	12.4	3.4	5.9	21.7	31	41	22	Protoclastic.
2	36.9	0.6	36.0	11.1	0	15.4	26.5	26	34	17	8.5 percent muscovite; protoclastic.
3	51.0	0	21.0	11.1	14.2	2.7	28.0	32	37	20	Hypidiomorphic.
4	54.7	0	22.5	11.6	7.6	3.6	22.8	34	50	26	Do.
5	48.1	.2	19.4	12.3	15.7	4.3	32.3	34	42	33	Protoclastic.
6	51.0	.1	16.4	.8	22.2	9.5	32.5	38	45	30	Hypidiomorphic.
7	44.7	4.7	24.4	14.4	3.7	8.1	26.2	26	34	18	Do.
8	42.9	0	20.8	14.0	12.4	9.9	36.3	31	40	28	Do.
9	38.1	.2	18.5	15.7	18.9	8.6	43.2	33	52	17	Do.
10	48.5	.4	14.4	14.4	14.6	7.7	36.7	30	50	23	Coarse, euhedral epidote; hypidiomorphic.
11	32.8	0	5.2	4.7	50.7	6.6	62.0	51	55	43	Quartz gabbro of contact complex; hypidiomorphic.
12	52.1	0	17.8	15.2	0	14.9	30.1	32	0	0	Protocluetic.
13	44.6	0	11.6	15.4	18.8	9.6	43.8	33	41	23	Subparallel andesine laths; hypidiomorphic.
14	49.3	15.8	25.3	6.7	0	2.9	9.6	27	31	8	Protoclastic.
15	44.8	.8	22.8	12.8	7.7	11.1	31.6	35	42	19	Hypidiomorphic.

TABLE 12.—*Chemical and spectrographic analyses and norms of composite rock samples from the Tenpeak and White Mountain plutons, Holden quadrangle*

[Standard rock analyses by Dorothy F. Powers. Spectrographic analyses by P. R. Barnett]

Sample	1	2
Chemical analyses (percent)		
SiO_2	62.30	59.67
Al_2O_3	16.89	16.34
Fe_2O_3	1.30	1.48
FeO	3.80	4.78
MgO	2.36	3.61
CaO	5.92	6.11
Na_2O	3.75	3.43
K_2O	1.39	1.67
H_2O+	.74	1.14
H_2O-	.08	.08
TiO_2	.74	.92
P_2O_5	.23	.27
MnO	.11	.13
CO_2	.00	.02
Total	99.61	99.65
Semiquantitative spectrographic analyses (parts per million)		
Ba	700	700
Co	7	15
Cr	30	70
Cu	15	15
Ga	15	15
Ni	7	15
Sc	15	15
Sr	1,500	700
V	150	150
Y	15	15
Yb	1.5	1.5
Zr	150	150
Norms		
q	18.22	13.95
or	8.31	10.02
ab	32.10	29.46
an	25.46	24.65
di	2.25	3.45
hy	9.78	13.82
mt	1.91	2.18
il	1.42	1.77
ap	.55	.65
cc	.00	.05
Total	100.00	100.00
Plagioclase composition		
an	44.2	45.5

Sample descriptions

1. Composite sample of biotite-hornblende-quartz diorite (Tenpeak).
2. Composite sample of hornblende-biotite-quartz diorite (White Mountain).

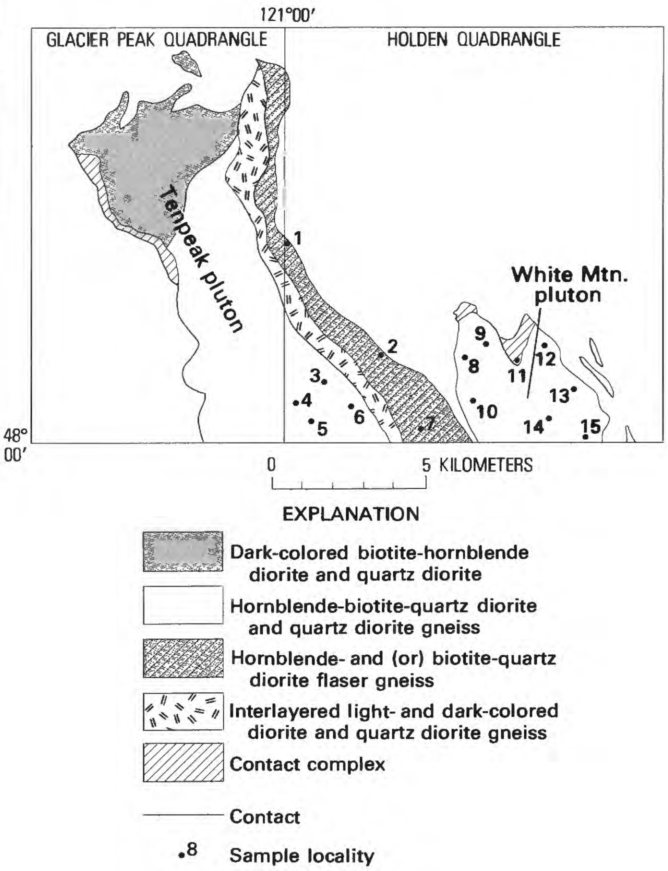

FIGURE 42.—Map showing location of modally analyzed samples from the Tenpeak and White Mountain plutons, Holden quadrangle.

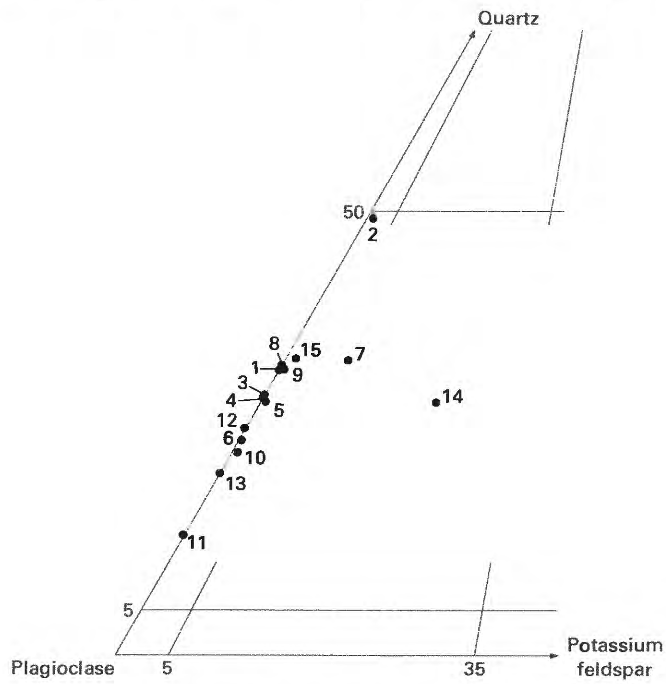

FIGURE 43.—Plot of modes of quartz diorite and quarts diorite gneiss samples from the Tenpeak and White Mountain plutons, Holden quadrangle, on a quartz-potassium feldspar-plagioclase diagram. Sample analyses are given in table 11.

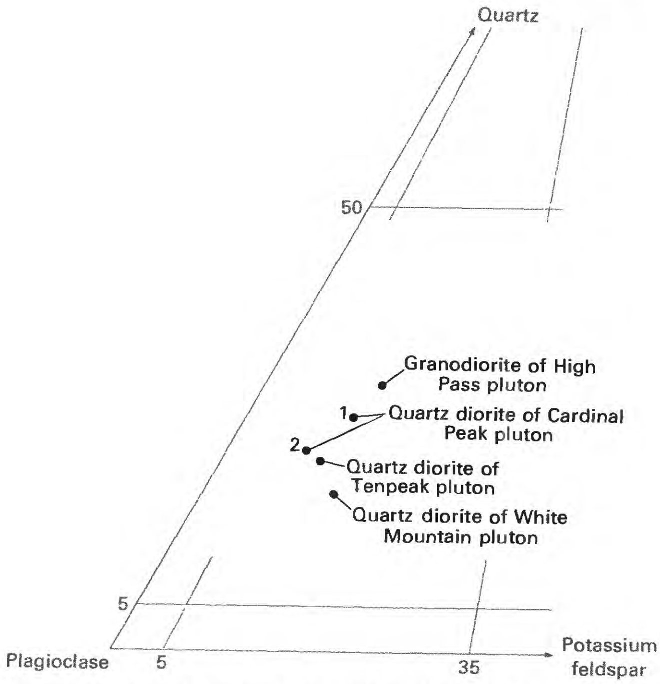

FIGURE 44.—Plot of norms of rock samples from the Tenpeak, White Mountain, Cardinal Peak, and High Pass plutons, Holden quadrangle, on a quartz-potassium feldspar-plagioclase diagram. Sample analyses are given in table 11.

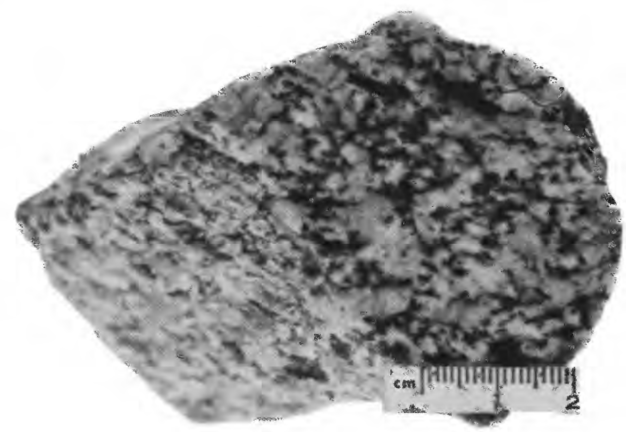

FIGURE 45.—Gneissic granodiorite from the Sulphur Mountain pluton, Holden quadrangle.

Holden quadrangle, but the pluton underlies a considerable area in the northern part of the adjacent Glacier Peak quadrangle. In the Holden quadrangle, the pluton consists of light- to medium-gray, medium-grained hornblende-biotite granodiorite and granodiorite gneiss (fig. 45). Much of it forms augen gneiss containing conspicuous eyes of quartz. Only a few isolated outcrops of the rock are nongneissic. Contacts with host rocks are variable, sharp in some places, gradational across a few meters in others, and in still others consisting of lit-par-lit zones of granodiorite and schist or gneiss. The contact with the younger High Pass pluton is particularly irregular, for numerous dikes and irregular masses of the High Pass extend varying distances into the Sulphur Mountain. Inclusions of schist and gneiss are generally common near contacts with the metamorphic host rocks.

The granodiorite at Sulphur Mountain consists of oligoclase, quartz, microcline, and biotite as major constituents; most of the rock also contains a few percent of hornblende, but it is absent locally. Crowder, Tabor, and Ford (1966) reported that considerable clinopyroxene occurs in the pluton in the Glacier Peak quadrangle. Sphene occurs in quantities greater than 1 percent, and coarse-grained, euhedral clinozoisite similar to that in the Tenpeak pluton is a common accessory; apatite is rare. Secondary minerals are chlorite, sericite, and fine-grained epidote. Both oscillatory and patchy zoning are common in the oligoclase. Textures range from xenomorphic to hypidiomorphic, and all show considerable protoclasis; the augen gneiss, in particular, shows intense protoclasis.

The age of the granodiorite at Sulphur Mountain relative to the Tenpeak-White Mountain rocks on a geologic basis is not known, but Engels (Engels and others, 1976) obtained a potassium argon Late Cretaceous age of about 70 m.y. for hornblende (table 38) from the Sulphur Mountain.

Modal analyses of the pluton are shown in table 13 and figure 46.

HIGH PASS AND BUCK CREEK PLUTONS

The closely related High Pass and Buck Creek plutons, unlike most of the larger intrusive masses in the region, are decidedly tabular, and the Buck Creek, in particular, is sill-like. Both masses are in the west-central part of the Holden quadrangle and together underlie an area of about 20 km^2. The rocks vary considerably in appearance from place to place because of grain size and degree of foliation, but the composition is fairly uniform, except locally near contacts where considerable reaction with host rocks has occurred. The High Pass pluton consists of light-colored, medium-grained biotite granodiorite and quartz diorite (fig. 47); the western part of the mass is mostly massive, but the eastern part has a distinct foliation resulting from protoclasis and is accentuated by a parallelism of biotite flakes (fig. 48). In the thick part of the mass, east of High Pass, the rock becomes progressively coarser grained and better foliated upward or from north to south in the mass. Foliation is most striking near the south contact of the pluton 1.6 km west of Buck Mountain. Here the rock is gneissic, and biotite aggregates form thin undulatory discontinuous folia that separate irregular layers of protoclastically deformed quartz and feldspar 1 to 3 mm thick. Much of the Buck Creek pluton is covered by

TABLE 13.—*Modal analyses of samples of hornblende-biotite granodiorite from the Sulphur Mountain pluton, Holden quadrangle*

Sample No.	Plagioclase	Potassium feldspar	Quartz	Biotite	Hornblende	Accessory and secondary minerals	Total mafic minerals	Anorthite in plagioclase crystals (percent)			Remarks
								Average	Core	Rim	
1	43.0	7.6	38.3	8.6	0.5	2.0	11.1	26	32	24	Porphyroclastic.
2	45.8	9.8	24.4	15.9	.3	4.8	21.0	27	32	18	Cataclastic.
3	52.1	13.8	18.7	11.4	.1	3.9	15.4	25	30	17	Protoclastic.
4	49.2	7.6	21.8	13.4	3.1	4.9	21.4	29	44	23	Porphyroclastic.
5	51.6	10.3	18.9	14.2	0	5.0	19.2	23	27	17	Protoclastic.
6	42.6	9.5	24.7	13.7	.1	9.4	23.2	21	25	16	Do.
7	44.3	10.6	31.4	10.9	0	2.8	13.7	21	24	19	Xenomorphic.

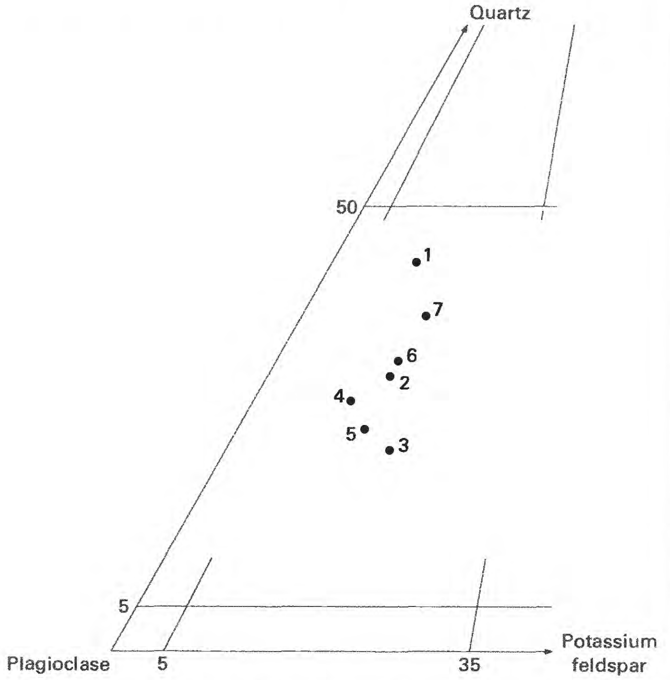

FIGURE 46.—Plot of modes of hornblende-biotite granodiorite samples from the Sulphur Mountain pluton, Holden quadrangle, on a quartz-potassium feldspar-plagioclase diagram. Sample analyses are given in table 13.

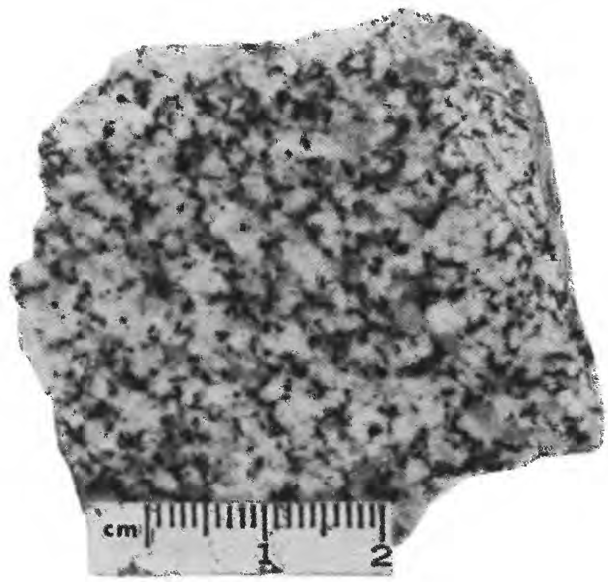

FIGURE 47.—Granodiorite from the High Pass pluton, Holden quadrangle.

glacial debris, and the mass exposed on Helmet Butte possibly is not connected with the mass northeast of King Lake, but the rocks in both localities are identical and are indistinguishable from the foliated granodiorite and quartz diorite of the High Pass pluton.

The relation of the High Pass and the Buck Creek plutons to their host rocks differs considerably. The sill-like Buck Creek pluton is emplaced along a zone of dislocation that, in part, followed the contact between the Swakane Biotite Gneiss and the much younger metamorphic rocks of the Napeequa River area. The High Pass pluton, on the other hand, is much more complex, being partly concordant and partly discordant. The narrow, southeastern part of the intrusive, in the valley of Alpine Creek, occupies the crest of a complex antiform (fig. 49). Northwestward, the pluton is a thick, south-dipping sheet that both cut out and wedged apart the metasediments and squeezed and distorted the large synform on Chiwawa Ridge.

The contacts of the plutons are mostly marked by lit-par-lit zones, but locally contacts are uncomplicated and sharp (fig. 50), as are the contacts between layers in the lit-par-lit zones. Gradational contacts more than a few centimeters thick were not observed; on the other hand, considerable pegmatite occurs in the intrusive layers of the lit-par-lit zones. In most places, the lit-par-lit zones are only a few meters to a few tens of meters thick, but the upper contact, south of High Pass, is exceedingly complex and hundreds of meters thick. Here, thick dikes and sills of granodiorite intrude the gneisses, and large sheets of gneiss are entrapped in the granodiorite. The contact between the High Pass pluton and the older Sulphur Mountain pluton on Triad Creek is also highly complex; numerous dikes and irregular masses of High Pass rocks cut the Sulphur Mountain and extend varying distances into it. Locally inclusions of gneiss and schist are fairly common, especially near contacts.

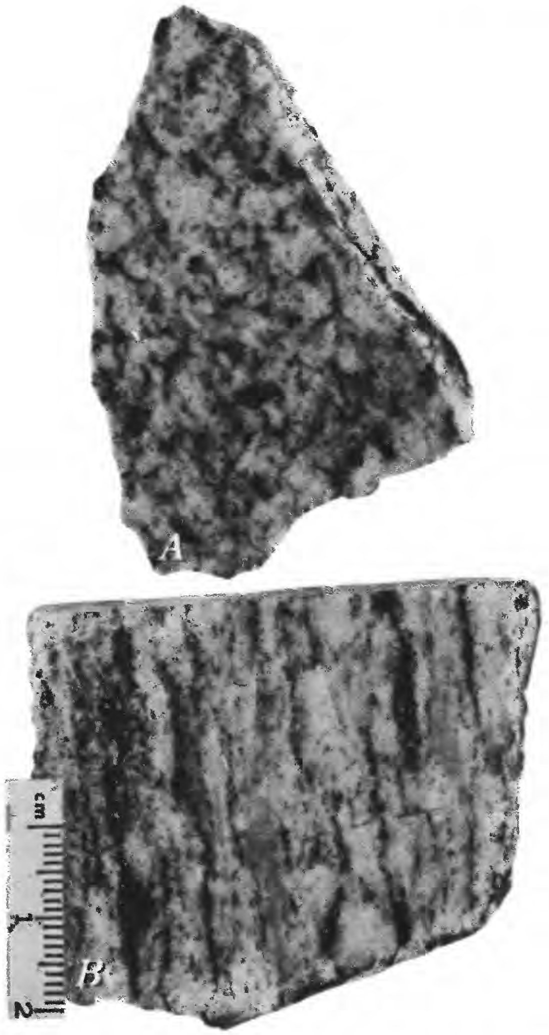

FIGURE 48.—Foliated granodiorite from the High Pass pluton, Holden quadrangle. A, Oriented across foliation; B, oriented parallel to foliation.

FIGURE 49.—Granodiorite of the High Pass pluton, Holden quadrangle, in the core of an antiform in upper Paleozoic metasedimentary rocks. Note many sills and dikes of leucocratic quartz diorite in the metasediments.

The High Pass and Buck Creek plutons consist of oligoclase, quartz, biotite, and potassium feldspar as primary minerals, and opaque minerals, apatite, zircon, and considerable titanite as accessory minerals. Clinozoisite-epidote and sericite are invariably present and chlorite occurs in most thin sections; less common are veinlets of prehnite and calcite. Hornblende and garnet occur locally near the contacts, apparently as unresorbed relicts derived from partly assimilated gneiss. Fractures in the granodiorite 1.6 km southwest of High Pass contain films of pink stilbite. Oligoclase, mostly as grains 1 to 3 mm across and ranging in composition between An_{22} and An_{26}, makes up 50 to 58 percent of the normal rock. Some crystals show oscillatory zoning within narrow compositional ranges, and patchy zoning is common. Myrmekitic intergrowths are also plentiful and are most abundant adjacent to potassium feldspar. The myrmekite crystallized later than potassium feldspar and locally replaces it. Quartz in amounts ranging from 22 to 30 percent occurs as interstitial grains and as interlocking mosaics of grains forming irregular lenticular patches. Curved lines of inclusions, most of which appear to be liquid, are characteristic features of quartz. Biotite makes up 4 to 10 percent of the rock and occurs mostly as irregular shreds, many of which are bent. In some thin sections, biotite is most common along and oriented parallel to minute zones of granulation; it is pleochroic in shades of yellow and cinnamon brown. Microcline and lesser quantities of orthoclase occur in combined amounts of 5 to 13 percent and irregularly replace oligoclase, quartz, and biotite, fill fractures, or replace microscopic zones of granulation. Some microcline is perthitic, the exsolved plagioclase being almost pure albite. Albite of identical composition also forms clear, thin rims locally on scattered oligoclase crystals, and it seems entirely possible that all the albite

FIGURE 50.—Contact of granodiorite of the High Pass pluton, Holden quadrangle, and hornblende schist. Note thin branching sills.

was derived by exsolution from microcline. Of the accessory minerals, only titanite occurs in any quantity or in other than minute grains; much of the titanite forms rhombs as much as 2 mm long.

Clinozoisite-epidote is the most plentiful of secondary minerals and makes up 1 to 5 percent of the rock. Crystals are mostly euhedral, as much as 2 mm long, and replace both oligoclase and biotite. The habit of the mineral is suggestive of a primary rather than a secondary origin; some of it is zoned around cores of allanite. Chlorite sparingly replaces biotite, and sericite replaces oligoclase. Garnet and hornblende are confined to contact zones and are clearly relicts left from partly assimilated gneiss.

Textures of the granodiorite and quartz diorite of the High Pass pluton vary considerably from place to place, depending largely on the degree of protoclasis. The nonfoliated rock is typically hypidiomorphic, whereas the highly foliated rock is severely granulated and protoclastic; all gradations between the two extremes exist. The Buck Creek mass is less variable because of widespread protoclasis.

Modal analyses of the two plutons are given in table 14, and chemical and spectrographic analyses and norms are given in table 15. Locations of modally analyzed specimens are shown in figure 51, and the modes are plotted in figure 52. The norms are plotted in figure 44, and the major oxides are plotted on the variation diagram of figure 13.

RIDDLE PEAKS PLUTON

The Riddle Peaks pluton was not investigated in the detail that would have been desirable for such an interesting mass of layered gabbro, and undoubtedly many features bearing on its emplacement and crystallization were either overlooked or not seen. Within the mapped area, the pluton is about 3.2 km wide and 6.5 km long, and it extends an unknown distance to the north. The original size of the pluton probably was considerably larger, for it is cut on all sides within the mapped area by later intrusions. Large blocks of the hornblende gabbro derived from the pluton occur as inclusions in the Cardinal Peak pluton south of Railroad Creek. Rocks of mineralogic composition and appearance identical to

TABLE 14.—*Modal analyses of samples of biotite-quartz diorite and granodiorite from the High Pass pluton, central Washington*

Sample No.	Plagioclase	Potassium feldspar	Quartz	Biotite	Hornblende	Accessory and secondary minerals	Total mafic minerals	Anorthite in plagioclase crystals (percent)			Remarks
								Average	Core	Rim	
1	54.5	2.7	29.9	10.6	0	2.3	12.9	24	27	7	Xenomorphic.
2	31.6	26.3	34.1	6.3	0	1.7	8.0	22	27	16	Protoclastic.
3	57.5	9.5	24.5	5.8	0	2.7	8.5	20	24	11	Do.
4	38.5	21.4	31.6	8.3	0	.1	8.5	20	27	20	Hypidiomorphic.
5	55.8	4.9	28.4	6.7	0	4.2	10.9	22	31	13	Protoclastic.
6	57.0	7.7	26.4	6.4	0	2.5	8.9	25	28	19	Do.
7	36.5	25.2	29.4	8.3	0	.6	8.9	27	33	14	Hypidiomorphic.
8	50.6	9.7	26.5	11.2	0	2.0	13.2	23	25	3	Do.
9	53.0	9.2	27.5	7.5	0	2.8	10.3	24	27	21	Protoclastic.
10	52.8	3.3	29.8	9.9	0	4.2	14.1	24	27	11	Do.
11	51.1	7.6	29.1	5.9	0	6.3	12.2	26	34	20	Do.
12	50.5	2.0	33.3	11.5	0	2.7	14.2	26	34	18	Do.
13	51.7	8.2	27.0	6.5	0	6.6	13.1	27	29	21	Do.
14	52.3	12.4	26.9	1.3	0	7.1	8.4	23	25	12	Do.
15	52.7	11.6	22.9	7.1	3.4	2.3	12.8	26	29	20	Hypidiomorphic.
16	50.1	9.6	24.3	8.9	5.1	2.0	16.0	29	31	21	Protoclastic.
17	42.5	10.8	31.4	10.7	.2	4.4	15.3	27	38	23	Xenomorphic.

TABLE 15.—*Chemical and spectrographic analyses and norms of a composite sample of biotite-quartz diorite from the High Pass pluton, central Washington*

[Standard rock analysis of composite sample by D. F. Powers; spectrographic analyses by P. R. Barnett]

Chemical analysis (percent)		Semiquantitative spectrographic analysis (parts per million)		Norms	
SiO_2	70.43	Ba	1,500	q	28.22
Al_2O_3	16.07	Be	1.5	or	10.55
Fe_2O_3	.36	Co	3	ab	39.83
FeO	1.51	Cr	1.5	an	15.55
MgO	.65	Cu	3	hy	3.63
CaO	3.24	Ga	15	c	.83
Na_2O	4.67	Ni	1.5	mt	.53
K_2O	1.77	Sr	1,500	il	.63
H_2O+	.42	V	15	ap	.21
H_2O-	.05	Zr	150	cc	.02
TiO_2	.33			Total	100.00
P_2O_5	.09			Plagioclase composition	
MnO	.03				
CO_2	.01				
Total	99.63			an	28.1

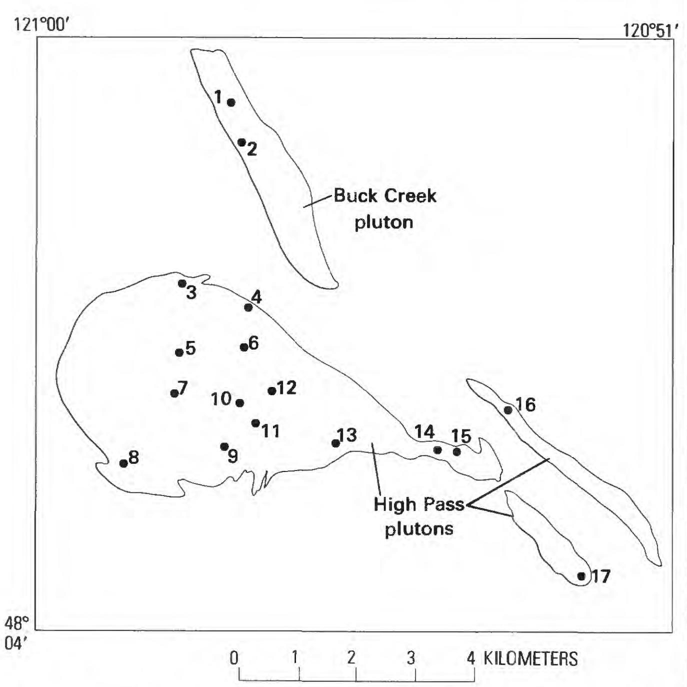

FIGURE 51.—Map showing locations of modally analyzed samples of biotite-quartz diorite and granodiorite from the High Pass and Buck Creek plutons, Holden quadrangle. Sample analyses are given in table 14.

unlayered parts of the pluton crop out in contact complexes surrounding the Seven-fingered Jack and Entiat quartz diorite plutons and, conceivably, there may be some tie between these plutons and the Riddle Peaks pluton.

Rocks forming the pluton range from nearly black, medium- to coarse-grained hornblendites to white, hornblende-bearing, medium-coarse-grained anorthosites. Much of the rock is conspicuously layered (fig. 53), but the lower part of the mass between Ninemile and

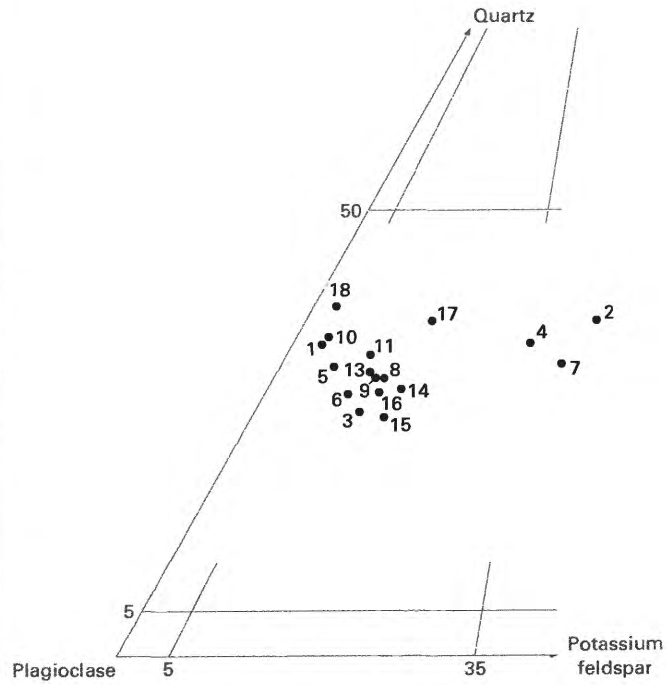

FIGURE 52.—Plot of modes of biotite-quartz diorite and granodiorite samples from the High Pass pluton, Holden quadrangle, on a quartz-potassium feldspar-plagioclase diagram. Sample analyses are given in table 14.

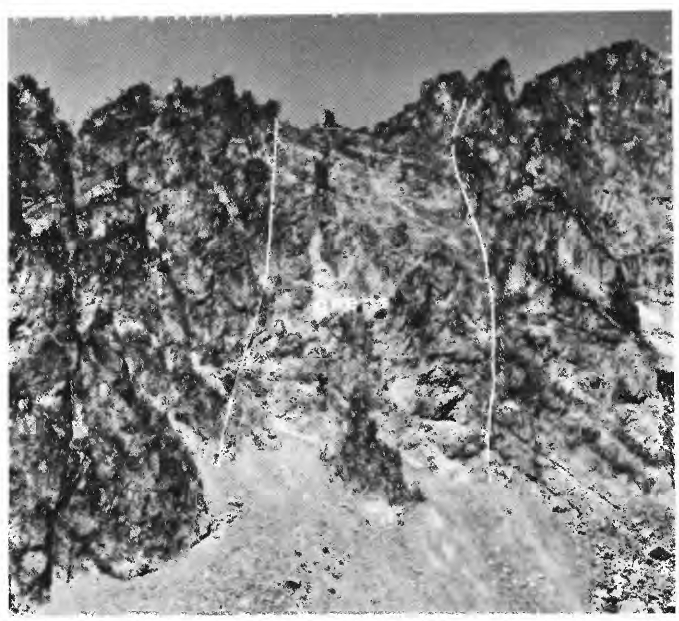

FIGURE 53.—Layered hornblende gabbro of the Riddle Peaks pluton and septum of gneiss in Riddle Peaks, Lucerne quadrangle. Septum of gneiss is about 80 m thick.

Tenmile Creeks is only vaguely layered or consists of nearly structureless, massive, mesocratic hornblende gabbro (fig. 54). Weathered surfaces of the gabbro have a rasp-like texture because the calcic plagioclase has dissolved more rapidly than hornblende, and the hornblende crystals stand out in relief as sharp angular projections.

The contact between the relatively massive, only vaguely layered hornblende gabbro and the overlying, conspicuously layered hornblende gabbro is gradational in most places where it was seen; the layering becomes increasingly evident through the distance of a number of meters, but in one or two traverses across the contact the transition is abrupt, and the lowermost layers of the layer unit are as conspicuous as those above. Within the layered rock, zones of nearly massive, only vaguely layered gabbro many tens of meters thick alternate with zones of rhythmically layered rocks of similar thickness; thus, there is both a large-scale and a small-scale layering, for the individual rhythmic layers rarely attain a thickness of 30 cm. The large-scale layering can be seen particularly well in the high parts of Riddle Peaks (fig. 53).

Individual layers are remarkably straight, uniform in thickness, and continuous; many only a few centimeters thick may be traced for several hundred meters, although local contortions do occur (fig. 55). Other than gravity-stratified layers that resemble graded beds in sedimentary rocks and may be similarly used to determine tops of layers, no other pseudosedimentary structures were seen, such as crossbedding, trough layering, or unconformities as have been described in other layered intrusions (Wagner and Deer, 1939; Bateman, 1965; Shawe and Parker, 1967; Irvine, 1967).

Layers consist of alternating hornblende-rich and hornblende-poor rocks (fig. 56). Hornblende-rich layers range from those only slightly enriched in hornblende to those of almost pure hornblendite. Such hornblendite

FIGURE 55.—Contorted layers in gabbro of the Riddle Peaks pluton, Holden and Lucerne quadrangles. Note nearly pure hornblendite layer bordered on each side by a thin layer of anorthosite. Scale is 18 cm long.

FIGURE 56.—Layered gabbro from the Riddle Peaks pluton, Holden and Lucerne quadrangles.

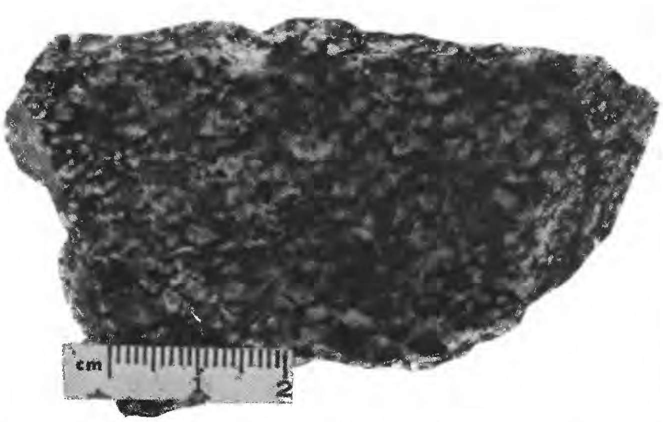

FIGURE 54.—Hornblende gabbro from the Riddle Peaks pluton, Holden and Lucerne quadrangles.

layers are rarely more than 10 cm thick, but a few are as thick as 25 cm. The hornblende-poor or felsic layers, on the other hand, nowhere attain the same degree of segregation that occurs in the hornblende-rich layers and rarely contain less than 10 percent hornblende. Contacts between layers may be either gradational or sharp, but where sharp the crystals interlock across boundaries. In general, lower contacts of hornblende-rich layers are sharp, whereas their upper contacts are gradational. In some localities, the grain size in layers also decreases upward.

A few layers were seen that are distinguished by grain size variations rather than composition; that is, relatively fine grained layers alternate with typical medium-grained ones. The fine-grained layers were not marked by any readily discernible variations in mineral proportions, and contacts with layers of normal grain size are generally gradational through the space of a fraction of a centimeter or more. Fine-grained layers are rarely more than 15 cm thick. In contrast to these fine-grained layers, some pegmatitic gabbro containing hornblende crystals as much as 2 cm wide and 8 cm long was seen in talus blocks, but none was seen in place, and the relation of this pegmatitic material to more normal types of gabbro is unknown.

Planar lamination (Jackson, 1961, and 1967, p. 22) resulting from arrangement of platy crystals with their long dimensions in the plane of layering is almost universal in the hornblende gabbro and imparts a somewhat gneissic appearance to the rock, whether layered or not. Because of the bladed nature of hornblende, the lamination is more prominent in the more hornblende rich varieties than in the anorthositic varieties. In the plane of lamination, however, the orientation of the crystals is random, and no tendency to lineation was observed.

Inclusions, some of them hundreds of meters across, are scattered throughout both the layered and unlayered gabbro (fig. 53). In the upper part of the pluton from the Edil mine northward, screens or great sheets of host-rock gneisses are interlayered with the gabbro. In all probability, the huge inclusions are but disrupted remnants of screens formed earlier in the intrusive process. The larger inclusions and screens or septa of metamorphic rocks weather red because of their relatively high content of iron sulfide and, hence, are readily visible from a distance. Intermixed with the interlayered gabbro and screens of gneiss is a bewildering mixture of probable hybrid rocks derived from the interaction and partial fusion by gabbro of various types of metamorphic host rocks that range in composition from marble and quartzite to hornblende schists. Rocks that are not obviously partly assimilated metamorphic species are mostly quartz diorite of various compositions, but some are hornblende-quartz gabbros that differ from the normal hornblende gabbros only in containing sodic labradorite instead of medium bytownite plus considerable quartz. Conceivably, some of the rocks, especially perhaps some of the irregular masses of very coarse grained, somewhat pegmatitic hornblende-quartz gabbro, may be differentiates of the normal gabbro. This complex zone of screens, gabbro, and mixed rocks is further complicated by upper Eocene dikes and irregular small intrusions that range in composition from quartz diorite to quartz monzonite. In fact, from the Edil mine both uphill and to the east, nearly every outcrop is of a different rock type.

Where intruded by the gabbro, many of the large inclusions split out along planes of foliation and, consequently, are either slabby or lenslike. Many of these slabby inclusions have attitudes that are parallel to the layering of the gabbro, but others, including most of the more blocky inclusions, lie at angles to the layering, and hence there is no parallelism between the foliation of the inclusions and the planar structures in the gabbro. Of the inclusions that were examined, none seemed to disturb the nearest laminae or layers of the gabbro, but nowhere was either lamination or layering seen to directly contact inclusions. Reasons for this relationship are not clear, but the lack of contact may be related to the contact phenomena associated with the inclusions. Contacts that are parallel to foliation of the inclusions are fairly sharp, although a coarsening of the grain size of the gabbro adjacent to the inclusions is pronounced, and layering and lamination fade. Where gabbro truncates foliation of the inclusions, on the other hand, the inclusion frays out into the gabbro; the contact is gradational through a considerable distance, the grain size of the gabbro is considerably coarser, and lamination and layering are nonexistent. In other words, where the gabbro magma had the opportunity to insinuate along rather than cut across foliation of all metamorphic rocks except marble, progressive assimilation of the inclusion by the magma was greatly enhanced and contacts are broadly gradational. Marble seems to be completely unaffected by the gabbro, and contacts with it are sharp.

In thin section the normal gabbro, whether layered or unlayered and where seemingly uncontaminated with digested host rocks, consists of varying proportions of bytownite and hornblende and lesser but still considerable quantities of magnetite. Titanite, apatite, interstitial pyrite, and rarely a little biotite are accessory. Although most of the rock is fresh, chlorite—mostly ripidolite—replaces some of the hornblende and some of the bytownite is either slightly sauseritized or sprinkled with small amounts of sericite. In some thin sections, scattered seams of epidote, prehnite, and rarely orthoclase cut the rock. Plagioclase varies in composition somewhat from place to place, ranging from about An_{75} to An_{52}, but most of it is in the bytownite range. The composition seems to be unrelated to vertical position within the mass. The plagioclase in some rocks that in hand specimen seem identical to normal gabbro may be as sodic as An_{52}, but rocks containing such plagioclase are associated with partly assimilated inclusions and are probably contaminated. Scattered crystals in nearly every thin section show a few rather faint oscillatory zones, and patchy zoning is fairly common. Thin rims of progressively zoned labradorite surround some crystals. Bytownite crystals range from anhedral to subhedral. Irregular, poikilitic crystals similar to those described from ultramafic layers in the Archean Stillwater Complex (Hess, 1960, p. 21 and 113; Jackson, 1961, p. 66 and 69) are scattered through hornblendite layers. They are believed to have grown largely from interstitial liquid and commonly contain small inclusions of euhedral hornblende. Bytownite replaces hornblende and is lobed against it; poikilitic crystals of bytownite in hornblendite, in particular, have grown around hornblende grains so that these grains project into bytownite (fig. 57).

