

## IGNEOUS ROCKS AND CONSTITUENT HORNBLENDES OF THE HENRY MOUNTAINS, UTAH

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### ABSTRACT

The dominant intrusive igneous rock in the Henry Mountains is diorite porphyry. This rock is chemically and mineralogically monotonous through the stocks, laccoliths, bysmaliths, and dikes. The aggregate volume exceeds 16 cubic miles. Locally the diorite porphyry is cut by and grades into monzonite porphyry which is more variable in composition but constitutes only 5 per cent of the exposed rock.

Most hornblende phenocrysts in the diorite porphyry are also chemically alike, with molecular proportions of FeO/MgO of about 0.9 to 1.1. In one coarse-grained laccolith the large hornblende phenocrysts have a molecular proportion of FeO/MgO of about 0.4. This more magnesian hornblende is compositionally similar to most hornblendes from the hornblendite and amphibolite inclusions in the diorite porphyry.

Except for relatively high Na content, the diorite porphyry of the Henry Mountains could have been derived by the tapping of the upper portions of a typical andesitic parent magma from which early formed crystals of hornblende and pyroxene have settled. The monzonitic variant appears to represent a differentiate of the diorite. The inclusions are interpreted to be early formed mafic hoods or crystal segregates from the parent magma. Possibly, however, they are xenoliths of amphibolite or basaltic crust.

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#### INTRODUCTION AND ACKNOWLEDGMENTS

This investigation is part of a program of the United States Geological Survey to determine the composition of igneous rocks. The porphyritic rocks of the Henry Mountains, Utah, were chosen because they are definitely igneous and include a variety of hypabyssal intrusive bodies closely related in space and time of development. The intrusive bodies are stocks, laccoliths, bysmaliths, and dikes and sills that are well exposed. Their form and distribution have been carefully determined (Hunt, 1953). The rocks are almost entirely diorite porphyry with rare monzonite porphyry.

The study reported herein had two major objectives. One of these was to determine the variations in physical properties and chemical composition of the porphyries from place to place within a single intrusive body and between bodies. A second objective, only partly accomplished, was to learn more of the properties of the hornblendes that are the principal mafic mineral in both porphyries and inclusions in the porphyries. This phase of the work has been limited because of widespread, although not extreme, alteration of the hornblendes.

Chemical analyses are reported for five hornblende phenocrysts and for one hornblende from a hornblende inclusion. Partial chemical data are reported for nine other hornblendes from hornblendite and amphibolite inclusions.

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#### GENERAL GEOLOGY

The general geology of the Henry Mountains region is well known from Gilbert's pioneer

work (1877) and later studies by Hunt (1953). The Henry Mountains are a series of structural domes that lie within a broad structural basin in the Colorado Plateau. The basin is diamond-shaped, measuring roughly 100 miles long and 50 miles wide. Its axis trends in a general northward direction in accordance with associated structural uplifts and depressions of the Colorado Plateau in southeastern Utah.

There are five Henry Mountain domes. Each of the four southern domes is 6-8 miles in diameter. The northern dome, the Mt. Ellen complex, is about 10 miles in diameter. Each of the domes has a structural relief of several thousand feet. They occur on the gentle east flank of the surrounding structural basin. The basin was developed probably in late Cretaceous or early Tertiary time. The intrusions and doming of the Henry Mountains appear to have followed the development of the basin, possibly in the early or middle Tertiary (Hunt, 1953, p. 88).

Each of the domes of the Henry Mountains consists of a central stock around which laccoliths, dikes, sills, and bysmaliths are clustered. All these intrusions were formed by the injection of magma into the sedimentary strata with little or no stoping, incorporation, or assimilation of the wall rock. The larger stocks contain minor deposits of metal sulfides that are rare or absent in the other intrusive bodies. Each stock is surrounded by a shattered zone of the enclosing sedimentary rocks variously injected by igneous rock. The laccoliths radiate from the central stocks and the surrounding shattered zone and are roughly concordant with the bedding in the intruded sedimentary rocks. Gilbert (1877) noted that the laccoliths raised the overlying sedimentary rocks by arching the beds. The outermost intrusive types, the bysmaliths, raised their roofs by faulting (Hunt, 1953, p. 90). Evidence assembled by Hunt suggests that the laccoliths and bysmaliths were injected radially from conduits now filled by the

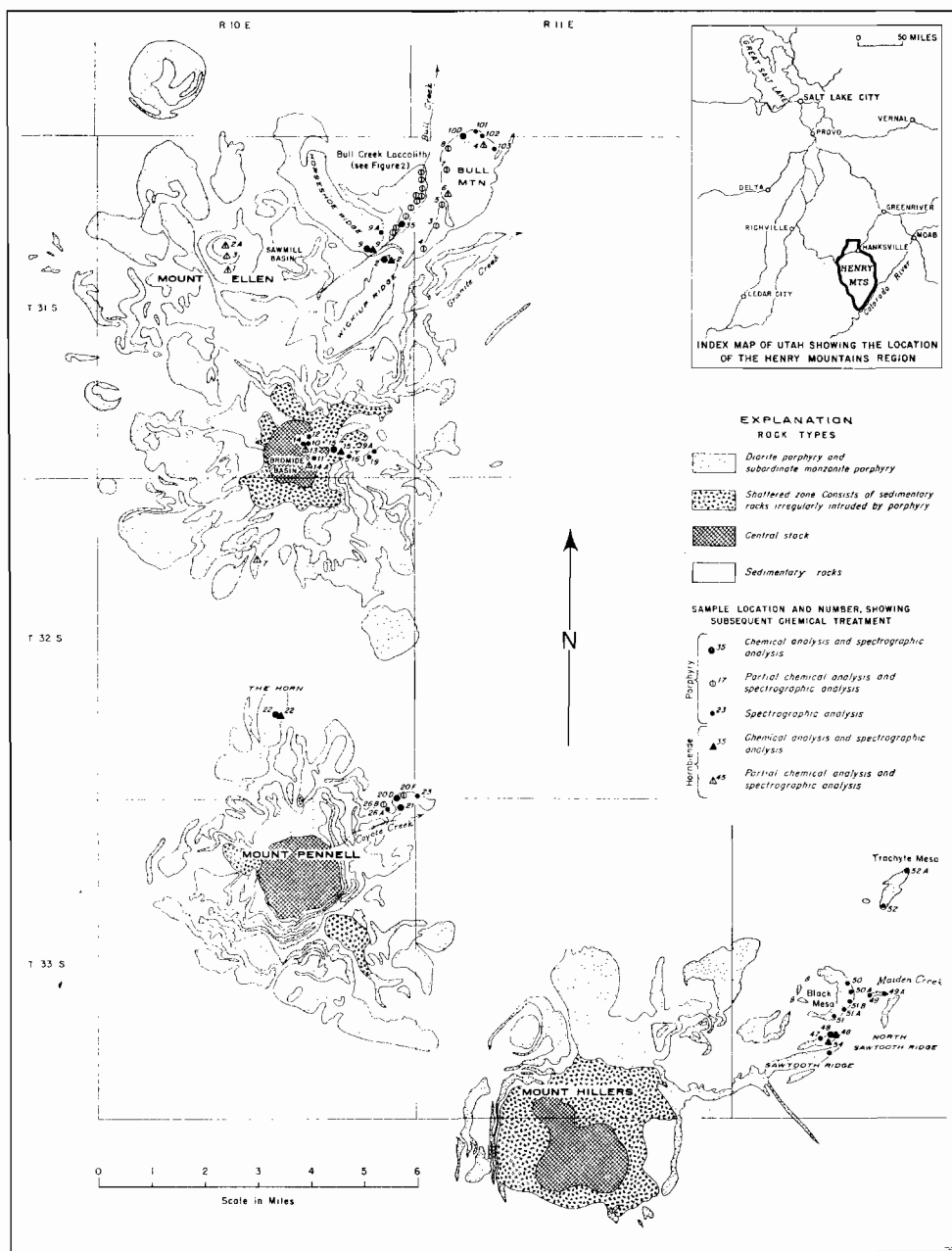


FIGURE 1.—GENERALIZED GEOLOGIC MAP OF PART OF THE HENRY MOUNTAINS, UTAH (After Hunt, 1953) Showing location and type of samples and subsequent chemical treatment.

central stocks. Metamorphism of the sediments adjacent to the intrusive bodies is very slight. Some of the shales and siltstones appear to be slightly baked and reconstituted at and within a few feet of the contact. Grain size of the sedi-

ments is not appreciably increased by the metamorphism.