Hornblende forms irregular laths that on surfaces parallel to planar lamination form a network that surrounds and encloses bytownite grains. This network fabric is rarely evident on surfaces normal to lamination, however. Hornblende is pleochroic from light greenish yellow brown to dark green and contains innumerable Schiller-like inclusions that may be spinel. The inclusions are mostly confined to the interior parts of crystals and the borders are clear, suggesting that the latest formed hornblende has a slightly different composition.

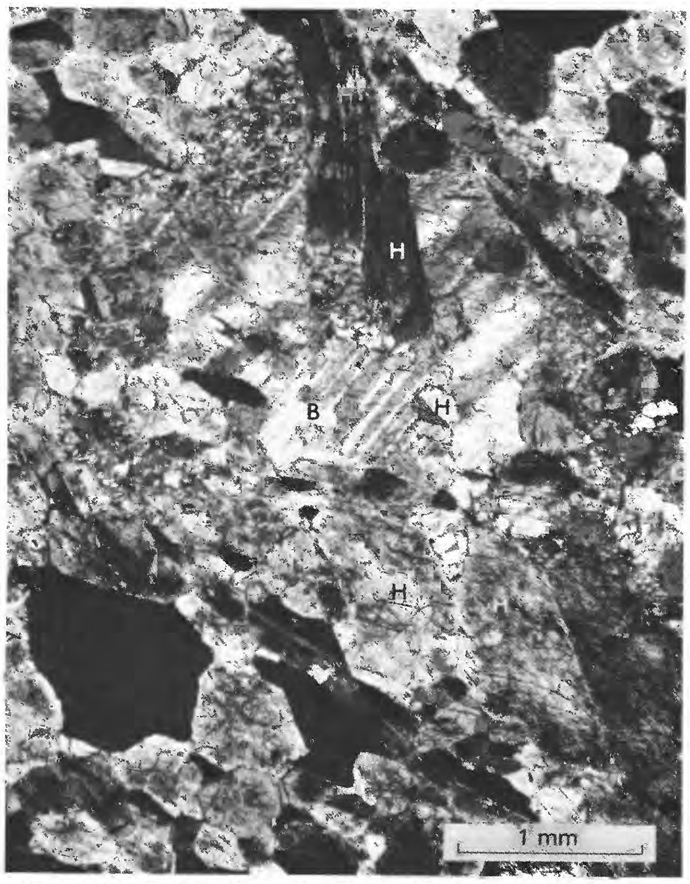

FIGURE 57.—Gabbro from the Riddle Peaks pluton, Holden and Lucerne quadrangles, showing poikilitic crystals of bytownite (B) that have grown around hornblende (H).

Hornblende was the first mineral to crystallize and shows no indication of being uralitic after pyroxene. Magnetite may form as much as 5 percent of some thin sections and is equally abundant in both hornblendic and anorthositic rocks; in fact, it is so abundant that the rock is highly magnetic. The magnetic forms small, anhedral, interstitial grains and was the last of the major constituents to crystallize. Pyrite is relatively abundant but there is little or no replacement of silicates by sulfides. Chlorite, having the optical properties of ripidolite, deserves special mention among the secondary minerals because of its occurrence as peculiar aggregates resembling a mass of rather stubby worms (fig. 58). This crystal habit has been called helminth structure (Troger, 1967, p. 598). The helminth-structure aggregates occupy thin seams within the rock or replace hornblende. In cross section, individual worms form rather rounded hexagons.

Textures range from hypidiomorphic to xenomorphic. Hornblende and bytownite are seriate, and in all but pegmatitic varieties of gabbro these minerals rarely form grains more than 6 mm long. Poikilitic textures occur only in hornblendite layers where scattered anhedral grains of bytownite have engulfed numerous small crystals of hornblende, many of them euhedral. Similar poikilitic crystals of plagioclase and other minerals are characteristic of layered mafic intrusions (Hess, 1960; Brown, 1956; Jackson, 1961).

Because it seems fairly certain the pseudosedimentary features in the gabbro formed from a cumulate or magmatic sediment, the textures, whether hypidiomorphic or xenomorphic, are a measure of postsettling addi-

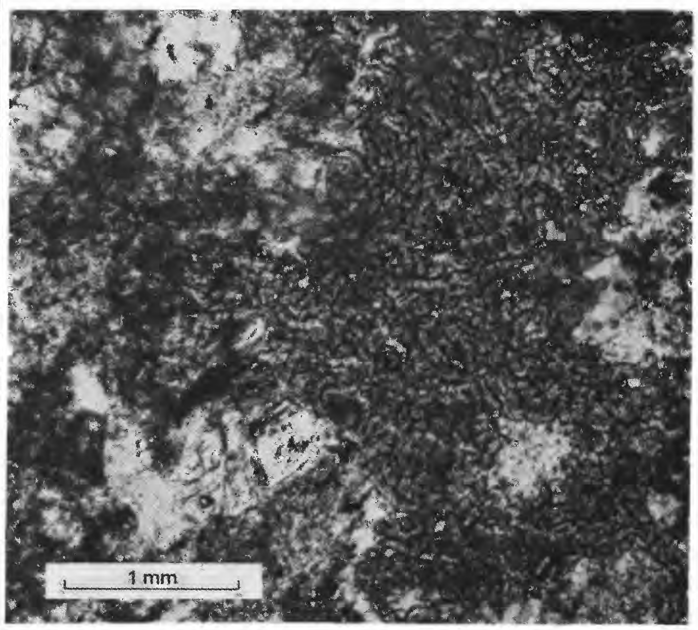

FIGURE 58.—Chlorite having helminth structure in gabbro of the Riddle Peaks pluton, Holden and Lucerne quadrangles.

tion to or growth of originally euhedral grains. Thus, where textures are hypidiomorphic, secondary enlargement (Hess, 1939, p. 431; 1960; Brown, 1956, p. 37; Jackson, 1961, p. 47–52) was insufficient to fill completely the intercumulus space, and, consequently, mutual interference between settled crystals due to overgrowths was incomplete; much of the intercumulus liquid remained to crystallize as interstitial grains. On the other hand, where postsettling enlargement was such that the settled crystals grew to occupy virtually all the intercumulus space and mutual interference between grains was almost complete, the textures are xenomorphic. Hess (1939, p. 431; 1960) has attributed this process of postcumulus overgrowth and expulsion of the original intercumulus liquid to diffusion when crystal accumulation is slow, thereby providing an opportunity for settled crystals to interact with the bulk of the remaining magma rather than merely with the adjacent intercumulus liquid. The process seems to have been markedly effective in the Riddle Peaks gabbros because overgrowths have been sufficient to permit extensive interlocking of grains with the attendant tendency to xenomorphism; the plagioclase, furthermore, generally does not have the type of zoned rims that would be expected were the crystals subject to addition only from the intercumulus liquid. The complete lack of nonhydrous mafic minerals normally present in gabbros suggests an abnormal abundance of water in the magma, which may have augmented the process of diffusion and transfer of material.

The Riddle Peaks gabbro pluton differs from other layered gabbro masses of which I am aware in only one major respect, the utter lack of minerals of either the pyroxene or olivine groups—a lack, incidentally, that is almost universally true of the other intrusive rocks in the area except for a few small, scattered masses of peridotite and serpentine. The role played by these anhydrous minerals has been entirely usurped by hornblende; biotite is a very minor mineral restricted to either pegmatitic or contaminated rocks. It could be argued, perhaps, that hornblende has replaced earlier mafic minerals, but not a shred of evidence could be found that pointed in this direction. The Schiller inclusions are not inherited—at least intact—from an earlier pyroxene because they follow crystal directions in the hornblende; no pseudomorphs after earlier crystals exist, and the hornblende inclusions in poikilitic bytownite are euhedral. Inasmuch as the gabbro consists essentially only of hornblende and bytownite in varying proportions, the small-scale layering is entirely rhythmic, and no phase contrast exists as in most layered masses.

As has been pointed out by numerous students of layered intrusions, most fully by Hess (1960, p. 133–137), magmatic currents of variable velocities, probably convection currents, seem to be the only satisfactory means of accounting for rhythmic layering. Both hornblende and bytownite were precipitated together throughout the crystallization of the Riddle Peaks mass because no layers are completely devoid of either mineral; therefore, ideas based on intermittent crystallization due to variations of pressure, gas escape, or extrusion of lava seem not to be applicable. As a matter of fact, both hornblende and bytownite precipitated at virtually equal rates throughout solidifying of the now visible parts of the mass, for the average composition of the rhythmic hornblendite and anorthosite pairs differs little, if at all, from the unlayered gabbro. Obviously, periods of current variability alternated with periods of current stability to produce the alternate zones of layered and unlayered rock, but I could find no evidence pointing to any specific cause for these oscillations.

The relatively even distribution of huge included blocks of metamorphic rocks throughout an exposed "stratigraphic" thickness of perhaps 2,500 m of layered and unlayered gabbro suggests that the specific gravity of the inclusions and the magma must have been similar. The fact that inclusions of all sizes are mostly surrounded by aureoles of contaminated and hybrid rocks also suggests long-continued contact with given volumes of magma, for rates of either rising or sinking were insufficient to sweep or scour away these aureoles. Of the inclusions examined, no trace of disturbance of underlying layers in the gabbro was detected; further evidence that the inclusions were little, if at all, denser than the magma. The aureoles were probably more viscous than the surrounding magma, which may have been the chief factor in inhibiting both layering and planar lamination adjacent to inclusions. Intuitively, one would think that an inclusion hundreds of feet across, even though of the same density as the magma, should have left some trace of its progress as it was dragged across the floor of settled crystals by magmatic convection currents; no traces were seen, but further search could perhaps reveal some.

The remarkably even and generally undisturbed layering and the planar lamination strongly suggest that crystal settling at now-visible levels occurred on only gently sloping surfaces. The exact position of the surviving gabbro relative to the entire pluton prior to its partial destruction by later intrusives is unknown, but the interlayered screens of gneiss along the northeast side of the remaining mass suggest that this is either part of or near the roof. The flattening of dips from southwest to northeast may indicate basining in that direction, but it may also merely be the result of postdepositional warping. In any event, the pluton as a whole has been faulted and rather steeply tilted northeastward since emplacement. Most of the faults strike northeast, but a large and complex northwest-trending breccia zone borders part of the pluton east of Fourth of July Basin. The breccia zone is largely confined to a screen of gneiss that separates the gabbro from quartz monzonite of the Railroad Creek pluton; the breccia contains many fragments of quartz monzonite but few, if any, of gabbro.

The age of the Riddle Peaks gabbro pluton has not been determined. The oldest of the known intrusive rocks to cut it are the quartz diorites and granodiorites of the Cardinal Peak pluton, probably of Late Cretaceous age. The Cardinal Peak probably is not much younger, however, than the gabbro. There is little evidence to indicate that the Cardinal Peak was emplaced at any great depth and some to suggest only moderate or mesozonal depths, as, for example, the plagioclase that shows both patchy and some oscillatory zoning—both are rarer among the older and deeper seated intrusive masses of the area.

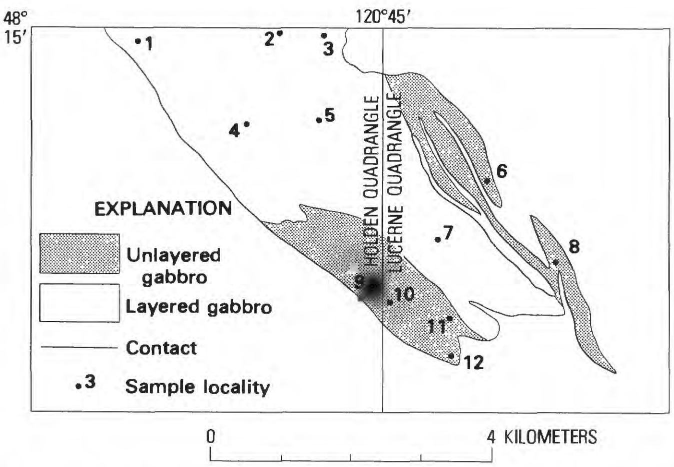

FIGURE 59.—Map showing location of modally analyzed samples of gabbro from the Riddle Peaks pluton, Holden and Lucerne quadrangles. Sample analyses are given in table 16.

The location of modally analyzed specimens of gabbro from the Riddle Peaks pluton are shown in figure 59. Model analyses are given in table 16, and chemical and spectrographic analyses are given in table 17.

CARDINAL PEAK PLUTON

The Cardinal Peak pluton, probably of Late Cretaceous age, is a mass of highly variable rocks both in appearance and composition. It extends a known distance of 30 km from the northeast corner of the Holden quadrangle southeastward across the Lucerne quadrangle; its total length is not known. The maximum width within the mapped area is about 4 km. One small mass of similar rocks cuts the gabbro and gneiss of Riddle Peaks in Fourth of July Basin in the extreme northeast corner of the Holden quadrangle. As is true of the other narrow, elongate plutons in the area, the Cardinal Peak pluton trends nearly parallel to the strike of the enclosing metamorphic rocks but crosscuts them locally, particularly downdip.

The rocks of the Cardinal Peak pluton make up a sequence ranging from rather coarse-grained, light-colored biotite granodiorite to extremely heterogeneous contact complexes containing hornblende gabbro and hornblendite. Three principal units were delineated on the quadrangle maps. The largest unit, which makes up the bulk of the pluton, consists of rocks ranging from hornblende-biotite-quartz diorite to leucocratic biotite granodiorite; the second unit is confined to the northwesterly part of the pluton and consists of calcic hornblende diorite and quartz diorite; the third unit is the contact complex, which intermittently rims the pluton northwest of Snow Brushy Creek.

TABLE 16.—*Modal analyses of samples of hornblende gabbro from the Riddle Peaks pluton, central Washington*

Sample No.	Plagioclase	Magnetite	Quartz	Biotite	Hornblende	Accessory and secondary minerals	Total mafic minerals	Anorthite in plagioclase crystals (percent) Average	Core	Rim	Remarks
1	46.7	0	0	0	52.4	0.9	53.3	75	0	0	Xenomorphic.
2	45.0	2.6	0	0	48.4	4.0	55.0	67	0	0	Do.
3	48.8	0	0	0.1	50.4	.7	57.2	74	84	68	Do.
4	45.6	2.1	0	0	52.3	0	54.4	78	83	75	Hypidiomorphic.
5	42.2	0	0	0	54.7	3.1	57.8	73	77	71	Xenomorphic.
6	57.7	5.0	0	0	37.3	0	42.3	64	70	60	Do.
7	57.0	.2	0	0	42.2	.6	43.0	78	80	65	Hypidiomorphic; planar orientation of crystals.
8	44.4	6.0	0	0	48.6	1.0	55.6	60	70	55	Hypidiomorphic; subparallel hornblende and plagioclase crystals.
9	53.0	0	0	0	42.4	4.6	47.0	71	0	0	Xenomorphic; parallel orientation of crystals.
10	60.7	5.2	0	0	33.9	.2	39.3	64	0	0	Hypidiomorphic.
11	75.7	2.6	.7	.2	20.4	.4	23.6	58	71	51	Xenomorphic.
12	71.1	4.4	0	0	24.4	.1	28.9	53	69	47	Hypidiomorphic.

TABLE 17.—*Chemical and spectrographic analyses of a composite sample of hornblende gabbro from the Riddle Peaks pluton, central Washington*

[Standard chemical analysis by Edythe Engleman. Spectrographic analysis by B. W. Lanthorn. Leaders (- - -), below sensitivity limit]

Chemical analysis (percent)		Spectrographic analysis (percent)	
SiO_2	45.08	Co	20
Al_2O_3	22.60	Cr	7
Fe_2O_3	3.68	Cu	30
FeO	5.24	Ni	15
MgO	5.43	Sc	30
CaO	11.67	Sr	1,000
Na_2O	2.85	V	300
K_2O	.23	Y	20
H_2O+	1.59	Zr	20
H_2O-	.09	Ga	30
TiO_2	1.31	Yb	3
P_2O_5	.16		
MnO	.10		
CO_2	.01		
Cl	.02		
F	.05		
Zn	---		
Total	100.09		

FIGURE 60.—Foliated hornblende-biotite-quartz diorite from the Cardinal Peak pluton, Lucerne quadrangle.

HORNBLENDE-BIOTITE-QUARTZ DIORITE AND BIOTITE GRANODIORITE

Rocks ranging from hornblende-biotite-quartz diorite to leucocratic biotite granodiorite form most of the pluton and change in both composition and appearance from northwest to southeast. At the northwest end of the pluton in the valley of Tenmile Creek, the rocks are rather dark-gray, medium-grained, massive or foliated hornblende-biotite-quartz diorite (fig. 60). South of Railroad Creek, however, the rock becomes lighter in color, coarser grained, and tends toward a flaser appearance because of moderate protoclasis. Some of these rocks contain sufficient potassium feldspar to classify them as granodiorite. Southeastward from the vicinity of the lakes at the head of Dole Creek, protoclasis intensifies, and the rocks become typical flaser gneisses. In the vicinity of Milham Pass, protoclasis is so extreme that the rocks superficially resemble dark porphyries; rounded, white porphyroclasts (fig. 61) of plagioclase as much as 7 mm across are embedded in a black, nearly aphanitic groundmass of almost phyllitic texture. South of Saska Peak, the rock becomes less protoclastic and gradually changes into a light-colored, coarse-grained biotite granodiorite flaser gneiss near Cardinal Peak, and from Pyramid Mountain southeastward it changes into a coarse-grained, leucocratic, nearly massive rock showing only incipient protoclasis (fig. 62). In general, the foliation resulting from protoclasis parallels the structure of the metamorphic host rocks, but at numerous localities along the contact the foliation is at a small angle to the contact, although parallel to the regional foliation of the host rocks or, more commonly, at an angle to the regional foliation or to both the contact and the regional foliation. In many places, protoclastic foliation is swirled and irregular.

Inclusions are not abundant in this main unit, but fragments and schlieren derived from various metamorphic rocks and numerous chunks of hornblende gabbro from the Riddle Peaks pluton occur locally, particularly near contacts northwest of Saska Peak. Some blocks of hornblende gabbro as much as 12 m across were seen between the lakes at the head of Dole Creek and Railroad Creek. Most inclusions of all kinds show only minor effects from immersion in the Cardinal Peak magma.

In the area between the lakes at the head of Dole Creek and Cardinal Peak where protoclasis is most extreme are peculiar spindle- and canoe-shaped masses ranging from 30 cm to a few meters across and from a few meters to a few tens of meters long that are either partly or completely enveloped by sheets or rinds of greenish-gray, fine-grained, sheared material, similar to the protoclastic groundmass of the pseudoporphyries of the area. The canoe-shaped masses occur in crests of folds in the protoclastic foliation, whereas the spindle-shaped masses appear to be completely enveloped in rinds of

FIGURE 61.—Quartz diorite from the Cardinal Peak pluton, Lucerne quadrangle, showing a pseudoporphyritic appearance resulting from extreme protoclasis.

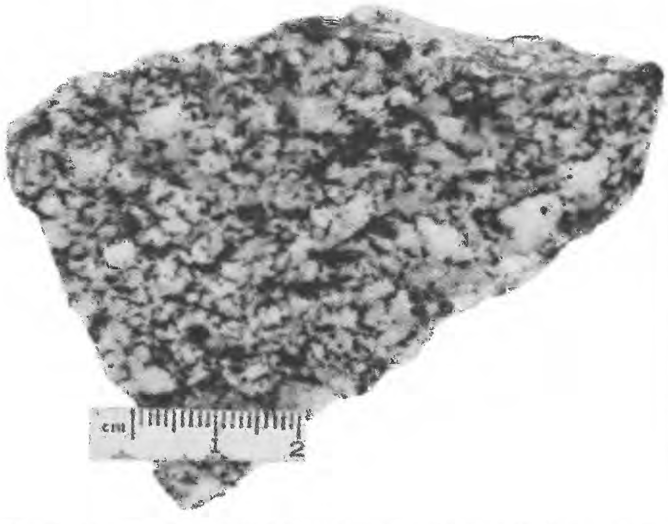

FIGURE 62.—Biotite granodiorite from the Cardinal Peak pluton, Lucerne quadrangle, showing only slight flaser texture.

sheared material. The interior parts of the masses are identical to the rest of the quartz diorites and granodiorites. These masses seemingly formed in response to differential shearing stresses as the crystal mush of the pluton was intruded; the spindle-shaped masses appear to have behaved much as roller bearings. It should be stressed at this point, however, that under the microscope, the last minerals to form in the sheared rinds, such as oligoclase overgrowths on shattered crystals of andesine, fine-grained hornblende, and biotite are mostly undeformed and show no indication of having crystallized under differential stress. Some of these masses are flat lying, but most dip south at angles of as much as 15° parallel to the plunge of elongate mineral clusters and elongate grains.

The contacts of quartz diorite and granodiorite with both metamorphic host rocks and with other units of the pluton are as diverse as the other aspects of the pluton. As has been previously mentioned, the northwestern part of the pluton is partly rimmed by contact complexes, described below, but the contact between these complexes and the main unit shows considerable variation. In many places, the rocks of the main unit seem to grade into or are intermixed with the extremely heterogeneous rocks of the contact complexes; in other places, main-unit rocks cut the complexes, and in still others, some rocks of the complexes intrude main-unit rocks. Where contacts between quartz diorite and granodiorite of the main unit and the calcic hornblende diorite and quartz diorite were observed, the calcic rocks are later, but field relations such as lack of angular inclusions of quartz diorite and granodiorite and the generally vague contacts between the two rock types suggest they are not much later. Where main-unit rocks are in direct contact with metamorphic host rocks, the contacts may be sharp, gradational, or form lit-par-lit zones of gneiss and quartz diorite or granodiorite. Such lit-par-lit zones should not be confused with the contact complexes, however, which are entirely different. Gradational contacts are less common than either those that are sharp or consist of lit-par-lit zones. Gradational zones between visually unaltered metamorphic rocks and igneous rock typical of the pluton are not more than several meters thick and generally are much thinner. In places, particularly along sharp contacts, the adjoining gneisses are much crumpled.

CALCIC HORNBLENDE DIORITE AND QUARTZ DIORITE

Calcic hornblende diorite and quartz diorite are of fairly common occurrence northwest of Snow Brushy Creek but are rare south of there, and no masses of sufficient size to map were seen. Most of these rocks are confined to the periphery of the pluton and commonly form one of the major constituents of contact complexes, but one sizable, dikelike mass crops out along the crest of the ridge between the Entiat River and Klone Creek. Other smaller, unmapped masses also occur at interior positions within the pluton. The rock is gray and ranges from rather fine grained, where few grains are more than 1 mm across, to medium grained, where hornblende forms blades 5 mm long. Most of the rock is massive and structureless, but some has a gneissic appearance because of protoclasis. Because of their mineralogical and compositional differences and, so far as known, a lack of varieties intermediate with main-unit rocks of the pluton, the possibility exists that these rocks bear little direct relation to the pluton other than a spatial one. Most likely, however, these factors are of less significance than the close spatial association of the rocks with the pluton, the close and intricate relationship to the contact complexes, and what locally appears to be marble-cake intermixing of main-unit rocks and the calcic hornblende diorite and quartz diorite.

CONTACT COMPLEXES

Rocks of the contact complexes closely resemble those associated with the White Mountain and Seven-fingered Jack plutons and are equally heterogeneous and wildly scrambled (figs. 63, 64). Because of the extreme heterogeneity, proportions of various rock types are difficult to estimate, but most abundant are hornblende diorites and gabbros of varied textures that range from fine grained to coarsely pegmatitic and have hornblende blades 5 to 8 cm long (fig. 63). Each of the textural variations grades into one or more of the others, although locally, contacts between types are sharp. Less abundant are rocks more typical of the interior of the pluton that are intricately interinjected into the more calcic rocks. Inclusions of several kinds of gneiss and schist oriented in all directions and in various states of assimilation, make up a considerable proportion of the complexes (fig. 64), but probably most characteristic are irregular masses of hornblendite a number of centimeters to several meters across. The hornblendites range from medium grained to very coarse grained, and crystal shapes range from stubby to bladed. Many grade outward from pure aggregates of hornblende into gabbros as proportions of labradorite increase, but other masses of pure hornblendite are sharply bounded. These mixtures of rock are cut by anastomosing dikes of the calcic hornblende diorite and quartz diorite described in the preceding paragraph. Contacts between these dikes and the remainder of the complexes may be either gradational or sharp.

Contact complexes in some places intrude metamorphic host rocks with no zone of gradation between them, but more commonly the heterogeneous mass of material in the complexes grades into the host rocks through an increase in the amount of included material, which in turn grades into a zone of host rocks cut by anastomosing dikes of igneous material.

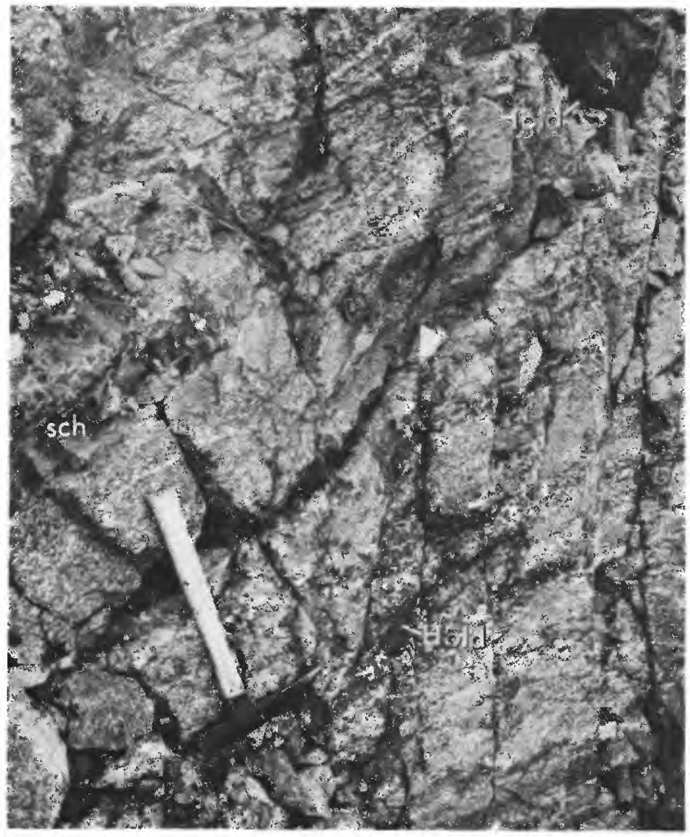

FIGURE 63.—Contact complex of Cardinal Peak pluton, Lucerne quadrangle, consisting largely of gabbro. Note large hornblende crystals (hbld).

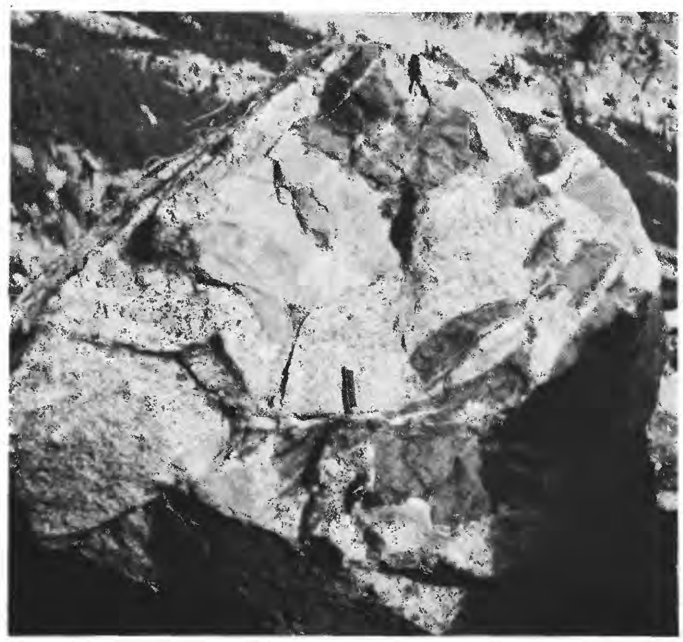

FIGURE 64.—Contact complex of Cardinal Peak pluton, Lucerne quadrangle, showing inclusions of metamorphic rocks, gabbro, and hornblendite in a matrix of quartz diorite.

Origin of the hornblendite inclusions is not well understood. No hornblendite masses other than the thin layers in the Riddle Peaks plutons and those in the various other contact complexes exist in the region, so it seems highly unlikely they could have been torn from such masses. More likely, they result from interaction of magma and inclusions torn from probably hornblendic varieties of metamorphic rocks. Many inclusions of hornblende gneiss have rims from which felsic material has been removed; complete removal would, of course, have produced hornblendite but would not explain the coarse-grained nature so typical of most hornblendite inclusions. Perhaps crystal growth resulted from the mildly pegmatitic environment in which the complexes formed.

PETROGRAPHY

Thin-section examination revealed many differences between the major units of the Cardinal Peak pluton, but within these units, variations from place to place of some magnitude also exist. Differences are most marked in hornblende-biotite-quartz diorite and the biotite-quartz diorite and granodiorite of the main unit. All these rocks contain andesine, quartz, and biotite, but only those northwest of Cardinal Peak contain more than traces of hornblende. Orthoclase, on the other hand, may or may not occur in rocks northwest of here (and mostly only in small amounts), but to the southeast it is a constant constituent, in places in sufficient quantity to classify the rocks as granodiorite. Apatite, opaque minerals, and titanite are accessory in all thin sections; a little clinopyroxene was seen in a few, and a single grain of allanite in one. Most of the rocks are fresh, although small amounts of chlorite, sericite, and clinozoisite-epidote occur in all.

Andesine makes up roughly half of the main-unit rocks. Northwest of Emerald Peak the average composition is close to An_{40}, but cores of some grains are sodic labradorite. Southeast of Emerald Peak, andesine gradually and irregularly becomes less calcic so that from the vicinity of Cardinal Peak southeastward the average composition is about An_{33}, although cores of some crystals are as calcic as those to the northwest. Andesine, having crystallized early, nearly everywhere shows the effects of protoclasis; grains are rounded, abraded, and distorted, and most are cracked into groups of individual fragments that are slightly rotated with respect to each other. Most porphyroclasts show a few oscillatory zones, and patchy zoning is ubiquitous. Thin overgrowths of calcic oligoclase have formed on many crystals subsequent to distortion and abrasion; furthermore, much of the fine-grained plagioclase in the matrix between the porphyroclasts is calcic oligoclase.

Quartz in the few nonprotoclastic rocks is interstitial or replaces the earlier formed andesine, but in the protoclastic rocks it forms anastomosing irregular seams and lentils of tiny interlocking grains that wrap around the porphyroclasts. These aggregates of interlocking quartz grains seem to have excluded other minerals in the protoclastic matrix so that the matrix does not consist of evenly distributed aggregates of various minerals. Orthoclase also is interstitial or forms irregular seams that partly replace plagioclase; it is most abundant in rocks where chlorite has extensively replaced mafic minerals and is commonly associated with chlorite.

Hornblende and biotite differ somewhat in their mode of occurrence and relation to protoclasis. Where present, hornblende crystallized earlier and generally formed larger grains that show the effects of protoclasis but not to the extent that andesine does. Much of it, however, is in the fine-grained matrix and seems to have formed after protoclasis largely ceased. Very few of the larger grains retain crystal faces; the fine-grained hornblende in the matrix material is decidedly shredlike but little deformed. Pleochroic colors mostly range from light yellowish brown to green. Biotite, on the other hand, mostly occurs as small, largely undeformed flakes and shreds in the groundmass. Some of it is euhedral but most is not. It is pleochroic from straw yellow to dark brown.

Textures range from hypidiomorphic granular to intensely protoclastic. In some places, protoclasis grades into cataclasis where even the latest formed minerals are deformed and shattered.

Calcic hornblende diorite and quartz diorite differ mainly in the abundance of quartz, and diorite is far less common than quartz diorite. All the rocks contain plagioclase, hornblende, and biotite as major constituents and all also contain at least some quartz. Orthoclase, titanite, apatite, and opaque minerals are accessory, and chlorite and epidote are secondary. Calcic andesine usually constitutes from 55 to 65 percent of the rock. The average composition of the plagioclase is rather difficult to estimate because of the large numbers of oscillatory zones, which range from some cores as calcic as An_{70} to rims that are less than An_{40}. Patchy zoning is also common, which adds to the risks of estimating compositions, but in general the plagioclase probably averages An_{45} to An_{50}. Crystals are subhedral to euhedral and, in many places, have a subparallel alinement resulting from flowage.

Quartz is interstitial, but in protoclastic rocks it occurs as irregular lentils of interlocking grains. The accessory orthoclase occurs interstitially or as fine seams that cut plagioclase.

Hornblende occurs as subhedral to anhedral blades and shreds as much as 4 mm long that are pleochroic in shades of light yellowish brown to green. Biotite forms anhedral shreds pleochroic from light straw yellow to bright reddish brown, a feature that combined with more calcic plagioclase serves to distinguish this rock from similar appearing dikes of late Eocene hornblende-biotite-quartz diorite. Much of the biotite replaces hornblende, and chlorite replaces small amounts of both minerals.

Textures are hypidiomorphic granular generally; some thin sections also have flow textures defined by subparallelism of elongate grains. Protoclasis is visible in some sections but is nowhere as extreme as in rocks of the main units.

Rocks of the contact complex show so many variations in thin section that a description of even part of them would require a great deal of space to no particular purpose. Many that in outcrop appear to be straightforward igneous rocks, in thin section are seen to be hybrid rocks containing crystals derived from invaded rocks, as, for example, hornblende crystals obviously derived from hornblende gabbro of the Riddle Peaks pluton. Most characteristic and invariably present are gabbroic rocks containing sodic labradorite showing both oscillatory and extreme patchy zoning, hornblende, biotite, and commonly a little quartz, and accessory magnetite, apatite, and titanite. The minerals in the gabbros are variable in composition and habit. Hornblende is pleochroic in yellows, greens, and browns, and many crystals are irregularly zoned. Biotite is pleochroic from straw yellow to bright brownish red or to very nearly opaque muddy brown. Textures range from xenomorphic to hypidiomorphic; some rocks show flow textures, and others are protoclastic.

Modal analyses of rocks from the Cardinal Peak pluton are shown in table 18 and chemical analyses in table 19. The locations of modally analyzed specimens are shown in figure 65. Modes are plotted in figure 66, and the major oxides are plotted in the variation diagram (fig. 13).

TABLE 18.—*Modal analyses of samples of diorite, quartz diorite, and granodiorite from the Cardinal Peak pluton, Lucerne quadrangle*

[Leaders (- - -), unable to determine]

Sample No.	Plagioclase	Potassium feldspar	Quartz	Biotite	Hornblende	Accessory and secondary minerals	Total mafic minerals	Anorthite in plagioclase crystals (percent)			Remarks
								Average	Core	Rim	
1	50.4	2.3	28.3	8.8	2.6	7.6	18.6	37	43	31	Protoclastic.
2	44.5	.9	8.2	3.6	37.7	5.1	46.4	38	46	23	Do.
3	61.3	1.3	23.9	6.6	2.6	4.3	13.5	40	51	23	Do.
4	64.8	.4	17.5	11.7	3.5	2.1	17.3	40	43	31	Hypidiomorphic.
5	54.1	1.9	29.3	12.5	.8	1.4	14.7	41	47	34	Protoclastic.
6	55.9	0	17.2	7.1	14.8	5.0	26.9	51	54	38	Quartz gabbro in contact complex; hypidiomorphic.
7	54.5	.9	27.1	11.2	4.5	1.8	16.5	39	50	27	Protoclastic.
8	59.3	.4	32.3	1.7	3.6	1.7	7.0	40	53	37	Xenomorphic seriate.
9	65.2	.1	15.2	0	8.2	10.3	18.5	50	59	22	Quartz gabbro in contact complex; hypidiomorphic.
10	66.6	0	2.3	2.6	20.3	8.2	31.1	52	---	---	Quartz gabbro in contact complex; hypidiomorphic.
11	54.1	0	14.3	12.1	18.0	1.5	31.6	50	70	40	Hypidiomorphic.
12	43.3	0	19.1	10.4	25.6	1.6	37.6	37	43	23	Xenomorphic.
13	53.9	0	10.2	8.5	26.6	.8	35.9	40	44	38	Protoclastic.
14	53.0	0	6.5	3.2	34.0	3.3	40.5	47	53	30	Do.
15	38.6	0	4.3	4.6	49.3	3.2	57.1	44	---	---	Do.
16	47.6	0	4.0	1.0	44.1	3.3	48.4	54	76	31	Hypidomorphic.
17	52.2	5.2	28.0	9.1	0	5.5	14.6	33	---	---	Porphyroclastic.
18	35.6	1.4	28.4	14.8	17.1	2.7	34.6	35	60	23	Do.
19	49.1	1.3	42.7	5.1	0	1.8	6.9	27	29	24	Do.
20	54.2	0	25.3	8.3	8.9	3.3	20.5	34	43	31	Protoclastic; accessory augite.
21	57.3	1.4	21.3	12.3	3.6	4.1	20.0	34	41	28	Hypidiomorphic; protoclastic.
22	59.0	1.8	28.5	8.4	0	2.3	10.7	33	38	27	Protoclastic.
23	64.8	4.5	15.1	13.0	0	2.6	15.6	33	39	17	Do.
24	58.5	1.7	18.6	14.3	5.0	6.9	21.2	34	39	24	Protoclastic-hypidiomorphic.
25	61.4	2.6	19.7	7.2	0	9.1	16.3	33	38	26	Hypidiomorphic.
26	61.3	2.6	16.4	15.5	0	4.2	19.7	34	41	23	Do.
27	63.2	2.1	15.4	9.3	0	10.0	19.3	33	39	19	Hypidiomorphic-protoclastic.
28	58.8	0	18.0	1.5	0	21.7	23.2	32	43	22	Hypidiomorphic.

TABLE 19.—*Chemical and spectrographic analyses and norms of composite samples of rocks from the Cardinal Peak pluton, Lucerne quadrangle*

[SiO_2 and Al_2O_3 determined colorimetrically; FeO determined volumetrically; Fe_2O_3, MgO, CaO, and Mn determined by atomic absorption; Na_2O and K_2O determined by flame photometer. Analysts: Wayne Mountjoy, J. D. Mensik, Claude Huffman Jr., G. T. Burrow, and H. H. Lipp. Spectrographic analyses by Barbara Tobin. N.d., not detected]

Sample	1	2
Chemical analyses (percent)		
SiO_2	66.9	65.3
Al_2O_3	16.5	18.5
Fe_2O_3	1.26	1.38
FeO	2.21	2.44
MgO	.96	.93
CaO	4.1	5.0
Na_2O	4.36	4.55
K_2O	1.61	1.17
Mn	.061	.092
Total	98	99
Semiquantitative spectrographic analyses (parts per million)		
Ba	1,000	700
Co	15	15
Cr	50	7
Cu	100	100
Ga	50	30
Ni	20	N.d.
Sc	10	15
Sr	1,500	1,000
V	100	100
Y	10	15
Yb	1.5	1.5
Zr	70	50
Norms		
q	24.25	20.82
or	9.71	6.96
ab	37.64	38.72
an	20.76	24.96
hy	5.63	5.86
c	.14	.67
mt	1.87	2.01
Total	100.00	100.00
Plagioclase composition		
an	35.5	39.2
Sample descriptions		

1. Composite, protoclastic hornblende-biotite-quartz diorite.
2. Composite, nonprotoclastic hornblende-biotite-quartz diorite.

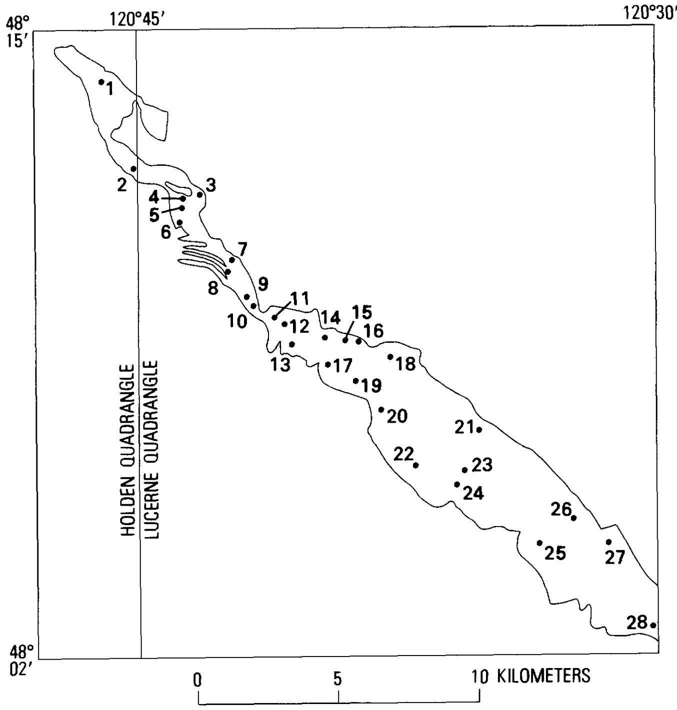

FIGURE 65.—Map showing location of modally analyzed samples of quartz diorite and granodiorite from the Cardinal Peak pluton, Holden and Lucerne quadrangles. Sample analyses are given in table 18.