Throughout the Henry Mountains the dominant intrusive rock (95 per cent by volume) is diorite porphyry. Subordinate monzonite

porphyry occurs on Mt. Pennell and very locally on Mt. Ellen (Fig. 1). Other igneous rock types, a few aplite and basalt dikes, total a fraction of 1 per cent of the total igneous rocks (Hunt, 1953, p. 152).

All the igneous rocks of the Henry Mountains show alteration effects which are either deuteric or hydrothermal. This alteration is manifested principally in sericitization of the feldspars and the replacement of hornblende by chlorite, calcite, epidote, iron oxides, and minor amounts of serpentine. The amount of alteration varies but reaches a maximum in parts of the stocks and shattered zones, in the roofs of laccoliths, and in some dikes which form outlying intrusive bodies. Alteration is only slight to moderate in many internal parts of the stocks, laccoliths, and bysmaliths.

#### PRESENT INVESTIGATION

The present investigation of the igneous rocks in the Henry Mountains was begun in July 1956 when Charles B. Hunt and T. S. Lovering accompanied me on a tour of the Henry Mountains and the La Sal Mountains. Hunt's maps and detailed knowledge of the geology and geography of the Henry Mountains were used as a basis for evaluating the intrusive rocks as a source of samples suitable for more detailed study of rock composition. After this trip my husband and I worked 5 weeks in the field, walking out the intrusive bodies and sampling them. The northern part of the area was revisited in September 1957 for additional samples. Hunt contributed samples of hornblende-rich inclusions from several relatively inaccessible areas which I did not visit.

#### SAMPLING

##### *General Program*

In the sampling program, an attempt was made to obtain least altered samples of igneous rock from the following occurrences: (1) central stocks, (2) peripheral shattered zones that envelop the stocks, (3) laccoliths radiating outward from the central stocks, (4) bysmaliths associated with the outlying laccoliths, and (5) outlying dikes and sills.

Specimens of hornblende, the dominant mafic mineral in the igneous rocks, were obtained from laccoliths and the Mt. Ellen shattered zone of the Henry Mountains. In addition hornblendes were obtained from the hornblendite and amphibolite inclusions which are

fairly abundant in the igneous rocks. The location of samples and description of chemical work employed are shown in Figure 1. The selection of sample sites was controlled by the abundance of altered rocks, by limited exposures, and by relative inaccessibility of many intrusives.

Most rock samples were taken from the Mt. Ellen intrusive complex<sup>1</sup> which is well exposed, not highly altered, and by far the most accessible. Within the Mt. Ellen complex studies were made of the major and minor element composition of the stock, its shattered zone, and intrusive bodies radiating to the northeast. These include the Wickiup Ridge, Horseshoe Ridge, and Bull Creek laccoliths and the Bull Mountain bysmalith (Fig. 1). Variations of composition within the Bull Creek laccolith were also studied. It was sampled from proximal to distal end and from exposures near the inferred floor to its roof.

Specimens of porphyry containing hornblende phenocrysts were obtained from the following intrusive bodies: (1) Mt. Ellen complex: Wickiup Ridge laccolith, Horseshoe Ridge laccolith, and shattered zone enveloping the central stock; (2) Mt. Pennell complex: Horn laccolith; (3) Mt. Hillers complex: North Sawtooth Ridge laccolith. Specimens of hornblende from hornblendite and amphibolite inclusions were obtained from the Mt. Ellen, Mt. Pennell, and Mt. Hillers complexes.

##### *Sample Collection*

Most of the porphyries are devoid of obvious planar and linear elements, although locally one or both of these features are well developed. Two types of samples were collected: (1) samples weighing approximately 2 pounds for petrographic study and chemical analyses, and (2) larger samples, weighing 10-20 pounds. The large samples were taken at localities where both total rock composition and the composition of the constituent hornblendes were to be studied. Many larger samples were rejected later because of alteration effects in the hornblendes not detected in the field.

All samples were collected at least 4 inches below exposed surfaces of rock. At each locality least altered rock types were sought, because the object of the study was to investigate primary differences in composition. As already

<sup>1</sup>The word complex is used to designate the variety of intrusive forms such as laccoliths, bysmaliths, dikes, and sills associated with each of the central stocks in the Henry Mountains.

noted, however, most of the rocks of the Henry Mountains have been altered by deuteric or hydrothermal processes, and in some places such as the upper parts of several laccoliths, unaltered rock is rare or nonexistent.

#### PETROGRAPHIC ANALYTICAL METHODS

Petrographic study of all samples was made to select those best suited for further analysis. From two to five thin sections were cut from each sample, depending upon its size and textural features. One section of each sample was etched with hydrofluoric acid, and the K feldspars were stained with a 50 per cent solution of sodium cobaltinitrite as described by Chayes (1952). Other sections were unstained. Although much of the K feldspar in the groundmass is less than .02 mm in diameter it acquired a faint yellow tint as a result of the staining. Inasmuch as the feldspar grains are dispersed almost uniformly through the groundmass it became more readily distinguished from coarser plagioclase and other phenocrysts. In several samples the groundmass is coarse—many grains between .009 and .02 mm—and in these stained sections about 30 per cent of the groundmass is K feldspar. Presumably rocks with finer groundmass but with the same amounts and kinds of phenocrysts and the same bulk chemical composition have about this same amount of K feldspar in the groundmass.

Phenocrysts of K feldspar appear principally in what Hunt (1953, p. 155) defines as monzonite porphyry. They acquire a bright yellow stain and are readily differentiated from plagioclase and from quartz.

Modal analyses of the minerals in thin section were made with a point counter. The amounts of each mineral were tabulated on a laboratory counter. Normally 1000–1500 counts were made per section. In coarser-grained samples, especially those from which hornblende was extracted, as many as five thin sections were counted. The sections were cut at intervals of about 2 inches in the rock specimens, and the remaining fragments were ground for chemical analysis and mineral separation.

In most specimens there is no sharp break in size between those grains defined as phenocrysts and groundmass. In the tabulated modes "groundmass" invariably includes grains less than .01 mm in size. The cutoff between groundmass and phenocrysts is not, however, precisely the same in all specimens. In many specimens where the groundmass is relatively coarse-

grained and involves a subtle transition in grain size to "phenocrysts", the cutoff between the two textural types is closer to .02 or .04 mm.

TABLE 1.—SIZE RANGE OF HORNBLENDE PHENOCRYSTS SEPARATED FOR CHEMICAL ANALYSES  
(In millimeters)

	1 (HM 15)	2 (HM 22)	3 (HM 9)	4 (HM 48)	5 (HM 2)
Maximum...	1.20	1.00	1.80	1.60	28.00
Minimum...	.04	.04	.04	.04	.04
Mean.....	.20	.15	.40	.35	1.00

1. (HM 15) Diorite porphyry, shattered zone, Mt. Ellen complex.
2. (HM 22) Diorite porphyry, Horn laccolith, Mt. Pennell complex.
3. (HM 9) Diorite porphyry, Horseshoe Ridge laccolith, Mt. Ellen complex.
4. (HM 48) Diorite porphyry, North Sawtooth Ridge laccolith, Mt. Hillers complex.
5. (HM 2) Diorite porphyry, Wickiup Ridge laccolith, Mt. Ellen complex.

Hornblende crystals were easily counted except where the hornblende is appreciably altered by iron oxides. In general hornblendes less than .04 mm are included in the groundmass. Grain size and locations of hornblende phenocrysts that have been analyzed chemically are given in table 1.

Grains of opaque minerals, largely magnetite and hematite, were counted if they were .02 mm or larger.

#### PREPARATION OF ROCK SAMPLES

Representative chips were crushed to approximately a quarter of an inch in a jaw crusher and pulverized on ceramic plates to -100 mesh. About 20 grams of the -100-mesh fraction was split off for chemical analyses of major and minor elements. Approximately 5 grams of the -100 mesh was pulverized to -200 mesh for spectrographic analysis of trace elements. The remainder of the -100-mesh sample (3–5 pounds) was used to obtain a hornblende separation where possible.

#### CHEMICAL ANALYTICAL METHODS

##### *Wet Chemical Analyses*

Wet chemical analyses of rocks and hornblendes were made by me. Analytical proce-

dures employed were largely classical gravimetric techniques slightly modified after Shapiro and Brannock (1956). A complete description of methods of analysis is published elsewhere (Engel and Engel, 1958).

During the analytical work on the rock specimens, the standard G-1 (Fairbairn *et al.*, 1951) also was partly analyzed as a means of establishing reproducibility and error.

The determinations for Na<sub>2</sub>O, K<sub>2</sub>O, TiO<sub>2</sub>, and MnO of the hornblende samples were run with the standard W-1. These determinations and the adjusted mean values of W-1 (Fairbairn, 1953), are given at the bottom of Table 12.

#### *Spectrographic Analyses*

Spectrographic analyses of rocks and hornblendes listed in Tables 3 and 15 were done twice, once by U. Oda and E. F. Cooley of the U. S. Geological Survey and independently by Elisabeth Godijn at the California Institute of Technology. All other rock and mineral samples were analyzed by Oda and Cooley.

The analytical method used by Oda and Cooley was largely designed by Alfred T. Myers (Personal communication). It is a semiquantitative method used for the rapid scanning of samples for many elements, where the spectral lines of the unknown samples are visually compared with the same spectral lines on standard films. Both sample and standard powders are weighed and arced under standardized conditions in the presence of added graphite powder. Ten mg of the samples or standard was mixed with 20 mg of graphite powder and arced for a 90-second exposure time on a 20-inch strip of film in the spectrograph to record the spectra. The spectral region from 2060 to 4840 Å is recorded in the second order. Each film is exposed to 16-18 samples. The spectrum of each sample is compared with standard spectra by means of a projection-type visual comparator, for the estimation of element concentration. Table 2 indicates the limits of detection of the analytical methods employed by Oda and Cooley.

Spectrographic analyses were made on 70 specimens. Fifteen of the analyses were made in duplicate at different times as one means of establishing reproducibility of the spectrographic analyses.

In general, the spectrographic analyses done at different times in the Denver laboratory are reproducible within 25-50 per cent of the number reported for all elements except Cu, Pb,

and Zr. Values for Cu from the same rock analyzed 2 months apart vary as much as 500 per cent. The Pb and Zr values differ by about 100 per cent.

TABLE 2.—LIMITS OF DETECTION FOR SEMIQUANTITATIVE SPECTROGRAPHIC ANALYSES BY MYERS AND ODA  
(In parts per million)

Ag	1	Cr	20	Sc	20
As	500	Cu	5	Sn	10
B	10	Ga	10	Sr	20
Ba	10	Ge	10	Ti	10
Be	1	La	50	V	10
Bi	5	Mo	10	Y	10
Cd	20	Mn	10	Zn	200
Co	10	Ni	5	Zr	10
		Pb	10		

Spectrographic analyses employed by the California Institute of Technology are described in Engel and Engel (1958).

## ROCK COMPOSITION

### *Introduction*

The chemical and mineralogical composition of the rocks in the Henry Mountains has been reported by Hunt, who published 22 chemical analyses (1953, p. 154). Although these chemical analyses were not accompanied by modes, they suggest a remarkable uniformity in composition of the rocks within the several bodies of a single intrusive complex as well as between complexes. It seemed useful to attempt a more extended study of the chemistry and mineralogy of the igneous rocks to evaluate these compositional relations in more detail.

In this work about 80 specimens of igneous rocks have been studied. About 50 of these specimens come from the Mt. Ellen complex, and the remaining specimens are from the Mt. Pennell and Mt. Hillers complexes. The distribution of these rocks in the various intrusives is shown in Figure 1. Detailed modal analyses were made on all the specimens. Thirty-nine modal analyses appear in Tables 3, 4, 5, 6, 7, and 9.

Most of the work was done on diorite porphyry. The only other rock type studied was monzonite porphyry.

The following generalizations may be made on the basis of the present investigation. The

diorite porphyry averages about 55 per cent groundmass, although variations from 35 to 63 per cent are recorded. Plagioclase feldspar (32 per cent) and hornblende (10 per cent) occur as phenocrysts in the groundmass. The remaining 3 per cent is composed of augite, rounded quartz grains, iron oxides, calcite, chlorite, epidote, sphene, biotite, zircon, and locally serpentine, allanite, and clinozoisite. The groundmass is dense, light gray, and contains abundant, evenly distributed large white phenocrysts of plagioclase and smaller amounts of dark, finer-grained hornblende. A few crystals of sphene are large enough to identify in the hand specimens. Marked variations in texture are common within some of the porphyries, and in a few cases important textural variations occur within a single intrusive body. These variations coincide locally, in both abrupt and subtle transitions to a more monzonitic rock that contains phenocrysts of augite and K feldspar as well as plagioclase. Hunt (1953, p. 91, 115) concludes that the monzonite is confined to the Mt. Pennell complex, but two samples that I collected in the Mt. Ellen stock contain phenocrysts of K feldspar and are similar to the monzonite from Mt. Pennell in total mineralogical composition. Within the diorite porphyry measurable variations are found in: (1) amount and grain size of the groundmass and phenocrysts; (2) mineralogy, especially the local appearance of augite or quartz as phenocrysts; (3) texture, from the widespread massive rocks to slightly foliated and lineated types; (4) degree of alteration of the rock.

Most variations in texture and mineralogy in the diorite porphyries are not large enough to cause systematic variations in the bulk composition of the rock that can be detected by conventional analytical methods. Slight to moderate alteration of the rock, unless obvious in the hand specimen, cannot be correlated with most changes in the measured compositions. An exception is the systematic increase in the  $\text{Fe}_2\text{O}_3:\text{FeO}$  ratio with increasing alteration, although total iron content remains constant. The most important textural changes introduced by alteration are a decrease in grain size resulting from the appearance of microcrystalline sericite, chlorite, and iron oxides.

The monzonite porphyry is much less uniform than the diorite porphyry. Some samples of monzonite contain abundant, coarse phenocrysts of K feldspar, whereas in others the K feldspar is confined to the groundmass. Hornblende and augite phenocrysts are present in

about equal amounts, but locally augite may be absent (Table 7). In general, the groundmass and feldspar and hornblende phenocrysts are more altered than in the diorite porphyries. Most phenocrysts of augite are fresh.