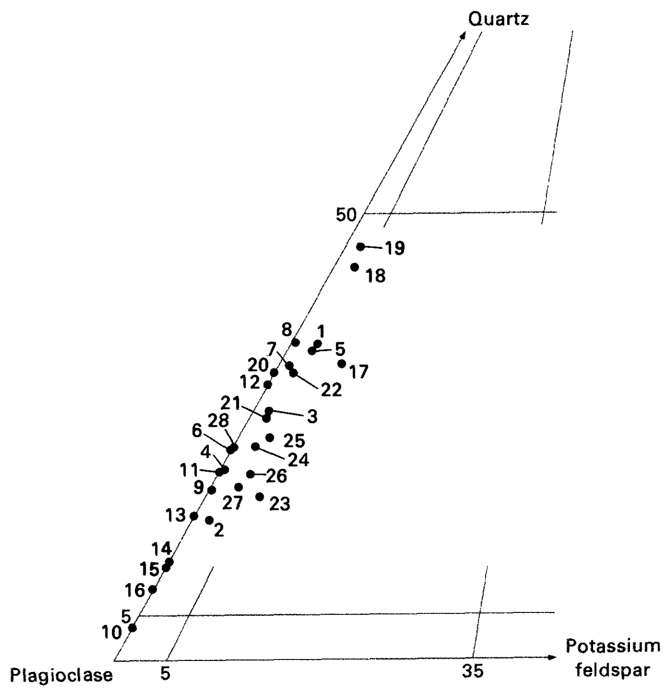

FIGURE 66.—Plot of modes of diorite, quartz diorite, and granodiorite samples from the Cardinal Peak pluton, Holden and Lucerne quadrangles, on a quartz-potassium feldspar-plagioclase diagram. Sample analyses are given in table 18.

TERTIARY INTRUSIVE ROCKS

Intrusive rocks of Tertiary age crop out extensively in the study area and elsewhere in the northern Cascade Range. Those in the study area are of three known ages, early Eocene, late Eocene, and Miocene; many additional dikes may be of other ages. The intrusives of early Eocene age are volumetrically minor and consist of four small stocks in the vicinity of Clark Mountain. Plutons of late Eocene age crop out extensively in the Lucerne and eastern part of the Holden quadrangles. The Miocene intrusions consist of a sizeable batholith, the Cloudy Pass, and a number of related plugs and masses of intrusive breccia.

Most of the Tertiary intrusions are somewhat elongate parallel to the regional trend of the metamorphic host rocks, and one, the large upper Eocene Duncan Hill pluton, resembles a greatly thickened dike as do so many of the pre-Tertiary intrusions. Overall compositions do not differ greatly from pluton to pluton but can range from gabbro to quartz monzonite within a single mass. Granodiorite, however, is most abundant and gabbro the least.

EARLY EOCENE INTRUSIVE ROCKS

CLARK MOUNTAIN STOCKS

In the vicinity of Clark Mountain in the southwestern part of the Holden quadrangle, four small stocks of quartz diorite and granodiorite crop out, no one of which underlies an area exceeding 2 km^2. The stocks are, in part, structurally controlled and tend to be elongated in the direction of host-rock trends. Locally they deflect and wedge apart the host rocks, but mostly they cut out large thicknesses of them. Contacts almost everywhere are sharp, although zones of interlayered intrusive material and schist or gneiss several tens of meters across occur, particularly where contacts are transgressive as in the area about 3 km east of Clark Mountain. In general, granodiorite and quartz diorite have been injected along planes of foliation and commonly wedge apart layers of schist and gneiss, but irregular dikes and apophyses trangress foliation. Near contacts, the stocks contain many inclusions showing various stages of assimilation; some of these resemble autoliths, whereas others are disoriented fragments of local wall rock. Rarely do the wall rocks show megascopically discernible contact effects; even marble, where cut by the intrusives, is virtually unmodified. Locally, aplite dikes are abundant in the vicinity of contacts.

In outcrop appearance there is no perceptible difference between granodiorite and quartz diorite; both

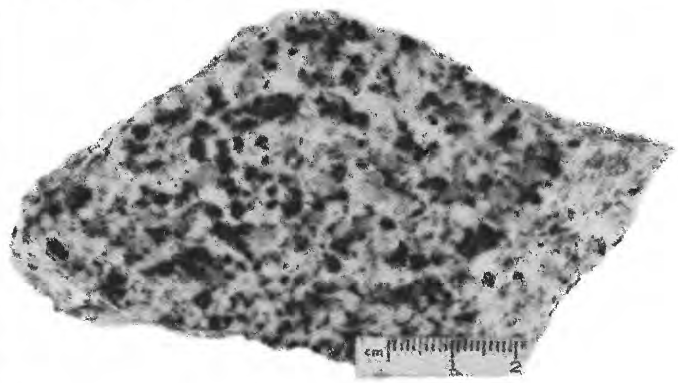

FIGURE 67.—Hornblende-biotite granodiorite from the Clark Mountain stocks, central Washington.

are gray, medium-grained, massive rocks of uniform appearance (fig. 67), although in places an obscure lineation is visible. The rock consists of 45 to 55 percent plagioclase, 20 to 26 percent quartz, 13 to 16 percent biotite, 0.2 to 10 percent potassium feldspar, and 0 to 2.5 percent hornblende. Accessory titanite occurs in amounts as high as 1.6 percent; apatite, magnetite, and zircon are less plentiful. Secondary minerals are clinozoisite-epidote, chlorite, and sericite.

Plagioclase crystals are commonly 1 to 3 mm across and range in composition from An_{18} on the rims of some crystals to An_{40} in the cores of the more calcic grains. The average composition varies little from place to place and is uniformly An_{29} to An_{30} and thus is either calcic oligoclase or sodic andesine. Many crystals show well-formed crystal outlines, and oscillatory zoning is common except in very small grains or where zoning has been destroyed by twinning; not uncommonly adjacent twin lamellae vary by as much as 3 or 4 percent in composition in sections where zoning has been destroyed. Patchy zoning is a common feature. Albite twinning is not as common as polysynthetic twinning on the 001 plane. A small amount of albite forms discontinuous, thin, clear rims on microcline and appears to be the result of exsolution. Myrmekite is also common in sections containing considerable microcline, especially on the rims of plagioclase crystals bordering microcline. Quartz occurs interstitially and as irregular grains; curved lines of tiny liquid inclusions occur in larger grains of quartz. Biotite occurs as small, irregular shreds and as well-formed crystals as much as 3 mm across. Some of the biotite replaces hornblende, but the coarser grains are primary; much of the fine-grained biotite appears to be later than quartz. Orthoclase and microcline commonly occur in irregular grains and as interstitial material. Both are most abundant along lines or zones of incipient fracturing and replace all other primary minerals. Hornblende is sparse, and most is extensively replaced by biotite. Of the accessory minerals, titanite is by far the most abundant and commonly occurs in two forms: as rhombs as much as 2 mm long and as irregular grains in and bordering biotite. These irregular grains associated with biotite formed during the replacement of hornblende by biotite, apparently because the biotite was unable to accommodate as much titanium as was hornblende.

The secondary minerals, clinozoisite-epidote, sericite, and chlorite are invariably present, although only clinozoisite-epidote occurs in amounts exceeding 1 percent. Most of the clinozoisite-epidote occurs as relatively well formed crystals as much as 0.3 mm long that replace plagioclase. Not uncommonly, these crystals are concentrated as clusters in the cores of plagioclase crystals. Chlorite replaces biotite, and sericite replaces plagioclase.

The texture of the quartz diorite and granodiorite is hypidiomorphic granular with protoclastic modifications. Potassium metasomatism is indicated by the concentration of potassium feldspar along zones of deformation; in none of the sections examined is potassium feldspar deformed or granulated, although adjacent plagioclase, quartz, and biotite are crushed and abraded.

Engels (Engels and others, 1976) obtained potassium/argon ages of about 57 m.y. from biotite and 59 m.y. from muscovite in the Clark Mountain rocks (table 39).

Modal analyses of rocks from the Clark Mountain stocks are given in table 20 and chemical and spectrographic analyses and norms in table 21; the major oxides are plotted on a variation diagram (fig. 70). Locations of modally analyzed specimens are shown in figure 68; a plot of the modes is presented in figure 69; and the norms in figure 71.

TABLE 21.—*Chemical and spectrographic analyses and norms of a composite sample of biotite granodiorite from the Clark Mountain stocks, Holden quadrangle*

[Standard rock analysis by D. F. Powers. Spectrographic analysis by P. R. Barnett]

Chemical analysis (percent)		Semiquantitative spectrographic analysis (parts per million)		Norms	
SiO_2	66.26	Ba	700	q	23.21
Al_2O_3	16.09	Co	3	or	11.52
Fe_2O_3	.74	Cr	15	ab	34.26
FeO	3.07	Cu	7	an	19.97
MgO	1.53	Ga	15	hy	7.80
CaO	4.30	La	30	c	.17
Na_2O	4.01	Ni	3	mt	1.08
K_2O	1.93	Sc	7	il	1.42
H_2O+	.65	Sr	1,500	ap	.50
H_2O-	.07	V	70	cc	.07
TiO_2	.74	Y	7	Total	100.00
P_2O_5	.21	Zr	150		
MnO	.06			Plagioclase composition	
CO_2	.03				
Total	99.69			an	36.8

LATE EOCENE INTRUSIVE ROCKS

Intrusive rocks of late Eocene age crop out extensively in the Lucerne and eastern part of the Holden quadrangle and are common elsewhere in the northern Cascades. Within the report area, they range in composition from quartz gabbro to quartz monzonite, but granodiorite is most abundant and quartz gabbro least abundant. In fact, the single most characteristic feature of upper Eocene and younger rocks is the presence of considerable potassium feldspar, a rare constituent in older intrusions.

The intrusive rocks form plutons of various shapes and sizes, large numbers of dikes, and a volcanic neck. The largest of the plutons that project into the mapped area is the Duncan Hill pluton, a mass about 48 km long and at least 9.6 km wide. This mass and some of the smaller ones parallel the strike of the metamorphic host rocks, but other masses are irregular and are unrelated to regional structural trends.

Some of the masses consist almost entirely of a single rock type, whereas others, particularly the Duncan Hill, contain rocks of diverse compositions. In a given pluton, contacts between rocks of different composition may be gradational or they may form complexes of sharply

TABLE 20.—*Modal analyses of samples of biotite-quartz diorite and granodiorite from the Clark Mountain stocks, Holden quadrangle*

Sample No.	Plagioclase	Potassium feldspar	Quartz	Biotite	Hornblende	Accessory and secondary minerals	Total mafic minerals	Anorthite in plagioclase crystals (percent)			Remarks
								Average	Core	Rim	
1	51.3	0.1	19.8	10.5	12.8	5.5	28.8	37	40	35	Hypidiomorphic.
2	50.6	.2	23.2	15.7	2.5	7.8	26.0	29	32	20	Hypidiomorphic; coarse, euhedral clinozoisite.
3	53.5	8.2	20.7	13.1	.1	4.4	17.6	30	40	18	Hypidiomorphic; abundant sphene.
4	52.3	.6	21.1	20.8	0	5.2	26.0	34	42	20	Hypidiomorphic.
5	45.3	3.3	25.2	1.7	0	11.5	26.2	29	34	27	Hypidiomorphic; coarse, euhedral clinozoisite.

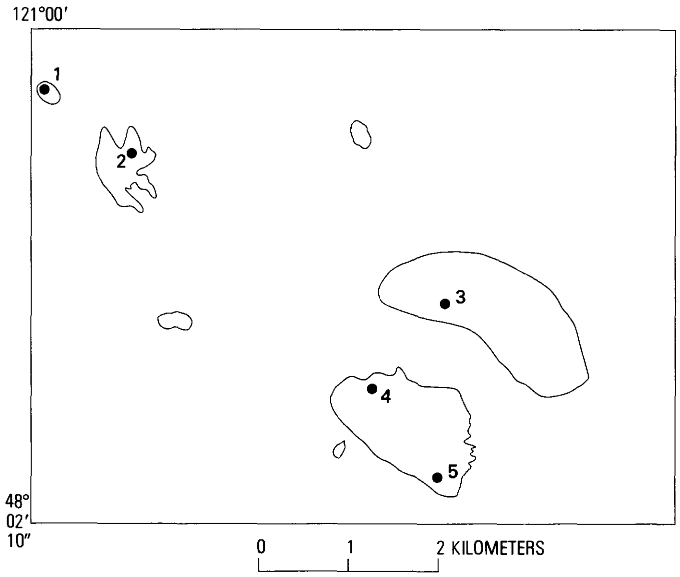

FIGURE 68.—Map showing location of modally analyzed samples of biotite-quartz diorite and granodiorite of the Clark Mountain stocks, Holden quadrangle. Sample analyses are given in table 20.

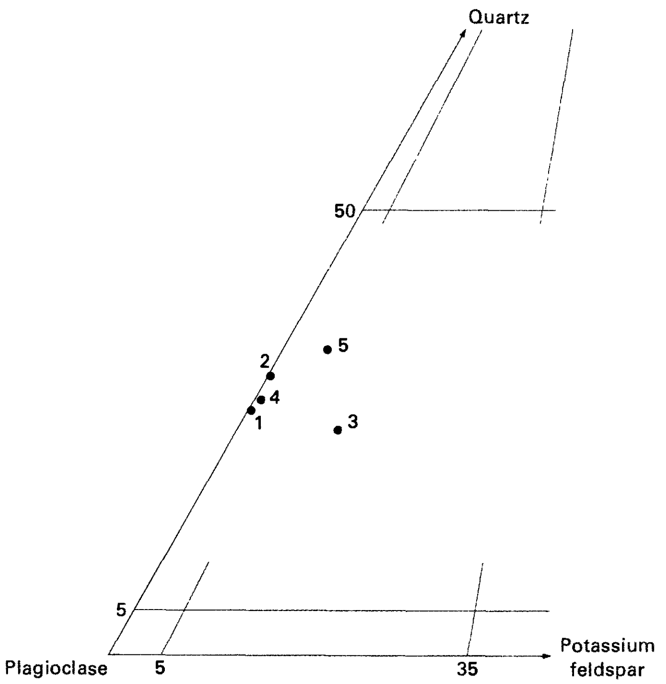

FIGURE 69.—Plot of modes of biotite-quartz diorite and granodiorite samples from the Clark Mountain stocks, Holden quadrangle, on a quartz-potassium feldspar-plagioclase diagram. Sample analyses are given in table 20.

bounded, separate intrusions. Where order of emplacement within a pluton is determinable, it is usually of increasing silica and alkali content with decreasing age, but probably because rocks of different composition were simultaneously molten, the orders of intrusion may differ from one locality to another or even in the area of a

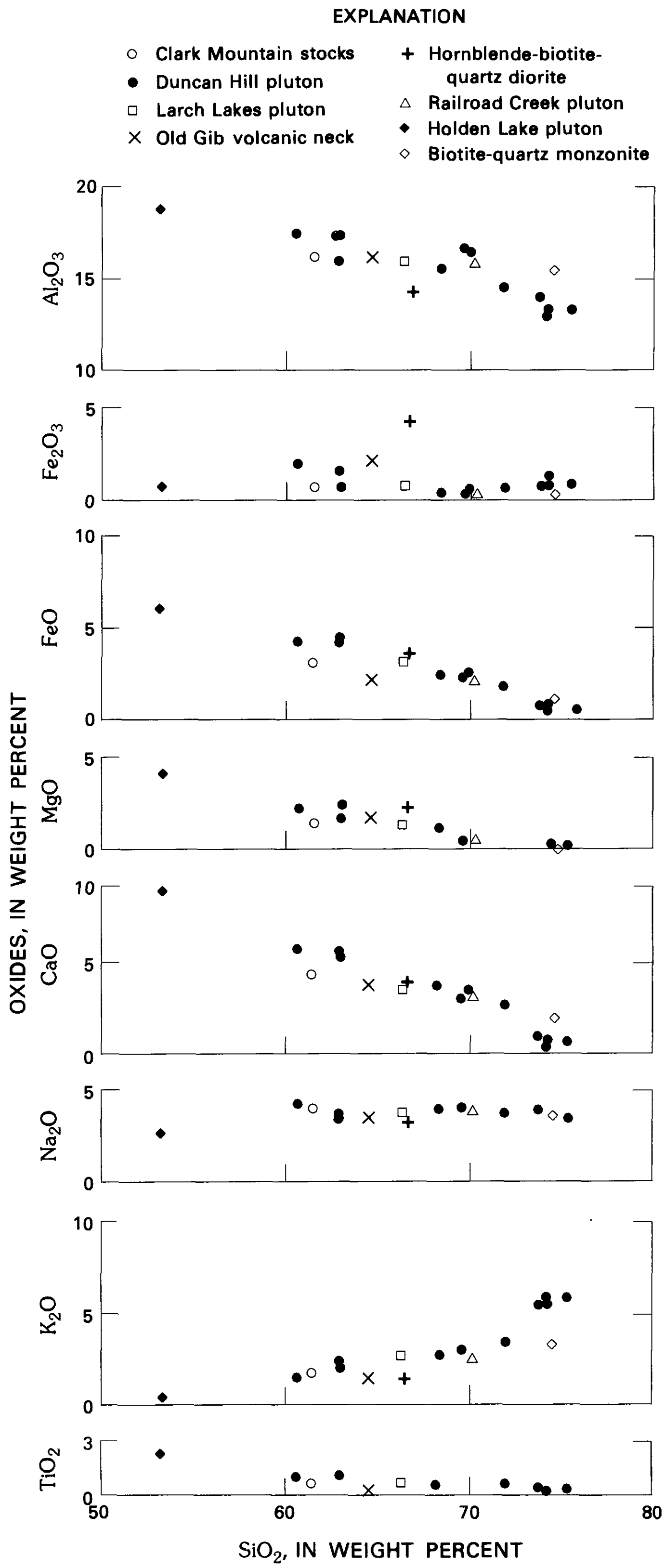

FIGURE 70.—Variation diagram of major oxides in rock samples from Eocene plutons, Holden and Lucerne quadrangles.

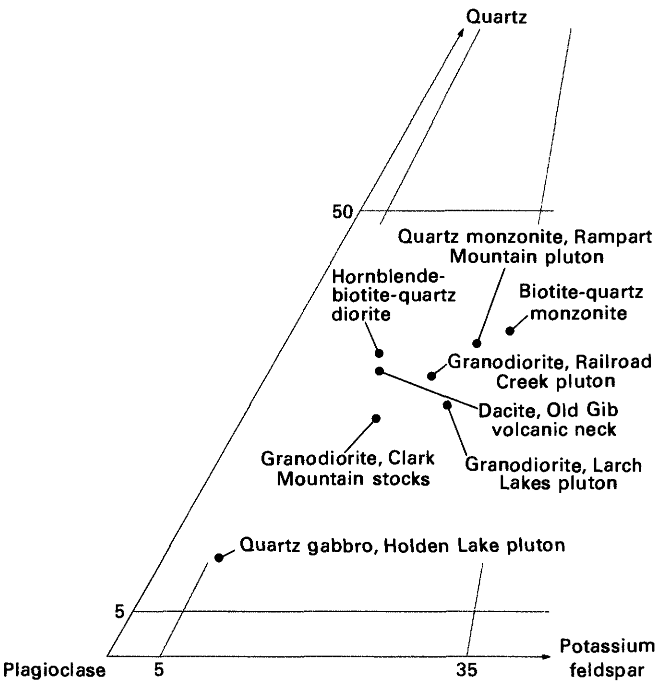

FIGURE 71.—Plot of norms of samples from small Tertiary intrusives, Holden and Lucerne quadrangles, on a quartz-potassium feldspar-plagioclase diagram.

single large outcrop. Relative ages of some of the larger intrusions are not determinable because they are not in mutual contact, or contacts were not observed; this was particularly true of contacts of the Larch Lakes and Rampart Mountain plutons with other large masses.

Radiometric ages of late Eocene intrusive rocks are in a fairly narrow range; the oldest pluton, the Duncan Hill, gave potassium/argon ages ranging from 43 m.y. to 46 m.y., the 46-m.y. date coming from the granophyritic rocks on Stormy Mountain at the shallow, hypabysal end of the pluton (Engels and others, 1976). Ore in the Holden mine replaces Duncan Hill rocks, and phlogopite gangue in the ore is about 44 m.y. old (Engels and others, 1976). The youngest of the larger upper Eocene plutons, the Railroad Creek, yielded ages of about 42 and 43 m.y. (Engels and others, 1976). Other late Eocene intrusions are in between in that they cut the Duncan Hill and are cut by the Railroad Creek. All post–Duncan Hill rocks that are exposed in the Holden mine also contain inclusions of ore, whereas ore replaces Duncan Hill and older rocks. Sulfides in some of the inclusions had been mobilized and sent short veinlets out into the engulfing rock.

MINERALOGY

The mineral content of the various rocks is similar. It consists of varying proportions of plagioclase, quartz, and biotite in all the rocks and either potassium feldspar or hornblende, or both, in most of them. Mineralogic differences that do occur are detailed in descriptions of individual rock types or plutons.

Commonly, more than half the rock volume in the intrusions consists of plagioclase. It occurs as seriate euhedral to anhedral grains reaching maximum lengths of about 6 mm in some rocks but not more than 1 mm in many. In general, plagioclase was the earliest mineral to crystallize and grains tend to larger sizes than other mineral grains. Nearly all grains show albite twinning, but twinning according to other laws, particularly Carlsbad and pericline, is common. Many crystals, particularly those in the smaller masses and dikes, have subparallel orientations indicative of flowage. Rounded and abraded grains resulting from protoclasis are common, particularly near contacts.

Nearly all plagioclase grains are zoned, and most of the larger ones show numerous oscillatory zones, but smaller grains commonly show only a few. In some of the finer grained rocks, only progressive zoning occurs. Oscillatory zoned crystals from some of the coarser grained rocks are surrounded by progressively zoned sodic rims of irregular and varying widths. The extreme range of composition of zoned crystals ranges from labradorite in the cores to sodic oligoclase in the rims; the average composition is generally medium andesine. In many of the younger rocks, the range of composition is fairly narrow and averages calcic oligoclase; cores are no more calcic than andesine. Plagioclase from most rocks, particularly the coarser grained ones, shows extensive patchy zoning.

Quartz occurs as anhedral grains as much as 2 mm across, as irregular, intricately interlocking aggregates, or interstitially. In rocks with protoclastic textures, interlocking aggregates also form anastomosing seams that wind about and wrap around abraided crystals of plagioclase. Larger individual grains are commonly broken and consist of mosaics whose elements are slightly rotated so that they do not extinguish simultaneously. Most grains, large or small, show undulatory extinction. Curved lines of minute inclusions of an unknown mineral or minerals cut across the larger grains; liquid inclusions are comparatively rare. Some quartz in rocks containing considerable potassium feldspar occurs as myrmekitic intergrowths with sodic plagioclase, mostly where such plagioclase is in contact with potassium feldspar.

Potassium feldspar is white and ranges in amount from 0 in some quartz diorite to as much as 35 percent in some quartz monzonite. All is invariably late and replaces other primary minerals, particularly plagioclase. It occurs as interstitial, irregular grains or as seams, and simultaneously extinguishing amoeboid splotches as much as 5 mm across that contain partly resorbed crystals of biotite and plagioclase and, less commonly, quartz. In some rocks, however, potassium feldspar and late quartz appear to have crystallized simultaneously. Some of the protoclastically deformed rocks contain numerous anastomosing seams of potassium feldspar and quartz that envelope rounded and abraded crystals of plagioclase. Most of the potassium feldspar is perthitic, and grid twinning indicative of microcline is uncommon in all rocks and absent in most.

Biotite is the principal mafic mineral and occurs in varying amounts in all the rocks to a maximum content of about 20 percent. Most of it is shredlike, and euhedral plates are rare. Crystal faces parallel to the basal cleavage, however, are generally well preserved and show as straight edges in thin section, but faces normal to the cleavage are mostly frayed and highly irregular. Biotite grains in protoclastic rocks are mostly warped, but some biotite seems to have crystallized after protoclasis, and grains are undeformed and cut across zones of granulation. Biotite tends to replace hornblende in rocks containing both hornblende and biotite. Characteristically, pleochroism is generally extreme and ranges from light straw yellow in the X direction to nearly opaque dark muddy brown or very dark red in the Z direction. Although none of the mineral was chemically analyzed, the extreme pleochroism and high index of refraction ($N_y \cong 1.66$) indicate a high iron content.

Hornblende occurs in all the rocks except the generally fine grained biotite granodiorite and quartz monzonite, although it is not present in all thin sections of the other rock types. Normally, hornblende-bearing rocks contain less than 10 percent of the mineral, but a few contain as much as 20 percent. It occurs both as prismatic euhedral crystals and as ragged grains. Poikilitic inclusions of plagioclase and opaque minerals are numerous in many crystals, especially the anhedral, ragged ones. Most of the hornblende is pleochroic in light shades of yellowish green or green, but some ranges from light green to dark green or greenish brown. Some hornblende has been partly replaced by either biotite or light-colored aggregates of acicular actinolite.

Accessory minerals commonly seen in thin section are magnetite, ilmenite, titanite, apatite, allanite, and zircon. Magnetite and ilmenite occur in all the rocks as scattered, usually irregular small grains, but some ilmenite forms skeletal crystals. Titanite occurs sparingly as rhombs as much as 2 mm long or secondary fine-grained aggregates replacing biotite. Many thin sections contain two or three grains of allanite, some of which are 2 mm across; some allanite crystals are zoned, the colors ranging from reddish orange to brownish red. Apatite is fairly common, usually as small stubby prisms. Zircon is rare and is almost entirely confined to biotite, in which it produces pleochroic halos.

Secondary minerals are chlorite, clinozoisite-epidote, actinolite, titanite, and sericite. Of these, chlorite, largely negative penninite, is most abundant, commonly as an alteration product of biotite and much less so of hornblende. Small amounts of clinozoisite-epidote replace the more calcic varieties of plagioclase and occasionally hornblende, but the most common alteration product of hornblende is nearly colorless (in thin section) actinolite. A little sericite was seen in nearly all thin sections, most frequently in the more calcic parts of plagioclase crystals.

TEXTURES

Textures of the various late Eocene rocks differ considerably, not only from mass to mass but within a single mass. Textures of each of the units shown on the maps (Cater and Crowder, 1967; Cater and Wright, 1967) are sufficiently distinctive, however, to permit ready field identification. The rocks in the smaller masses are generally fine grained and some are porphyritic, whereas most of the rocks in the Duncan Hill, Railroad Creek, and Rampart Mountain plutons are medium grained. Grain sizes decrease toward the contacts of some masses, but more striking are the streaky and, in places, gneissic textures resulting from protoclasis near the margins of a few masses and almost throughout the constricted northern part of the Duncan Hill pluton.

Normally both fine- and medium-grained rocks are hypidiomorphic granular. Directive textures manifested by subparallel orientations of tabular crystals are common locally, especially in some of the finer grained rocks. Crystals in most of the rocks tend to be seriate, but some rocks are equigranular and a few are porphyritic. Grain sizes of fine-grained rocks are in the range of 0.1 to 1.0 mm, and those of medium-grained rocks from 1 to 6 mm; phenocrysts of porphyritic varieties are generally 3 to 6 mm across.

In porphyritic rocks, plagioclase, hornblende, and, less commonly, biotite form phenocrysts. The plagioclase is euhedral and is the same size and habit as the plagioclase in the medium-grained rocks, whereas the groundmass plagioclase is subhedral.

Protoclastic textures are common in the larger masses and in dikes of biotite granodiorite and quartz monzonite. Granulation ranges from that which is barely perceptible under the microscope to the streaked, pseudogneissic varieties particularly common in the Duncan Hill pluton where granulation is readily apparent to even the unaided eye. The microscope is generally needed, however, to discern the late-crystallized minerals that grew across zones of granulation.

Cataclastic modifications of primary textures are locally common; these grade into mylonite along fault zones.

ANALYTICAL DATA

The compositions of the various upper Eocene intrusive rocks in the area were determined by 18 complete rock analyses using flame-photometric, atomic-absorption, and colorimetric methods for the major oxides. Nine of these were composite samples consisting of numerous chips of representative specimens of given rock types; the others are of single specimens of typical rocks in the various plutons, or of different facies within the Duncan Hill pluton. The minor elements were determined by semiquantitative spectrographic analyses. The analyses and calculated CIPW norms are given in the various accompanying tables and plotted on triangular diagrams. As might be expected, plots of the finer grained rocks show less scatter than do those of the coarser grained rocks.

DESCRIPTION OF ROCKS

The various plutons are described in order of known or inferred decreasing age. Only the Larch Lakes and Rampart Mountain plutons are isolated, and so far as is known, they are only in contact with each other and some dikes, but their general similarity to other upper Eocene rocks and their relation to certain dikes strongly suggest they are of the same general age, although no radiometric age determinations have been made. Because the order of emplacement of the rocks, where the order is known, is generally the order of increasing silica and alkali content, the Rampart Mountain pluton is presumed to be slightly younger than the Larch Lakes pluton because it contains more of these constituents. As is explained later, however, the increase in silica and alkalis may be more nearly related, at least for some plutons, to the position of a rock in the pluton rather than to its position in an emplacement sequence; this is more specifically true of the Duncan Hill pluton.

DIKES

Dikes, in many places closely grouped in swarms, are particularly numerous east of the Chiwawa River. Some of those designated on the geologic quadrangle maps without a symbol for geologic system are probably older than late Eocene, and those that have undergone regional metamorphism are unquestionably older and are, in fact, the oldest intrusive rocks in the mapped area. Such dikes, however, are rare. In areas where dikes are numerous, only a small percentage are shown on the maps, but these are selected to show the prevailing strike and distribution. Where little doubt existed concerning the affinities of late Eocene dikes, they were given appropriate letter symbols such as those given to the Railroad Creek pluton, but many of the dikes could not be assigned with confidence to any of the larger intrusive masses. Most dikes are less than 50 m thick, but a few are as much as 60 m or more thick.

The dikes consist of a rather wide variety of types; the aphanitic types designated on the geologic quadrangle maps are particularly diverse. Many that appear nearly identical megascopically differ greatly in composition, and, conversely, many that appear to be different in outcrop appearance are seen to be of similar composition when viewed under the microscope. Spessartite, hornblende-quartz diabase or pawdite, porphyritic diabase, augite minette, and kersantite have been identified. Nonporphyritic granitoid dikes designated on the maps consist of biotite-quartz monzonite and granodiorite, hornblende-biotite granodiorite and quartz diorite, and a few consist of alaskite.

PAWDITE

Probably commonest of the dark, fine-grained rocks is biotite-hornblende-quartz rock, called pawdite by Johannsen (1937, p. 319). From the Chiwaukum graben eastward, except for the northeast part of the Holden quadrangle, most of the dark, fine-grained dikes are pawdite, and they are particularly numerous in and around the south end of the Duncan Hill pluton. None, however, were seen to cut the Railroad Creek pluton. Throughout this area, most of the dikes strike northeast, but in the highly sheared contact zone bordering the Entiat pluton, east of Garland Peak and Rampart Mountain, swarms of pawdite and rhyodacite dikes strike north-northwest. In the area near the east edge of the Holden quadrangle west of Larch Lakes, the Larch Lakes pluton invades and forms a sort of migmatite with fine- to medium-grained pawdite; the pluton in turn is cut by dikes of spessartite that have chilled margins against the granodiorite of the pluton, showing thereby a considerable time lapse between the intrusion of pawdite and spessartite, despite their similarity of appearance. Most of the dikes are only a few meters thick, but a few are as thick as 8 m. The thinner dikes are aphanitic or very fine grained throughout, but the thicker dikes commonly grade from chilled margins of aphantic rock to central parts that approach medium grain.

Pawdite ranges from medium-gray, even-granular, fine-grained rocks having a salt and pepper appearance to those that are nearly black and almost aphanitic. Many are porphyritic, having conspicuous blades of shiny black hornblende in a fine-grained or aphanitic groundmass; this is particularly true of the dikes within the Chiwaukum graben and of the sills cutting conglomerate of the Swauk Formation west of the Chiwawa River; in these sills shiny black hornblende blades occur in a greenish gray aphanitic groundmass. The finer grained groundmass and the difference in appearance between the pawdite of dikes and sills in the graben and those outside it are thought to be due to emplacement at shallower depths. Pawdite contains plagioclase, hornblende, and quartz as essential minerals in all the dikes and biotite in most of them; rather abundant magnetite, titanite, and apatite are accessory. Chlorite, actinolite-tremolite, epidote, sericite, and calcite are secondary. The average composition of plagioclase ranges from calcic andesine to bytownite, but in all thin sections examined the mineral is characterized by extreme zoning, commonly ranging from bytownite cores to albite rims. Hornblende occurs as anhedral to euhedral crystals pleochroic in various shades of brown, but in some sections the brown hornblende grades outward into green and from green into nearly colorless rims. Biotite, usually as shredlike grains, may occur in amounts of as much as 10 percent in some dikes, but in a few it appears to be absent. Quartz, commonly not more than about 5 percent, occurs in all the dikes as interstitial grains and in a few as rounded, resorbed phenocrysts, which are surrounded by halos of green hornblende crystals. The degree of alteration varies considerably; some rocks are almost entirely fresh, whereas others are so badly altered that almost none of the primary minerals remain. Textures also are variable, ranging from hypidiomorphic to xenomorphic and porphyritic.

The diaschistic dikes and irregular masses of pawdite in and satellitic to the southern end of the Duncan Hill pluton strongly suggest that all the pawdite is related to that pluton.

KERSANTITE

Kersantite differs megascopically from the finer grained varieties of pawdite and some spessartite only in the presence of a few small, visible phenocrysts of biotite. The dikes are probably rare, although because of their close resemblance to other types of dikes, they may be more common than was suspected during the course of field mapping. Kersantite is a dark-gray, somewhat porphyritic rock, in which small phenocrysts (as much as 1 mm long) of plagioclase and scarce flakes of biotite can be detected in a very fine grained groundmass. The rock consists mostly of calcic andesine and biotite and minor amounts of hornblende and less than 1 percent augite and quartz. The phenocrysts of andesine are euhedral and show both oscillatory and patchy zoning; the scattered phenocrysts of biotite have partly recrystallized around their margins to a felted mass of lighter colored biotite and a little magnetite. Scattered grains of partly resorbed quartz are surrounded by coronas of tiny green hornblende needles; these quartz grains may be xenocrysts. The groundmass consists of a mat of small andesine laths and shreddy flakes of biotite showing a trachytic texture.

AUGITE MINETTE

In the northeastern part of the Lucerne quadrangle are a number of very dark greenish gray dikes of minette. Most of these strike northeast as do most other dikes, but one was seen that had a northwesterly trend. Some are very fine grained, and only phenocrysts of biotite are visible, but others are medium grained, and biotite, feldspar, and light-green augite are visible. Some grade into pegmatitic facies containing biotite and orthoclase crystals as much as 2 cm across; miarolitic cavities are numerous. Microscopic examination showed the dikes to consist largely of biotite, orthoclase, microcline, augite, unusual amounts of accessory titanite, magnetite, and apatite, and a few grains of hornblende. Sericite, epidote, and calcite are secondary. Much of the feldspar is perthitic; cores of biotite crystals are considerably lighter in color than are the marginal parts. The texture is striking; euhedral crystals of the mafic minerals are enclosed in an anhedral mass of feldspar grains.

SPESSARTITE

Dikes of spessartite are numerous in two areas, in the southwest part of the Lucerne quadrangle and in the Holden mine area. The spessartites in the two areas differ somewhat in both appearance and composition. Those from the Holden area are uniformly very fine grained and nonporphyritic, whereas those from the Lucerne quadrangle are more variable and range from nearly aphanitic to medium fine grained, and many are porphyritic. Both range from dark greenish gray to nearly black. The Holden mine spessartite consists mostly of brown hornblende and albite in roughly equal proportions but contains, in addition, accessory quartz, apatite, magnetite, titanite, and, in a few sections, a little primary orthoclase. Biotite is absent. Secondary minerals are sericite, calcite, epidote, chlorite, orthoclase, and sulfides. Textures approach panidiormorphic. A few of these dikes are crowded with light-green ovoids as much as 1 cm across that consist of more or less radiate masses of albite laths and some epidote; a few of the ovoids have cores of quartz or epidote. Around these ovoid bodies, hornblende blades are packed as though forced out of the ovoids. Where the dikes cut the Holden ore body, they contain more numerous grains of sulfides, mostly pyrite, that are commonly associated with replacement splotches of chlorite. Some of the relationships of the dikes to the ore body, such as an enrichment in sulfides, suggest that the dikes were intruded during the end stages of the epoch of sulfide mineralization. On the other hand, dikes of biotite-quartz monzonite and granodiorite that cut the ore are unquestionably younger, are unaltered, and contain inclusions of mineralized rock and sulfides. These siliceous dikes are, in turn, cut by spessartite and, hence, are older than spessartite; furthermore, some of the spessartite dikes have chilled margins against ore. The increased abundance of sulfides where spessartite cuts ore is probably the result of picking up or assimilating some sulfides during the course of intrusion—as did biotite-quartz monzonite and granodiorite.

The spessartite dikes in the southwestern part of the Lucerne quadrangle also consist largely of plagioclase and hornblende, but the plagioclase is oligoclase rather than albite, and a few of the dikes also contain a little biotite. All dikes contain a small amount of quartz and magnetite and some have interstitial accessory orthoclase, but as compared with the Holden spessartites, apatite and titanite are rare. The usual secondary minerals—sericite, chlorite, epidote, calcite, and pyrite—occur in varying amounts. Many of the dikes have phenocrysts of hornblende as long as 5 mm. Some dikes are notably miarolytic, and most of the miarolytic cavities are surrounded by bleached zones from a fraction of a millimeter to 3 mm thick in which the hornblende has altered to chlorite, but oligoclase is unaltered. Otherwise, textures are similar to those of the Holden spessartites.

The relationship, if any, between the two types of spessartite dikes is not known. Both types cut other late Eocene intrusions and seem to be among the youngest of dikes, although none cut either the Old Gib volcanic neck (late Eocene) or the early Miocene Cloudy Pass batholith and related rocks. However, because of the close spacial relation between these dikes and other late Eocene rocks, they are believed to be related to them.

OTHER FINE-GRAINED, DARK DIKES

Sparsely scattered over the area are dark, fine-grained rocks having the composition of diabase or diorite. They consist of varying proportions of andesine or labradorite and hornblende, but a few contain a little clinopyroxene. Some appear to be similar to the diabase and fine-grained diorite that characterize the contact complexes bordering various plutons, but the affinities of others are unknown. Most have not been affected by regional metamorphism, but a few have been recrystallized to form amphibolite dikes.

HORNBLENDE DIORITE OF UPPER ROCK CREEK

In the upper part of the Rock Creek watershed and adjacent areas are dikes of hornblende diorite that rather closely resemble the pawdite dikes and may, in fact, be related to them. These dikes range from perhaps 20 cm thick to one nearly 1.6 km long and 100 to 130 m thick; many are highly irregular and have amoeboid shapes. The rocks in the larger masses range from black and very fine grained in the chilled margins to mesocratic and relatively coarse grained in the central parts where euhedral hornblende needles are as long as 7 mm. The thinner masses are dark and fine grained throughout. In the larger masses, coarser grained rocks of the central parts of the dikes have intruded the chilled border rocks and torn off fragments of them.

The hornblende diorite consists mostly of hornblende and andesine with 2 to 3 percent biotite and a little accessory quartz, orthoclase, and apatite. Sericite, chlorite, and actinolite are secondary. Hornblende, the most abundant mineral, is euhedral and brown, but in the coarser grained varieties it is zoned, the borders of many crystals ranging from light green to nearly colorless. Unlike the otherwise rather similar pawdite dikes, the average composition of the plagioclase is andesine, and the compositional range of the normally zoned crystals is narrower, ranging from calcic andesine to oligoclase. Quartz occurs either interstitially or as myrmekitic intergrowths with oligoclase. A very small amount of late orthoclase locally replaces plagioclase or forms granophyric intergrowths with quartz.

GRANITOID DIKES

Scattered through the area are numerous, rather light-colored, generally nonporphyritic, fine- to rather coarse-grained dikes of granitoid textures. The dikes range in composition from alaskite to quartz diorite, but most are quartz monzonite and granodiorite. Some of the dikes are clearly related to various larger plutons; thus, dikes designated as granitoid rocks in the southeast part of the Glacier Peak and adjacent parts of the Holden quadrangles are probably satellitic to the Tenpeak pluton. Others possess mineralogic and textural characteristics that relate them broadly to late Eocene plutons, but many that cut the metamorphic rocks, although unaffected by metamorphism, have no clear affinities. In general, none of the granitoid dikes have chilled borders, although some of those believed to be of late Eocene age are finer grained near their margins. On the other hand, many contain patchy-zoned plagioclase suggestive of transport through a considerable range of temperature-pressure conditions. Most of the gneissic dikes that might thereby suggest a premetamorphic age are seen under the microscope to have protoclastic rather than crystalloblastic or metamorphic textures and, hence, were intruded following regional metamorphism.