#### *Mt. Ellen Complex*

The bulk compositions of five diorite porphyries from the Mt. Ellen complex are given in Table 3. The samples are HM 9, HM2, HM 15, HM 100, and HM 35. Three of these samples were chosen for analysis of constituent hornblendes because they were texturally and compositionally like the bulk of the diorite porphyry, and the hornblende phenocrysts were unaltered. The other two analyses are of samples of diorite porphyry from the Bull Creek laccolith and the adjacent Bull Mountain bysmalith.

**BULL CREEK LACCOLITH:** The Bull Creek laccolith, at the northeast edge of Mt. Ellen, is exposed for about 9000 feet along Bull Creek, in a valley about 900 feet deep at the bulged northeast end of the intrusion. Samples were collected along the entire exposed length of the laccolith, and two vertical traverses were made from the creek floor to the roof of the laccolith. Additional samples were collected throughout the body. Figure 2 is a generalized vertical section drawn approximately along Bull Creek, showing the form of the laccolith and the sample locations. The rock specimens collected from this laccolith were taken principally for studies of the compositional variations within a single intrusive. The mineralogical and chemical data are given in Table 4.

The porphyry in this intrusive has a uniformly fine-grained groundmass containing large phenocrysts of plagioclase, hornblende, and minor quartz. Both groundmass and phenocrysts are partially replaced by sericite and calcite. This alteration is similar to that in nearby laccoliths but greater and more pervasive than in the adjoining Bull Mountain bysmalith. Hornblende throughout the Bull Creek laccolith is more altered than that in the adjacent Wickiup Ridge and Horseshoe Ridge laccoliths but is like that in the Bull Mountain bysmalith. Hornblende is replaced mainly by iron oxides (principally magnetite) that rim and corrode the margins of the hornblende crystals and are speckled throughout the grains.

Quartz is fairly abundant in samples collected along the floor of Bull Creek and consists of round grains large enough to be seen in hand specimens. Maximum quartz content exclusive

TABLE 3.—MODAL AND CHEMICAL ANALYSES OF DIORITE PORPHYRIES OF THE HENRY MOUNTAINS, UTAH

	1 (HM 9)	2 (HM 2)	3 (HM 15)	4 (HM 48)	5	6 (HM 100)	7 (HM 35)	8 (HM 22)	9	10							
Modal Analyses																	
Groundmass	62.0	36.6	56.5	61.8	...	52.0	61.3	59.9	53.8	...							
Plagioclase phenocrysts	25.2	46.9	30.3	22.1	...	35.4	27.2	33.0	32.0	...							
Hornblende	11.6	10.1	10.7	13.1	...	10.6	7.0	4.7	11.2	...							
Augite	...	1.2	...	...	...	...	...	tr	.2	...							
Quartz	...	1.0	.7	...	...	...	1.9	...	.4	...							
Calcite	.7	.1	.5	1.4	...	.5	.7	...	.6	...							
Opaque minerals	.4	3.4	.5	1.2	...	.5	.4	1.9	1.2	...							
Others*	.1	.7	.8	.4	...	1.0	1.5	.5	.6	...							
Total	100.0	100.0	100.0	100.0	...	100.0	100.0	100.0	100.0	...							
Chemical Analyses																	
SiO <sub>2</sub>	62.45	61.63	63.52	62.22	62.88	62.51	65.03	67.65	62.47	62.58							
Al <sub>2</sub> O <sub>3</sub>	18.01	18.29	17.95	17.82	17.13	18.60	17.60	17.05	18.13	18.00							
Fe <sub>2</sub> O <sub>3</sub>	1.37	1.69	1.35	2.49	1.86	1.50	1.77	1.09	1.68	2.27							
FeO	2.79	2.68	2.55	2.10	2.58	2.11	1.20	1.35	2.45	2.12							
MgO	1.29	1.33	1.32	1.42	1.48	1.06	.88	.82	1.28	1.21							
CaO	5.58	5.75	5.50	5.94	5.39	5.86	5.24	2.93	5.73	5.28							
N <sub>2</sub> O	4.84	4.92	4.71	4.66	4.50	5.11	4.78	5.79	4.85	4.91							
K <sub>2</sub> O	1.96	1.97	1.72	1.88	2.25	1.97	1.70	2.82	1.90	2.11							
H <sub>2</sub> O+	.76	.77	.54	.63	.58	.49	.88	.44	.64	.84							
H <sub>2</sub> O-	.20	.20	.13	.07	...	.06	.18	.02	.13	...							
TiO <sub>2</sub>	.48	.45	.47	.50	.51	.29	.40	.21	.44	.39							
P <sub>2</sub> O <sub>5</sub>	.18	.27	.16	.18	n.d.	.25	.16	.15	.21	n.d.							
MnO	.18	.14	.15	.10	.16	.16	.12	.06	.15	.09							
Total	100.09	100.09	100.07	100.01	99.32	99.97	99.94	100.38	100.06	99.80							
Trace-Element Analyses																	
Analyst	A	B	A	B	A	B	A	B	A	B	A	B	A	B			
Ba	750	1300	750	1250	1000	1150	1000	1300	...	1000	1350	750	1500	2200	900	1300	...
Co	<10	8	<10	7	<10	6	<10	6	...	<10	5	<10	<10	3	<10	6	...
Cr	<20	11	<20	9	<20	7	<20	8	...	<20	6	<20	<20	5	<20	8	...
Cu	10	30	5	21	5	12	15	16	...	3	8	3	15	28	8	17	...
Mn	1500	1100	2000	1100	1000	900	1500	1100	...	1500	940	1500	500	380	1500	1000	...
Ni	<5	4	<5	3	<5	2	<5	3	...	<5	2	<5	<5	tr	<5	3	...
Pb	10	...	10	...	10	...	10	tr	...	10	tr	10	35	40	10	...	
Sc	<20	10	<20	9	<20	9	<20	9	...	<20	7	n.d.	<20	...	<20	~9	...
Sr	1500	790	1500	790	1500	830	1500	730	...	1500	970	1500	2000	1200	1500	820	...
Ti	2000	2100	1500	2100	1500	2300	2000	1900	...	2000	1700	3500	750	760	1800	2000	...
V	100	117	75	96	75	92	75	90	...	100	93	100	75	93	80	100	...
Y	35	32	35	32	15	tr	15	20	...	20	25	15	10	...	24	~20	...
Zr	150	150	200	140	100	120	100	140	...	150	130	350	75	71	140	140	...

Analyst A—U. Oda, U. S. Geological Survey; analyst B—Elisabeth Godijn, California Institute of Technology.

\* Chiefly chlorite, apatite, epidote, sphene, zircon, and microcrystalline sericite and limonite.

- (HM 9) Horseshoe Ridge laccolith, Mt. Ellen complex (average of 5 samples). Analyst, C. G. Engel.
- (HM 2) Wickiup Ridge laccolith, Mt. Ellen complex (average of 3 samples). Analyst, C. G. Engel.
- (HM 15) Shattered zone, Mt. Ellen complex. Analyst, C. G. Engel.
- (HM 48) North Sawtooth Ridge laccolith, Mt. Hillers complex. Analyst, C. G. Engel.
- Black Mesa bysmalith, Mt. Hillers complex. The bysmalith is adjacent to No. 4 above. (Analysis taken from Hunt, 1953, Table 7, col. 11) Analyst, J. F. Fairchild.
- (HM 100) Bull Mountain bysmalith, Mt. Ellen complex. Analyst, C. G. Engel.
- (HM 35) Bull Creek laccolith, Mt. Ellen complex. Analyst, C. G. Engel.
- (HM 22) Horn laccolith, Mt. Pennell complex. Analyst, C. G. Engel.
- Mean of samples 1, 2, 3, 4, and 6 (least altered porphyries).
- Mean of 7 diorite porphyries cited by Hunt (1953, p. 154). Analysts, R. E. Stevens and J. F. Fairchild.



of groundmass is 3.5 per cent in the specimens collected. Accessory minerals are green spherulitic chlorite, iron oxides, apatite, sphene, epidote, calcite, and rare allanite.

samples at or near the roof contain colorless, spherulitic serpentine.

The alteration of the porphyry is reflected in the chemical analyses of the samples. Al-

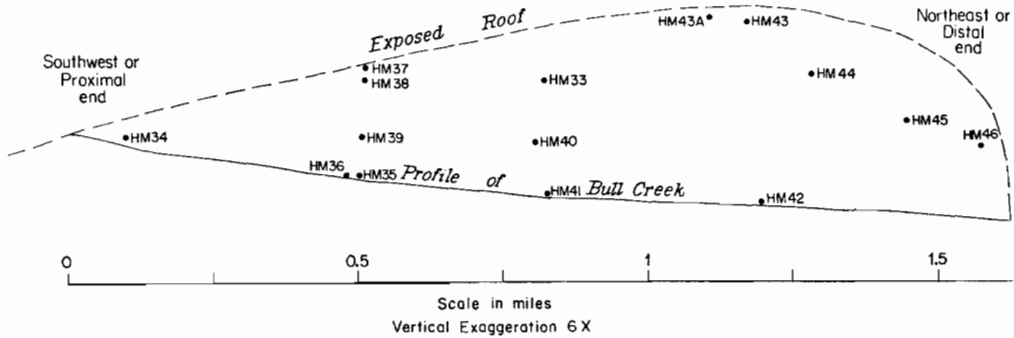


FIGURE 2.—VERTICAL SECTION ALONG BULL CREEK LACCOLITH SHOWING LOCATION OF SAMPLES CITED IN TABLE 4

The floor of the laccolith is not exposed.

The modal analyses of rocks from the Bull Creek laccolith indicate moderate variations in texture and mineralogy but that all the primary rock is diorite porphyry. The composition of the one specimen analyzed in detail is only slightly different from the average diorite porphyry of the Henry Mountains (Table 3; compare column 7 with columns 9 and 10). The Bull Creek laccolith contains somewhat more groundmass and fewer phenocrysts (including hornblende and opaques) than the average diorite. The slightly lower content of mafic minerals is reflected in a decrease in total Fe.

The trace-element composition of the Bull Creek laccolith is, within the limits of analytical error, essentially that of the average diorite porphyry of the Henry Mountains.

The groupings in Table 4 of samples from the Bull Creek laccolith are based upon the location of the samples in the body. Group I consists of samples along or within 50 feet of the exposed floor of the laccolith. Group II consists of samples collected from internal parts of the laccolith. Group III consists of samples collected at or within 100 feet of the roof of the laccolith. The only differences appear in the rocks very near the roof (Group III), which contain hornblendes that are especially "bleached" and altered to iron oxides. Two samples taken within 15 feet of the contact of porphyry with overlying sedimentary rock (roof) contain only small relics and crystal outlines of hornblende which have been almost completely replaced by iron oxides and calcite. The groundmass of the

though the total Fe content is approximately constant throughout the laccolith the ratio of  $\text{Fe}_2\text{O}_3/\text{FeO}$  increases abruptly, by a factor of 5, in the rocks within 15 feet of the roof (Table 4, samples 43 and 37). This ratio also seems slightly greater in the internal parts of the laccolith (Group II) than in the lower part (Group I). These changes in the valency of Fe reflect the mineralogical alteration of hornblende and spinels to hematite and limonite. The development of iron oxides is accompanied by the appearance of some chlorite and serpentine as well as calcite. The development of chlorite and serpentine suggests that the alteration is either deuteric or hydrothermal. The arched apical area of the laccolith is an obvious locus for rising deuteric or hydrothermal fluids.

The spectrographic analyses of the samples taken from the Bull Creek laccolith show no significant variations from floor to roof or from proximal to distal ends (Table 4; Fig. 2).

**BULL MOUNTAIN BYSMALITH:** The Bull Mountain bysmalith, a very prominent landmark at the northeast corner of the Mt. Ellen complex, stands isolated between Bull Creek on the west and Granite Creek on the southeast. The summit is about 2000 feet above the creeks. Along the west side of Bull Mountain the contact of the intrusive porphyry with the sedimentary rock is poorly exposed. Along the steep north face of the intrusive, the porphyry is emplaced against steeply dipping beds of the Morrison formation. The floor of the bysmalith is not exposed. Most of the samples were collected along the west and north sides of

TABLE 4.—MODAL AND CHEMICAL ANALYSES OF DIORITE PORPHYRY IN THE BULL CREEK LACCOLITH

	Group I (Lowermost exposures of laccolith, floor hidden)						Group II (Internal parts of the laccolith)							Group III (At or within 100 feet of roof of laccolith)				
	1 (HM 34)	2 (HM 36)	3 (HM 35)*	4 (HM 41)	5 (HM 42)	6 Mean	7 (HM 39)	8 (HM 40)	9 (HM 33)	10 (HM 44)	11 (HM 45)	12 (HM 46)	13 Mean	14 (HM 38)	15 (HM 43)	16 (HM 37)	17 (HM 43A)	18 Mean
Modal Analyses																		
Groundmass.....	63.7	62.2	61.3	64.4	68.5	....	66.9	65.6	64.3	63.6	69.7†	65.8	....	68.4	64.0	69.7	66.1	....
Plagioclase phenocrysts..	29.5	28.4	27.2	26.8	22.5	....	23.5	23.1	24.6	28.6	21.9	25.2	....	23.8	28.3	18.9	23.8	....
Hornblende.....	4.5	7.4	7.0	6.9	7.1	....	6.1	5.9	6.2	6.2	7.1	6.7	....	5.4	4.4	....	3.0	....
Quartz.....	....	tr	1.9	.5	.4	....	.9	3.5	2.2	.8	....	2.0	....	tr	....	....	....	....
Calcite.....	.4	....	.7	.5	tr	....	.1	.3	.2	....	tr	tr	....	....	.2	.8	1.0	....
Opaque minerals.....	.8	.5	.4	.3	1.1	....	1.9	1.1	1.7	.4	1.0	.1	....	1.6	2.6	10.2††	4.7††	....
Others**.....	1.1	1.5	1.5	.6	.4	....	.6	.5	.8	.4	.3	.2	....	.8	.5	.4	1.4	....
Total.....	100.0	100.0	100.0	100.0	100.0	....	100.0	100.0	100.0	100.0	100.0	100.0	....	100.0	100.0	100.0	100.0	....
Partial Chemical Analyses (Analyst, C. G. Engel)																		
Total Fe*** (as Fe <sub>2</sub> O <sub>3</sub> )..	2.99	3.09	3.09	2.84	3.11	3.02	3.03	2.99	3.00	3.06	2.90	2.99	3.00	2.90	2.71	2.90	2.01	2.88
Fe <sub>2</sub> O <sub>3</sub> .....	1.76	1.77	1.77	1.52	1.67	1.70	2.15	2.15	1.89	2.14	1.58	1.81	1.95	1.89	2.31	2.37	2.23	2.20
FeO.....	1.12	1.20	1.20	1.20	1.32	1.21	.80	.76	1.00	.84	1.20	1.05	.94	.92	.36	.48	.70	.61
Na <sub>2</sub> O.....	4.76	4.78	4.78	4.67	4.87	4.77	4.87	4.87	4.72	5.11	5.00	5.07	4.94	4.91	5.14	4.98	5.01	5.01
K <sub>2</sub> O.....	1.71	1.72	1.70	1.68	1.73	1.71	1.68	1.72	1.69	1.71	1.64	1.71	1.69	1.72	1.71	1.17	1.69	1.57
MnO.....	.13	.14	.12	.12	.13	.13	.13	.12	.13	.13	.11	.12	.13	.12	.13	.12	.12	.12