The dikes consist of varying proportions of andesine or oligoclase, quartz, potassium feldspar, and biotite. Hornblende occurs in many but nearly everywhere in lesser quantities than biotite. Most show only minor alteration to sericite, chlorite, and epidote, but in a few, relatively little of the original components remain.

DUNCAN HILL PLUTON

The Duncan Hill pluton, the oldest, probably the largest, and certainly the most intriguing of the late Eocene intrusions in the general area differs markedly in a number of respects from the other Tertiary plutons and, for this reason, was investigated in reconnaissance beyond the mapped quadrangles. The pluton has a length of about 48 km, extending from Buckskin Mountain in the Holden quadrangle to Stormy Mountain about 23 km southeast of the Lucerne quadrangle. It is tadpole shaped and tapers from a width of about 9.6 km at its so-called head on Stormy Mountain to a width of a little more than 1 km at its so-called tail on Buckskin Mountain. The outcrop area is about 260 km^2.

The Duncan Hill pluton rather closely parallels the northwesterly trend of its host rocks, as do the older plutons in the area, but it cuts across them downdip. The north half of the pluton intrudes the west limb of a southeast-plunging antiform of upper Paleozoic metamorphic rocks. Southward, the relation of the pluton to host rocks is less clear because exposures are poor and the structure of the host rocks is less well known. Unlike other plutons in the area, the Duncan Hill pluton not only is compositionally zoned along its length—the rocks grading from hornblende-quartz diorite in the northern part to rocks as silicic as rhyolite porphyry at the south end on Stormy Mountain—but it also exposes rocks ranging in depth zones from mesozonal in the northern part to hypabyssal in the southern. In a few places and most conspicuously in the vicinity of Fern Lake, the rock consists of intrusive complexes and marble-cake mixtures of hornblende-biotite-quartz diorite and granodiorite (fig. 72).

The great vertical range of exposure in the pluton is the result of differential uplift since intrusion. The north-trending northern Cascade Range uplift transects the northwest-trending pluton, and the north end of the pluton nearer the center of the uplift, where uplift was greatest, is much more deeply eroded than the south end on the east flank, where uplift and depth of erosion are only moderate. The amount of tilting since the Miocene is evident locally from the dip of Miocene basalt flows that cap some of the ridges near the southeast end of the mass, and much, possibly more, uplift occurred between intrusion of the pluton and extrusion of basalt. Some of the discussion of the shallow southeast end of the pluton is based on unpublished information contributed by C. A. Hopson of the University of California, Santa Barbara, to whom I am particularly indebted.

The contact relations of the pluton to its host rocks differ radically along its length. The northwest part of the pluton is mantled by a complex similar to those associated with many of the older plutons and consists of hornblendite, hornblende gabbro, diorite, quartz diorite, dikes of various compositions, and inclusions of host rocks. The complex is particularly thick and extends nearly 5 km beyond the discordant northwest end of the core of the pluton where intrusive material had an opportunity to insinuate itself along foliation planes of the metamorphic rocks. The complex thins southward on both sides of the core; on the southwest side it is traceable nearly to Cottonwood Guard Station, but on the northeast side, a mappable complex extends only to the North Fork of the Entiat River, although a few thin lenses occur as far south as South Pyramid Creek. South of where the contact complexes pinch out, the contact, where exposed, is generally fairly sharp; hornfels, migmatites, or thin granitized zones in the host rocks are at most only a few tens of meters thick. At the southern end of the pluton, for example, south of sample 42 (fig. 76), the contact is almost knife sharp, and the pluton had a minimal effect on the host rocks.

FIGURE 72.—Marble-cake mixture of biotite-quartz diorite and granodiorite in Duncan Hill pluton at Fern Lake, Lucerne quadrangle.

Quartz diorite makes up nearly all the main body of the pluton north of Snow Brushy Creek and occurs sparingly throughout most of its length. North of Snow Brushy Creek, the rock is gray, medium grained, and somewhat gneissic (fig. 73). The pervasive gneissic or foliated fabric of the rock resulted from protoclasis and is strongest near the contacts; south of Snow Brushy Creek, where quartz diorite occurs sparingly, the rock is nonprotoclastic and, hence, nonfoliated.

Quartz diorite consists of andesine, quartz, biotite, and hornblende, but hornblende may be locally absent. Magnetite, ilmenite, titanite, apatite, allanite, zircon,

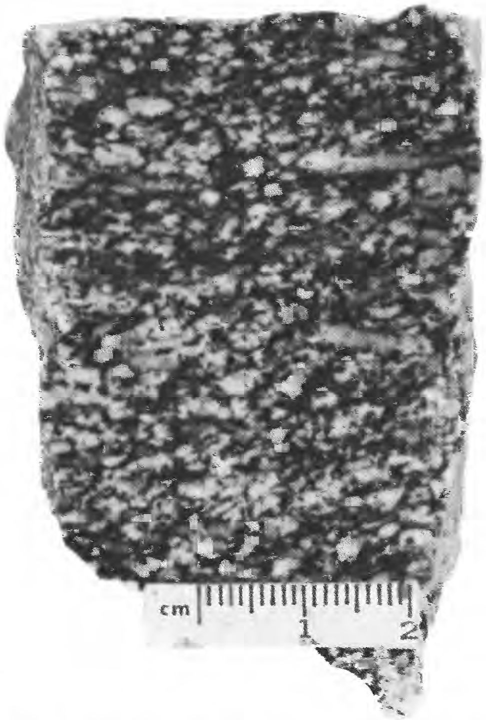

FIGURE 73.—Protoclastic hornblende-biotite-quartz diorite near the north end of Duncan Hill pluton, Holden quadrangle.

and rare xenotime are accessory. Orthoclase occurs sparingly as tiny veinlets or as late replacements of plagioclase. Plagioclase shows both oscillatory and patchy zoning; cores are as calcic as An_{60} and rims as sodic as An_9. In a given thin-section slide, the average composition of crystals can range from An_{33} to An_{43}. Hornblende is light yellowish brown in the X direction to green and brownish green in the Z direction; color in much of the hornblende is splotchy, and in some grains the rims tend to be greener. Biotite is pleochroic from yellow to reddish brown or nearly opaque muddy brown. Quartz forms irregular lenses and streaks of interlocking grains. Textures range from hypidiomorphic to thoroughly protoclastic; plagioclase and hornblende are commonly bent, broken, and abraded, but the later quartz and biotite are either undistorted or only slightly so. Modal composition of quartz diorite ranges from 45 to 55 percent andesine, 10 to 35 percent quartz, 13 to 20 percent biotite, and 0 to 15 percent hornblende; orthoclase, where present, rarely exceeds 1 percent (table 22). Southward the mafic minerals, particularly hornblende, decrease irregularly and potassium feldspar, mostly perthite, increases.

The bulk of the Duncan Hill pluton consists of either granodiorite or quartz monzonite, but of the two rocks, granodiorite is considerably more abundant. Although granodiorite occurs sparingly north of Snow Brushy Creek, the creek's drainage basin roughly marks the transitional zone from quartz diorite to granodiorite. Within this zone, a distinction between quartz diorite and granodiorite for much of the rock would be impossible except in thin section, but, in general, rocks containing visible hornblende are likely to be quartz diorite. Granodiorite and quartz monzonite are light-colored, massive, medium-grained rocks in which books of euhedral biotite are conspicuous (fig. 74). Both consist of oligoclase or andesine, quartz, orthoclase or perthite, biotite, and locally a little hornblende. Titanite, opaque minerals, allanite, a little zircon, and, rarely, muscovite are accessory. Alteration products are saussurite and chlorite, but neither are abundant. Plagioclase shows both oscillatory and patchy zoning; oscillatory zones in a single grain are numerous and range in composition from An_{10} to An_{55}; larger grains have thick, progressively zoned rims of sodic oligoclase. The average composition ranges from medium oligoclase to medium andesine, but rocks containing andesine are much more abundant. Some orthoclase is not visibly perthitic, but most of it is. Potassium feldspar is late and mostly replaces plagioclase; in some thin sections the potassium feldspar forms a mesostasis that extinguishes simultaneously over wide areas. Quartz mostly forms irregular interstitial grains or splotches that have replaced earlier formed minerals. Biotite and hornblende differ little from that in quartz diorite except that biotite in nonprotoclastic rocks is mostly euhedral. Modal compositions range between wide limits, but in granodiorite, plagioclase usually constitutes about half the rock, quartz about one-quarter, and potassium feldspar, biotite, and hornblende in varying proportions make up the rest. In quartz monzonite, plagioclase, quartz, and potassium feldspar occur in roughly equal proportions; biotite is present in amounts ranging between 5 and 15 percent, and hornblende is absent.

Textures of granodiorite and quartz monzonite are typically hypidiomorphic, modified in places by minor protoclasis. Protoclastic textures are fairly common near the contacts as far south as Cottonwood Guard Station, but south of there they seem to be virtually absent. In the interior of the pluton, protoclastic textures occur sparingly as far south as Duncan Hill but no farther.

The hornblende-biotite-quartz diorite and granodiorite of intrusive complexes and marble-cake mixtures, such as those around Fern Lake (fig. 72), differ somewhat in outcrop appearance and in microscopic texture, but they are mineralogically practically identical. The quartz diorite is somewhat finer grained, darker, and slightly more foliate than the granodiorite, and in thin section a flow structure is indicated by a subparallel

TABLE 22.—*Modal analyses of samples of biotite- and hornblende-biotite-quartz diorite and granodiorite from the Duncan Hill pluton, Holden and Lucerne quadrangles*

[Leaders (- - -), unable to determine]

Sample No.	Plagioclase	Potassium feldspar	Quartz	Biotite	Hornblende	Accessory and secondary minerals	Total mafic minerals	Anorthite in plagioclase crystals (percent) Average	Core	Rim	Remarks
1	50.1	1.1	34.0	14.1	0	0.7	14.8	40	45	30	Protoclastic.
2	50.9	.5	25.2	18.3	4.6	.5	23.4	43	48	28	Do.
3	46.2	4.1	35.4	13.5	0	.8	14.3	40	45	28	Do.
4	55.1	0	29.3	14.1	.1	1.4	15.6	38	44	31	Do.
5	64.1	.2	15.1	12.0	7.3	1.3	20.6	28	38	21	Do.
6	46.7	.7	19.8	19.7	11.3	1.8	0	40	61	27	Do.
7	53.3	.7	31.4	12.9	1.5	1.4	14.8	40	---	---	Porphyroclastic.
8	21.9	32.8	38.9	6.2	0	.2	6.5	---	---	---	Hypidiomorphic; some slight mortar texture.
9	55.1	0	8.7	20.1	15.3	.8	36.2	43	50	27	Hypidiomorphic.
10	58.6	0	17.1	15.8	8.3	.2	24.3	38	---	---	Hypidiomorphic; slight granulation.
11	65.9	0	11.3	13.4	8.2	1.2	22.8	37	---	---	Protoclastic.
12	47.9	3.6	7.9	14.4	23.3	2.9	50.6	37	---	---	1.9 percent sphene.
13	59.2	.2	13.8	20.7	5.5	.6	26.8	35	---	---	Near contact; moderately protoclastic.
14	52.2	7.6	25.1	13.8	0	1.3	15.1	35	---	---	Do.
15	50.6	3.1	32.6	13.6	0	.1	13.7	35	---	---	Do.
16	42.7	9.1	41.8	2.1	0	4.3	6.4	28	---	---	Do.
17	54.1	.9	24.5	20.3	0	.2	20.5	36	---	---	Hypidiomorphic.
18	52.5	8.0	26.0	10.3	3.0	.2	13.5	39	51	27	Slightly protoclastic.
19	61.2	1.6	19.1	15.4	1.1	1.6	18.1	37	---	---	Rather fine-grained; hypidiomorphic.
20	62.3	1.7	16.2	11.0	7.9	.9	19.8	37	45	20	Hypidiomorphic.
21	39.9	15.6	21.4	18.1	3.9	1.1	23.1	38	---	---	Somewhat protoclastic.
22	51.7	4.8	21.1	19.1	3.0	.3	22.4	37	63	22	Rather fine grained; subparallel plagioclase crystals.
23	49.1	9.2	25.1	13.9	2.3	.4	16.6	35	57	15	Hypidiomorphic.
24	47.2	14.7	21.8	15.1	0	1.2	16.3	37	---	---	Near contact; somewhat protoclastic.
25	62.2	.1	15.7	17.1	4.4	.5	22.0	37	---	---	Seriate; hypidiomorphic.
26	50.7	11.1	30.6	7.3	.1	.2	7.6	33	39	20	Hypidiomorphic.
27	41.0	13.7	36.3	8.9	0	.2	9.1	32	37	18	Do.
28	53.1	4.6	30.1	9.9	.8	.5	11.2	36	39	20	Do.
29	48.6	14.5	28.1	7.7	.3	.8	8.8	28	---	---	Do.
30	62.3	.1	15.7	17.1	4.4	.4	21.9	37	---	---	Hypidiomorphic; seriate.
31	61.9	17.6	13.4	5.0	1.0	1.1	7.1	36	40	19	Hypidiomorphic.
32	39.2	19.3	28.7	12.0	0	.8	12.8	32	54	17	Coarse grained; hypidiomorphic.
33	41.9	16.5	31.8	8.7	.7	.4	9.8	31	50	19	Hypidiomorphic.
34	33.5	24.7	31.1	9.9	.5	.3	10.7	33	44	15	Do.
35	52.3	13.5	21.4	11.6	.5	.7	12.8	40	52	18	Do.
36	43.8	18.7	19.6	15.6	1.6	.7	17.9	33	44	13	0.2 percent allanite; hypidiomorphic.
37	36.1	24.2	23.5	16.1	0	.1	16.2	32	55	15	Hypidiomorphic.
38	33.2	25.1	26.5	15.1	0	.1	15.2	33	48	15	Hypidiomorphic-porphyritic.
39	24.9	42.7	28.8	3.2	.1	.3	3.6	24	33	8	Contains mordenite veinlets.
40	24.7	35.8	34.1	5.2	0	.2	5.4	25	27	16	Plagioclase, progressively zoned; hypidiomorphic-miarolytic.
41	29.8	35.6	29.7	4.2	0	.7	4.9	19	25	7	Xenomorphic; progressively zoned plagioclase.
42	25.7	39.7	30.2	4.3	0	.1	4.4	15	29	7	Calcic cores of plagioclase sericitized.

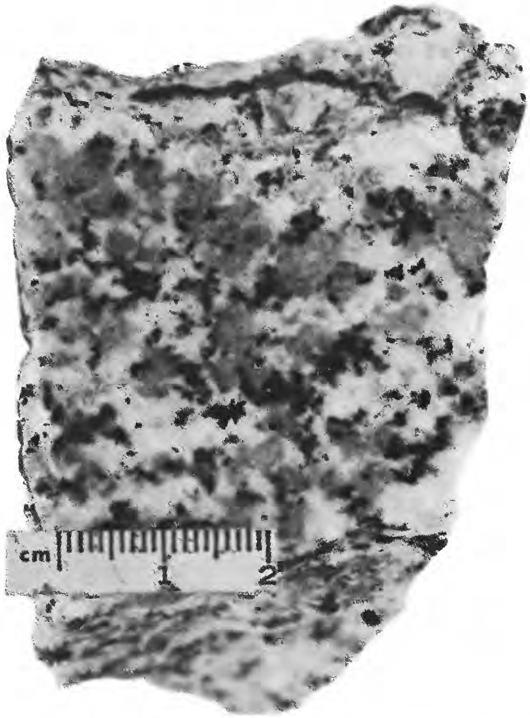

FIGURE 74.—Biotite granodiorite from the Duncan Hill pluton at south edge of the Lucerne quadrangle.

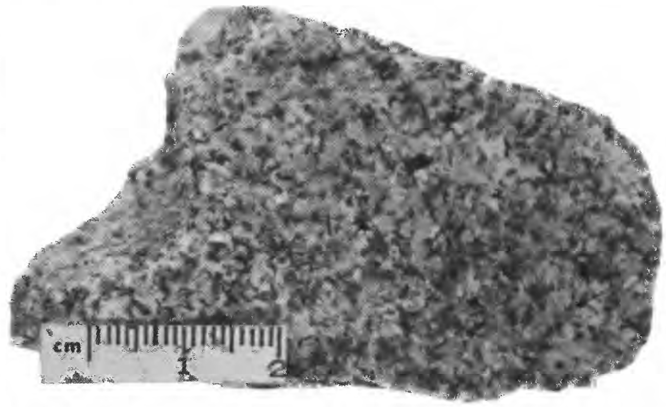

FIGURE 75.—Miarolytic biotite-quartz monzonite from the Duncan Hill pluton on Stormy Mountain, central Washington.

arrangement of andesine laths. The granodiorite contains a little more perthitic orthoclase than the quartz diorite, and both differ from the normal granodiorite of the general area in that the biotite is shredlike rather than euhedral. Examination of thin sections confirms the impressions gained from examination of outcrops that the quartz diorite had not solidified when invaded by granodiorite. Many andesine crystals in both rocks are bent, broken, and abraded, but the perthitic orthoclase that partly replaces andesine in both rocks is undeformed. The intrusive complexes are probably slightly younger than the main mass of granodiorite in this part of the pluton inasmuch as inclusions typical of the main mass containing euhedral books of biotite are common. These inclusions are rounded and have blurred borders but otherwise show no effects from immersion in magmas of the complex. No intrusive contacts between the complexes and the main mass of granodiorite were observed.

Near the south end of the pluton surrounding and below Stormy Mountain, the rocks are miarolytic biotite-quartz monzonite and granite (fig. 75) that grade upwards into quartz latite and rhyolite porphyry and downward and northward into granodiorite and quartz monzonite. These gradations are gradual, and except for later dikes, no intrusive or abrupt contacts between rock types exist. Above an altitude of about 1,450 m on Stormy Mountain, the rocks are miarolytic, some of them strikingly so, for they contain almost 10 percent voids; below this altitude, the rocks are nonmiarolytic.

The miarolytic quartz monzonite and granite vary considerably in appearance; the rocks lower down are light colored, massive, medium grained, and contain books of euhedral biotite so characteristic of the granodiorite and quartz monzonite that make up the bulk of the pluton. Higher up the slopes of Stormy Mountain, the rocks become increasingly porphyritic and finer grained. In thin section, the textural differences are greater than are differences in outcrop appearance, although compositions are fairly uniform. Above an altitude of about 1,700 m on the southwest spur of Stormy Mountain, the rocks are conspicuously granophyric; below that altitude, the textures more nearly resemble those of normal granodiorite and quartz monzonite. The granophyric rocks tend to be more porphyritic and the nongranophyric rocks more granitoid. Chemically and mineralogically, they are virtually identical (sample 8, granophyre, and samples 10 and 11, quartz monzonite, table 23).

A vast array of dikes and irregular masses of biotite-hornblende-quartz diorite, lamprophyres, pawdite, and aplite characterize the south end of the pluton, particularly near the contacts and as satellitic dikes extending far out into the host rocks. The granophyric core rocks are somewhat later than the dark rocks and cut them in most places. Both composition and texture are highly variable.

All the rocks at higher altitudes in the vicinity of Stormy Mountain, except for the dikes, consist of perthite, quartz, oligoclase, a little biotite, and very rarely hornblende. In outcrop, it is impossible to distinguish between rocks having the composition of quartz monzonite and those of granite. All the feldspar, except the exsolved albite in the perthite, is clouded with numerous, highly birefringent, unresolvable inclusions. Generally the clouding is of uniform intensity throughout the feldspars, and most of the minute inclusions are oriented along crystal directions of the feldspar. The oligoclase only rarely shows any zoning except progressive. A few oligoclase crystals have cores that have been saussuritized, and for a few where it was possible to determine the composition those cores are sodic labradorite, but for most crystals, the composition ranges between An_{33} in the core and An_8 on the rims; the average composition is about An_{24}. Biotite is partly altered to opaque minerals, and much of it greenish or mottled in brown and green colors. Some of the miarolytic cavities are partly filled with mordenite. The pervasive cloudy feldspars and partly altered biotite strongly suggest much deuteric activity, perhaps associated with degassing of the pluton.

The intricate intermixture of diverse igneous rocks, hornfels, and varied inclusions forming the contact complex around the north end of the pluton is probably best described as an agmatite. The igneous rocks in this agmatite are mostly either hornblende gabbro or quartz diorite, but intermediate varieties exist. The gabbroic parts of the complex are commonly sharply bordered, irregular masses, but the more granitic rocks may have either sharp or gradational contacts with any of the other rocks. Much of the igneous part of the complex, particularly the more felsic rocks, shows a pronounced streakiness resulting from strong protoclasis. Inclusions in the complex range from sharply bordered angular fragments of metamorphic rocks showing little effect from their sojourn in the igneous material to shadowy, rounded xenoliths with gradational borders. Many inclusions consist of slightly older igneous rocks in dikes of younger ones. Common also are masses of coarse-grained hornblendite as much as several meters across; these are commonly veined and seamed by dikelets of gabbro, diorite, or quartz diorite.

Although age sequences of various igneous rocks in an outcrop may be consistent, different sequences may occur in another outcrop, indicating that the rocks were for the most part nearly simultaneous injections, an impression that is heightened by the marble-cake mixtures of rocks in some outcrops. Much of the rock in the complex closely resembles rocks in nearby plutons, some of which are older and some younger than the Duncan Hill. Thus, some of the gabbro in the complex is practically identical to the nearby and older hornblende gabbro of the Riddle Peaks pluton. The small amounts of granodiorite and quartz monzonite in the complex apparently are later and closely resemble some of the post–Duncan Hill rocks in the area; however, the quartz diorite is probably from the Duncan Hill.

Most of the rocks in the contact complex are fairly fresh, although locally plagioclase is partly saussuritized, and mafic minerals are altered to chlorite. Uncontaminated hornblende gabbro consists of roughly equal proportions of plagioclase and hornblende with accessory opaque minerals and apatite. Plagioclase shows both oscillatory and patchy zoning, the zones ranging from rims as sodic as An_{33} to cores as calcic as An_{85}; the average composition ranges between calcic labradorite and sodic bytownite. Textures are either xenomorphic or hypidiomorphic; protoclastic modifications are common.

Quartz diorite in the contact complexes differs somewhat from most of the quartz diorite of the core but consists of plagioclase, quartz, biotite, and, in some places, hornblende as essential minerals. Opaque minerals, titanite, apatite, and a little allanite are accessory. Plagioclase is andesine, much of it showing both oscillatory and patchy zoning; zones range from about An_{25} on rims to An_{55} in some cores. Quartz may constitute as much as 25 percent of some of the rock and occurs either as a replacement of earlier formed minerals or as irregular folia, consisting of mosaics of interlocking grains. Textures range from hypidiomorphic to highly protoclastic; the decidedly protoclastic rocks are either streaky or strongly foliate. Seams of orthoclase are common in much of the quartz diorite and occur in some of the gabbro. Hybrid rock consisting of intricate mixtures of both gabbro and quartz diorite contain all the minerals common to the parent species; most striking is the occurrence of both bytownite and andesine in a single thin section in addition to plagioclase intermediate to these two extremes. Where not abraded by protoclasis, sodic rims on calcic plagioclase tend to be thicker in hybrid rock than in uncontaminated gabbro. All the hornblende, whether in gabbro, quartz diorite, hybrid rocks, or inclusions, is optically similar and is pleochroic in various shades of green. In some thin sections, the hornblende has been partly replaced by actinolite or biotite or both. Biotite is a late mineral in all the rocks, and even in some of the highly protoclastic varieties commonly shows little of the distortion or grinding that is so prevalent in plagioclase and hornblende. Alteration to chlorite is common only locally and may be related to other later small intrusions in the area, satellitic dikes of which cut the Duncan Hill pluton.

Inclusions range from little-changed blocks of host rocks to vague schlieren that differ little from the enclosing gabbro or quartz diorite. Most striking, however, are masses of hornblendite that may be several meters across. The hornblendite is coarse grained; the crystals commonly attain a length of 3 cm or more. The origin of the hornblendite is in doubt. The hornblende is optically similar to hornblende in the enclosing igneous rocks, and perhaps the hornblendite is merely made over from hornblende gneiss and schist inclusions brought up from depth that had spent a long time immersed in the magmas.

TABLE 23.—*Chemical and spectrographic analyses and norms of rocks from the Duncan Hill pluton, central Washington*

[For samples 1, 2, 4, 5, and 7, SiO_2, Al_2O_3, CaO, and K_2O determined by X-ray fluorescence; total Fe and MgO determined by atomic absorption; FeO determined volumetrically; Na_2O determined by flame photometer; TiO_2 determined by Tiron-colorimetric method; and P_2O_5 determined colorimetrically. Analysts: Violet Merritt, G. T. Burrow, J. P. Cahill, G. D. Shipley, and J. S. Wahlberg. For samples 3 and 6, SiO_2 and Al_2O_3 determined colorimetrically; Fe_2O_3, MnO, Zn, MgO, and CaO determined by atomic absorption; Na_2O and K_2O determined by flame photometer; FeO determined volumetrically. Analysts: G. T. Burrow, J. D. Mensik, Claude Huffman Jr., Wayne Mountjoy, and H. H. Lipp. For samples 8–11, SiO_2, Al_2O_3, Fe_2O_3, CaO, and K_2O determined by X-ray fluorescence; FeO and TiO_2 determined volumetrically; MgO and Na_2O determined by atomic absorption; and P_2O_5 determined colorimetrically. Analysts: G. T. Burrow, Johnnie Gardner, and S. D. Shipley. Spectrographic analyses by H. G. Neiman, Barbara Tobin, and L. A. Bradley. N.d., not determined. Leaders (- - -), below sensitivity level]

Sample	1	2	3	4	5	6	7	8	9	10	11
					Chemical analyses (percent)						
SiO_2	60.7	63.0	63.0	66.4	68.3	70.0	72.0	73.9	74.2	75.4	74.2
Al_2O_3	17.4	15.9	17.3	16.0	15.5	16.4	14.4	13.9	13.2	13.1	12.8
Fe_2O_3	1.97	1.52	.76	.73	.53	.49	.60	.71	1.11	.76	.52
FeO	4.34	4.40	4.45	3.06	2.13	2.53	1.86	.80	.62	.58	.52
MgO	2.23	2.47	1.6	1.33	1.13	0.81	.97	.16	.09	.11	.08
CaO	5.7	5.5	5.2	3.6	3.6	3.6	2.6	.90	.7	.6	.8
Na_2O	4.13	3.57	3.56	3.73	3.90	3.86	3.67	3.83	3.43	3.30	3.50
K_2O	1.5	2.0	2.13	2.8	2.6	2.40	3.3	5.3	5.6	5.7	5.5
TiO_2	.95	1.03	N.d.	.64	.44	N.d.	.42	.12	.12	.07	.06
P_2O_5	.39	.41	N.d.	.24	0.17	N.d.	.14	.08	.08	.08	.08
MnO	N.d.	0.15	.36	N.d.	N.d.	.055	.081	.02	.05	N.d.	N.d.
Zn	N.d.	N.d.	.009	N.d.	N.d.	.006	N.d.	.004	N.d.	N.d.	N.d.
Total	99	100	99	99	98	100	100	100	99	100	98
					Semiquantitative spectrographic analyses (parts per million)						
Ba	700	700	1,500	1,500	700	1,000	1,000	1,000	700	1,000	500
Be	1.5	1.5	---	1.5	---	---	---	1.5	1.5	1.5	1.5
Co	15	15	50	7	10	7	20	7	---	---	---
Cr	30	30	50	15	30	15	30	15	10	5	7
Cu	7	20	30	10	7	5	10	7	3	---	1
La	---	50	---	70	---	---	---	---	100	---	---
Nb	10	10	---	10	7	10	---	10	---	---	---
Ni	7	7	20	---	---	---	10	---	---	---	---
Pb	70	200	---	20	150	70	---	70	20	20	15
Sc	15	15	20	15	15	7	20	7	50	5	---
Sr	700	500	700	500	500	500	700	300	70	70	70
V	100	100	150	70	70	70	150	30	10	---	---
Y	15	15	15	15	15	10	15	15	30	15	10
Zn	---	---	---	150	500	300	---	---	---	---	---
Zr	150	150	70	150	30	70	70	150	150	70	70
Ce	---	---	---	---	---	---	---	---	200	---	---
Ga	30	30	20	20	15	15	20	20	30	20	20
Li	---	---	---	---	---	---	---	---	50	50	50
Yb	1.5	1.5	2	1.5	1.5	1.5	2	2	3	1.5	1
Nd	---	---	---	70	---	---	---	---	---	---	---
					Norms						
q	14.46	18.52	16.85	23.53	25.96	27.44	30.33	29.18	31.63	33.14	31.60
or	8.91	11.82	12.73	16.79	15.62	14.16	19.49	31.40	33.35	33.78	33.20
ab	35.27	30.20	30.45	32.01	33.55	32.59	31.02	32.48	29.24	27.99	30.24
an	24.55	21.46	25.22	16.53	17.03	17.83	11.97	3.95	2.97	2.46	3.04
di	1.07	2.59	.73	0	0	0	0	0	0	0	.40
hy	10.13	10.27	12.90	7.38	5.66	6.36	4.79	1.12	.34	.60	.44
c	0	0	0	.88	.14	.91	.40	.42	.42	.61	0
mt	2.87	2.21	1.12	1.07	.78	.71	.87	1.03	1.62	1.11	.77
il	1.81	1.96	0	1.23	.85	0	.80	.23	.23	.13	.12
ap	.93	.97	0	.58	.41	0	.33	.19	.19	.19	.19
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

TABLE 23.—*Chemical and spectrographic analyses and norms of rocks from the Duncan Hill pluton, central Washington*—Continued

Sample	1	2	3	4	5	6	7	8	9	10	11
					Plagioclase composition						
an	41.0	41.6	45.3	34.1	33.7	35.4	27.9	10.8	9.2	8.1	9.2

Sample descriptions

1. Hornblende-biotite-quartz diorite; north of Cool Creek.
2. Composite sample of hornblende-biotite-quartz diorite; Borealis Ridge.
3. Composite sample of hornblende-biotite-quartz diorite; Snow Brushy Creek.
4. Biotite granodiorite; Fern Lake.
5. Biotite granodiorite; Duncan Hill.
6. Composite sample of biotite granodiorite; ridge north of Crow Creek.
7. Composite sample of biotite granodiorite; Shady Pass road from1.5 to 3 km south of Lucerne quadrangle.
8. Miarolytic biotite-quartz monzonite granophyre; about 2.5 km northeast of Stormy Mountain.
9. Miarolytic biotite-quartz monzonite; 1.25 km southeast of Stormy Mountian, altitude 1,900 m.
10. Biotite-quartz monzonite, slightly miarolytic; 3 km southwest of Stormy Mountain, altitude 1,600 m.
11. Biotite-quartz monzonite; 5 km southwest of Stormy Mountain, altitude 1,450 m.

The composition and zoning of plagioclase provides considerable information on the course of differentiation in the pluton and imposes certain restrictions on the possible processes of differentiation. The most notable compositional change that takes place in plagioclase is a progressive decrease in average anorthite content from north to south in the pluton. On the other hand, except for the hypabyssal rocks at the south end of the pluton, the range of composition of cores of individual crystals remains virtually the same throughout its length; southward, however, the rims of crystals become increasingly thick and sodic. The plagioclase in quartz diorite north of Snow Brushy Creek has an average composition of medium andesine, commonly between An_{38} and An_{40}; the cores of larger crystals are sodic labradorite (An_{50} to An_{55}), but the rims are rarely more sodic than An_{33}. Plagioclase from rocks south of Snow Brushy Creek is sodic andesine and ranges in composition from about An_{33} to An_{37}, becoming more sodic to the south. The rims are as sodic as An_{18}, but the cores are similar to those in the plagioclase from quartz diorite to the north. Plagioclase in the hypabyssal rocks in the Stormy Mountain area is oligoclase, having a composition of about An_{24}; rims are as sodic as An_7, and few cores are more calcic than An_{30}.

Zoning of plagioclase crystals occurs in two contrasting styles, one confined to the hypabyssal rocks, the other to the rest of the pluton. Plagioclase in the hypabyssal rocks is progressively zoned; almost no crystals show either oscillatory or patchy zoning, and the rare ones that do are highly sericitized and show evidence of extensive resorbtion. Plagioclase from the remainder of the pluton typically shows both oscillatory and patchy zoning. Plagioclase in granodiorite and quartz monzonite is mostly rimmed by progressively zoned oligoclase. The width of these progressively zoned rims increases southward along the length of the pluton. Andesine in quartz diorite north of Snow Brushy Creek has no such rims or very thin ones.

The lack of oscillatory and patchy-zoned plagioclase crystals in the hypabyssal rocks is in marked contrast to the plagioclase crystals in the hypabyssal rocks in the nearby Miocene Cloudy Pass batholith and points to some marked differences in the late histories of the two intrusions; these are discussed later in the section on "Composition and differentiation."

Modal analyses of rocks from the Duncan Hill pluton are given in table 22 and the sample locations are shown in figure 76; modes are plotted in figure 77. Chemical analyses and calculated norms for various rocks in and related to the Duncan Hill pluton are given in table 23, appear on the variation diagram of figure 78, and are plotted on a traingular diagram in figure 79. The variation diagram illustrates well two rather striking features of the pluton: first, the uniformity of composition of the quartz diorite at the north end and the hypabyssal rocks at the south end of the pluton, and second, the wide variability of the rocks in between. The progressive changes in composition that occur along the length of the Duncan Hill pluton, aside from a few minor exceptions such as the small intrusive complexes in the vicinity of Fern Lake, are almost imperceptibly gradational and almost certainly are a reflection of vertical rather than lateral zoning. The differentiation processes responsible for the compositional zoning are discussed later in the section on "Composition and differentiation."

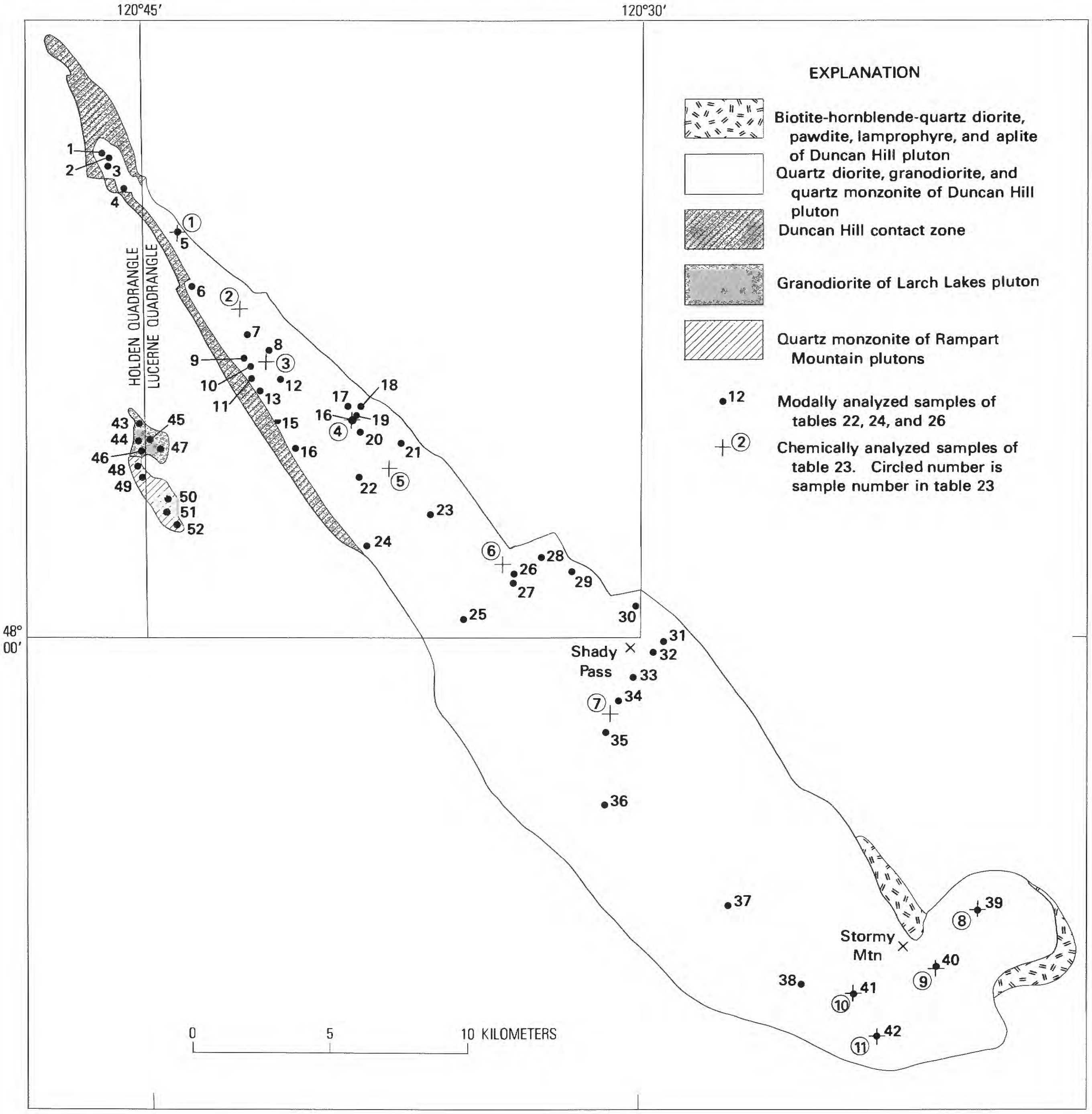

FIGURE 76.—Map showing location of chemically and modally analyzed samples of Duncan Hill, Larch Lakes, and Rampart Mountain plutons, central Washington.

LARCH LAKES PLUTON

Cropping out in the Larch Lakes cirque and on the ridge to the west, Lucerne quadrangle, is the biotite granodiorite of the Larch Lakes pluton. The pluton, an irregular mass nearly 2 km across in greatest dimension, intrudes the Entiat pluton, but its absolute age and relation to other dated intrusions are not known. Its close resemblance to known late Eocene intrusions and the fact that it cuts pawdite dikes and is cut by types of dikes that cut the plutons dated as late Eocene but not the Miocene Cloudy Pass batholith indicates that it, too, is late Eocene.

Rocks of the Larch Lakes pluton are light gray, usually

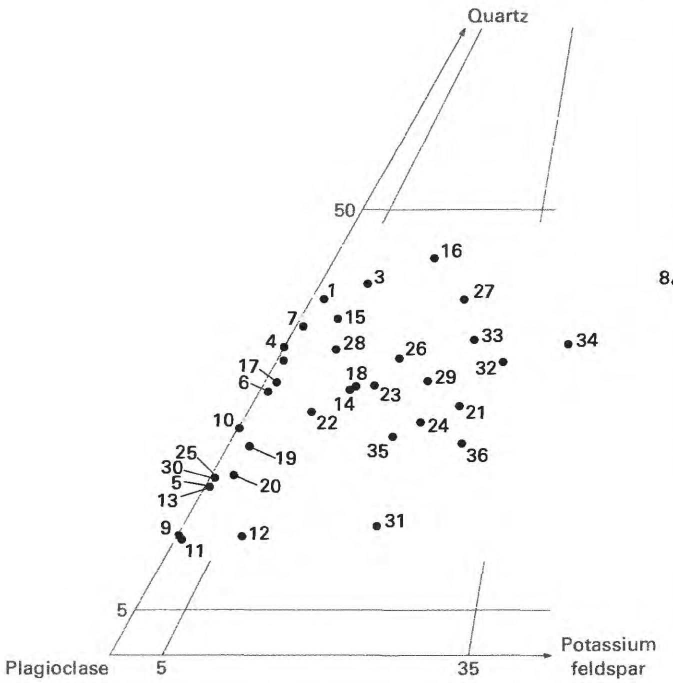

FIGURE 77.—Plot of modes of rock samples from the Duncan Hill pluton, central Washington, on a quartz-potassium feldspar-plagioclase diagram. Sample analyses given in table 22.

fine grained, homogeneous, and massive, but locally they are medium grained (fig. 80). They range in composition from quartz diorite to quartz monzonite, but most are granodiorite. Some show a slight foliation because of the parallel orientation of biotite flakes, and locally vague clusters of biotite crystals define a faint lineation in the plane of the foliation. Wherever observed, contacts are sharp and commonly transect the foliation of the host rocks.