Trace-Element Analyses (ppm) (Analyst, U. Oda)

Ba.....	1000	1000	750	1000	1500	.....	1500	1000	1000	1500	750	750	.....	1000	1000	1000	750	.....
Co.....	<10	<10	<10	<10	<10	.....	<10	<10	<10	10	<10	10	.....	10	10	10	<10	.....
Cr.....	<20	<20	<20	<20	<20	.....	<20	<20	<20	20	<20	20	.....	20	20	20	<20	.....
Cu.....	10	5	3	35	3	.....	10	3	5	3	2	15	.....	3	3	5	5	.....
Mn.....	2000	1500	1000	1500	1000	.....	1500	1500	1000	1000	1000	1500	.....	1500	1500	1000	1500	.....
Ni.....	<5	<5	<5	<5	<5	.....	<5	<5	5	5	<5	5	.....	5	5	5	<5	.....
Pb.....	15	10	10	75	10	.....	10	10	10	10	<10	10	.....	10	10	10	10	.....
Sn.....	10	<10	10	<10	<10	.....	10	<10	<10	10	<10	10	.....	10	10	10	10	.....
Sr.....	3500	2000	1500	1500	1500	.....	2000	1500	1500	1500	1500	1500	.....	1500	1500	1000	1500	.....
Ti.....	3500	1500	3500	2000	1500	.....	3500	3500	3000	1500	3500	2000	.....	2000	3500	2000	2000	.....
V.....	75	50	75	75	75	.....	75	50	50	75	35	75	.....	50	50	75	75	.....
Y.....	10	10	15	20	15	.....	20	15	15	20	10	20	.....	10	10	20	15	.....
Zr.....	350	200	350	350	200	.....	350	350	200	150	150	350	.....	350	200	350	200	.....

\* For complete chemical analysis see column 7 of Table 3.

† Includes 0.6 per cent K-feldspar grains larger than .2 mm.

\*\* Chiefly chlorite, apatite, epidote, sphene, biotite, and microcrystalline sericite and limonite.

†† Iron-oxide stains penetrate and obscure identity of other minerals.

\*\*\* Determinations of total Fe were made in succession using G-1 as a reference. (See Fairbairn *et al.*, 1951.)

Bull Mountain, at intervals of about a quarter of a mile, along the exposed length (2½ miles) of the intrusive.

The Bull Mountain porphyry consists of large, zoned, and twinned plagioclase crystals, hornblende, and accessory minerals in a very fine-grained groundmass. The groundmass is stained in thin sections treated with sodium cobaltinitrite but is too fine-grained to permit an estimate of K feldspar content. The plagioclase is rather fresh with a few intergrowths of K feldspar. The hornblende is highly altered. It is chloritic, embayed by groundmass, and surrounded and riddled by small opaque grains. Quartz is present in most of the sections, usually as one or two large, round grains per thin section. Veinlets of quartz are present in some sections. Calcite is present as irregular films replacing the groundmass and as discrete grains replacing the hornblende and groundmass. Rare biotite appears as shreds in the hornblende crystals. Euhedral sphene and apatite are also present.

Studies of the Bull Mountain bysmalith were confined to the total rock because of the extreme alteration of hornblende. The data on rocks from the Bull Mountain bysmalith are in Table 5.

Modal analyses indicate a remarkable uniformity in mineral composition and texture throughout the Bull Mountain bysmalith. The average of nine modal analyses (Table 5) indicates a mineralogical composition and texture very close to the average for diorite porphyry collected from the Henry Mountains.

Spectrographic analyses and partial chemical analyses for TiO<sub>2</sub>, total Fe, Na<sub>2</sub>O and K<sub>2</sub>O substantiate the modes: within the limits of analytical error, there appear to be no differences in the composition of the bysmalith from one end to the other.

**HORSESHOE RIDGE AND WICKIUP RIDGE LACCOLITH:** The Horseshoe Ridge laccolith adjoins the Bull Creek laccolith on the west but is not so well exposed and is less accessible. The Wickiup Ridge laccolith lies between the Mt. Ellen stock and the Horseshoe Ridge and Bull Creek laccoliths (Fig. 1).

Samples were collected from the Horseshoe Ridge and Wickiup Ridge laccoliths where they converge with the southwestern part of the Bull Creek laccolith (Fig. 1). Modal and chemical analyses of the three intrusions and chemical analyses of hornblende from them offer a means of comparing the properties of the three laccoliths at points separated by only a few hundred feet of sedimentary wall rock.

Texturally and mineralogically the Horseshoe Ridge laccolith is like the Bull Creek laccolith except that its hornblendes are relatively fresh. An average modal analysis of 5 thin sections of the Horseshoe Ridge laccolith cut from specimens collected approximately 10 feet apart is given in column 1 of Table 3. This average is slightly higher in groundmass and lower in plagioclase phenocrysts than the mean modal composition of Henry Mountain diorite porphyries. The chemical composition (Table 3, column 1) is similar to that of the average of Henry Mountain diorite porphyries (Table 3, columns 9, 10).

Hunt (1953, p. 105) noted that the Wickiup Ridge laccolith is petrographically different from the other laccoliths. This is partly because the phenocrysts of hornblende are very large; a few are 28 mm long. These hornblendes also contain a higher Mg/Fe ratio than hornblende analyzed from other intrusives in the Henry Mountains (Table 12). The phenocrysts of plagioclase and groundmass also are coarser-grained than most other diorite porphyries of the Henry Mountains. Commonly a little augite is present, and locally it is more abundant than hornblende. The rock at the northeast end of the laccolith is coarsely crystalline and contains very little augite. The hornblendes average about 1 mm in length (Table 1). An average modal analysis of 3 thin sections of rocks collected about 20 feet apart is given in column 2 of Table 3. The small amount of groundmass (36.6 per cent) reflects the coarse texture of diorite porphyry in the Wickiup Ridge laccolith.

The variations in petrography of the Wickiup Ridge diorite porphyry from the mean diorite porphyry are not reflected in chemical composition. The chemical analyses of major, minor, and trace elements of a typical Wickiup Ridge porphyry (Table 3, column 2) are approximately those of the average of diorite porphyries in the Henry Mountains.

**CENTRAL STOCK AND SHATTERED ZONE:** The Mt. Ellen stock and shattered zone occur along the southern part of the Mt. Ellen complex at altitudes up to 11,000 feet. As Hunt notes (1953, p. 91) the stock is roughly circular in plan and consists of diorite porphyry. It is surrounded by a shattered zone that consists of sedimentary breccias variously injected by igneous rocks. The proportions of sedimentary to igneous rocks vary widely in the shattered zone. In general, however, large masses of igneous rock are most abundant in the inner part of the shattered zone, whereas most of

TABLE 5.—MODAL AND CHEMICAL ANALYSES OF DIORITE PORPHYRY FROM THE BULL MOUNTAIN BYSMALITH

	2½ miles									
	Proximal					Distal				
	1 (HM 4)	2 (HM 3)	3 (HM 5)	4 (HM 7)	5 (HM 8)	6 (HM 100)*	7 (HM 101)	8 (HM 102)	9 (HM 103)	10 Mean
Modal Analyses										
Groundmass	51.3	47.9	48.0	49.9	50.8	52.0	49.7	50.5	48.6	49.9
Plagioclase phenocrysts	40.5	39.2	40.9	38.6	35.6	35.4	38.0	36.9	39.0	38.2
Hornblende	6.4	9.4	8.7	8.3	11.3	10.6	8.7	10.1	9.9	9.3
Calcite	.2	.4	.7	.7	.6	.5	.7	.7	.5	.5
Opaque minerals	.3	.7	.8	.6	.8	.5	.7	.6	.6	.6
Others†	1.3	2.4	.9	1.9	.9	1.0	2.2	1.2	1.4	1.5
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Partial Wet Chemical Analyses (Analyst, C. G. Engel)										
Total Fe (as Fe <sub>2</sub> O <sub>3</sub> )	3.88	3.88	4.21	3.91	3.80	3.78	n.d.	n.d.	n.d.	3.91
Na <sub>2</sub> O	5.00	5.04	4.83	4.89	5.01	5.11	n.d.	n.d.	n.d.	4.98
K <sub>2</sub> O	1.97	1.94	2.15	2.00	2.01	1.97	n.d.	n.d.	n.d.	2.06
TiO <sub>2</sub>	.31	.35	.29	.32	.30	.29	n.d.	n.d.	n.d.	.31
Trace-Element Analyses (ppm) (Analyst, U. Oda)										
Ba	1500	1500	1000	1500	1000	1000	1000	1000	1000	1200
Co	<10	<10	10	<10	<10	<10	<10	<10	<10	<10
Cr	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20
Cu	5	3	10	5	3	3	2	2	5	5
Mn	1500	1000	1500	1500	1500	1500	1500	1500	1500	1500
Ni	<5	<5	5	<5	<5	<5	<5	<5	<5	<5
Pb	20	20	35	20	20	10	20	20	35	20
Sn	<10	<10	<10	<10	10	<10	<10	<10	<10	<10
Sr	1500	1500	2000	1500	1500	1500	1500	1500	1500	1500
Ti	3500	1500	1500	1500	1500	2000	3500	3500	3500	2500
V	100	75	75	100	75	100	75	100	75	85
Y	20	20	20	20	20	20	15	20	20	20
Zr	150	200	200	350	350	150	350	500	500	300

\* For complete chemical analysis see column 6 of Table 3.

† Chiefly biotite, chlorite, apatite, epidote, sphene, zircon, and microcrystalline sericite and limonite.

the outer part is broken sedimentary rock. Exposures of the central stock and shattered zone are locally good, but large areas are poorly exposed or unexposed.

Alteration of the igneous rocks in the stock and in the shattered zones is well developed and widespread. The alteration involves sericitization of the plagioclase and extensive replacement of the hornblende by magnetite, epidote, and chlorite. Veinlets and disseminated masses

of pyrite, chalcopyrite, and other sulfides occur in the central stock in the Bromide Basin area. Specimens that show little effect of alteration may be obtained, however, as is indicated by porphyry HM 15 (Table 3). This rock is relatively unaltered and is the source of the hornblende HM 15 (Table 12). Hunt concluded (1953, p. 93) that diorite porphyry and quartz-bearing diorite porphyry within the stock were separate intrusive masses. However, field and

TABLE 6.—MODAL AND SPECTROGRAPHIC ANALYSES OF DIORITE PORPHYRIES FROM THE MT. ELLEN STOCK AND SHATTERED ZONE

	1 (HM 10)*	2 (HM 11)	3 (HM 12)	4 (HM 14)	5 (HM 15)	6 (HM 19)
Modal Analyses						
Groundmass . . . . .	46.3	36.6	48.2	56.5	2.0	
Plagioclase phenocrysts . . . . .	44.0	46.1	40.9	30.3	70.8	
Hornblende . . . . .	1.8	5.6	5.5	10.7	20.0	
Augite . . . . .		.8				
Quartz . . . . .	1.0	2.8	4.0	.7	1.6	
Calcite . . . . .	3.0				.5	
K-feldspar . . . . .	.6	3.0				
Epidote . . . . .		1.5	.5	.2	4.2	
Opaques . . . . .	1.4	2.9	.6	.5	.8	
Others† . . . . .	1.9	.7	.3	.6	.6	
Total . . . . .	100.0	100.0	100.0	100.0	100.0	
Trace-Element Analyses (ppm) (Analyst, U. Oda)						
Ba . . . . .	500	1000	1000	1000	1000	750
Co . . . . .	20	<10	<10	<10	<10	20
Cr . . . . .	75	<20	<20	<20	<20	75
Cu . . . . .	150	750	15	15	5	75
Mn . . . . .	2000	750	1500	1500	1000	1000
Ni . . . . .	20	<5	<5	<5	<5	20
Pb . . . . .	10	35	10	10	<10	10
Sn . . . . .	<10	<10	<10	<10	<10	<10
Sr . . . . .	1000	1500	1500	2000	1500	1500
Ti . . . . .	3500	2000	3500	2000	1500	5000
V . . . . .	350	100	75	75	75	500
Y . . . . .	15	15	35	20	15	20
Zr . . . . .	350	350	350	350	100	200

\* Very chloritic, epidotic porphyry. Coarse-grained like HM 19 with very little Groundmass. Hornblende abundant like HM 19 but is "bleached" and altered to chlorite.

† Chiefly chlorite, sphene, zircon, sericite.

HM 10, HM 11, HM 12, HM 14. Mt. Ellen stock, Bromide Basin.

HM 15. Shattered zone, Mt. Ellen. (Chemical analysis of this sample appears in column 3 of Table 3.)

HM 19. Laccolith 1 mile east of the Mt. Ellen stock.

petrographic studies show that in some parts of the stock there are all gradations between diorite porphyry and porphyry with almost 7 per cent quartz. The relative proportions of

quartz-bearing and quartz-free samples of porphyry are unknown.

Modal analyses of four porphyries from the central stock and two from the shattered zone (Table 6) indicate some interesting compositional features in the central stock. The low hornblende content and the local appearance of orthoclase phenocrysts indicates "monzonitic" rock types much like those found in the Mt. Pennell complex. For example, specimen HM 12 (Table 6) contains only 5.6 per cent hornblende but contains 3 per cent orthoclase phenocrysts. Some of the rocks on Mt. Pennell that Hunt refers to as monzonites approximate this composition (Table 7, specimen HM 21). The dominant diorite porphyry of the Henry Mountains shows no orthoclase as phenocrysts and contains approximately 10 per cent hornblende.

The concentrations of trace-elements in the rocks from the stock and the shattered zone (Table 6) are essentially like those from other parts of the Henry Mountains except that two of the samples show a high Cu content. This is a reflection of minor chalcopyrite disseminated through the rock.

#### Mt. Pennell Complex

Mt. Pennell, like Mt. Ellen, consists of a central stock and shattered zone surrounded by laccoliths and numerous dikes and sills. As at Mt. Ellen, most laccoliths radiate from the central stock. Hunt (1953, p. 115) notes several rock types in the Mt. Pennell complex. He states that the central stock consists of diorite porphyry, monzonite porphyry intrusive into the diorite porphyry, and aplitic dikes. The Horn laccolith north of Mt. Pennell is described by Hunt as a "biotite-bearing" porphyry. Many dikes and sills in the Mt. Pennell complex are reported to be composed of monzonite porphyry. A brief investigation was undertaken of the biotite-bearing porphyry in the Horn laccolith and of the monzonite porphyries in the Coyote Creek laccolith. The rocks in the central stock were not studied.