Thin-section examination shows rocks of the pluton to consist of varying proportions of andesine, quartz, potassium feldspar, and biotite as primary minerals, and titanite, apatite, and opaque minerals as accessory constituents. Chlorite, sericite, and clinozoisite-epidote are secondary. Textures are hypidiomorphic granular and tend toward subparallel arrangements of andesine laths in some thin sections. The subhedral to euhedral crystals of andesine are strongly zoned and many show both oscillatory and patchy zoning. The range of composition of various zones in some crystals is as great as An_{15} to An_{45}, but the average composition in the biotite-quartz monzonite is about An_{32} and in the quartz diorite is between An_{37} and An_{40}. Quartz and potassium feldspar are interstitial; most of the potassium feldspar is slightly perthitic orthoclase but a little microcline was seen in one or two sections. Biotite occurs as reddish brown, highly pleochroic, anhedral shreds, much of it showing a rude alinement. Chlorite replaces a little of the biotite, and sericite and clinozoisite-epidote replace the

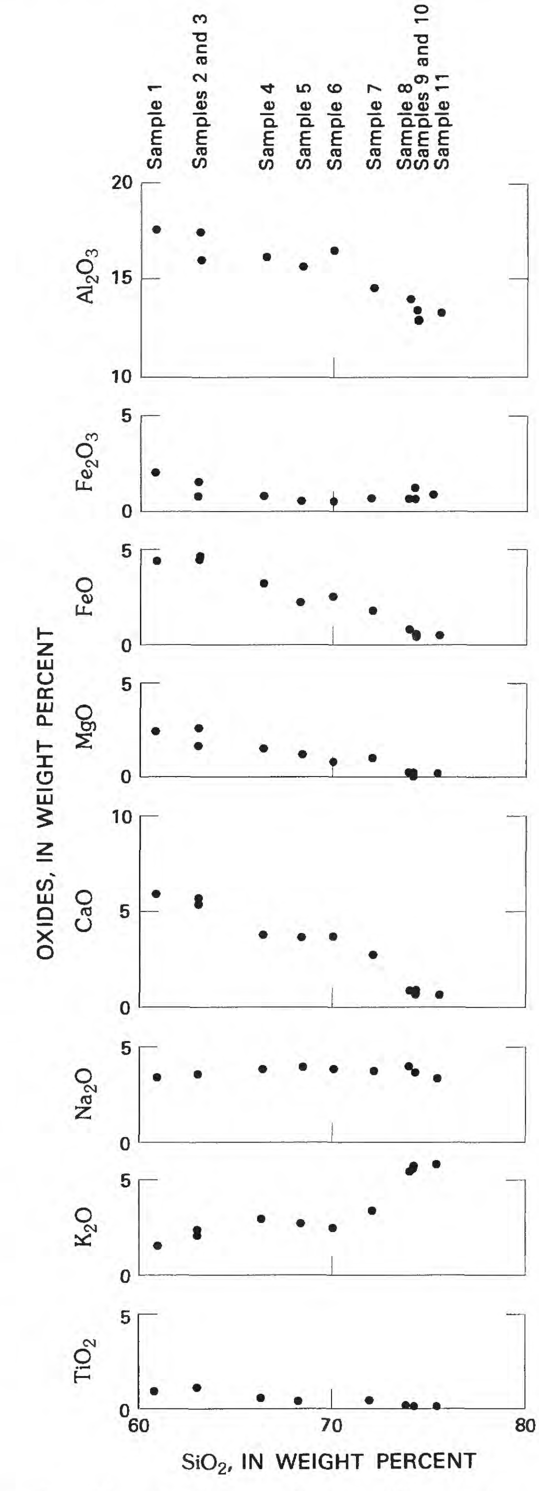

FIGURE 78.—Variation diagram of major oxides in rock samples from the Duncan Hill pluton, central Washington.

andesine, but the amounts of these minerals are small as the rocks are largely unaltered.

Locations of modally analyzed specimens are shown in figure 76. Modal analyses (fig. 81; table 24) indicate that

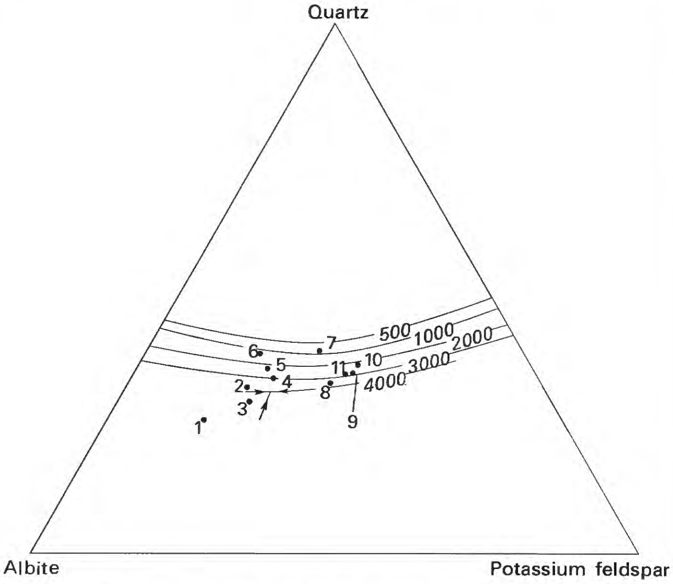

FIGURE 79.—Plot of norms of rock samples from the Duncan Hill pluton, central Washington, on a quartz-potassium feldspar-plagioclase diagram. Sample analyses are given in table 23. Isobaric lines mark position of the quartz-feldspar boundary at various water pressures. Arrows show position of ternary eutectic.

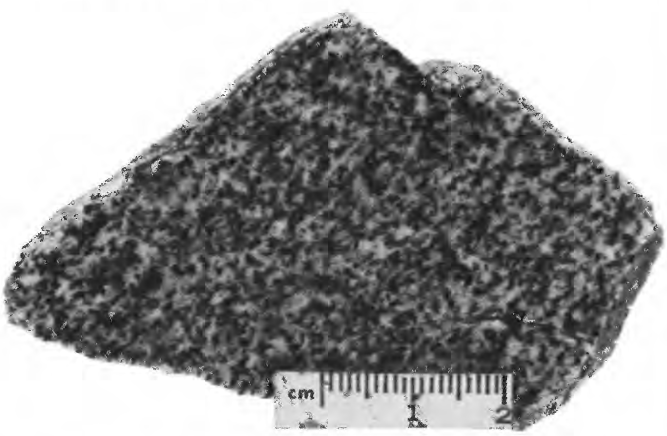

FIGURE 80.—Biotite granodiorite from the Larch Lakes pluton, Lucerne quadrangle.

the compositions of rocks in the Larch Lakes pluton occupy two distinct fields, one near the border between quartz diorite and granodiorite and the other near the middle of the quartz monzonite field. The chemical analyses (table 25) were made of specimens selected from the quartz diorite-granodiorite grouping. The differences between these rock types is scarcely apparent in hand specimen, and the two varieties were not separately mapped. A plot of the norms of the pluton is shown on figure 71.

The Larch Lakes pluton has removed and displaced its host rocks, which show no tendency toward being shouldered aside. The lack of inclusions or foundered blocks of host rocks in the pluton suggests that stoping was not particularly efficacious in providing space for the pluton.

RAMPART MOUNTAIN PLUTON

The Rampart Mountain pluton, cropping out between Rampart Mountain and Larch Lakes, is about 3 km long and about 1 km wide. It trends north-northwest more or less parallel to the trend of enclosing host rocks, cuts the Entiat pluton, and is in turn cut by porphyritic dikes. The north end of the pluton is in contact with the Larch Lakes pluton, but where observed it was impossible to determine which cut the other. The observed contact is gradational through a distance of 2 to 30 cm, and the faint foliation in both rocks is parallel to the contact. Neither rock includes fragments of the other, and the general appearance of the contact suggests that regardless of which was older, it was probably still partly molten when intruded by the younger.

The rocks in the Rampart Mountain pluton consist of light-gray, medium-grained, massive biotite granodiorite and quartz monzonite nearly identical to some of the more alkalic rocks of the Larch Lakes pluton (fig. 82). Some of the rocks are vaguely foliated because of the alinement of biotite flakes. Most of the rock is probably quartz monzonite, but the differences between quartz monzonite and granodiorite are not detectable in

TABLE 24.—*Modal analyses of samples of granodiorite from the Larch Lakes pluton, central Washington*

[Leaders (- - -), unable to determine]

Sample No.	Plagioclase	Potassium feldspar	Quartz	Biotite	Accessory and secondary minerals	Total mafic minerals	Anorthite in plagioclase crystals (percent)			Remarks
							Average	Core	Rim	
43	46.0	11.2	32.4	8.9	1.5	10.4	40	---	---	Fine grained; hypidiomorphic.
44	36.5	28.3	27.0	6.5	1.5	8.0	32	35	15	Fine grained; hypidiomorphic.
45	46.4	7.4	32.1	13.3	.8	14.1	40	60	20	Subparallel andesine crystals; fine grained.
46	53.1	5.2	27.2	13.5	1.0	14.5	37	---	---	Fine grained; hypidiomorphic.
47	36.3	28.1	29.1	4.7	.8	5.5	40	51	17	Subparallel andesine crystals; fine grained.

TABLE 25.—*Chemical and spectrographic analyses and norms of a composite sample of biotite granodiorite from the Larch Lakes pluton, central Washington*

[SiO_2 and Al_2O_3 determined colorimetrically; Fe_2O_3, MgO, CaO, and MnO determined by atomic absorption, FeO determined volumetrically; Na_2O and K_2O determined by flame photometer. Analysts: Wayne Mountjoy, J. D. Mensik, Claude Huffman, Jr., G. T. Burrow, H. H. Lipp. Spectrographic analyses by Barbara Tobin]

Chemical analyses (percent)		Semiquantitative spectrographic analysis (parts per million)		Norms	
SiO_2	69.5	Ba	1,000	q	25.85
Al_2O_3	16.7	Co	10	or	17.87
Fe_2O_3	.31	Cr	15	ab	33.66
FeO	2.33	Cu	3	an	14.95
MgO	.63	Ga	20	hy	5.73
CaO	3.0	Sc	10	c	1.49
Na_2O	3.96	Sr	700	mt	.45
K_2O	3.01	V	70	Total	100.00
MnO	.06	Y	15		
Total	100.00	Yb	1.5	Plagioclase composition	
		Zr	70		
				an	30.8

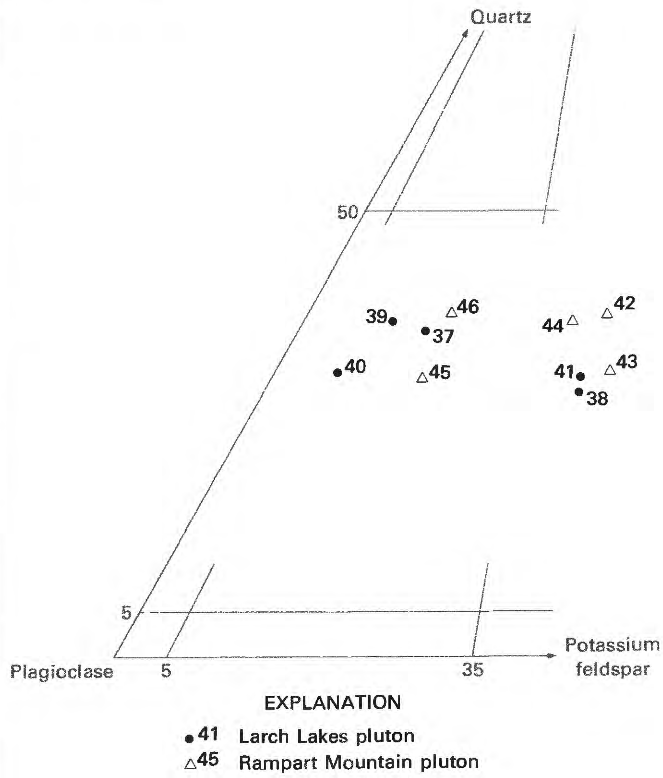

FIGURE 81.—Plot of modes of rock samples from the Larch Lakes and Rampart Mountain plutons, Holden and Lucerne quadrangles, on a quartz-potassium feldspar-plagioclase diagram. Sample analyses are given in tables 24 and 26.

outcrop. Contacts of the pluton with rocks other than the Larch Lakes pluton are sharp but irregular, and near the contact in some places, particularly on the west flank of Rampart Mountain, stoped blocks of host rocks are numerous and many dikes of biotite-quartz monzonite project short distances into the enclosing rocks.

The granodiorite and quartz monzonite of Rampart Mountain pluton consist of roughly equal amounts of oligoclase and quartz and more variable amounts of potassium feldspar. Biotite makes up 5 to 12 percent of the rock and muscovite 1 to 4 percent. Titanite, apatite, allanite, and magnetite are accessory. Epidote and sericite (some of the sericite is coarse enough to be called muscovite) replace both biotite and oligoclase, particularly the more calcic cores of oligoclase; chlorite and magnetite are alteration products of biotite.

Oligoclase is subhedral to anhedral, and shows oscillatory or progressive zoning and also patchy zoning. Some crystals are bordered by myrmekite where they are in contact with potassium feldspar. The oligoclase has an average composition of about An_{26}; the extreme range of composition within zones of a single crystal are from An_{15} on the rims to An_{32} in the cores, but commonly the range is only from about An_{20} to An_{28}. Quartz is interstitial or forms aggregates of small, interlocking grains. The potassium feldspar is either interstitial or forms irregular grains 2 or 3 mm across that enclose partly resorbed oligoclase crystals. Potassium feldspar mostly shows the grid twinning of microcline, but some is untwinned and presumably is orthoclase. In some crystals, parts are twinned and the rest untwinned. Untwinned material, whether making up either a part of or an entire

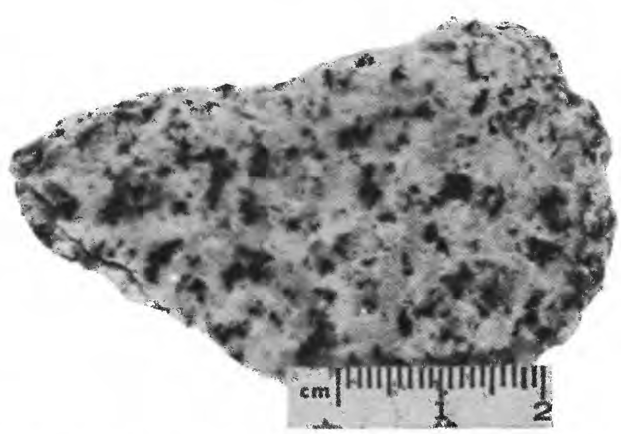

FIGURE 82.—Biotite-quartz monzonite from the Rampart Mountain pluton, Holden and Lucerne quadrangles.

crystal, is perthitic, whereas feldspar showing grid twinning is either nonperthitic or only slightly so. Biotite occurs as irregular, somewhat shreddy crystals that vary considerably in pleochroic characteristics; in some thin sections, the biotite is pleochroic in shades of brown, and in others, it is from light straw yellow to deep, almost opaque muddy brown. The relatively abundant muscovite in these rocks is unique among the late Eocene intrusives. It ranges from fine-grained sericitic material that is obviously secondary to flakes 1 mm across, some of which may be primary.

Epidote occurs in two distinct forms, that which replaces oligoclase and forms irregular small grains or granular masses, and that associated with or replacing biotite, which forms rather large, euhedral crystals as much as 1 mm or more across. One crystal of allanite was seen that was mantled by a thick overgrowth of epidote in crystal continuity. Chlorite is mostly negative penninite.

Textures are hypidiomorphic and seriate. Some sections show a vague subparallel arrangement of oligoclase grains suggestive of flowage. A slight tendency to protoclasis is apparent in a few sections.

Modal analyses are shown in fig. 81 and table 26, and a chemical analysis of a composite of a number of chips of typical rock is shown in table 27.

The Rampart Mountain pluton mostly removed the intruded rock, but the south end of the pluton on the west flank of Rampart Mountain thrust aside the enclosing rocks to some degree, and the prevalance of stoped blocks of these rocks suggests stoping was also effective in making room for the pluton.

OLD GIB VOLCANIC ROCKS AND ASSOCIATED DACITE PORPHYRY

Old Gib volcanic rocks and associated dacite porphyry were formerly thought to be correlative with the petrographically and chemically almost identical chilled rocks associated with the Miocene Cloudy Pass batholith (Cater, 1960), but a radiometric potassium/argon age by Joan Engels in 1967 indicates these rocks are 44 million years old and, hence, temporal equivalents of the other upper Eocene rocks of the area. The Old Gib rocks crop out in the southeastern part of the Holden quadrangle and are confined to the Chiwaukum graben, which downdropped prior to emplacement of the Cloudy Pass batholith but after or during emplacement of Old Gib rocks—which is probably why erosion did not completely remove them long ago. The amount the graben has been downdropped, relative to rocks outside the graben, cannot be measured, but unquestionably it must have been thousands of feet. Presumably the present exposed part of the Old Gib volcanic neck was fairly close to the surface at the time the neck formed because the rocks are of typical volcanic aspect and show columnar jointing. On the other hand, rocks of nearly if not exactly the same age, less than 2.8 km away but east of the graben—the Larch Lakes and Rampart Mountain plutons—have typical plutonic affinities rather characteristic of rocks emplaced at depths at least approaching the mesozone, that is, lack of chilled borders, miarolytic cavities, granophyric textures, or finer grained or porphyritic satellitic dikes.

The partly eroded volcanic neck on Old Gib Mountain is about 2.5 km long and about 1 km wide. It is elongated in a north-northwesterly direction parallel to the Entiat fault and the foliation of the enclosing rocks. Identical rocks also crop out near the floor of the Chiwawa River valley, west of Old Gib Mountain, but neither the shape of these masses nor their true size are known because they are largely concealed by glacial deposits. On Old Gib Mountain, cliffs of dacite porphyry in which vertical to steeply outward plunging, generally poorly defined columns a few meters across are visible locally, rise abruptly 300 to 450 m above the lower slopes underlain by metamorphic rocks (fig. 83). From some vantage points, the neck has a typical pillar-like form. The neck is devoid of fragmental or vesicular material, except for the remnants of a beveled Peléan spine exposed on the summit of the mountain. The lack of layered or bedded pyroclastic material, the nearly vertical contacts between volcanic and metamorphic rocks, and the generally poorly defined columnar joints suggest that none of the presently remaining neck was actually above ground level when the volcano was active. The dacite on Basalt Peak about 3.2 km south of the mapped area is identical to the dacite of the Old Gib neck and crops out at about the same elevation. The fact that Willis (1953,

TABLE 26.—*Modal analyses of samples of quartz monzonite from the Rampart Mountain pluton, central Washington*

[Leaders (- - -), unable to determine]

Sample No.	Plagioclase	Potassium feldspar	Quartz	Biotite	Accessory and secondary minerals	Total mafic minerals	Anorthite in plagioclase crystals (percent): Average	Core	Rim	Remarks
48	29.4	26.9	34.8	4.9	4.0	8.9	25	27	20	Orthoclase and microcline; protoclastic.
49	30.6	28.0	27.4	6.3	7.7	14.0	25	27	20	Some tourmaline; protoclastic.
50	32.8	23.5	33.8	9.0	.9	9.9	26	---	---	Hypidiomorphic.
51	43.6	12.0	24.8	10.2	9.4	19.6	26	---	---	Hypidiomorphic; coarse-grained, euhedral epidote.
52	37.8	11.1	30.5	10.5	10.1	20.6	26	32	15	Hypidiomorphic; coarse-grained, euhedral epidote.

TABLE 27.—*Chemical and spectrographic analyses and norms of a composite sample of biotite-quartz monzonite from the Rampart Mountain pluton, central Washington*

[SiO_2 and Al_2O_3 determined colorimetrically; Fe_2O_3, MgO, CaO, and MnO determined by atomic absorption; FeO determined volumetrically; Na_2O and K_2O determined by flame photometer. Analysts: Wayne Mountjoy, J. D. Mensik, Claude Huffman Jr., G. T. Burrow, and H. H. Lipp. Spectrographic analysis by Barbara Tobin]

Chemical analysis (percent)		Semiquantitative spectrographic analysis (parts per million)		Norms	
SiO_2	73.2	Ba	1,000	q	35.54
Al_2O_3	15.4	Cr	10	or	17.67
Fe_2O_3	.76	Cu	10	ab	32.01
FeO	1.57	Ga	20	an	11.33
MgO	.53	Sc	7	hy	3.66
CaO	2.3	Sr	500	c	1.69
Na_2O	3.81	V	70	mt	1.10
K_2O	3.01	Y	10	Total	100.00
MnO	.06	Yb	1		
Total	101	Zr	70	Plagioclase composition	
				an	26.1

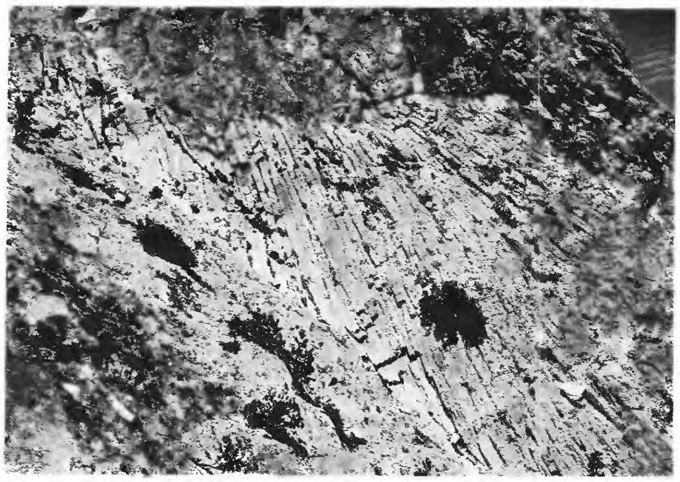

FIGURE 83.—Columnar joints in Old Gib volcanic neck and crosscutting basaltic dike, Holden quadrangle. Thickness of dikes about 4 m. Trees are less than 3 m high.

p. 793) believed these rocks formed a laccolith rather than a flow lends support to the supposition that the remaining rocks were below ground level when emplaced.

The contact of the neck and the enclosing gneiss is visible in only a few places, but in these it is sharp and is either vertical or dips steeply inward. The porphyry adjacent to the contact is chilled and contains scattered small inclusions of gneiss. Both gneiss and porphyry are slightly sheared and altered along the contacts and the porphyry has a vertical streakiness. Locally, the contact is slickensided as though the neck had moved upward as a solid pillar. No dikes were observed to radiate from the neck, although dikes believed to be related are common in nearby faults and shear zones. The northeast edge of the neck is faulted against gneiss and quartz diorite; the fault has been active both before and after the neck was intruded, for numerous small, unmapped dacite porphyry dikes have been intruded along the fault zone, and some of these have been sheared by post-intrusion movements along the fault.

The root of the Peléan spine near the center of the neck has an outcrop area about 200 m by 150 m but it is no longer preserved as a distinct topographic feature. The contact between the spine and the surrounding porphyry is a vertically fluted, slickensided surface that, in many places, dips steeply inward. Caught in the spine along the contact are scattered fragments of metamorphic and granitoid rocks that have been faceted and striated by dragging along the walls so that they look like glaciated pebbles. Some of the rocks in the spine possess a strong vertical sheeting that probably resulted from shear stresses that developed as the highly viscous lava moved upward (fig. 84). Parts of the spine have been shattered by explosions so that rocks range from fairly large masses of unbrecciated massive porphyry to thoroughly brecciated material containing scattered fragments of gneiss and granitoid rocks ripped from the walls of the conduit at depth. Solfataric emanations have altered some of the breccia to limonite-stained clay. Surrounding the spine are a few concentric, steeply dipping dikes that differ little from the rest of the porphyry. Gently dipping dikes of amygdaloidal basalt also cut the volcanic neck, but these are probably unrelated to the porphyries.

The Old Gib volcanic rocks, including the mass near the river west of Old Gib Mountain, Basalt Peak just south of the Holden quadrangle, and related nearby dikes, are medium-dark-greenish-gray, conspicuously porphyritic dacites and labradorite andesites. Most of

FIGURE 84.—Vertical sheeting in Peléan spine in Old Gib volcanic neck, Holden quadrangle.

the rock, particularly in masses west of Old Gib Mountain, is dacite and contains phenocrysts of sodic labradorite or calcic andesine, quartz, hornblende, biotite, and pseudomorphic nontronitic material; these are embedded in a greenish, fine-grained but holocrystalline groundmass. The labradorite andesite differs from dacite only in the lack of quartz phenocrysts. The phenocrysts of sodic labradorite, or calcic andesine, are euhedral and oscillatory zoned; zones within a single crystal may range from An_{75} to An_{35}. Many of these crystals are veined by albite. Most of the quartz crystals are rounded and resorbed, but a few are doubly terminated unresorbed pyramids. Fresh hornblende is rare as most of it has altered to fine-grained aggregates of chlorite, green nontronitic material, and lesser quantities of titanite and magnetite. Some of the hornblende and its alteration products preserve the outline of pyroxene crystals, but no unaltered pyroxene was seen. Biotite as brown euhedral crystals is fairly common in some localities but absent in others. Stilbite is common, some of it occurring along and wedging apart cleavage plates of biotite as does rare prehnite. The groundmass is a very fine grained aggregate of andesine, quartz, nontronite, and magnetite. Most plagioclase grains in the groundmass are equidimensional, have irregular indistinct borders, and contain numerous mafic inclusions, but some are lathlike and arranged in flow lines. In addition to andesine is considerable clear, fine-grained albite that replaces earlier formed minerals. The greenish color of the groundmass is due to chlorite and nontronite.

Chemical and spectrographic analyses and norms of dacite from Old Gib Mountain are given in table 28. The major oxides are plotted on a variation diagram (fig. 70) and the norms are plotted on figure 71.

TABLE 28.—*Chemical and spectrographic analyses and norms of a composite sample of dacite from the Old Gib volcanic neck, Holden quadrangle*

[Standard analysis by D. F. Powers. Spectrographic analysis by Harry Bastron and P. R. Barnett]

Chemical analysis (percent)		Semiquantitative spectrographic analyses (parts per million)		Norms	
SiO_2	64.46	B	15	q	27.24
Al_2O_3	16.15	Ba	700	or	9.26
Fe_2O_3	2.10	Co	7	ab	33.33
FeO	2.08	Cr	3	an	15.97
MgO	1.75	Cu	15	hy	6.19
CaO	3.93	Ga	7	c	2.63
Na_2O	3.82	Ni	3	mt	3.14
K_2O	1.52	Sc	15	il	.75
H_2O+	1.68	Sr	700	ap	.32
H_2O-	1.08	V	70	cc	1.17
TiO_2	.38	Y	15	Total	100.00
P_2O_5	.13	Yb	1.5		
MnO	.10	Zr	70	Plagioclase composition	
CO_2	.59				
Total	99.77			an	32.4

JOINTING IN VOLCANIC NECK

Well-defined curved columns, not to be confused with the columns previously mentioned, several centimeters to 1.5 m across but mostly less than 1 m, are common in the marginal porphyry. At the contact, these are horizontal and, hence, nearly normal to it, but within 3 to 5 m they bend upward to steep or nearly vertical attitudes. Farther inward these columnar joints die out, and the rock is irregularly jointed.

The growth of these curved columns poses a problem, for, as a rule, columns in volcanic rocks grow normal to isothermal surfaces (Waters, 1960; James, 1920). They grow in this direction because a mass of cooling magma is free to move or shrink normal to a cooling or isothermal surface (a contact, for example), whereas there is no freedom of movement parallel to this surface unless fracturing occurs. However, it is difficult to visualize how isothermal surfaces could curve sharply enough at the depths at which the columns probably formed around the base of Old Gib volcanic neck to account for the bending of the columns. Hunt (1938) offered an explanation for curved columns in volcanic necks that seems adequate to explain the phenomena he described when he pointed out that "At any given point, fracturing may be along either of two sets of planes, one dipping outward toward the sides of a pipe, the other dipping inward. The set dipping outward is favored by cracks extending downward from the surface because contraction is greater toward the sides than toward the center of the pipe." This mechanism, however, seems inadequate to explain the curved columns in the Old Gib volcanic neck because these formed at considerable depth, remote from the upper cooling surface, and the joints die out not many meters from the contact into irregular fractures. Obviously, columnar joints will grow normal to the surface of greatest tensile stress, a surface which normally is parallel to isothermal surfaces. But a column of magma, the molten core of which is moving as the marginal parts are solidifying and freezing to the walls of the conduit, develops dynamic stresses in these marginal parts, which are at angles to the thermal stresses resulting from cooling. Under these circumstances, columnar joints will not form normal to isothermal surfaces but to a surface of maximum tensional stress that will be some resultant plane; such joints would curve down if, at the time of their formation, the magma is moving up. It seems likely, however, that the magma was moving up at the time the marginal columns in the Old Gib volcanic neck formed, and if this is true, then the columns are curved in a direction opposite to what they should be if they are strictly tensional features. What seems to be a reasonable and possible explanation is that these columns started in the normal manner because of tension resulting from cooling, but that they were then extended partly because of continued tensional stresses resulting from continued cooling and partly because of shear stresses resulting from movement of the magma. Furthermore, they would curve to conform to direction of maximum shear and would therefore bend upward. Those joints more or less radial to the neck would continue as tensional fractures, whereas those more or less concentric to the walls of the neck would become shear fractures.

INTRUSIVE BRECCIA

On the east side of the valley at the head of Klone Creek are outcroppings of an intrusive breccia. Along the southwest side of the largest outcrop of breccia, hornblende-biotite diorite is exposed, but contacts with the breccia were not seen, and the relation of the breccia to other rocks is not known. Possibly the intrusive breccia may be related to the Cardinal Peak pluton, but the nature of the hornblende-biotite granodiorite forming much of the matrix of the breccia strongly suggests a kinship with the late Eocene intrusions. Some of the granodiorite closely resembles biotite-quartz monzonite and granodiorite, and some resembles the hornblende-biotite-quartz diorite. The intrusive breccia consists of blocks and lenses of various types of gneiss engulfed in granodiorite, and the whole is cut by much leucocratic granodiorite. The blocks and lenses of gneiss have a rude parallelism and trend N. 30°–70° E. and dip east at moderate angles. Much of the breccia and some of the porphyry dikes that cut it are badly shattered.

HORNBLENDE-BIOTITE-QUARTZ DIORITE

Hornblende-biotite-quartz diorite crops out extensively in the northwest quarter of the Lucerne quadrangle and the adjacent parts of the Holden quadrangle. Most of the bodies are dikes a few meters to a few tens of meters thick, but two masses, one on Ninemile Creek and the other south of Entiat Meadows, are 1.5 km or more across, and a third at the mouth of Tenmile Creek is nearly 1 km wide. Numerous dikes branch from these larger intrusions, and many of these—especially where they intrude the Cardinal Peak pluton—are rather low dipping. In many places, the hornblende-biotite-quartz diorite is closely associated with biotite-quartz monzonite and granodiorite, which it resembles in outcrop appearance, but wherever crosscutting relations could be determined, the quartz diorite is generally older and commonly occurs as inclusions in quartz monzonite and granodiorite. In the vicinity of the lower part of Ninemile Creek where biotite-quartz monzonite intricately intrudes the quartz diorite, however, the quartz diorite appears to have been at least still partly molten when the quartz monzonite was intruded. In the Holden mine, dikes and irregular masses consisting of intricate intermixtures of the hornblende-biotite-quartz diorite unit and the biotite-quartz monzonite and granodiorite unit containing abundant inclusions of gneiss, schist and ore are of common occurrence in Duncan Hill rocks (fig. 85).

Hornblende-biotite-quartz diorite is a gray, commonly foliated rock ranging from very fine grained (grains mostly 0.1 mm across or less) to fine medium grained (grains as much as 1.5 mm across) (fig. 86); some is distinctly porphyritic, containing phenocrysts of andesine and biotite about 5 mm across. Grain size seems to bear little relation to the size of intrusion; the larger masses are rather fine grained throughout but vary somewhat from place to place; dikes are more variable and include both the finest and coarsest grained rocks. Probably the most characteristic feature is a pervasive foliation resulting from the parallelism of biotite flakes. This foliation, which ranges from nearly imperceptible to strong, is a flowage feature and usually parallels the nearest contacts, but in some places it is swirled.

Contacts with older rocks are sharp in most places or gradational through only a centimeter or two, but where the hornblende-biotite-quartz diorite invades hornblende gabbro of Riddle Peaks the contact is highly irregular, although sharp. Near the contact with hornblende gabbro, the quartz diorite contains abundant inclusions of gabbro, but inclusions of other rocks, such as quartz diorite and granodiorite of Cardinal Peak,

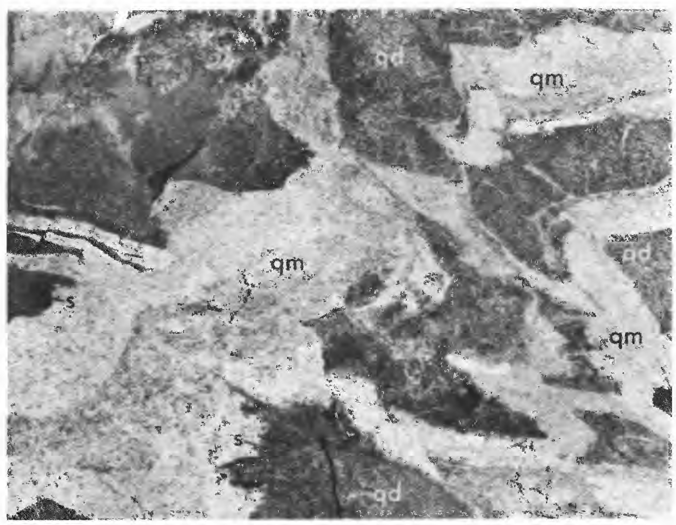

FIGURE 85.—Intermixed hornblende-biotite-quartz diorite (qd), biotite-quartz monzonite (qm), and inclusions of biotite schist(s), showing various stages of alteration, at the Holden mine, Holden quadrangle. Width of photographed area about 1 m.

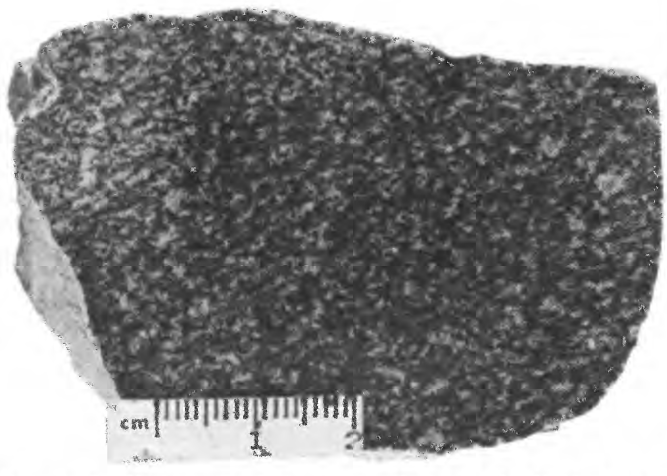

FIGURE 86.—Hornblende-biotite-quartz diorite in the Holden mine, Holden quadrangle.

or of metamorphic rocks, are rare. Where the hornblende-biotite-quartz diorite has been intruded by later rocks, particularly the biotite-quartz monzonite and granodiorite, the contacts are complex and irregular. East of Ninemile Creek is an intrusive contact between the Railroad Creek pluton and the hornblende-biotite-quartz diorite. Here the Railroad Creek pluton has numerous irregular dikes in the quartz diorite, and the Railroad Creek rocks have a streaky appearance owing to protoclasis that parallels the contact.

Thin sections of hornblende-biotite-quartz diorite show the rock to consist of 50 to 60 percent plagioclase, 20 to 30 percent quartz, 7 to 15 percent biotite, 0 to 8 percent hornblende, and generally less than 1 percent potassium feldspar. Titanite, allanite, and apatite are accessory. Andesine, having an average composition of about An_{40}, is the predominant plagioclase, but in some rocks, otherwise indistinguishable, the plagioclase may have an average composition as sodic as An_{32}, and in the mass centering around Ninemile Creek, much of the plagioclase is sodic labradorite and the rock is a quartz gabbro. Plagioclase is strongly zoned; some crystals range from cores of An_{60} to rims of An_{20}. Scattered crystals occurring as phenocrysts in the slightly porphyritic varieties have patchy zoning and numerous oscillatory zones, whereas the crystals in the groundmass show fewer oscillatory zones but very strong progressive zoning. Quartz is either interstitial or occurs as an aggregate of interlocking, sutured grains. Orthoclase is rare and interstitial. A little myrmekite borders some of the orthoclase grains where they are in contact with plagioclase. Biotite occurs as highly pleochroic shreds ranging from light straw yellow to dark, almost opaque muddy brown. Hornblende is either anhedral or subhedral; most of it is pleochroic in shades of green, but some, especially that in some of the gabbroic facies, is nearly colorless and only slightly pleochroic. Alteration products are rare in most rocks, but some of the mafic minerals are chloritized, and most sections contain a little epidote.

Textures are typically hypidiomorphic and commonly have a fairly strong alinement of plagioclase laths, biotite flakes, and hornblende needles, suggestive of flowage. Much of the rock is slightly porphyritic and is characterized by a few scattered phenocrysts of euhedral plagioclase.

Modal analyses (table 29; fig. 87) show that these rocks vary in composition more than most of the late Eocene intrusive rocks. Chemical analyses are shown in table 30, and the norms are plotted in figure 71. Locations of modally analyzed specimens are shown in figure 88.

TABLE 29.—*Modal analyses of samples of late Eocene hornblende-biotite-quartz diorite, central Washington*

Sample No.	Plagioclase	Potassium feldspar	Quartz	Biotite	Hornblende	Accessory and secondary minerals	Total mafic minerals	Anorthite in plagioclase crystals (percent)			Remarks
								Average	Core	Rim	
9	52.2	0.3	32.2	14.7	0.3	0.3	15.3	43	60	20	Hypidiomorphic.
11	56.4	.4	29.5	10.8	2.7	.2	13.7	41	60	22	Do.
12	56.2	.7	33.1	2.6	1.1	6.3	10.0	37	55	22	Subparalled mineral alinement; hypidiomorphic.
21	50.5	1.4	29.4	13.5	5.0	.2	18.7	40	56	23	Slightly porphyritic.
22	54.0	.3	25.7	13.0	5.9	1.1	20.0	40	52	21	Subparallel mineral alinement; hypidiomorphic.
23	54.7	1.6	27.3	11.3	3.6	1.5	16.4	37	43	23	Hypidiomorphic-protoclastic.
42	52.2	.3	32.2	14.7	.3	.3	15.3	38	51	21	Hypidiomorphic.
43	61.8	.1	18.8	12.9	6.0	.4	19.3	38	42	29	Subparallel mineral alinement; hypidiomorphic.
44	61.2	1.6	19.1	15.4	1.1	1.6	18.1	37	47	20	Subparallel andesine laths; hypidiomorphic.
45	57.6	0	22.9	16.1	2.8	.6	19.5	40	54	30	Subparallel mineral alinement; hypidiomorphic.
46	53.8	2.5	26.4	13.4	2.7	1.2	17.3	37	43	23	Subparallel mineral alinement; xenomorphic.

TABLE 30.—*Chemical and spectrographic analyses and norms of a composite sample of late Eocene hornblende-biotite-quartz diorite, central Washington*

[SiO_2 and Al_2O_3 determined colormetrically; Fe_2O_3, MgO, CaO, and Mn determined by atomic absorption; Na_2O and K_2O determined by flame photometer; FeO determined volumetrically. Analysts: Violet Merritt, H. H. Lipp, G. D. Shipley, and G. T. Burrow. Spectrographic analysis by Harriet Neiman]

Chemical analysis (percent)		Semiquantitative spectrographic analysis (parts per million)		Norms	
SiO_2	66.5	Ba	500	q	28.52
Al_2O_3	14.4	Co	15	or	8.35
Fe_2O_3	4.45	Cr	30	ab	28.72
FeO	3.5	Cu	15	an	19.48
MgO	2.16	Ga	20	hy	8.29
CaO	3.92	Ni	10	c	.18
Na_2O	3.39	Pb	10	mt	6.46
K_2O	1.41	Sc	20	Total	100.00
MnO	.08	Sr	700		
Total	100.00	V	150	Plagioclase composition	
		Y	20		
		Yb	2	an	40.4
		Zr	100		

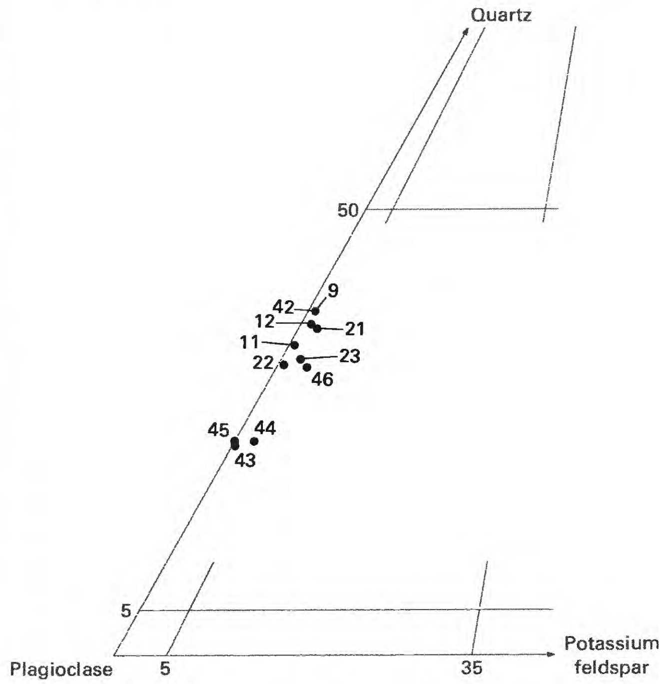

FIGURE 87.—Plot of modes of hornblende-biotite-quartz diorite samples from Holden and Lucerne quadrangles on a quartz-potassium feldspar-plagioclase diagram. Sample analyses are given in table 29.

RAILROAD CREEK PLUTON AND ASSOCIATED ROCKS

The Railroad Creek pluton occupies the northwest part of the Lucerne quadrangle, adjacent parts of the Holden quadrangle, and extends an undetermined but probably short distance farther north. It has a maximum width of about 6.5 km. Identical rocks believed to connect with the pluton under Bearcat Ridge crop out between Bear Creek and Lake Chelan; smaller masses crop out west of Mirror Lake and on the ridge north of the head of Little Creek. Satellitic dikes and small irregular masses are widely scattered over much of the northern part of the Lucerne quadrangle.

The Railroad Creek pluton, consisting largely of granodiorite, is elongate roughly parallel to the strike of the foliation of the host rocks, and locally the contact is concordant, but in most places the contact cuts across the foliation or layering at various angles. In general, contacts are sharp, but the characteristics of the contact and the border rocks near the contact vary from place to place. East of Domke Lake, the contact is sharp, the granodiorite is massive, and the enclosing gneiss appears to be unaffected. In most places, however, the granodiorite becomes increasingly foliated as the contact is approached, and a few meters of the adjacent host rocks are somewhat granitized. In many places, the host rocks near the contact are interlayered with and cut by numerous dikes of granodiorite. Particularly complex is the contact between the Railroad Creek pluton and the hornblende gabbro north of Riddle Peaks. Here a septum of hornblende gneiss separating the hornblende gabbro from the pluton is intricately riddled with dikes of granodiorite, some of which extend into the hornblende gabbro. Abundant inclusions of both gneiss and hornblende gabbro occur in the granodiorite near the contact. Inclusions are also numerous in many other places near the contact, but are generally rare nearer the center of the pluton. At no place were seen contact complexes characterized by coarse hornblendite similar to those bordering some of the older hornblende-quartz diorite plutons. The pluton widens at depth; the southwest contacts dip outward, whereas the northeast contact is nearly vertical and dips steeper than the enclosing gneisses.

Contacts of dikes and small masses related to the Railroad Creek pluton are sharp, and margins of some of the smaller dikes are chilled. The contact of the large dike on Ninemile Creek locally forms lit-par-lit zones.

There has been some tendency for the pluton to force or shoulder aside the host rocks; gneisses adjacent to the contact are crumpled, but for the most part the pluton seems to have made room for itself by some other means as is evident near Lucerne Mountain and near Bear Creek, where enclosing rocks were removed or destroyed. Undoubtedly, stoping was one means by which the pluton made room for itself, but the scarcity of inclusions of country rocks, except locally near contacts, suggests the process was not a major factor. Replacement and granitization fusion seem to have played even a smaller role in solving the pluton's room problem—at least to the depth presently exposed.

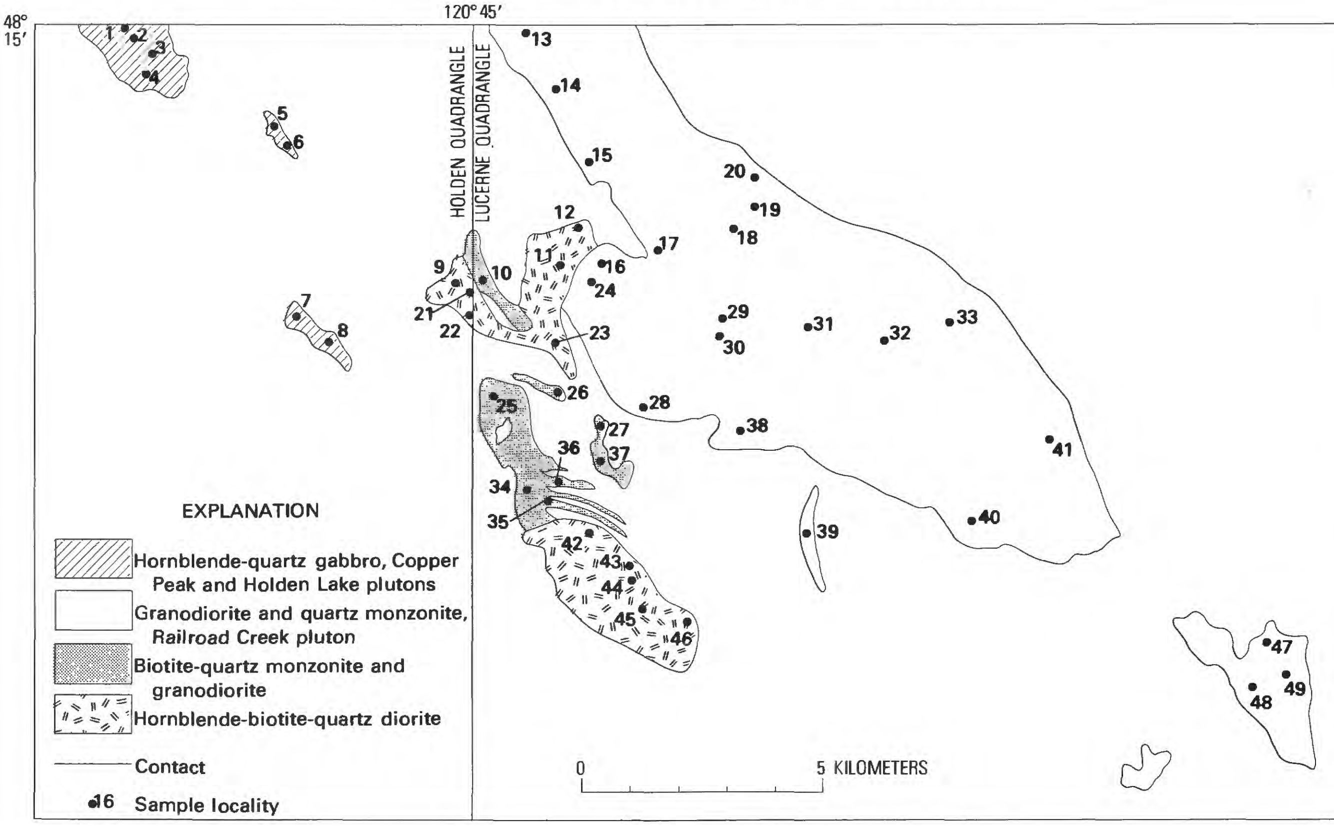

FIGURE 88.—Map showing location of modally analyzed samples from late Eocene plutons, central Washington.

The rocks of the pluton vary both in composition and in texture. Most of the rock is granodiorite but also included are quartz diorite and quartz monzonite. Quartz monzonite, in particular, is conspicuous because it forms lighter colored, irregular masses that in some places cut the somewhat older granodiorite; elsewhere quartz monzonite grades into granodiorite as does quartz diorite. The typical granodiorite and quartz diorite are indistinguishable in outcrop and are light gray and medium grained (fig. 89). Most of the rock is massive and structureless, but near contacts, some is foliated and commonly contains more hornblende than elsewhere. The quartz monzonite is texturally similar but is light gray to white, and some is stained because of oxidized pyrite, a rather common constituent mineral in much of the quartz monzonite. No attempt was made to separate the different kinds of rock on the map because of their generally gradational nature, the mapping time limitations, and dense brush, but the impression was that distribution of rock types was erratic.

The rocks of the Railroad Creek pluton contain variable amounts of plagioclase, quartz, potassium feldspar, biotite, and hornblende; titanite, apatite, and zircon are accessory. Chlorite, sericite, epidote-clinozoisite, and opaque minerals are alteration products. Other minerals found in some specimens are

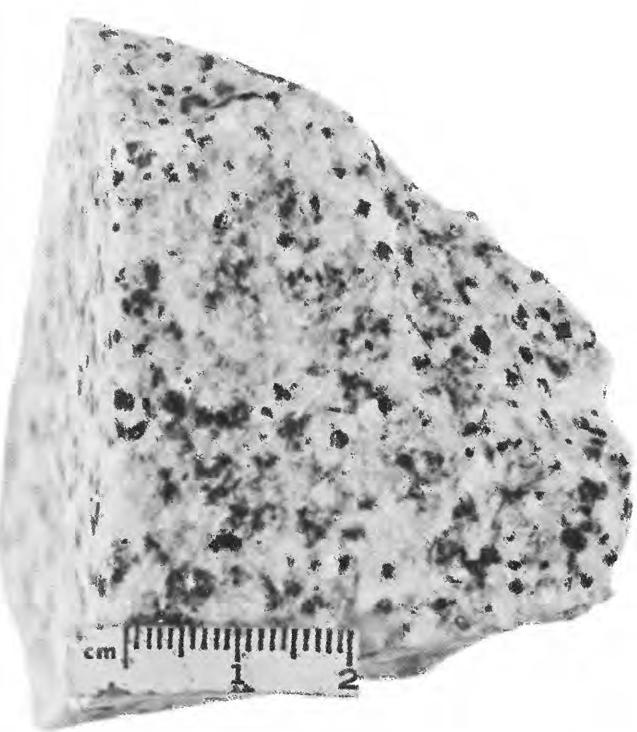

FIGURE 89.—Biotite granodiorite from the Railroad Creek pluton, Lucerne quadrangle.

muscovite, allanite, and pyrite. Most of the rocks are hypidiomorphic granular, but near the contacts some of the rocks are protoclastic. Plagioclase occurs as irregular to euhedral grains from a fraction of a millimeter to as much as 3 mm across. Most of the larger grains are oscillatorily zoned, and many show patchy zoning; the extreme observed range of composition was from An_{16} on the rims of crystals to An_{58} in the core, but the usual range was about An_{20} to An_{40}. Average composition of plagioclase in most of the quartz diorite and granodiorite was about An_{37}, but in some of the leucocratic quartz monzonite, the average composition was An_{25}. Calcic cores of crystals in some sections are clouded with sericite. Nearly all grains show albite twinning, and combined Carlsbad-albite twinning is common; twinning according to other laws, particularly pericline, occurs but is less common. Grains of plagioclase that are in contact with orthoclase are mostly rimmed by myrmekite.

Most of the potassium feldspar is orthoclase, but some microcline occurs in a few sections. Most of the orthoclase is microperthitic. All the potassium feldspar is anhedral and is either interstitial or replaces earlier formed minerals.

Quartz is also late and either replaces other minerals or is interstitial. Much of it occurs as irregular mosaics of grains having interlocking, sutured borders; but single interstitial grains and myrmekitic intergrowths are numerous. Nearly all the quartz, except for that in myrmekite, is strained and shows flamboyant extinction.

Biotite is the most abundant of the mafic minerals and in some thin sections, the only primary mineral. Much of it occurs as irregular anhedral shreds, but faces of many crystals parallel to cleavage are well defined. Locally, particularly near the contacts, the biotite flakes are subparallel and impart a foliation to the rock. The pleochroic formula is generally X, light yellow; Y = Z, reddish-brown. Some of the biotite has partly altered to chlorite. Small amounts of hornblende are present in most sections, but generally only rocks near the contacts contain more than 1 or 2 percent. Crystals form elongate anhedra that have been partly resorbed, or they may be euhedral and show well-formed six-sided sections. Some show replacement by biotite. Most hornblende is pleochroic in various shades of green. In the pass at the head of Riddle Creek, hornblende in rocks near the contact are pleochroic from yellowish brown to bluish green. This hornblende may be relict from the invaded gabbro; in fact, much of the hornblende commonly present near contacts may be the result of contamination.

Titanite is the most conspicuous of the accessory minerals but is less common than in many other plutons of the area. Most of it occurs as typical diamond-shape grains as much as 2 mm long, but some is anhedral. A grain or two of allanite was seen in a few sections, but it is far less common than in the Duncan Hill pluton. Tiny scattered needles of apatite are ubiquitous. Grains of zircon much less than 1 mm across are common in biotite flakes where they are bordered by pleochroic halos.

Most of the Railroad Creek rocks are fairly fresh, and none are badly altered. In most thin sections, however, a little of the biotite has altered to chlorite, and less commonly, calcic cores of plagioclase show some dusting with sericite. Occasional granular aggregates of clinozoisite replace plagioclase, and epidote replaces mafic minerals. Pyrite replaces biotite in some of the light-colored quartz monzonite.

Larger dikes and irregular intrusive masses related to the Railroad Creek pluton closely resemble rocks in the pluton, but smaller dikes and masses are generallv finer grained or slightly porphyritic (fig. 90). Some have chilled, fine-grained margins. A greater range of compositions occurs in the dikes than in the main pluton. Some of the dikes in the Riddle Peaks area are rather fine grained, nearly white, and contain only 5 to 7 percent dark minerals and yet have no potassium feldspar and hence are quartz diorites. These have hypidiomorphic, seriate textures. Other dikes of similar appearance in the same area have almost xenomorphic textures and contain nearly equal amounts of plagioclase and potassium feldspar. Most of these are foliated because of alined biotite flakes.

Modal analyses (table 31; fig. 91) indicate a considerable spread in composition. Location of modally analyzed specimens are shown in figure 88. Chemical and spectrographic analyses and norms are given in table 32, and a plot of the norms in figure 71.

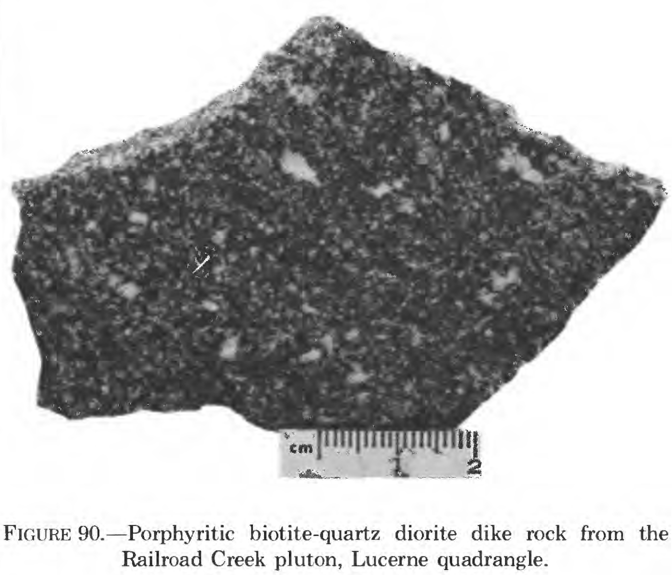

FIGURE 90.—Porphyritic biotite-quartz diorite dike rock from the Railroad Creek pluton, Lucerne quadrangle.

TABLE 31.—*Modal analyses of samples of granodiorite and quartz monzonite from the Railroad Creek pluton, Lucerne quadrangle*

[Leaders (- - -), unable to determine]

Sample No.	Plagioclase	Potassium feldspar	Quartz	Biotite	Hornblende	Accessory and secondary minerals	Total mafic minerals	Anorthite in plagioclase crystals (percent) Average	Core	Rim
13	52.7	7.3	23.3	0.3	1.9	14.5	16.7	35	38	25
14	43.7	1.5	36.4	7.5	10.5	.4	18.4	38	40	23
15	65.7	0	25.9	6.7	.6	1.1	8.4	38	48	33
16	35.4	26.0	27.7	3.6	6.4	.9	10.9	---	---	---
17	59.4	3.2	20.6	13.9	2.5	.4	16.8	---	---	---
18	31.3	32.1	32.7	3.3	0	.6	3.9	---	---	---
19	39.2	4.7	40.9	14.2	.8	.2	15.2	36	---	---
20	38.6	18.0	32.3	10.7	0	.4	11.1	---	---	---
24	45.9	15.0	27.1	11.2	0	.8	12.0	---	---	---
28	44.0	8.8	27.2	16.9	2.1	1.0	20.0	32	40	18
29	36.4	12.0	26.3	23.3	1.0	1.0	25.3	---	---	---
30	55.6	4.4	27.0	10.0	1.8	1.2	13.0	---	---	---
31	52.0	11.2	30.8	5.3	.4	.3	6.0	37	58	17
32	46.0	6.4	38.1	9.0	.3	.2	9.5	38	40	20
33	48.0	9.3	28.7	8.2	3.9	1.9	14.0	28	41	18
38	54.3	13.1	21.1	17.3	3.7	.5	21.5	---	---	---
39	54.1	12.9	23.4	8.4	.6	.6	9.6	---	---	---
40	40.9	20.4	32.3	5.7	0	.7	6.4	---	---	---
41	51.2	17.3	26.4	4.8	0	.3	5.1	---	---	---
47	31.6	26.1	39.8	1.8	0	.7	2.5	---	---	---
48	37.5	20.6	32.2	9.2	0	.5	9.7	---	---	---
49	59.3	4.3	28.6	7.6	0	.2	9.8	40	48	16

TABLE 32.—*Chemical and spectrographic analyses and norms of a composite sample of biotite granodiorite from the Railroad Creek pluton, Lucerne quadrangle*

[SiO_2 and Al_2O_3 determined colorimetrically; Fe_2O_3, MgO, CaO, and MnO determined by atomic absorption; FeO determined volumetrically; Na_2O and K_2O determined by flame photometer. Analysts: Wayne Mountjoy, J. D. Mensik, Claude Huffman Jr., G. T. Burrow, and H. H. Lipp. Spectrographic analyses by Barbara Tobin]

Chemical analysis (percent)		Semiquantitative spectrographic analysis (parts per million)		Norms	
SiO_2	70.1	Ba	1,000	q	28.95
Al_2O_3	15.6	Co	10	or	15.01
Fe_2O_3	.34	Cr	20	ab	33.60
FeO	2.13	Cu	5	an	15.63
MgO	.66	Ga	30	hy	5.47
CaO	3.1	Ni	10	c	.84
Na_2O	3.91	Sc	10	mt	.50
K_2O	2.50	Sr	500	Total	100.00
MnO	.05	V	100		
Total	98	Y	15	Plagioclase composition	
		Yb	1.5		
		Zr	150	an	31.7

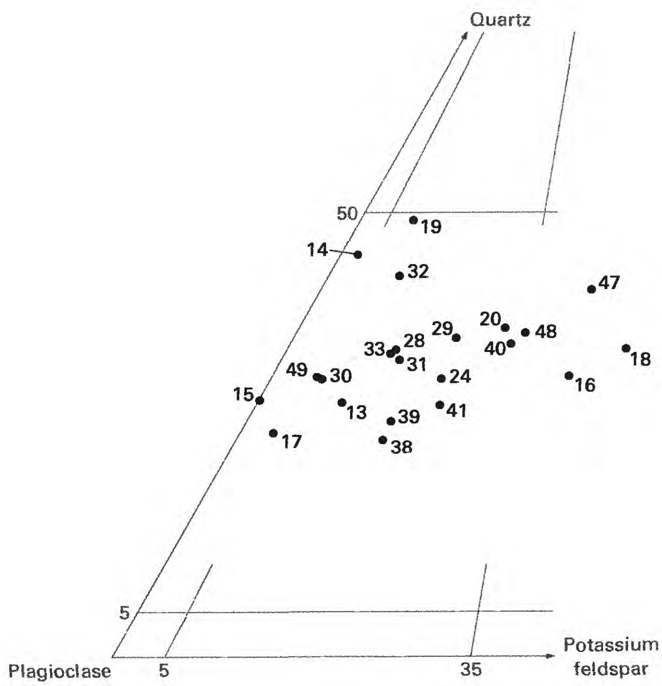

FIGURE 91.—Plot of modes of granodiorite and quartz diorite samples from the Railroad Creek pluton, Lucerne quadrangle, on a quartz-potassium feldspar-plagioclase diagram. Sample analyses are given in table 31.

COPPER PEAK AND HOLDEN LAKE PLUTONS

The Copper Peak and Holden Lake plutons are shown on the geologic map of the Holden quadrangle (Cater and Crowder, 1967) as of questionable Miocene age. They were so considered because of their general lack of similarity to other late Eocene rocks, their rather close resemblance to the labradorite quartz diorites of the Miocene Cloudy Pass batholith, and the fact that dikes satellitic to the Copper Peak pluton in the Holden mine are postore, whereas the ore is genetically related to the Duncan Hill pluton. Later investigation, however, indicated that in places these plutons are cut by the late Eocene biotite-quartz monzonite and granodiorite and, hence, are older, but because the quartz gabbro of the plutons cuts ore, the plutons are also late Eocene.

The Copper Peak and Holden Lake plutons consist of hornblende-quartz gabbro, a rock that also forms numerous dikes and an elongate mass about 2.5 km east of Holden Lake. Largest of the intrusions is the Holden Lake pluton north of Holden Lake, which has a width of about 1.5 km and extends from an unknown distance north of the quadrangle more than 2 km into it. The Copper Peak pluton crops out on the north side of Copper Peak and is a little more than 1.5 km long and about 0.5 km wide, although dikes of the rock are widespread as much as 1.5 km farther west.

Contacts of all masses, except in the two larger plutons, are sharp, but in these two, contacts are either sharp or consist of spectacular contact complexes. Complexes associated with the Copper Peak pluton are particularly spectacular because much of the pluton intrudes the intricate melange of rocks constituting the contact complex surrounding the northwest end of the Duncan Hill pluton. Here, unfortunately, exposures are rather poor, the brush dense, and it was impractical to attempt to unravel the incredibly complicated mixture of rock types. Hornblendite, gabbro, diorite, quartz-bearing rocks, partly assimilated gneisses, and all possible gradations between rock types are stirred together in chaotic jumbles. The contact complex bordering the southwest side of the Holden Lake pluton is well exposed, however, and here the hornblende-quartz gabbro intrudes its own contact complex, and the contact between the two is sharp. Where visible elsewhere, the hornblende-quartz gabbro grades into its bordering complex. At contacts of gabbro and hornblende-quartz diorite gneiss, the host gneiss loses its foliation, the grain size coarsens, and the rock becomes compositionally heterogeneous. Irregular dikes and masses of mostly leucocratic gabbro engulf blocks of host rocks or penetrate them as lit-par-lit injections. Many of the thinner dikelets of leucocratic gabbro contain a central layer of coarse hornblende crystals. Examination of thin sections shows that minerals of the host rocks in the complex have reverted to the same compositions as those of the minerals in the injected igneous material, although the crystalloblastic texture of the nonigneous material is retained.

Hornblende-quartz gabbro is a medium-grained, gray, massive rock, in which plagioclase, hornblende, quartz, and varying quantities of biotite are visible to the unaided eye (fig. 92). The rather sizeable mass east of Holden Lake contains more biotite than hornblende but is otherwise identical to the rest of the quartz gabbro. The rock within a given mass or within different masses varies little in appearance, except in the contact complexes that border parts of the two larger plutons. In thin section, the texture is seen to range from xenomorphic to hypidiomorphic. The plagioclase is labradiorite, mostly having an average composition of about An_{60}, but some crystals are as low as An_{55}, and others as high as An_{65}. Many of the grains show a few oscillatory zones, but the compositional range is rather small, mostly less than 10 percent variation in anorthite content. Patchy zoning is ubiquitous. Sericitic alteration of plagioclase is fairly common, particularly in the more calcic cores of grains. Hornblende is distinctive; it occurs as mottled light-olive-green and light-brown, irregular, anhedral grains and shreds. Much of it has altered to fine-grained mats of actinolite or, in places, chlorite. Biotite occurs as separate grains and as replacements of amphibole; the pleochroism is very strong and ranges from nearly colorless light straw yellow to deep, bright red. Magnetite, which commonly makes up about 5 percent of the rock, is generally closely associated with biotite and may have separated as hornblende altered to biotite. Quartz is interstitial. Orthoclase is rare and occurs only along tiny seams and fractures in the rock. Apatite and titanite in varying amounts are accessory.

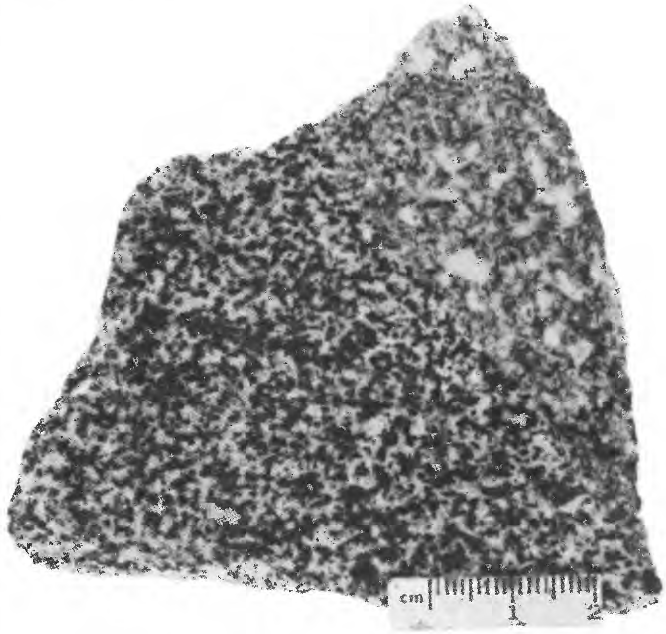

FIGURE 92.—Hornblende-quartz gabbro (finer grained) cut by biotite-quartz monzonite (coarser grained) from the Holden Lake pluton, Holden quadrangle.

Modal analyses of hornblende-quartz gabbro are given in table 33 and a chemical analysis in table 34. The modes are plotted in figure 93 and the norms in figure 71.

TABLE 33.—*Modal analyses of samples of hornblende-quartz gabbro from the Copper Peak and Holden Lake plutons, Holden quadrangle*

Sample No.	Plagioclase	Potassium feldspar	Quartz	Biotite	Hornblende	Accessory and secondary minerals	Total mafic minerals	Anorthite in plagioclase crystals (percent) Average	Core	Rim	Remarks
1	64.3	0	4.4	3.1	22.1	6.1	31.3	54	70	41	Hypidiomorphic.
2	62.3	0.3	5.4	1.2	15.5	15.3	32.0	54	70	33	Do.
3	61.4	0	5.6	8.9	20.7	3.4	33.0	58	75	42	Hypidiomorphic; subparallel plagioclase crystals.
4	51.5	0	11.9	11.3	22.2	3.1	36.6	52	58	35	Hypidiomorphic.
5	58.0	.2	18.8	16.3	6.2	.5	23.0	57	64	26	Hypidiomorphic-cataclastic.
6	54.7	.1	18.9	14.7	6.3	5.3	26.3	56	65	9	Hypidiomorphic; subparallel plagioclase crystals.
7	55.3	0	5.6	1.2	35.5	2.4	39.1	56	77	28	Hypidiomorphic.
8	37.0	1.6	5.5	.6	34.5	20.8	35.9	56	78	16	Do.

TABLE 34.—*Chemical and spectrographic analyses and norms of quartz gabbro from the Holden Lake pluton, Holden quadrangle*

[Standard rock analysis by E. S. Daniels]

Chemical analysis (percent)	Semiquantitative spectrographic analysis (parts per million)	Norms
SiO_2 ---------- 53.26	Ba ------------ 500	q ------------ 9.36
Al_2O_3 ---------- 18.91	Co ------------ 20	ab ------------ 26.87
Fe_2O_3 --------- .72	Cr ------------ 50	an ------------ 31.84
FeO ---------- 6.21	Cu ------------ 50	hy ------------ 15.97
MgO --------- 4.01	Ga ------------ 20	bi ------------ 6.35
CaO --------- 8.95	Ni ------------ 15	c ------------ 2.11
Na_2O --------- 2.95	Sc ------------ 30	mt ------------ .77
K_2O ---------- .66	Sr ------------ 700	tn ------------ 4.91
H_2O+ --------- 1.17	V ------------ 200	ap ------------ 1.47
H_2O- --------- .02	Y ------------ 30	fr ------------ .27
TiO_2 --------- 2.31	Zr ------------ 50	cc ------------ .05
P_2O_5 --------- .69		hl ------------ .03
MnO --------- .12		Total ------- 100.00
CO_2 ---------- .02		
Cl ----------- .01		Plagioclase composition
F ------------ .06		
Subtotal ---- 100.07		an ------------ 54.2
Less O ------- .03		
Total ------- 100.04		

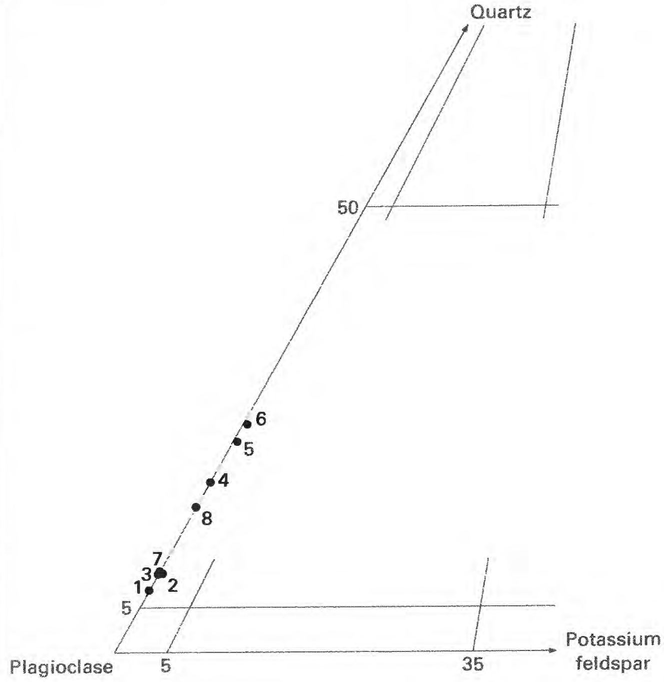

FIGURE 93.—Plot of modes of hornblende-quartz gabbro samples from the Copper Peak and Holden Lake plutons, on a quartz-potassium feldspar-plagioclase diagram. Sample analyses are given in table 33.

BIOTITE-QUARTZ MONZONITE AND GRANODIORITE

Biotite-quartz monzonite and granodiorite crop out more or less coextensively with hornblende-biotite-quartz diorite, but unlike the quartz diorite, occur as far south as Fern Lake. The two units seem to be closely related, but biotite-quartz monzonite and granodiorite are somewhat younger. In many places in the Lucerne quadrangle, the two units are so intricately scrambled that separate mapping was impractical, and areas of such mixed rocks are shown as being underlain by the dominant type; thus, masses labeled as biotite-quartz monzonite and granodiorite in the Sevenmile Creek drainage, in places, are almost half quartz diorite. The intrusive relations between the two units are particularly well displayed in the roadcut near the east edge of the Holden quadrangle east of Holden. In many places, however, distinguishing between the two units in isolated outcrops is difficult because of their locally very similar appearances.

The largest of the intrusions of biotite-quartz monzonite and granodiorite crops out east of Wilson Creek and has a spectacular array of dikes of various sizes that follow a system of flat joints; these dikes are most numerous in the Cardinal Peak pluton. Similar flat dikes are also satellitic to the mass between Tenmile and Ninemile Creeks but are less common. Where the rock intrudes the Duncan Hill pluton, it forms highly irregular small masses that were not separately mapped. These are particularly abundant in the contact complex at Buckskin Mountain and between Anthem Creek and Fern Lake.

The biotite-quartz monzonite and granodiorite are mostly fine- to medium-grained, light-gray to nearly white rock, the quartz monzonite tending to be lighter because of generally less biotite (fig. 94). Most of the rock has a pronounced foliation due to alined biotite flakes. Some rocks are slightly porphyritic. Foliation is mostly parallel to the attitudes of the dikes, but, surprisingly, some dikes have a foliation parallel to that of the regional foliation, regardless of the trend of the dikes themselves. Pitcher and Berger (1972) described similar oblique foliation in dikes cutting the Donegal pluton and ascribed the obliquity to movement of the dike walls relative to each other. The general aspect conveyed by these relations in the quartz monzonite and granodiorite, however, is that of rocks that have been regionally metamorphosed and recrystallized to the regional alinement. Microscopic study quickly dispels this erroneous assumption, however, because the texture of both the quartz diorite and the slightly younger dikes that cut it is typically protoclastic. Euhedral crystals of plagioclase showing numerous oscillatory zones are broken and abraded, and late quartz, orthoclase or perthite, and biotite have crystallized along shearing planes that paralleled the regional metamorphic fabric of the area. Some of the biotite has been warped by still later movement. At one locality, west of Gopher Mountain, a dike of biotite granodiorite cuts the quartz diorite of the Duncan Hill pluton up to, but not beyond, the contact between the quartz diorite and the enclosing clinopyroxene-biotite-quartz schist; beyond the contact, a fracture continues in the schist along the projection of the dike. All these rocks, the quartz diorite, the dike, and the schist, have a parallel foliation.

Contacts with older rocks are either sharp or gradational through a few centimeters; with the hornblende-biotite-quartz diorite, or Duncan Hill pluton, the contacts are commonly not only sharp but highly irregular, and near such contacts, inclusions of the older rock are numerous. Where the quartz monzonite-quartz diorite contact is exposed in the roadcut 1.5 km east of Holden, the quartz monzonite contains pyrite-bearing inclusions of hornblende gabbro of Riddle Peaks. The pyrite occurs along chlorite-filled fractures confined to the gabbro. The quartz monzonite adjacent to these inclusions is nearly devoid of mafic minerals, whereas the inclusions are bordered by selvages of biotite a fraction of a centimeter thick; some of these selvages are slickensided. The contacts of quartz monzonite and quartz diorite are mostly gradational through the space of a millimeter or two, but the quartz diorite is otherwise unaffected by the quartz monzonite. Dikes of biotite-quartz monzonite and granodiorite farthest from the main large mass on the east side of Wilson Creek are notable for their generally gradational contacts; these are best seen underground in the Holden mine. Here, many of these dikes are bordered by mafic-free zones of quartz and feldspar, and in places these, in turn, are bordered by mafic-rich layers in the enclosing gneiss and schist that form a sort of "basic behind." Where these dikes are parallel to the foliation of the gneiss and schist, the contacts are generally sharper and the mafic-free borders are narrower than where dikes transgress the foliation. The contacts of transgressive dikes are extremely irregular, and felsic border material insinuates and replaces the foliated host rocks away from the dikes for varying distances along planes of foliation. Some dikes consist of little but felsic material and seem to have formed almost entirely by replacement. Many of these replacement dikes can be seen to emanate from dikes of biotite-quartz monzonite and granodiorite, and some, in fact, cut and replace the parent dikes. Of particular interest is the fact that in the Holden mine these dikes are postore inasmuch as they contain inclusions of the ore and in places seem to have remobilized the adjacent sulfides to a small extent. The sulfides form tiny veinlets in the otherwise completely fresh dikes that show no other sign of having been subjected to mineralizing solutions.

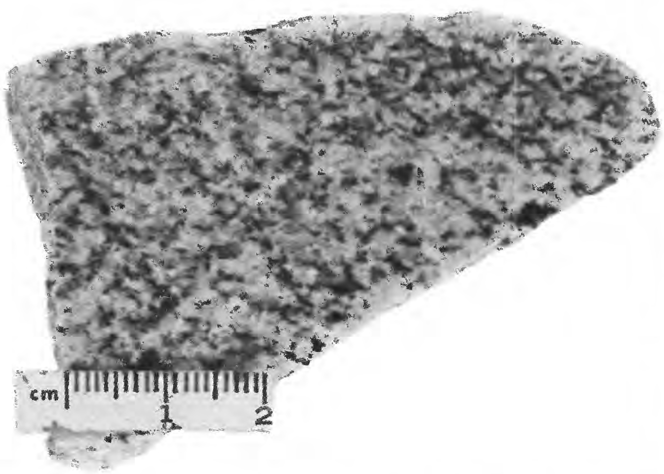

FIGURE 94.—Biotite-quartz monzonite, north of Railroad Creek, 2 km east of Holden, Lucerne quadrangle.

As seen in thin section, the biotite-quartz monzonite and granodiorite resemble the hornblende-biotite-quartz diorite, except for the relative abundance of potassium feldspar. Most of the plagioclase has an average composition of about An_{22}, but locally the average composition of plagioclase is about An_{32}. As with the quartz diorite, the range of composition within crystals is large, from An_{55} in the cores of some to An_{15} in some rims. Orthoclase, much of it perthitic, constitutes nearly 30 percent of some specimens and occurs either interstitially or as a mesostasis that encloses and replaces plagioclase. Myrmekite is common along borders between orthoclase and plagioclase. Quartz is interstitial or forms lenticular aggregates of interlocking, sutured grains. Biotite occurs as highly pleochroic (light straw yellow to dark muddy brown) ragged shreds. Primary muscovite was seen in a few thin sections, and relatively coarse secondary muscovite as blades 0.1 mm or more in length replaces plagioclase in most thin sections. Titanite, allanite, zircon, and apatite are accessory. Secondary minerals other than muscovite are chlorite, epidote, and pyrite.

Textures are either hypidiomorphic or, unlike hornblende-biotite-quartz diorite, protoclastic. The hypidiomorphic varieties commonly show flow-oriented features and are texturally identical to the quartz diorite. Plagioclase crystals of protoclastic rocks are broken and abraded, but most of the later minerals—potassium feldspar, quartz, and biotite—are undeformed, although scattered biotite flakes are bent.

Modal analyses indicate that variations in composition are relatively minor (table 35; fig. 95). Chemical and spectrographic analyses and norms are given in table 36, and the norms are plotted in figure 71.

POST-LATE EOCENE INTRUSIVE ROCKS

DIKES OF BIOTITE DACITE AND RHYODACITE

A few dikes of gray, fine-grained, slightly porphyritic dacite and rhyodacite that bear little resemblance to any other rock in the area cut the Railroad Creek pluton in the Riddle Creek drainage. None of the observed dikes are thicker than 3 m, and all strike northeast, or less commonly, nearly east. The rock consists of calcic andesine, quartz, biotite, and potassium feldspar; some of the dikes contain sufficient potassium feldspar to classify them as rhyodacite. Most of the rock consists of various intergrowths of plagioclase, quartz, and potassium feldspar; of the intergrowths, myrmekite is most abundant and forms a groundmass enclosing crystals of biotite and oscillatorily and patchy zoned andesine; the rest forms overgrowths around some andesine crystals. The plagioclase fraction of the myrmekitic overgrowths is progressively zoned from oligoclase to albite, and some of the albite is antiperthitic. The more potassic rocks contain considerable granophyre, much of it also as overgrowths on andesine. Prehnite occurs in some of the dikes.

The age of these dikes is not known, except that they are younger than the Railroad Creek pluton. The pluton had cooled by the time the dikes were injected, and they possibly are as young as Miocene.

RHYODACITE

Dikes mapped as rhyodacite porphyry are numerous in the area between the Chiwaukum graben and Lake Chelan. Included in this class of rocks is an altered, porphyritic plug a few hundred meters across that cuts highly brecciated rocks of the Cardinal Peak pluton northeast of Milham Pass. The dikes range from several centimeters thick to one in the southwest corner of the Lucerne quadrangle that is more than 60 m thick. Strikes vary, but most trend either northeast, or more rarely, northwest. All are conspicuously porphyritic and light to medium gray or greenish gray; thinner ones have aphanitic groundmasses, whereas the thicker ones may be merely fine grained. These rhyodacite dikes rather closely resemble the younger dacite and the rhyodacite dikes which are more consistently characterized by quartz phenocrysts.

The composition of rocks mapped as rhyodacite ranges between rather wide limits; although by far the largest number of dikes are rhyodacite, some are dacite and others probably contain enough potassium feldspar to be classed as quartz latite. The ages of these dikes may cover a considerable span; although they cut late Eocene plutons, a minimum age cannot be established on geologic grounds.

Phenocrysts of plagioclase ranging in average composition from oligoclase (about An_{26}) to andesine (about An_{45}), biotite or hornblende and both in some rocks, and, less commonly, quartz are set in aphanitic to fine-grained mats of plagioclase, quartz, biotite, hornblende, and orthoclase. Plagioclase phenocrysts show prominent

TABLE 35.—*Modal analyses of samples of biotite-quartz monzonite and granodiorite of post-late Eocene age, Holden and Lucerne quadrangles*

Sample No.	Plagioclase	Potassium feldspar	Quartz	Biotite	Hornblende	Accessory and secondary minerals	Total mafic minerals	Anorthite in plagioclase crystals (percent)			Remarks
								Average	Core	Rim	
10	53	7.6	22.8	15.4	0	0.9	16.3	26	41	20	Protoclastic.
25	43.9	11.1	37.5	4.0	2.5	1.0	7.5	24	26	21	Porphyritic.
26	31.6	27.2	35.5	1.5	2.4	1.8	5.7	23	29	19	Xenomorphic.
27	47.9	11.1	32.2	7.9	0	.9	8.8	28	33	15	Hypidiomorphic.
34	41.4	19.6	29.1	9.6	0	.3	9.9	26	40	18	Subparallel andesine laths; hypidiomorphic.
35	35.1	26.5	31.9	2.4	.8	3.3	6.5	20	22	18	Hypidiomorphic.
36	25.9	22.1	44.2	1.6	5.0	1.0	7.6	23	27	21	Protoclastic.
37	34.8	26.3	31.6	6.9	0	.4	7.3	25	30	17	Hypidiomorphic.

TABLE 36.—*Chemical and spectrographic analyses and norms of a composite sample of biotite-quartz monzonite, Holden and Lucerne quadrangles*

[SiO_2 and Al_2O_3 determined colorimetrically; Fe_2O_3, MgO, CaO, and MnO determined by atomic absorption; FeO determined volumetrically; Na_2O and K_2O determined by flame photometer. Analysts: Wayne Mountjoy, J. D. Mensik, Claude Huffman Jr., G. T. Burrow, and H. H. Lipp. Spectrographic analyses by Barbara Tobin]

Chemical analysis (percent)		Semiquantitative spectrographic analysis (parts per million)		Norms	
SiO_2	74.5	Ba	700	q	34.17
Al_2O_3	15.6	Co	7	or	19.05
Fe_2O_3	.38	Cr	7	ab	31.27
FeO	1.28	Cu	3	an	9.81
MgO	.32	Ga	15	hy	2.89
CaO	2.0	Ni	7	c	2.26
Na_2O	3.74	Sc	5	mt	.55
K_2O	3.26	Sr	300	Total	100.00
MnO	.04	V	30		
Total	101	Y	10	Plagioclase composition	
		Yb	1		
		Zn	70	an	23.9

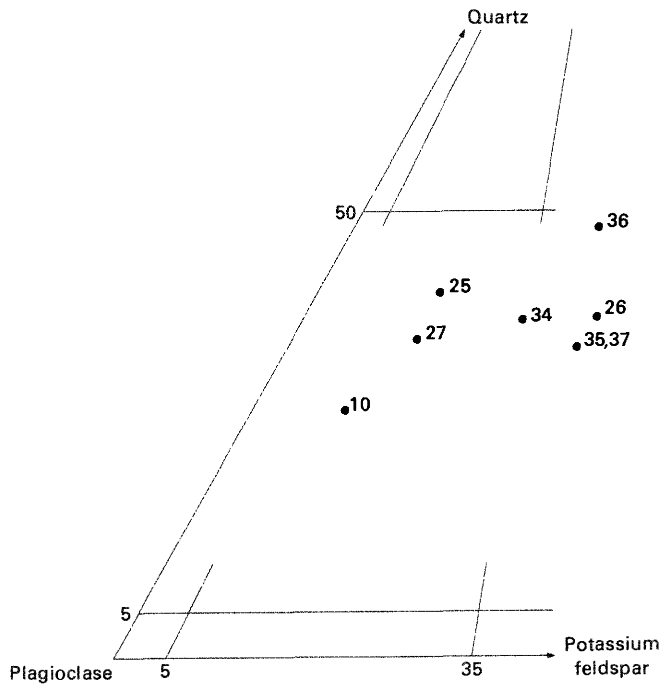

FIGURE 95.—Plot of modes of biotite-quartz monzonite and granodiorite samples from Holden and Lucerne quadrangles on a quartz-potassium feldspar-plagioclase diagram. Sample analyses are given in table 35.

oscillatory zoning, and patchy zoning is common; quartz phenocrysts are usually anhedral, but scattered, partly resorbed bipyramidal crystals occur. Granophyre is common in some dikes. Both hornblende and biotite are generally shredlike, but fine-grained aggregates of biotite or actinolite pseudomorphing euhedral hornblende crystals are numerous. A little augite was seen in a thin section from a dike on Crow Hill in the southeast corner of the Lucerne quadrangle. Mafic minerals show varying degrees of alteration to chlorite and, less commonly, nontronite; plagioclase, where altered, is saussuritized or sericitized.

The dacite porphyry plug northeast of Milham Pass is extensively altered, and outcrops are highly stained with limonite derived from disseminated iron sulfides, but no unoxidized sulfides or staining from oxidation of metallic minerals other than those of iron were seen. Even the freshest outcrops have largely disintegrated to a grus, and most are deeply weathered and rotten as attested by debris from a caved adit or two. Thin-section examination showed the freshest rock to consist of phenocrysts of labradorite, quartz, hornblende, and biotite in a fine-grained groundmass of the same minerals plus their alteration products. The age of the plug is unknown but is almost certainly post-Eocene.

DACITE AND RHYODACITE DIKES

Dacite and rhyodacite dikes crop out in two general areas. In the drainage basin of Railroad Creek upstream from Holden, and in the southeastern part of the Holden quadrangle east of the Chiwaukum graben and adjacent parts of the Lucerne quadrangle. Because of their similarity to various chilled phases of the Miocene Cloudy Pass batholith, the dikes were considered satellitic to the batholith as was the volcanic neck of Old Gib. A radiometric age of the Old Gib rocks determined by Joan Engels (Engels and others, 1976) indicates that these rocks are late Eocene and are of the same age as the Duncan Hill and other plutons of late Eocene age east of the Chiwaukum graben. Very likely the scattered dikes of dacite and rhyodacite in the Railroad Creek area are related to Cloudy Pass Rocks, but the affinities of those east of the Chiwaukum graben are much less certain. These dikes appear identical to the rocks of Old Gib, yet they cut the Larch Lakes and Rampart Mountain plutons, and the Duncan Hill pluton, which has the same radiometric age as the Old Gib volcanic neck. They also have chilled margins against the plutons through thousands of meters vertically. Obviously, these plutons had cooled before the dikes were intruded. Therefore, although they are indistinguishable from Old Gib rocks, it seems likely that the dikes are considerably younger and may, in fact, be related to the Cloudy Pass. In one or two localities among the dike swarms near Garland Peak, dacite and rhyodacite dikes were observed to cut rhyodacite dikes. Careful search, however, may discover opposite crosscutting relations. In any event, until the dikes east of the graben are dated radiometrically, little more definite age assignment than probable post Eocene seems justifiable.

MIOCENE INTRUSIVE ROCKS

Intrusive rocks of Miocene age comprise a number of plutons, stocks, and small plugs of different compositions, mostly in the Glacier Peak and Holden quadrangles, and great numbers of dikes, particularly in the Holden and Lucerne quadrangles. The diversity of rock types in each intrusive epoch during the Tertiary, combined with the similarity in appearance of rocks of similar composition, regardless of age, complicates the process of determining relationships. West of Garland Peak in the Lucerne quadrangle, a dike or two of rhyodacite porphyry was seen that was cut by dacite or rhyodacite containing prominent quartz phenocrysts. Both types of dikes cut plutons of known late Eocene age and have chilled margins against them through thousands of vertical meters. For this reason, these dikes are all thought to be appreciably younger than the plutons of late Eocene age and possibly as young as Miocene.

Most of the dacite and rhyodacite dikes strike northeast, but west of Rock Creek many strike north-northwest parallel to both the regional trend of the metamorphic host rocks and the pervasive shear zones. Dacite and rhyodacite are indistinguishable in outcrop; both are light gray and conspicuously porphyritic, and in this respect are very similar to some of the rhyodacite dikes that are thought to be older; in fact, some dikes were probably misidentified because of similar outcrop appearance. Phenocrysts of plagioclase as much as 5 mm across and of quartz, biotite, and more rarely hornblende as much as 3 mm in greatest dimension are scattered through an aphanitic to fine-grained, light-gray groundmass. Thin dikes are aphanitic throughout but only the chilled margins of the thicker dikes are aphanitic. Plagioclase phenocrysts in both dacite and rhyodacite are high-temperature andesine, showing numerous oscillatory zones in addition to patchy zoning; the average composition of plagioclase in most sections is about An_{32}, but in some is as calcic as An_{50}. Most quartz phenocrysts are rounded and resorbed, but a few are euhedral bipyramids. Biotite and hornblende occur as euhedral to anhedral grains; hornblende commonly shows some replacement by biotite, and both are variously replaced by chlorite. The groundmass consists of an equigranular, interlocking mosaic of oligoclase, quartz, and biotite in all the dikes, plus hornblende in some. Rhyodacite differs from dacite only in its higher content of orthoclase; a few dikes also contain a little microcline. Some granophyre occurs in the groundmass of scattered dikes of both dacite and rhyodacite. Rather characteristically, phenocrysts of plagioclase and quartz have corroded margins of moth-eaten appearance suggestive of resorption by the groundmass. Some dikes intruded along shear zones have been intensively sheared since emplacement so that phenocrysts appear as augen in a finely comminuted groundmass.

CLOUDY PASS BATHOLITH AND RELATED ROCKS

Youngest of the major intrusions in the area is the early Miocene Cloudy Pass batholith and its satellitic intrusive breccias, plugs, and stocks. The batholith is now being deroofed, and about 80 km^2 of it are either exposed or covered by surficial debris in the northern parts of the Glacier Peak and Holden quadrangles. Adjacent parts of the mass lie under a relatively thin cover of metamorphic roof rocks. The part of the batholith lying within the Glacier Peak quadrangle has been described in detail by Tabor and Crowder (1969) and that in the Holden quadrangle by Cater (1969). Grant (1966; 1969, p. 30–34) and Tabor (1963) reported on the part cropping out north of these two quadrangles. The following description mostly summarizes the reports by Tabor, Crowder, and Cater.

The Cloudy Pass batholith is a discordant intrusion characterized by a wide variety of rocks and a remarkable array of subvolcanic features, including a complex of chilled border rocks along its northeast contact called the complex of Hart Lake (Cater, 1969, p. 8–17). A belt of plugs and small stocks of Cloudy Pass rocks associated with a zone of thermally metamorphosed gneisses strongly suggest that a southwesterly trending nose of the batholith lies at rather shallow depths, and a southeasterly trending line of satellitic porphyry plugs and intrusive breccia suggests a similar nose beneath Phelps Ridge.

Contacts, except for those with flat-lying roof rocks, are steep to vertical. The nature of the contact, however, is variable depending on whether border rocks are chilled and whether the contact truncates foliation planes of the host rocks or is conformable. In the large areas where the margins of the batholith consist of chilled porphyritic rocks, the host rocks are crumpled and brecciated, but where the core of the batholith has cut through the chilled border rocks, or where they do not exist, the host rocks are hornfelsed or granitized in a narrow zone. Where the batholithic contacts are strongly discordant and chilled border rocks are absent, the enclosing gneiss was subject to considerable diking, stoping, and migmatization.

Most of the batholith consists of light-gray, medium-grained, massive rock ranging in composition from quartz gabbro to granodiorite; of the various rock types granodiorite is most abundant, and most of this is labradorite granodiorite (granogabbro). Scattered through these similar-appearing main-facies rocks are masses of light-colored rocks, the largest mass of which caps the western part of the batholith on and in the vicinity of Miners Ridge. Contacts between contrasting rock types are gradational in most places, but on the north flank of the North Star Mountain the contact between normal and light-colored facies consists of a marble-cake mixture of the two.

Granodiorite and quartz gabbro are mostly structureless, but near some contacts a vague layering of lighter and darker rocks is visible that roughly parallels the contact. Lineation defined by alined hornblende crystals occurs locally. Inclusions of chilled border rocks and gneiss in various stages of assimilation are fairly well restricted to the uppermost parts of the batholith where they are locally abundant. Granodiorite consists of euhedral oscillatorily and patchy-zoned plagioclase, quartz, biotite, and hornblende; orthoclase, some of it microperthitic, is a major but quantitatively variable constituent. Quartz diorite and quartz gabbro differ from granodiorite only in the content of orthoclase and in these rocks it is generally absent. Clinopyroxene and hypersthene are rare except in the small intrusions in the Glacier Peak quadrangle and tend to occur only in the more rapidly cooled rock; both minerals are generally rimmed by uralitic hornblende. Plagioclase generally has an overall composition of sodic labradorite, but westward in the Glacier Peak quadrangle it tends to be more sodic and is mostly andesine. Quartz occurs both as partly resorbed euhedral crystals and as irregular grains with orthoclase as a mesostasis engulfing all earlier formed minerals. Orthoclase is invariably late and is of erratic distribution and abundance. All the orthoclase seems to be of metasomatic origin.

Light-colored facies are of two types, an oligoclase-bearing granophyre and a metasomatized quartz gabbro or labradorite granodiorite. In the Holden quadrangle, the metasomatized rock containing labradorite is most prevalent and occurs as irregular masses apparently associated with zones of brecciation that formed in the cooling batholith. The rock has a psuedoporphyritic texture; larger crystals of labradorite and quartz are engulfed in and partly replaced by a xenomorphic aggregate of fine-grained quartz, albite-oligoclase, and orthoclase. Mafic minerals not replaced by this felsic material are mostly altered to chlorite. Much of the megacrystic labradorite has been fractured and the resulting crystal fragments slightly rotated with respect to each other; fractures are healed by veinlets of albite. The granophyric rock much resembles the metasomatized labradorite-bearing light-colored rock megascopically; but the mode of occurrence is generally different, particularly in the Holden quadrangle. Here the granophyre forms either dikes or the matrix of intrusive breccia, but in the Glacier Peak quadrangle where light-colored rocks are far more abundant, the granophyre forms much of the western part of the batholith. Most of the plagioclase in the granophyre is euhedral and oscillatorily zoned, but some of the most sodic plagioclase is interstitial. Compositions range widely; cores of scattered crystals are as calcic as An_{55}, but cores of most crystals are no more calcic than An_{30}, and the groundmass is highly granophyric. Sparse biotite is mostly altered to chlorite. Miarolitic cavities containing drusy quartz and a little pyrite are common in the granophyre. Modal data of Cloudy Pass rocks are given in table 37 and figure 97. Figure 96 is a map showing the location of the modally analyzed specimens.

Our views concerning the origin of these rocks differ somewhat. Tabor and Crowder (1969, p. 9–10) contended that all the "light-colored rocks formed by normal magmatic differentiation, not by replacement of an earlier formed phase by introduced residual solutions." They based their contention on the similarity in composition of the light-colored rocks to the composition of rocks in the area of the minimum melting trough of Tuttle and Bowen (1958, p. 55), and believed that the composition of these rocks is rather limited, which "would be unlikely if replacement by residual solution had been significant." I (Cater, 1969, p. 9–10) agree that the granophyre is an end product of normal differentiation, albeit a wet one; but I think that the labradorite-bearing, light-colored rock formed as solutions rich in alkalies and silica partly replaced quartz gabbro. I base my view on the fact that in the Holden quadrangle, all gradations from quartz gabbro through granodiorite to the light rock exist, yet the core of all plagioclase is labradorite, and the light rock was shattered prior to replacement, thereby aiding transmission of fluids. In any event, addition of alkalies and silica to quartz gabbro would change the composition of the rock toward the minimum melting trough.

CHILLED BORDER ROCKS

Chilled porphyritic rocks occur at many places along the contacts of the Cloudy Pass batholith, and somewhat similar chilled rocks from the Tatoosh pluton in Mount Rainier National Park have been described by Fiske, Hopson, and Waters (1963). Most spectacular of the chilled rocks associated with the Cloudy Pass are those in the vicinity of Hart Lake. Here a chilled complex consisting of separately injected, contrasting layers of porphyry, having a thickness of more than 1 km, borders the northeast side of the batholith. Oldest is an outer layer of dacite porphyry that north of the complex grades directly into the core of the batholith, and south of Hart Lake diverges from the batholith as a prong. Next oldest is an inner layer of dacite and labradorite-bytownite andesite, and in the middle, a still younger layer of autobreccia of a composition similar to that of the inner layer. The inner layer extends from Hart Lake north to the head of Glacier Creek, but neither end of the layer is exposed. Where the contact of the inner layer and the core of the batholith is visible, the core intrudes or cuts the inner layer, but the amount of movement by the core magma could not have been great because north of the pinchout of the inner layers, the outer layer grades into

TABLE 37.—*Modal analyses of samples of granodiorite from the Cloudy Pass batholith, Holden quadrangle*

Sample No.	Plagioclase	Potassium feldspar	Quartz	Biotite	Hornblende	Accessory and secondary minerals	Total mafic minerals	Anorthite in plagioclase crystals (percent): Average	Core	Rim	Remarks
1	47.4	21.8	26.8	3.0	0	1.0	4.0	55	69	34	Porphyritic.
2	48.3	3.4	14.1	11.2	17.7	5.3	34.2	52	54	32	Slightly porphyritic.
3	45.4	12.8	26.1	9.3	5.2	1.2	15.7	53	55	32	Hypidiomorphic.
4	60.6	4.9	24.2	7.3	0	3.0	10.3	54	63	33	Prophyritic-protoclastic.
5	33.4	13.0	28.7	18.9	4.2	2.8	25.9	50	58	25	Hypidiomorphic.
6	55.0	1.4	28.7	10.8	2.6	2.5	15.9	54	62	25	Porphyritic.
7	25.6	31.8	35.6	1.5	0	5.5	7.0	35	51	18	Do.
8	51.5	12.6	21.1	7.3	5.0	2.5	14.8	54	63	29	Hypidiomorphic.
9	49.3	5.6	20.2	7.3	12.1	5.5	24.9	50	61	26	Do.
10	48.8	5.6	26.9	7.4	11.0	.3	18.7	53	67	27	Do.
11	46.2	6.3	28.4	8.0	3.1	3.0	19.1	50	67	38	Do.
12	37.0	18.3	23.6	11.1	4.3	5.7	21.1	53	58	40	Do.
13	49.7	15.7	16.2	8.4	5.9	4.1	18.4	51	54	24	Do.
14	49.8	10.3	23.6	7.1	7.0	2.2	16.3	50	55	11	Do.
15	46.3	2.6	23.5	22.3	4.2	1.1	27.6	54	61	18	Do.
16	57.3	6.1	13.4	9.3	8.7	5.2	23.2	51	54	0	Contains augite.
17	41.0	16.6	26.1	3.3	5.2	7.8	16.3	51	56	9	Slightly porphyritic.
18	50.8	12.0	25.4	2.1	7.5	2.2	11.8	50	0	0	Contains a little augite.
19	30.4	27.6	34.3	2.5	0	5.2	7.7	44	56	22	Porphyritic.
20	30.4	27.5	35.1	1.4	0	5.6	7.0	52	44	22	Reversed zoning of plagioclase; porphyritic.
21	50.5	15.0	23.1	6.6	4.4	.4	11.4	50	61	31	Hypidiomorphic; a little augite.
22	42.3	18.9	23.8	10.3	3.6	1.1	15.0	52	55	24	Hypidiomorphic.
23	45.2	13.9	22.4	5.2	12.3	1.0	18.5	53	64	29	Do.
24	46.0	.5	16.0	18.3	17.7	1.5	37.5	53	0	0	Porphyritic.

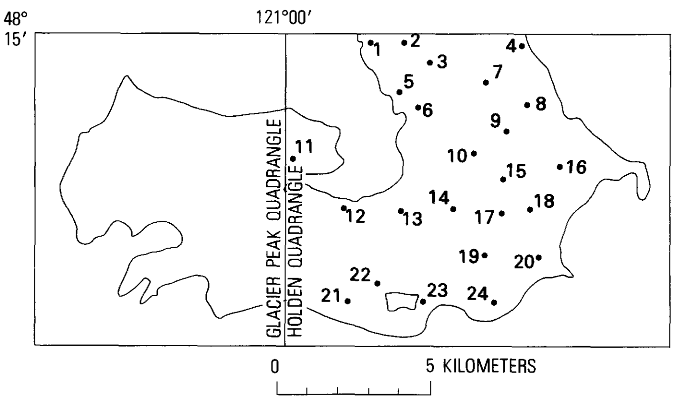

FIGURE 96.—Map showing locations of modally analyzed samples of granodiorite from the Cloudy Pass batholith, Holden quadrangle. Sample analyses are given in table 37.

the core with no evidence of disturbance. The middle layer is more complex and consists of dacite and andesite autobreccia and resembles a volcanic flow breccia in appearance. The contact with the inner layer is gradational, but the contact with the outer layer is intrusive. This intrusive contact, however, is evident only at higher altitudes where the outer layer had solidified before intrusion of the middle layer. At lower altitudes near Hart Lake, the contact with the outer layer is partly gradational and partly mixed as though the outer layer were still plastic when the middle layer was injected.

The dacite porphyry of the outer layer consists of

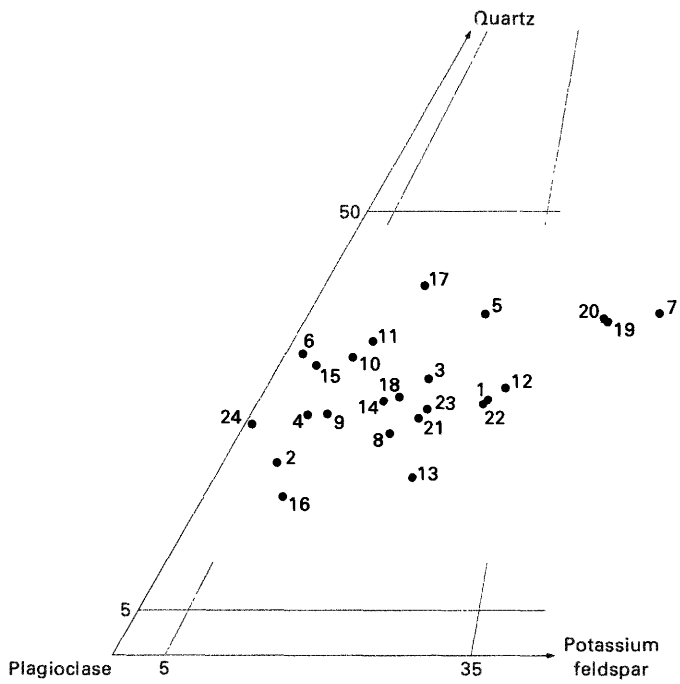

FIGURE 97.—Plot of modes of samples from the Cloudy Pass batholith, Holden quadrangle, on a quartz-potassium feldspar-plagioclase diagram. Sample analyses are given in table 37.

phenocrysts of sodic labradorite, quartz, hornblende, and sparse augite in a fine-grained matrix of andesine, quartz, hornblende, biotite, chlorite, a little orthoclase, and in some rocks, nontronite. Porphyries of the inner layer are dark gray to black and consist of intermixed andesite and dacite porphyry. The dacite is similar to the dacite of the outer layer; the andesite contains phenocrysts of labradorite-bytownite and hornblende in a groundmass of andesine, hornblende, biotite, and sparse quartz. Dacite and andesite of the middle layer are similar to those in the inner layer but are more highly altered, and fracture surfaces are coated with pyrite and pyrrhotite. At higher levels, chalcopyrite also becomes fairly common, and alteration is more severe.

Both porphyry plugs of various sizes and intrusive breccia puncture metamorphic rocks adjacent to the batholith; a few scattered pipes of intrusive breccia also cut the batholith. The plugs consist of dacite porphyry and, although somewhat more siliceous, are petrographically indistinguishable from dacite in the chilled borders. Intrusive breccias are of two types: one consists entirely of batholithic rocks and is confined to the pipes that cut the batholith; the other type cuts the metamorphic rocks and consists of varying proportions of both batholithic rocks and shattered fragments of the host rocks. This latter type is most common around the porphyry plugs and many of these breccia masses seem to have been injected explosively in a manner probably similar to fluidization processes as elucidated by Reynolds (1954). Breccia confined to the batholith consists of rounded fragments of both batholithic core rocks and chilled rocks contained in matrices of calcic quartz diorite and white quartz monzonite; the rocks in this type of breccia are unaltered. Rocks in breccias cutting metamorphic rocks, on the other hand, commonly show varying degrees of alteration, and some contain considerable amounts of sulfides, mostly pyrite and pyrrhotite but, locally, a little chalcopyrite and sphalerite.

The Cloudy Pass batholith, at least to the depth presently exposed, appears to have made room for itself mostly by lifting its roof. The discordant irregular shape of the batholith, plus the lack of any evidence for shouldering aside of the wall rock, lends strong support to this hypothesis, an hypothesis appropriate to a batholith at such shallow depths. The chilled complex at Hart Lake formed along the zone of dislocation where the host rocks in the roof of the batholith rose past those on the northeast flank. Along this zone of dislocation, the outer layer of the complex was injected as a dike ahead of and above the rising batholith. The inner and middle layers of the complex rose along this same zone of dislocation; the core of the batholith apparently continued rising somewhat after the inner layer had solidified at least to the depths presently exposed. Cooling by conduction seems to be totally inadequate to explain the rapid and uniform chilling of these two thick layers, particularly when the evidence indicates they were intruded between the still hot rocks of the outer layer and the still fluid rocks of the batholithic core. The only process adequate to explain such rapid and uniform chilling of so large a mass of magma in such an environment is the refrigerating effect of expanding gases expelled from the large reservoir of magma at depth (Cater, 1969, p. 48). As freezing by degassing progressed, the breccia probably formed as partly solidified rock adjacent to channels of most vigorous gas flow and mixed with the more molten fractions as new magma was added from below. The more highly altered and fractured nature of these rocks and the presence of sulfides lend indirect support to the supposition that these layers and particularly the middle layer did indeed serve as escape routes for volatiles.

A number of marked differences exist between rocks in the upper parts of the Cloudy Pass and Duncan Hill masses; however, rocks in the upper part of the Duncan Hill pluton are highly miarolytic, suggestive of abundant water, and strikingly granophyric in contrast to rocks in the upper part of the Cloudy Pass. Plagioclase in even the most potassic of the main-facies rocks in the upper part of the Cloudy Pass mass, furthermore, is identical to the plagioclase elsewhere in the main body of the intrusive and shows extensive oscillatory and patchy zoning. Plagioclase in the upper part of the Duncan Hill pluton shows virtually no zoning, except progressive, and lacks the rather highly calcic cores characteristic of plagioclase elsewhere in the pluton. Compositions of the hypabyssal rocks in the Duncan Hill pluton are remarkably uniform; those in the Cloudy Pass batholith vary greatly over short distances. Rocks in the upper part of the Cloudy Pass seem to have been converted to more alkalic varieties by alkali-rich solutions passing through them after they had largely solidified, whereas the alkalic rocks of the Stormy Mountain area in the Duncan Hill pluton show no evidence of a similar conversion after solidifying and seem to have crystallized directly from a completely liquid, alkalic magma.

LEUCOCRATIC BIOTITE-QUARTZ MONZONITE

About 1.5 km south-southwest of Mirror Lake in the Lucerne quadrangle, a mass of leucocratic biotite-quartz monzonite, having an exposed length of about 1 km, crops out west of Tumble Creek. The rock is medium grained and massive and on fresh surfaces is nearly white, but because it disintegrates and weathers rapidly, outcrops are limonite stained and deeply rotted. Contacts with the enclosing quartz diorite gneiss of the Bearcat Ridge pluton are knife sharp where observed.

The leucocratic biotite-quartz monzonite consists of 40 to 45 percent quartz, 30 to 35 percent oligoclase, 20 to 25 percent perthite, and less than 3 percent accessory biotite, magnetite, and zircon; small amounts of sericite, epidote, and pyrite are secondary. Oligoclase occurs as subhedral to euhedral crystals having an average composition of about An_{24}; oscillatory and patchy zoning show in most crystals, and some have rims of normally zoned material grading into albite on the outer edge. Quartz either forms irregular grains that replace oligoclase, or it occurs interstitially; most of it is strained. Irregular grains of perthite are as much as 8 mm across and it replaces both oligoclase and quartz. Irregular shreds of biotite as much as 3 mm across are pleochroic from light yellowish brown to dark muddy brown. Zircon occurs only as minute grains in biotite where it forms pleochroic halos. Magnetite most commonly forms lenticular grains wedging apart cleavage flakes of biotite. Pyrite occurs as fine dust along grain borders and in altered cores of oligoclase or as larger grains along fractures. The more calcic cores of oligoclase are partly altered to sericite and epidote. The texture is hypidiomorphic but shows protoclastic modifications; some grain borders are granulated but are healed by quartz and perthite.

The age of the leucocratic biotite-quartz monzonite is uncertain; it does, however, cut the Bearcat Ridge pluton and, hence, is younger. It resembles no other rock seen in the area, but its texture and appearance are those of a shallow intrusive, and no dikes were seen to cut it. On no really sound evidence, I believe it to be younger than the Eocene intrusives—possibly as young as Miocene.

CONTACT COMPLEXES

The contact complexes associated with the Seven-fingered Jack, White Mountain, Cardinal Peak, Duncan Hill, Holden Lake, and Copper Peak plutons in the Holden and Lucerne quadrangles, and the Tenpeak and Sulphur Mountain plutons in the Glacier Peak quadrangle (Crowder, Tabor, and Ford, 1966) are the most heterogeneous and perplexing intrusive rocks in the area. All consist of extremely diverse mixtures of rocks that differ little in overall characteristics from one pluton to another. All are composed of mixtures of coarse hornblendite, gabbro, diorite, quartz diorite, and inclusions in various stages of digestion or incorporation. The igneous fractions of these complexes—rocks as divergent as gabbro and quartz diorite—appear to have been simultaneously molten. Mixtures of these rocks range from those resembling marble cake, where contacts between different rock types are sharp, to rare, thoroughly homogenized hybrid rocks containing both calcic and sodic plagioclase that resemble the mixed magmas described by Larsen and others (1938). Probably these complexes most nearly resemble appinite, a group of rocks of highly variable composition but characterized by much coarse-grained hornblendite and gabbro or peridotite (Bailey and Maufe, 1960, p. 190–194, 214–215; Bowes and others, 1964; Hall, 1967; Pitcher and Berger, 1972). The contact complexes differ from the appinites, however, in nowhere forming discrete intrusives disconnected from a parent pluton.

The distribution of the complexes tends to be somewhat erratic and spotty. The contact complex of the White Mountain pluton, for example, is virtually confined to the crosscutting north end of the mass, whereas the complexes of the other plutons also occur along concordant margins, and in the Seven-fingered Jack plutons, rocks identical to the complexes also occupy internal positions. The contact complexes associated with the Tertiary Duncan Hill pluton are confined to the mesozonal north end, whereas complexes rim a good part of the Holden Lake and Copper Peak intrusives.

The origin of these contact complexes is obscure. With the exception of the quartz gabbro Holden Lake and Copper Peak plutons, the complexes seem to be confined to mesozonal plutons or, in the Duncan Hill, to the mesozonal end of the pluton. The cores of the plutons cut the complexes, but generally the complexes seem not to have been solidified when they were invaded by the cores. The diorite and quartz diorite in the complexes are sufficiently similar in composition to the core rocks to have been derived directly from them, but this relationship cannot be true for the ubiquitous hornblende gabbro or coarse-grained, generally pegmatitic hornblendite, the rocks most characteristic of the complexes. The unhomogenized marble-cake mixtures of gabbros and siliceous igneous rocks would suggest such mixtures are not far traveled, and the presence of both calcic and sodic plagioclase in homogenized hybrid rock indicates that their disequilibrium sojourn in the mixed magma before solidifying could not have been prolonged. Sodic rims on labradorite commonly are broader in the hybrid rocks than on labradorite in normal hornblende gabbro, however. Intimate associations of mafic and felsic rocks in various intrusive and extrusive masses have been described repeatedly, more recently by Walker and Skelhorn (1966) and Blake and others (1965). These authors reached the conclusion that separate and probably unrelated magmas were involved that by one means or another utilized the same plumbing systems simultaneously in their rise through the Earth's crust. It seems entirely likely that the same circumstances prevailed in the formation of these contact complexes. Possibly small quantities of hornblende gabbro magma lower in the crust or upper mantle were forced up along the same channels and at the same time as much larger quantities of more felsic magma from somewhat higher but still low in the crust. Yoder (1973) postulated that small batches of contrasting magmas are melted as a result of adiabatic decompression, and each magma is extracted at separate invariant points. The melting temperatures of gabbroic or basaltic magmas are 100°–200°C higher than are those of siliceous magmas (Yoder and Tilley, 1962), and the mixing of gabbroic magma from probably deeper in the crust would raise the temperature of the siliceous magma in the contact complexes. In a few outcrops, the gabbro adjacent to quartz diorite is finer grained as though it had been chilled against quartz diorite (fig. 33). Perhaps the higher temperatures and consequent greater mobility of the mixed magmas of the complexes accounts for the greater number of wall-rock inclusions and the more highly modified nature of wall rocks adjacent to the complexes than where core rocks of the pluton are in direct contact with the host rocks.

The hornblende gabbro of Riddle Peaks at least demonstrates that a sizeable reservoir of gabbroic magma existed at one time in the area; furthermore, this gabbro is nearly identical to most of that occurring in the contact complexes. Such magma then could have used conduits that subsequently were used by quartz diorite magma from a different source. The possibility exists, nonetheless, that hornblende gabbro in the contact complexes is a differentiate from a parent magma of the diorite and quartz diorite, although the evidence does not lend a great deal of support to the existence of a comagmatic series of gabbro and quartz diorite. To test the possibility that the gabbro and quartz diorite had different lineages, gabbro and quartz diorite from intrusive complexes associated with the Seven-fingered Jack plutons were analyzed for initial strontium isotopic ratios (Zell Peterman, written commun., 1975). The results are shown in table 38.

The initial strontium isotope ratios are low, comparable to those of Cascade Range volcanic rocks (Peterman and others, 1970) and are suggestive of a source in the upper mantle. The agreement of ratios for gabbro and quartz diorite neither proves nor disproves a genetic relationship between the two rocks, but an anatectic origin from crustal rocks does seem to be precluded.

GENERAL GEOLOGIC PROBLEMS RELATING TO THE INTRUSIVE ROCKS

Discussion of problems relating to compositional and mineralogical variations, differentiation, and emplacement of the intrusive rocks of the area is complicated by the fact that the intrusions in the northern Cascades are perhaps the most diverse group of Phanerozoic plutons in the entire country. In composition, they range from ultramafic to granite, a range that may be present elsewhere, but in one important aspect they are unique—the range of depths to which they are exposed. Within the confines of single 15-minute quadrangles are exposed plutons ranging from those having subvolcanic features to those of the catazone. For more than 200 m.y., or since the accretion of the microcontinent of Cascadia to the North American continent (Davis and others, 1978, p. 15), the region has been the scene not only of continuous tectonic activity but of intermittent, if not continuous, intrusive activity (Yeats and Engels, 1971), and if the present volcanoes are any criterion, magma is still being pumped into and through upper crustal rocks. Gilluly (1973, p. 503–505) has pointed out that in the Cordillera, as a whole, magmatism has been continuous since early Mesozoic time and that "there is no sign whatever of any periodicity," and Silberman and McKee (1971, p. 20) concluded that only in areas smaller than 50,000 km^2 does plutonism seem to be episodic. The conclusion of Yeats and Engels (1971, p. D38) that there was no evidence of plutonism in the northern Cascades between about 48 to 90 m.y. ago has been refuted by later work (Engels and others, 1976).

The older intrusives, such as the Dumbell Mountain plutons, have been carved to levels many kilometers deep, whereas the youngest, such as the Cloudy Pass batholith, are only now being deroofed. Study of intrusive rocks in such a terrane tends to enfeeble ones faith in the validity of such terms as "post-" and "synkinematic" or "post-" and "syntectonic," when applied to intrusive granitoid rocks. Such faith can degenerate into outright skepticism when one views a pluton, such as the Duncan Hill, which is synkinematic on one end, the deep one, and postkinematic on the other or shallow end—and this in an area where tectonism is still progressing at a rate probably as lively as ever. Buddington (1959, p. 731) has pointed out that epizonal plutons are posttectonic, mesozonal plutons are either post- or occasionally late- kinematic, and catazonal plutons are syntectonic and synkinematic. Most likely, all postkinematic plutons are synkinematic at depth.

The plutons making up great composite batholiths such as the Idaho, the Sierra Nevada, or the Southern California seem to possess a common heritage; the plutons of the northern Cascades lack this overall unity. Only the most intrepid would genetically relate the Dumbell Mountain plutons to the 200-m.y.-younger Cloudy Pass batholith, for example. The more or less systematic chemical changes that correlate roughly with the order of emplacement of plutons in the great batholiths are largely lacking in the northern Cascades, although single, moderate-size batholiths such as the Snoqualmie (Erikson, 1969) and the groups of plutons of approximately the same age, do have such features. Nevertheless, certain broad characteristics do seem to vary with time of emplacement, but these variations appear to be related more to the level of exposure than to close genetic ties.

TABLE 38.—*Initial strontium isotope ratios of gabbro and quartz diorite from intrusive complexes associated with the Seven-fingered Jack plutons, Holden quadrangle*

[Analysts: Sr^{87}/Sr^{86}, K. Futa (chemistry) and R. Hildreth (mass spectrometry), Rb and Sr concentrations: W. Doering (by X-ray analysis). Analytical uncertainties: Sr $^{87}/Sr^{86}$: ±0.002 (2 sigma). Concentrations: ±5 percent of values]

Rock type	Rb (ppm)	Sr (ppm)	Rb/Sr	Sr^{87}/Sr^{86}	$(Sr^{87}/Sr^{86})_0$[1]
Quartz diorite --	52.9	556	0.095	0.7042	0.7040
Gabbro --------	7.2	395	.018	.7037	.7037

[1]Initial Sr^{87}/Sr^{86} corrected for in-situ growth of radiogenic Sr^{87} for 64 m.y.

RELATION OF INTRUSIVES TO HOST ROCKS AND THE ROOM PROBLEM

All the major intrusives in the study area reflect some degree of structural control, but such control is more pronounced in the older plutons. The older plutons are elongate and relatively concordant, whereas the younger ones tend to be areally more nearly equidimensional but irregular in outline and show less influences by structure of enclosing rocks. Even the youngest major intrusive in the area, the Cloudy Pass batholith, however, has a northeast contact that parallels the trend of the wall rock of gneissic quartz diorite of Dumbell Mountain.

Both faults and structural trends of the metamorphic country rocks influenced the form of various major plutons, but faulting seems to have had controlling influence only on the Seven-fingered Jack and less certainly on the Dumbell Mountain and High Pass plutons. The almost dikelike Seven-fingered Jack plutons are strongly controlled by the ancient fault system later reactivated and bounding the northeast side of the Chiwaukum graben; the equally elongate but much older Dumbell Mountain plutons possibly may have been injected along early dislocations in this same fault system. The relation of the High Pass pluton to enclosing rocks is much more complex than are relations to host rocks of other plutons in the area. The High Pass pluton is a thick, low-dipping sheet that truncates a synform of upper Paleozoic metasedimentary rocks at a low angle; much of the pluton is sill-like, but the narrow, southeasterly part of the mass cuts across the synform, and in the valley of Alpine Creek, it occupies the crest of a small antiform. Two separate bodies of probable High Pass rocks to the northeast, called the Buck Creek plutons of the main mass have intruded the contact between the Paleozoic metasedimentary rocks and the lower Paleozoic or older Swakane Biotite Gneiss. The contact may be a thrust plane because the structural relations between the metasediments and the Swakane strongly suggest that the metasediments were thrust over the Swakane—much in the manner of a tractor tread—before the sediments were metamorphosed to amphibolite grade.

Plutons where the only apparent structural influence seems restricted to the attitude of enclosing rocks range from those showing a close adherence to trends of the host rocks throughout their lengths, as does the Duncan Hill, to those that are largely discordant but have some contacts that are concordant for considerable distances, as illustrated by the Clark Mountain stocks. The Duncan Hill, Cardinal Peak, and to only a slightly less degree the Bearcat Ridge plutons, virtually parallel the strike of the enclosing metamorphic rocks or diverge but little throughout their mapped lengths. The parallelism of these plutons to the host rocks, however, is restricted to strike; downdips all are crosscutting. The Cardinal Peak pluton cuts a large, southeast-plunging, overturned antiform; the Bearcat Ridge plutons dip more nearly conformable to but do cut the host rocks at low angles, and the vertically dipping Duncan Hill pluton transects the moderate to steeply dipping host rocks downdip. Within the mapped area, the Tenpeak pluton is essentially a thick sill. Only the north end of the elongate oval White Mountain pluton crops out in the mapped area, and here it replaces a considerable thickness of metasediments. To the south, the contacts of the White Mountain that were examined are concordant. The gabbro of Riddle Peaks is cut off by later intrusives, but the screens of gneiss that in many places parallel the layering in the gabbro at least suggest that it too had strong structural control.

With the exception of the Duncan Hill pluton, the forms of the larger Tertiary intrusives were notably less subject to control by the structure of host rocks than were pre-Tertiary plutons, and the smaller intrusives, such as those of hornblende-biotite-quartz diorite and biotite-quartz monzonite, seem unshaped by obvious structures. The Cloudy Pass batholith and the sizeable Railroad Creek pluton both replace large thicknesses of host rocks of various kinds, but the northeast contacts of both are more or less concordant. The tadpole-shaped Duncan Hill pluton, however, is unique in that here in a single pluton is illustrated well the progression from strongly concordant relations to discordant relations to host rocks that otherwise is seen only in a succession of different plutons. The mesozonal, thin tail part of the pluton at the northwest end shows a degree of structural control comparable to that of most of the pre-Tertiary plutons, whereas the relatively thick hypabyssal head part of the mass is structurally similar to the Cloudy Pass batholith and cuts out large thicknesses of host rocks.

The assumption that batholiths widen downward and extend to great depth has been challenged by a number of geologists, including Cloos (1923), Chamberlin and Link (1927), Land (1931), and more recently, by

Hamilton and Myers (1967). Moehlman (1948) has noted that Tertiary plutons in the southwest narrow downward. These authors argued variants of the theme that batholiths are floored, rather thin masses that may be completely detached from their sources in the upper mantle and lower crust because semiplastic wall rock, at depth, flowed downward and inward as buoyant masses of magma rose. Seismic and gravity data, such as exist for the Sierra Nevada batholith and summarized by Hamilton and Myers (1967, p. C3–C5), do not exist for the plutons in this study area, but the geologic relations do suggest the behavior of the plutons here was much the same as that of the Sierra Nevada. The youngest major intrusive, the Cloudy Pass batholith, and the nearby Snoqualmie batholith are only now becoming unroofed but have wide lateral extents and show none of the dikelike tendencies prevalent in the older, more deeply eroded masses. The outline of the Duncan Hill pluton indicates only an upward widening of the mass, but the lack of extensive spreading at shallow depths in the preserved parts of the pluton may be deceptive in indicating the original form. Only the terminal end of the upper part of the pluton is preserved, and it is possible that farther north the upper part, since removed by erosion, was much wider.

If batholiths do indeed narrow downward, the ever-present and often vexing problem of how crustal rocks accommodate to large intrusions assumes much smaller proportions. Strontium isotopic data (Hurley and others, 1962, 1965; Fairbairn and others, 1964a, 1964b; Hedge and Walthall, 1963; Taylor and White, 1966; Ewart and Stipp, 1968) indicate that most granitic magmas are derived from upper mantle and lower crustal rocks and not from anatexis of silicic rocks higher in the crust. Trace- and rare-earth-element abundances indicate the same source (Taylor and White, 1966). Somewhat scanty data from the northern Cascades indicate a similar deep-seated source for the plutons there. As masses of buoyant magmas rise through deep-seated and semiplastic rocks, these move aside and then back and downward into the space vacated by the rising magma. Such a process would continue until at higher levels the magma met cooler and more brittle rock. Magmatic spreading probably occurs in the transition zone between plastic and brittle rocks or, as Hamilton and Myers (1967) suggested near the surface beneath a covering crust of its own volcanic ejecta. Upwelling magma may lift or fracture or do both to brittle roof rocks.

The nature of the emplacement process is commonly reflected in the contacts of plutons; thus, as Buddington (1959, p. 715–731) has summarized, at catazonal depths there is general conformity between country rocks and intrusives, and chill zones bordering such intrusives are absent. Gradational and granitized contacts are prevalent. These features are characteristic of the oldest plutons in the northern Cascades, such as those of Dumbell Mountain, whereas plutons exposed only to epizonal depths, such as the Cloudy Pass, give ample evidence of emplacement in cool, brittle rocks. Here the room problem has been solved by lifting of the roof rocks, partly by upbowing and partly by upthrusting along marginal faults as at Hart Lake. The Duncan Hill pluton wedged apart country rocks at the lowest exposed levels and cuts abruptly across them at the uppermost levels. Inasmuch as there is no evidence that any of the rocks cut out by the pluton foundered in the magma, it can only be presumed they were lifted when cut off and, subsequently, were removed by erosion. Thus, the Duncan Hill pluton illustrates well the methods whereby an intrusion can make room for itself at depths ranging from mesozonal to hypabyssal.

AGES OF INTRUSIVE ROCKS AND RELATED PROBLEMS

Until the advent of radiometric dating, the ages of older intrusive rocks in the northern Cascades were generally designated vaguely as pre-Late Jurassic or pre-Late Cretaceous, and indeed there are few grounds on geologic evidence alone for more precise designations. Within the study area, relative ages of most intrusions can be determined, but here again, nearly all of the intrusions are contained only in metamorphic rocks, the ages of which were unknown until recently. Potassium/argon dating of most Tertiary plutons presented few problems, but because of reheating and the resetting of radiometric clocks, most of the older plutons were not accurately datable by this method. Even the oldest unit in the region, the Swakane Biotite Gneiss, and its equivalents, yielded Eocene ages (Engels and others, 1976). In recent years, however, dating by other methods has provided a framework of reliable determinations sufficiently broad so that it is now possible on geologic grounds to date even most of the plutons for which radiometric dates are not yet available rather closely and with fair assurance.

Some of the most significant age dating in the northern Cascades was done by Mattinson (1972). He not only dated a number of the older plutons, but also established the Precambrian age of parent material in the Swakane Biotite Gneiss and the Precambrian age for a unit in Misch's (1966) Yellow Aster Complex. He also determined a late Paleozoic age for the "younger metamorphic rocks of the Holden area." Mattinson also proposed two periods of regional metamorphism, one of middle Paleozoic age occurring about 415 m.y. ago, and the other of middle to Late Cretaceous age, occurring from 60 to 90 m.y. ago. A minimum age of early Paleozoic or older is assigned to the Swakane. The ages of plutons in the mapped area for which area determinations have been made are summarized in table 39 from

TABLE 39.—*Radiometric ages of intrusive rocks in the Holden and Lucerne quadrangles, Washington*

Intrusive body	Mineral	Method	Rock type	Age (10^6 years)	Geochronologist	Source
Cloudy Pass batholith	Biotite	K-Ar	Granodiorite	22.1±2.2	H. H. Thomas, R. F. Marvin, J. D. Obradovich.	Tabor and Crowder, 1969, p. 3.
Do	Zircon	U-Pb	do	20±20	T. W. Stern	Do.
Do	do	U-Pb	do	30±20	do	Do.
Do	Biotite	K-Ar	do	22.5±2.0	H. H. Thomas, R. F. Marvin, J. D. Obradovich.	Do.
Do	Zircon	U-Pb	do	30±20	T. W. Stern	Do.
Dike, associated with Cloudy Pass batholith.	Altered biotite.	K-Ar	Dacite	26.2±4.5	J. C. Engels	Unpublished U.S. Geological Survey data.
Railroad Creek pluton	Hornblende	K-Ar	Quartz monzonite	42.6±2.0	H. H. Thomas, R. F. Marvin, J. C. Engels.	Do.
Railroad Creek pluton	Biotite	K-Ar	do	43.7±1.3	J. C. Engels	Do.
Old Gib volcanic neck	do	K-Ar	Andesite porphyry	43.9±1.5	do	Cater and Crowder, 1967.
Duncan Hill pluton	Zircon	U-Pb	Granodiorite	40±10	T. W. Stern	Unpublished U.S. Geological Survey data.
Do	Biotite	K-Ar	do	43.2±2.2	P. L. D. Elmore, H. Smith, H. H. Thomas, R. F. Marvin.	Cater and Crowder, 1967.
Do	Hornblende	K-Ar	do	44.9±1.8	J. C. Engels	Do.
Do	Biotite	K-Ar	do	46.2±1.4	do	Unpublished U.S. Geological Survey data.
Holden mine	Phlogopite	K-Ar	Gangue	44.1±3.0	do	Do.
Clark Mountain stock	Biotite	K-Ar	Granodiorite	57.1±2.3	J. D. Obradovich	Cater and Crowder, 1967.
Do	Muscovite	K-Ar	do	59.2±2.4	do	Do.
Sulphur Mountain pluton.	Hornblende	K-Ar	Quartz diorite	70.4±2.1	J. C. Engels	Unpublished U.S. Geological Survey data.
Do	Biotite	K-Ar	do	57.7±1.7	do	Do.
Tenpeak pluton	Hornblende	K-Ar	Quartz diorite gneiss	82.4±2.5	do	Do.
Do	Biotite	K-Ar	do	66.0±2.0	do	Do.

Do	Muscovite	K-Ar	do	70.1 ± 2.1	do	Do.
Do	Biotite	K-Ar	Gneissic quartz diorite	75.4 ± 2.4	do	Do.
Do	Hornblende	K-Ar	do	90.5 ± 3.1	do	Do.
Do	Muscovite	K-Ar	do	70.4 ± 3.4	do	Do.
Do	Biotite	K-Ar	do	70.1 ± 2.2	do	Do.
Do	Hornblende	K-Ar	do	88.2 ± 3.2	do	Do.
Entiat pluton	do	K-Ar	Quartz diorite	64.3 ± 1.9	do	Do.
Do	Biotite	K-Ar	do	61.2 ± 1.8	do	Do.
Chelan Complex[1]	Zircon	Pb^{207}/Pb^{206}	Quartz diorite gneiss	193 ± 10	J. M. Mattinson	Mattinson, 1972, p.3774, 3781.
Do	Biotite	K-Ar	Quartz diorite	60.1 ± 2.0	J. C. Engels	Unpublished U.S. Geological Survey data.
Do	Hornblende	K-Ar	do	82.2 ± 2.5	do	Do.
Do	Zircon	Pb^{207}/Pb^{206}	Trondjhemite	183 ± 10	J. M. Mattison	Mattinson, 1972, p. 3774, 3781.
Do	do	Pb^{206}/U^{238}	do	132	do	Do.
Do	do	Pb^{206}/U^{238}	do	111	do	Do.
Do	do	Pb^{207}/Pb^{206}	do	134 ± 10	do	Do.
Do	Sphene	Pb^{206}/U^{238}	do	71	do	Do.
Do	Zircon	Pb^{207}/Pb^{206}	Quartz diorite gneiss	107 ± 25	do	Do.
Do	Sphene	Pb^{206}/U^{238}	Quartz diorite	82	do	Do.
Do	Zircon	Pb^{207}/Pb^{206}	do	111 ± 15	do	Do.
Do	do	Pb^{206}/U^{238}	do	100	do	Do.
Do	do	Pb^{206}/U^{238}	do	101	do	Do.
Do	Sphene	Pb^{206}/U^{238}	do	87	do	Do.
Dumbell Mountain pluton.	Zircon	Pb^{206}/U^{238}	Quartz diorite gneiss	215 ± 10	do	Do.
Do	do	Pb^{206}/U^{238}	do	230 ± 15	do	Do.
Do	do	Pb^{206}/U^{238}	do	216 ± 10	do	Do.
Do	do	Pb^{207}/Pb^{206}	do	221 ± 35	do	Do.
Do	do	Pb^{207}/Pb^{206}	do	215 ± 15	do	Do.
Do	do	Pb^{207}/Pb^{206}	do	278 ± 15	do	Do.
Do	Hornblende	K-Ar	do	88.3 ± 3.3	J. C. Engels	Unpublished U.S. Geological Survey data.
Do	Zircon	Pb^{207}/Pb^{206}	do	233 ± 10	J. M. Mattinson	Mattinson, 1972, p. 3774, 3781.
Do	do	Pb^{207}/Pb^{206}	do	243 ± 10	do	Do.

[1] Hopson (1964)

data presented by Engels and others (1976). Not included are those determinations that they, for various reasons, considered suspect or for geologic reasons are untenable. All the data presented by Mattinson (1972) concerning the Dumbell Mountain, Seven-fingered Jack, and Entiat plutons are included, however, to show the spread that different methods give.

The middle to Late Cretaceous period of metamorphism proposed by Mattinson, during which he believed the upper Paleozoic rocks and the Dumbell Mountain plutons together were metamorphosed to amphibolite grade, was also a period when a number of larger plutons or batholiths in the region were intruded. These include the about-90-m.y.-old Mount Stuart and Black Peak batholiths and the Tenpeak and White Mountain plutons (Engels and others, 1976). There can be no question that potassium/argon radiometric clocks were reset in many rocks 60 to 90 m.y. ago, but as is discussed later, there is little or nothing to suggest rather intense regional metamorphism at that time other than what has been interpreted as the metamorphic nature of the Dumbell Mountain and Seven-fingered Jack plutons and their correlatives (Mattinson, 1972, p. 3772; Misch, 1966; Crowder, Tabor, and Ford, 1966; Crowder, 1959). The upper Paleozoic rocks of the Holden area believed by Mattinson to have been metamorphosed to gneisses 60 to 90 m.y. ago were already gneisses when intruded by the Dumbell Mountain plutons 220 m.y. ago as proved by disoriented inclusions of gneiss and schist within the plutons. To regionally metamorphose the Dumbell Mountain (and Seven-fingered Jack) plutons to amphibolite grade and leave untouched the discordant metamorphic fabric of these inclusions seems unlikely. Rocks as susceptible to recrystallization as the contact complexes, characterized by abundant gabbro and very coarse grained hornblendite, that border the Entiat pluton (fig. 25) and other supposed premetamorphic plutons are equally unlikely to have completely escaped any metamorphic changes. All these complexes also contain abundant inclusions of disoriented fragments of metamorphic country rocks. More likely, the host rocks were metamorphosed before or near the time Dumbell Mountain quartz diorite was intruded. Potassium/argon radiometric clocks were as widely reset in late Eocene time as during mid- and Late Cretaceous time, as is indicated by late Eocene potassium/argon ages obtained from rocks such as the Leroy Creek pluton and the Swakane Biotite Gneiss and its equivalents (Engels and others, 1976), but no one has credited this heating event with producing such dire effects on the terrane as had the proposed earlier event.

Mattinson considered the Chelan Complex of Hopson (Mattinson, 1972, p. 3772) to be a metamorphosed, migmatized, and mobilized extension of Misch's (1966) Marblemount belt, which includes the Dumbell Mountain plutons (Mattinson, 1972, fig. 1, p. 3770). Moreover, the Dumbell Mountain plutons, and hence the Marblemount belt, pinches out in the southern part of the Lucerne quadrangle, and the correlation of the Chelan Complex with the Marblemount belt is invalid.

The Chelan Complex of Hopson probably correlates with the Seven-fingered Jack plutons, although a strip of Entiat pluton rocks, just southwest of the location of Mattinson's sample 23 (1972, fig. 1, p. 3770), is designated as "Late Cretaceous and Tertiary." This designation is based on potassium/argon ages of about 61 and 64 m.y. obtained from biotite and hornblende (Engels and others, 1976), roughly the same as the potassium/argon ages (60 to 82 m.y.) obtained from rocks nearby in the Chelan Complex from which Mattinson (1972) obtained zircon Pb^{206}/U^{238} ages ranging from 100 to 183 m.y., and sphene ages of 71 to 87 m.y. No zircon Pb^{206}/U^{238} age determinations from the strip of Seven-fingered Jack rocks labeled as "Late Cretaceous and Tertiary" have been made, and until this is done, there is no more reason for calling these rocks Late Cretaceous and Tertiary than for calling the Chelan Complex Late Cretaceous and Tertiary on the basis of potassium/argon ages and ignoring the zircon lead/uranium ages. The Seven-fingered Jack rocks, including the Chelan Complex, are far more nearly akin, petrologically, to the older intrusives than to any of the Tertiary intrusive rocks, including the about-60-m.y.-old (Engels and others, 1976) Clark Mountain stocks.

The lower beds in Paleocene Swauk Formation in the Chiwakum graben, in the Holden quadrangle, contain numerous pebbles and boulders identical to nearby outcrops of both the Dumbell Mountain and the Seven-fingered Jack intrusive rocks, indicating thereby that these rocks were exposed during that time. On the other hand, the formation contains pebbles and cobbles of extrusive rocks, but the affinities of these rocks are unknown, unless, perhaps, they are extrusive equivalents of the Clark Mountain stocks or somewhat older plutons. But it does seem unlikely that the Dumbell Mountain plutons, in particular, could have been eroded to catazonal depths during or so soon after the time they were supposed to have been metamorphosed about 90 m.y. ago.

COMPOSITION AND DIFFERENTIATION

Compositions of the various intrusive rocks in the study area were determined by 47 chemical analyses and more than 300 modal analyses. Of the chemical analyses, 7 were by standard methods and 40 by various rapid methods; all chemically analyzed samples were also analyzed by spectrographic means for semiquantitative determination of minor elements. Modes were determined on thin sections of standard size with a point counter of the type described by Chayes (1949). Analyses of rocks from the Cloudy Pass batholith have been reported earlier (Cater, 1969; Tabor and Crowder, 1969) and are not repeated here. Inasmuch as none of the rocks are particularly coarse grained, stained slabs were not used for modal determinations.

For most of the smaller intrusions of relatively uniform compositions only single, representative, mostly composite samples were chemically analyzed, but for larger plutons that are zoned or are otherwise of variable composition, a number of samples were commonly analyzed. The chemical analyses supplemented by numerous modal analyses are thought to give a fairly representative view of the compositions of each intrusive. Even for the salic, quartz-bearing plutons, apart from the gabbroic contact complexes associated with some of them, the range is fairly wide; SiO_2, for example, ranges from about 56 to about 76 percent. The range for some of the larger, compositionally variable plutons, moreover, is nearly as large as the range for the entire group of plutons. A number of plutons are closely similar in composition, some because they are closely related in time and probably in source; but other compositionally similar plutons are probably unrelated, being separated in time by scores of millions of years. All, however, probably originated under somewhat similar conditions and from similar materials presumably from the upper mantle and lower crust. The older, narrow, quartz-bearing plutons mostly show much less diversity in composition than do the latest Cretaceous and younger plutons. In fact, only the largest plutons, mostly Tertiary, are compositionally zoned or have considerable variability at exposed levels. However, as explained earlier, presumably only the roots or feeders of the older intrusions remain, and these narrow conduits would seem to be physically unfavorable locations for demonstrable zoning resulting from differentiation to occur, particularly in more or less horizontal planes, although these narrow masses certainly seem to represent levels in vertical zones.

Probably the most characteristic feature distinguishing the intrusive rocks of the area is their low content of K_2O, relative to average intrusive rocks (Nockolds, 1954) of similar SiO_2 content. This low K_2O content is true regardless of age of an intrusive, although in general, the older the rock the lower the content of K_2O even where SiO_2 is high. Indeed, the older pre-Tertiary plutons, even the most quartzose, are virtually devoid of potassium feldspar, and biotite is not common. Of the pre-Tertiary plutons, only the Bearcat Ridge, Sulphur Mountain, and High Pass plutons contain more than rare, interstitial amounts of potassium feldspar. The Sulphur Mountain pluton has a radiometric age of 70 m.y. (Engels and others, 1976), indicating a Late Cretaceous age; the undated High Pass pluton cuts the Sulphur Mountain, and possibly the High Pass may be as young as Tertiary. The undated Bearcat Ridge plutons both structurally and in megascopic appearance closely resemble the Dumbell Mountain plutons and were shown on the Lucerne geologic quadrangle map as being contemporaneous. The Bearcat Ridge rocks, however, are not in contact with any of the older dated rocks, so their age relative to older intrusive rocks is not known. Norms and modal data indicate that, compositionally, the Bearcat Ridge rocks are more nearly akin to far younger rocks, and it may be that these rocks are younger than was indicated on the map.

Hietanen (1975) has proposed an explanation for the origin of the potassium-poor magmas in the northern Sierra Nevada that may explain the potassium-poor intrusive rocks in the northern Cascades. Her explanation was based on the experimental work by Allen, Modreski, Haygood, and Boettcher (1972) and Modreski and Boettcher (1972) on stabilities of amphiboles and biotite or phlogopite at high temperatures and pressures. Their experimental work indicated that amphiboles become unstable at depths of about 75 km, whereas phlogopite only begins to decompose at depths greater than 100 km and is unstable below 175 km. Hence, in a subducting lithospheric plate, amphibole would break down to release water and sodium to magmas forming at depths shallower than 100 km, whereas potassium would be retained in phlogopite or biotite and would only be released to magmas formed at depths greater than 100 km. Thus, possibly the magma for the potassium-poor intrusions in the study area were formed at relatively shallow depths.

The Dumbell Mountain plutons, the oldest of the major intrusives in the area (there may possibly be some older metamorphosed dikes and sills in the Swakane Biotite Gneiss), have compositions that appear to be unique. In fact, a search of the literature, albeit not an exhaustive one, failed to disclose any analyses of igneous rocks having comparable contents of silica, iron, magnesium, and calcium where K_2O was so astonishingly low; the rocks are extremely potassium-deficient quartz diorites (table 3). The perhaps not much younger but undated Leroy Creek pluton is about equally deficient in K_2O, but its trondhjemitic composition is not particularly unusual. Both younger pre-Tertiary and Tertiary plutons also are without exception poorer in K_2O than is normal for rocks of otherwise comparable compositions. In fact, only in the porphyries and granophyres at the top of the Eocene Duncan Hill pluton does the content of K_2O reach levels normal for rocks of similar silica contents.

Rocks from the Dumbell Mountain plutons have a considerable compositional range, the analyzed samples containing from 52.5 to 73.7 percent SiO_2. All other major constituents decrease as silica increases except Na_2O, which remains fairly constant, and K_2O, which also remains constant but very low (table 3; figs. 12, 13). Hornblende-quartz diorite gneiss is compositionally the most variable of the Dumbell Mountain rocks, possibly because of considerable but locally variable quantities of partly assimilated hornblendic host rocks. The quartz diorite augen gneiss is considerably more siliceous than the slightly younger gneissic hornblende-quartz diorite and contains a little less K_2O. The variations of compositions within the plutons, as indicated by modal analyses of numerous samples (table 2; fig. 11), are erratic and indicate no systematic zoning. Systematic zoning, as indicated by modal analyses, also appears to be lacking in the rest of the pre-Tertiary intrusives within the area, although local variations of composition are appreciable and common. In the Glacier Peak quadrangle, however, Crowder, Tabor, and Ford (1966) mapped a dark, mafic facies in the northern part of the Tenpeak pluton; the other mapped units in the pluton differ from each other not so much in composition as in structure and texture.

Tertiary intrusive rocks are compositionally more varied on the whole, and the distribution of compositional variations is generally more systematic than is true of the older intrusive rocks. The smaller plutons are relatively homogeneous, and variations in content of K_2O are rather small. The two largest plutons, the Cloudy Pass and Duncan Hill, on the other hand, contain rocks of widely different compositions. In the Duncan Hill pluton the compositional variations, in general, are systematic and show progressive changes along the length of the pluton, whereas in the Cloudy Pass variations are largely erratic and range between wide limits across short distances. The composition, the variations therein, and the reasons for these variations in the Cloudy Pass batholith were discussed at length by Cater (1969) and Tabor and Crowder (1969). The parts of the batholith described by each of these reports differ somewhat in the abundance of rock facies exposed and in the relative significance of differentiation processes operative in the batholith to produce these facies. The core of the batholith in the Holden quadrangle, described by Cater (1969), is characterized by rocks containing labradorite, the composition of which changes little from place to place. The abundance of orthoclase can range from none to abundant within distances measured only in a few meters. Rocks containing sodic plagioclase are rare and mostly confined to late dikes. To the west in the part of the batholith described by Tabor and Crowder (1969), much of the rock is a light-colored, oligoclase-bearing quartz monzonite, containing fairly constant amounts of potassium feldspar. Inasmuch as the batholith is only now in the process of being deroofed and is exposed only to depths not exceeding 1.6 km, it afforded a particularly advantageous opportunity to study subvolcanic phenomena associated with the upper part of a batholith. The Duncan Hill pluton, on the other hand, affords an opportunity to view a large intrusion not only from a similarly shallow level but also to depths of a fair number of kilometers.

Other plutons, because of their narrow vertical ranges of exposure or ranges, at any event, that show little or no consistent compositional variation, seem to correspond more or less to given narrow levels within the broad spectrum of depth zones observable along the length of the Duncan Hill pluton. Older intrusives, such as the Dumbell Mountains plutons, may indicate the kinds of rocks existing at deeper levels in the Duncan Hill. Not all plutons that are older than the Duncan Hill, however, seem to have been eroded as deeply as the north end of the Duncan Hill. The older Clark Mountain stocks to the west, on the opposite side of the Chiwawa graben, for example, have the general characteristics of rocks near the midpoint along the length of the Duncan Hill. In fact, in the Holden quadrangle, the terrane on the west side of the graben, in general, seems not to have been as deeply eroded in Tertiary times as that on the east side. The only lower Paleozoic or older Swakane Biotite Gneiss exposed west of the graben is in the roof of the Cloudy Pass batholith, and plutons older than or equal in age to those east of the graben have the characteristics of shallower intrusions.

Because the compositional and textural difference present in plutons of progressively younger ages roughly parallel the changes that occur at increasingly shallow depths in the Duncan Hill pluton, probably the differentiation processes that were active in the Duncan Hill were equally active in the other granitoid intrusives of the area. In the Duncan Hill, however, the processes can be interpreted with reasonable assurance without recourse to a series of extrapolative leaps that would be necessary were the evidence only a series of fragments preserved in a series of separate intrusives. Hence, the Duncan Hill was investigated in more detail outside the mapped quadrangles because of information it probably gives on the history of differentiation of other plutons in the area.

The plot of modes of rocks from the Duncan Hill pluton in figure 77 shows a wide scatter consistent with the wide compositional range of the rocks in the pluton; the plotted norms (fig. 79), on the other hand, although showing a considerable scatter, are confined to a narrow field extending from near the center of the triangle towards the albite corner. As shown by the variation diagram (fig. 78), in which major oxides are plotted against SiO_2, only K_2O increases as SiO_2 increases, although somewhat erratically, but as is well known, K_2O is commonly the most variable oxide in granitic rocks. Na_2O remains nearly constant; for that matter, it ranges between narrow limits in all the granitoid plutons of the area. Bateman and Dodge (1970, p. 414) also found that the Na_2O content is about the same in the plutons in the central part of the Sierra Nevada batholith. As they pointed out, the content of SiO_2 in granitic rocks is a measure of differentiation, but it appears that the content of Na_2O does not vary systematically with differentiation.

Of particular interest is figure 98, a diagram showing the variations in SiO_2, K_2O, Na_2O, and CaO along the length of the pluton. SiO_2 and K_2O are the only constituents that increase higher in the pluton, and Na_2O remains virtually constant throughout. As indicated in figure 98, the only abrupt changes in composition of the Duncan Hill occur in the miarolitic and granophyric rocks at the south end of the pluton where the content of K_2O about doubles and CaO decreases to a third of its value lower in the pluton. As shown in table 23, ferric oxide also increases slightly at the expense of ferrous oxide in the miarolitic rock, possibly the result of contamination with atmospheric oxygen at these shallow levels. Although a gap of about 15 km separates analyzed-sample 7 from the analyzed samples at the south end of the pluton around Stormy Mountain, the reality of the abrupt change is confirmed by study of thin sections of samples in the intervening interval. The change in composition is as abrupt and occurs in the same interval as does the change in megascopic appearance in the rather narrow transition zone between biotite granodiorite and miarolitic quartz monzonite. Furthermore, unlike the underlying biotite granodiorite, the highly gas-charged miarolitic quartz monzonite appears to have been totally molten immediately prior to final crystallization. The oscillatory and patchy zoned plagioclase having labrodorite cores in the rock below the quartz monzonite is replaced by oligoclase showing progressive but little or no oscillatory zoning; cores of labradorite are either nonexistent or where rarely present are highly saussuritized and nearly resorbed. That the Duncan Hill magma was moderately wet is suggested by the occurrence of hornblende and biotite to the total exclusion of pyroxene. Yoder (1969, p. 83–84) has pointed out that only at elevated water pressures can plagioclase of high anorthite content form at temperatures of less than 1250°C. The labradorite and a few bytownite cores in plagioclase having average compositions of generally sodic to medium andesine indicates high water pressures at the beginning of crystallization. Hence, a sufficient source of water at depth in the pluton for eventual transfer upward seems probable.

Abundant evidence indicates the Cloudy Pass batholith also contained considerable water (Cater,

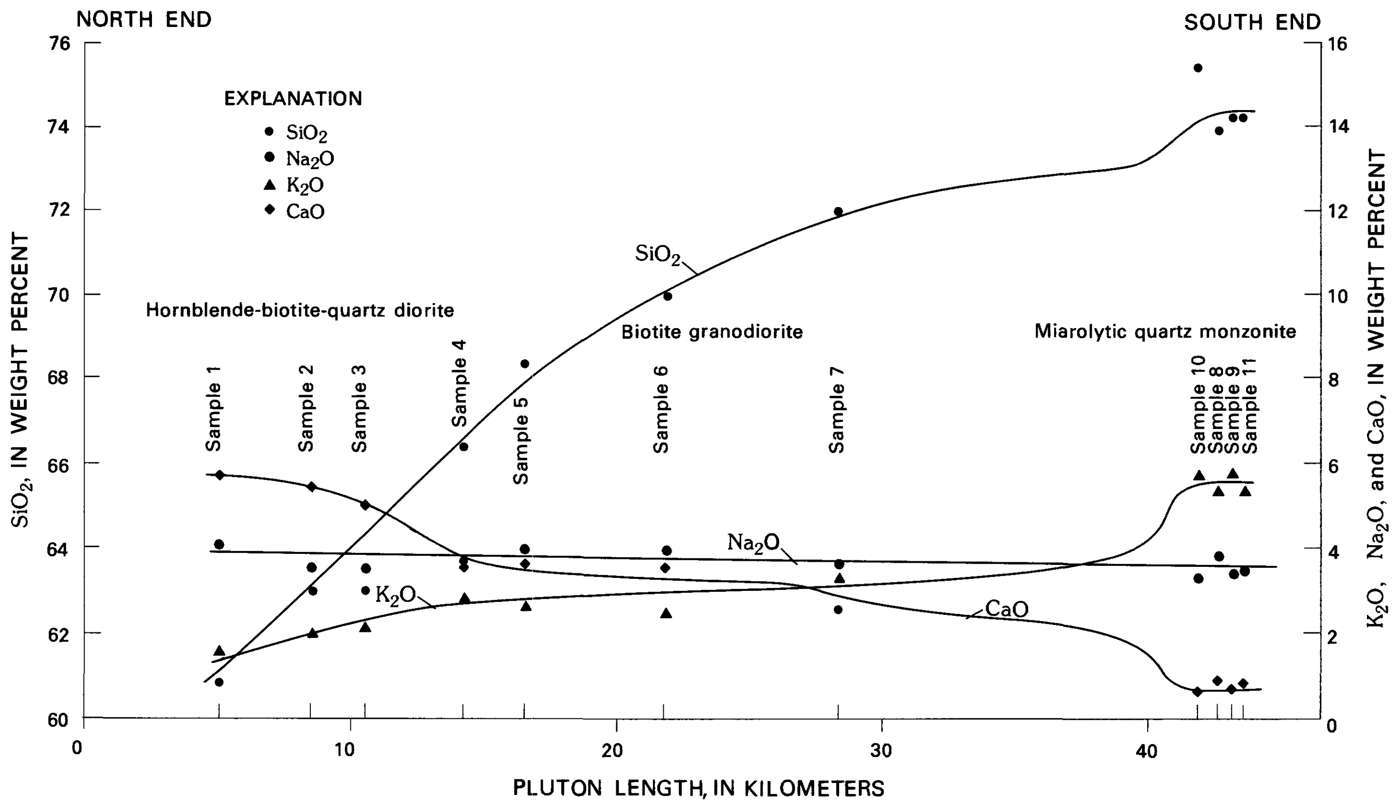

FIGURE 98.—Diagram showing variation in content of SiO_2, K_2O, Na_2O, and CaO along the length of the Duncan Hill pluton, central Washington. Sample analyses are given in table 23; sample locations (fig. 76) are projected to the center line of the pluton. Hornblende-biotite-quartz diorite probably crystallized at least 8-10 km below the miarolytic quartz monzonite. Biotite granodiorite probably crystallized at least 3-6 km below the miarolitic quartz monzonite.

1969), but the compositional changes in the rocks in the Cloudy Pass resulting from degassing of the cooling batholith are markedly different from those that occurred in the Duncan Hill pluton. There are no indications, for example, that rocks in the upper part of the Cloudy Pass were remelted prior to final crystallization; only large-scale but erratic metasomatism occurred along with features indicative of violent expulsion of gas and extrusive activity. The remaining uppermost part of the Duncan Hill pluton shows no features suggestive either of explosive escape of gas or extrusion of lava. One seems forced to the conclusion that the roof of the Cloudy Pass was leaky, whereas that of the Duncan Hill was tight and permitted only slow escape of volatiles as the pluton crystallized. Had volatiles from the Duncan Hill been able to escape readily, there seems little likelihood that water-vapor pressures could have risen to the point where labradorite cores of the plagioclase crystals, with which the magma must have been charged, could have gone back into solution in a magma now almost completely liquid. The miarolitic and granophyric quartz monzonite then finally crystallized from this almost completely liquid magma to a rock bearing little outcrop resemblance to the underlying granodiorite into which it grades.

The depth at which the miarolitic quartz monzonite crystallized is not known, but if the water vapor was approximately equal to the lithostatic pressure when the quartz monzonite crystallized, as indicated by the position of samples of quartz monzonite on the isobaric lines (Tuttle and Bowen, 1958, p. 74–75) in figure 79 (a pressure of about 150,000 kilopascals), then the quartz monzonite solidified at a depth of 8 or 9 km—a depth, however, that seems excessive for such volcanic-appearing rocks. Perhaps the water-vapor pressure considerably exceeded the lithostatic load. Certainly considerable water pressure was necessary to accomplish resolution of the plagioclase. The probable depths of samples of granodiorite and quartz diorite below the miarolitic quartz monzonite are interpreted from the dips of remnants of Miocene lava caps remaining on ridges south of the Lucerne quadrangle and are believed to be minimal.

The progressive enrichment upward of SiO_2 and K_2O in the Duncan Hill pluton probably resulted from transfer of these components in supercritical aqueous solutions, rather than from differentiation by crystal fractionation. However, the decrease in CaO and mafic constituents higher in the pluton seems to be more than would be likely if the only changes were the addition of SiO_2 and K_2O strictly by metasomatism, so possible sinking of heavier minerals in the magma may have had a minor effect on composition. Furthermore, the protoclastic texture of the quartz diorite in the northern—and lower—part of the pluton suggests that filter pressing upward of the still fluid, more silicic fraction of the magma may also have been effective. In any event, the protoclastic textures do indicate crowding and mutual interference of crystals while the magma was still in motion.

Metasomatic transfer of SiO_2 and K_2O was equally effective in causing compositional variation in the Cloudy Pass batholith (Cater, 1969), but the variations there were much more haphazard than in the Duncan Hill. The efficacy of potassium metasomatism in altering compositions of intrusions has been documented by many geologists as, for example, Boone (1962), Kennedy (1953), and Taubeneck (1967) and is supported by a large body of experimental work (Burnham, 1967; Jahns and Burnham, 1958; Kennedy, in citing Mosey, 1955, p. 498; Luth and others, 1964; Orville, 1963; Tuttle and Bowen, 1958, p. 90–91). Possibly this same process has operated effectively in other plutons in the area and may explain the extreme poverty of K_2O in the Dumbell Mountain plutons. Potassium added to one rock or magma must have been taken from another somewhere else, and commonly only rocks enriched in potassium have elicited much attention because evidence of enrichment is far more obvious than evidence of depletion. The remaining parts of the Dumbell Mountain, Leroy Creek, and Seven-fingered Jack plutons may have been sites of potassium depletion.

The numerous Tertiary dikes in the area of widely differing compositions suggests that differentiation probably by crystal fractionation was also effective. Many of the dikes are aschistic and some are directly traceable into or are identical in composition and appearance to some of the larger plutons, but others are diaschistic and unlike the rocks of any of the larger plutons as, for example, the swarm of mafic dikes and irregular masses associated with the south end of the Duncan Hill pluton. The localities or magma chambers where the differentiation occurred, however, either have not been recognized or are not exposed. The large number of late Eocene intrusives in and adjacent to the mapped area that differ but little in age certainly suggests a widespread and copious source for large quantities of magma. Inasmuch as available data from strontium isotopes (Hedge and others, 1970; Church and Tilton, 1973; Peterman and others, 1970; Zell, Peterman, written commun., 1975) indicates the source of most magmatic material is the lower crust and upper mantle, then plenty of room exists in the remainder of the crust below the presently exposed surface for magma chambers to have formed. Such chambers not only could have fed the exposed plutons but also were sites where differentiates could have accumulated that were later forced into the dikes and small, irregular masses of widely different compositions that cut the area.

TEXTURES AND DEPTH ZONES

The fact that textures of igneous rocks vary with rate of cooling and with depth of emplacement is well known, but much that has been written concerning textures applied only to mesozonal or shallower intrusions—rocks with so-called typical igneous textures. Deep-seated igneous rocks, on the other hand, often have been interpreted as recrystallized or as having been formed by replacement, because the textures were considered metamorphic. Thus, Crowder (1959), from his study of thin sections of the Dumbell Mountain, Leroy Creek, and Seven-fingered Jack plutons, considered these rocks to be either largely recrystallized or to have formed by replacement or granitization. Van Diver (1967) considered the rather deeply eroded 90-m.y.-old White Mountain pluton to be recrystallized; he interpreted the protoclastic texture to be a recrystallized cataclastic texture, although the foliation of the protoclastic rock is conformable to the nearest contact of the pluton and over large areas transects the regional foliation of the metamorphic host rocks. Identical textures also exist in most of the Tertiary plutons, including the Miocene Cloudy Pass batholith, as previously discussed in the section on "Ages of intrusive rocks and related problems." Mattinson (1972) also considered the Dumbell Mountain plutons and their correlatives and Hopson's Chelan Complex—probably correlative of the Seven-fingered Jack plutons—to be metamorphosed, the Chelan Complex to the point of anatexis.

Misch (1966, p. 106 and fig. 7-1) considered the northward correlative of the Dumbell Mountain plutons—his Marblemount Meta Quartz Diorite—a part of his "basement complex" that had undergone his "Skagit metamorphism," an event, incidentally, by which he derived his "Skagit Gneiss"—our Swakane Biotite Gneiss—from the "Cascade River Schist" (p. 113). Mattinson (1972) has dated the Cascade River Schist as late Paleozoic and the Skagit Gneiss as Precambrian. Misch also showed the Dumbell Mountain plutons (his fig. 7-1) as overthrust by the upper Paleozoic gneisses, rather than intrusive into them but did concede (his p. 114), "the meta quartz diorite has relict gross igneous textures." These examples illustrate some of the interpretations of deep-seated intrusive rocks in the area that have been published by various geologists, but there are, however, a number of reasons for believing these rocks have not been metamorphosed, or only weakly so, since they were intruded. These reasons are discussed below.

As Crowder (1959, p. 843) noted, the hornblende-quartz diorite augen gneiss of the Dumbell Mountain plutons contains unoriented inclusions of schist and gneiss. He considered these inclusions to be mobilized breccias resulting from granitization. In addition to containing these unoriented inclusions, much of the rock in both the Dumbell Mountain and Leroy Creek plutons has swirled foliation that is independent of regional foliation in the metamorphic host rocks; furthermore, foliation in the Leroy Creek pluton tends to parallel its contacts. Had regional metamorphism occurred after emplacement of the plutons, then the disoriented foliated fabric of the inclusions could not have survived regional recrystallization of supposed amphibolite grade. Were the inclusions confined to the central parts of plutons, it could be argued, perhaps, that the competent plutonic rocks shielded the inclusions from strong metamorphic effects; however, disoriented inclusions are most common near contacts, as other inclusions are. Also, it is difficult to account for the swirled foliation resulting from regional metamorphism where no swirled foliation exists in the enclosing gneiss and schist. Although the textures of the plutons resemble crystalloblastic textures, most thin sections contain plagioclase that shows both vague oscillatory and patchy zoning. Furthermore, younger plutons such as the Seven-fingered Jack have textures that verge on crystalloblastic in appearance in most places but not to the extent that is characteristic of the older and deeper seated plutons; textures of some of the Seven-fingered Jack rocks are typically hypidiomorphic. It is equally difficult to explain how the spectacular coarse-grained contact complexes associated with the Seven-fingered Jack and other presumed premetamorphic plutons and containing innumerable foliated metamorphic rock in all orientations, completely escaped recrystallization while their consanguineous plutons were being reduced to amphibolite-grade gneisses.

Rocks crystallized from magma intruded into material where conditions of amphibolite grades of metamorphism exist would probably differ texturally from rocks crystallized from magma injected into material where conditions of greenschist metamorphic facies or cooler conditions prevail. If, as Buddington (1959, p. 676) estimated, rock temperatures at the top of the catazone are about 500°C, then plagioclase in a crystallizing magma, for example, would have ample opportunity to equilibrate, and oscillatory and patchy zoning, so characteristic of plagioclase in mesozonal and epizonal rocks, would be largely destroyed, as is true in rocks from the Dumbell Mountain and Leroy Creek plutons and in most of the rocks in the Seven-fingered Jack and Entiat plutons. Extremely slow rates of cooling of magma intruded into regionally hot rocks should not be expected to yield rock having textures usually referred to as typically igneous. Most likely, textures more nearly resembling crystalloblastic textures should result. The generally pseudocrystalloblastic textures of the Dumbell Mountain and Leroy Creek plutons and much of the rock in other older pre-Tertiary plutons, and the gneissic fabric of these rocks, can hardly have been formed by metamorphic recrystallization, leaving unaffected the attitudes of gneissic foliation in disoriented inclusions and slabs. The gneissic fabric of the quartz diorite is probably the result of overgrowths on crystals oriented by flowage at early stages of crystallization.

It is true, nevertheless, that rocks in the area have been sufficiently reheated periodically to yield anomalously low potassium/argon ages for both metamorphic and pre-Tertiary intrusive rocks (Engels and others, 1976). Moreover, in many places leucocratic and trondjhemitic clots, dikes, and small irregular bodies have either segregated from or been injected into the metamorphic rocks and the Seven-fingered Jack and older plutons; but the abundance of these leucocratic rocks everywhere in the Swakane and their localized distribution in the younger metamorphic rocks and the plutons strongly suggests that they are not of the same age. Some of the masses in the Swakane may well be Precambrian. In any case, there is little to suggest strong regional metamorphisms subsequent to intrusion of the Dumbell Mountain plutons.

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