**HORN LACCOLITH:** The Horn laccolith is the most northerly intrusion in the Mt. Pennell complex. Its component igneous rocks are more widely and extensively altered than those in the other intrusive rocks studied in the Henry Mountains. This is especially true of the plagioclase phenocrysts and groundmass which have a soft, pithy texture and are partly replaced by hydrous sheet-structure silicates. In contrast, some of the hornblende phenocrysts are little altered. One specimen of hornblende

(Table 12, specimen HM 22) is from altered porphyry of the Horn laccolith. Modal and chemical analyses of this rock are given in column 8 of Table 3. This rock and numerous other specimens studied from the Horn laccolith do not contain biotite.

The groundmass of the Horn porphyries when etched and stained with sodium cobaltinitrite appears to be more deeply colored in thin section than most porphyries, which suggests a higher percentage of K feldspar. Hornblende is less abundant than in typical diorite porphyry. There is little or no quartz. The chemical analysis of the rock from the Horn laccolith differs from the other porphyries I studied and from those described by Hunt (1953, p. 154, Table 7, specimens 16, 17). The Na and K content of the rock analyzed from the Horn laccolith appears to be intermediate in amount between that in typical diorite porphyry and the rocks of the Mt. Pennell complex that Hunt refers to as monzonite. Unfortunately, Hunt's analyses on monzonite are of rock with some of the large crystals of K feldspar removed (1953, p. 157). Therefore detailed comparisons between Hunt's analyses and analyses given in this report are not appropriate.

**COYOTE CREEK LACCOLITH:** The Coyote Creek laccolith extends northeast from Mt. Pennell to the perimeter of the exposed igneous complex. Hunt noted the presence of monzonite porphyry along the southeast flank of the laccolith, although other parts of it are diorite porphyry. Six specimens of the monzonite were studied in detail (Table 7), and thin sections of 11 others were examined. In general the monzonitic rocks contain less hornblende and more augite than typical diorite porphyries. Most of them contain large phenocrysts of K feldspar and opal-filled vugs with associated subhedral crystals of calcite, clinozoisite, and sphene. The hornblende and augite phenocrysts show interesting differences. Most of the augite is in large euhedral crystals that are only slightly altered even in the most altered host rocks. Most of the hornblendes are partly replaced by groundmass and are riddled and surrounded by opaque minerals.

Two types of monzonitic porphyry are present, one in which there is little or no K feldspar as phenocrysts, the other in which K feldspar is present as large phenocrysts. In a few specimens of the first type phenocrysts of plagioclase have an outer rim or sheath of K feldspar. In samples of the second type, K feldspar embays the plagioclase phenocrysts. In the rocks where K feldspar either sheaths the

plagioclase or embays it, K feldspar is a relatively late-forming mineral.

The textural variations, especially the appearance of large phenocrysts of K feldspar, make it difficult to obtain representative samples. The modal and chemical analyses in Table 7 are of less coarse-textured monzonites and are fairly representative of these types. In general, the chemical composition of the monzonite porphyries is not so uniform as the diorite porphyries. The monzonites are lower in Si, Ca, and Mg, although these constituents, especially Si and Ca, show wide variations; Na, K, and Al are highly concentrated in the monzonites. The  $\text{Na}_2\text{O}/\text{K}_2\text{O}$  ratio in the monzonite porphyry is about 1.50. It should be noted that the monzonite rock devoid of K feldspar phenocrysts contains almost as much  $\text{K}_2\text{O}$  as monzonites with 9 per cent K feldspar phenocrysts (Table 7, columns 2, 4).

The mean and range in concentrations of trace elements in the monzonitic rocks from Mt. Pennell are compared with analogous data on diorites from the Henry Mountains (Table 8). Trace elements Cu, V, Pb, Sr, and Ba are more abundant in the monzonite porphyry than in the diorite porphyry. In the monzonite, Cu is 6 times more abundant, V 4 times more abundant, Pb and Sr about 3 times more abundant, and Ba twice as abundant. These seemingly significant differences in means were checked statistically, using the Student's T-test (Mood, 1950, Chap. 9). The results show that for each of the elements Cu, Pb, V, Sr, and Ba the probability of the means being due to chance is less than 0.01. The enrichment of the monzonite in Pb, Sr, and Ba is consistent with its higher content of K feldspar. The enrichment in Cu and V suggests that these elements were concentrated in the liquid fractions of the Henry Mountain magma types during the early stages of their differentiation.

#### *Mt. Hillers Complex*

The Mt. Hillers complex is the most southerly dome from which samples were obtained. Samples were obtained from the North Sawtooth Ridge laccolith, the Black Mesa byssalith, the Maiden Creek laccolith, and the Trachyte Mesa laccolith in the northeast part of the complex (Fig. 1). The samples from the North Sawtooth Ridge laccolith are about 5 miles northeast of the central stock. Those collected from the Trachyte Mesa laccolith are about 8 miles northeast of the central stock. Both the Maiden Creek laccolith and the

TABLE 7.—MODAL AND CHEMICAL ANALYSES OF MONZONITE PORPHYRY, MT. PENNELL COMPLEX

	1 (HM 26A)	2 (HM 26B)	3 (HM 20D)	4 (HM 20F)	5 (HM 21)	6 (HM 23)
Modal Analyses						
Groundmass.....	58.5	61.7	53.9	44.1	46.7	65.3
Plagioclase phenocrysts.....	28.1	27.0	32.5	42.0	42.0	28.4
Hornblende.....	2.2	1.4	4.5	3.0	5.0	1.7
Augite.....	4.8	6.1	2.0	1.2	?	2.1
K-feldspar phenocrysts.....			4.3	8.7	3.3	
Opal (vugs)*.....	3.7	2.2				1.5
Opaque minerals.....	1.0	1.1	.5	.1	.1	.5
Others†.....	1.7	.5	2.3	.9	2.9	.5
Total.....	100.0	100.0	100.0	100.0	100.0	100.0
Chemical Analyses (Analyst, C. G. Engel)						
SiO <sub>2</sub> .....			59.21		57.01	
Al <sub>2</sub> O <sub>3</sub> .....			19.43		19.11	
Fe <sub>2</sub> O <sub>3</sub> .....		1.53	1.03	1.22	2.30	
FeO.....		2.02	2.98	1.59	3.00	
MgO.....			.90		1.37	
CaO.....			3.78		5.01	
Na <sub>2</sub> O.....		6.40	6.20	6.33	6.50	
K <sub>2</sub> O.....		3.89	4.18	4.40	3.80	
H <sub>2</sub> O+.....			.80		.75	
H <sub>2</sub> O-.....			.49		.06	
TiO <sub>2</sub> .....			.49		.57	
P <sub>2</sub> O <sub>5</sub> .....			.20		.15	
MnO.....			.18		.23	
Total.....			99.87		99.86	
Trace-Element Analyses (ppm) (Analyst, U. Oda)						
Ba.....			2000	2000	2000	2000
Co.....			<10	<10	<10	<10
Cr.....			<20	<20	<20	<20
Cu.....			50	75	75	75
Mn.....			1000	1500	1500	1500
Ni.....			<5	<5	<5	<5
Pb.....			20	100	35	75
Sn.....			10	10	10	10
Sr.....			3500	7500	3500	3500
Ti.....			3500	3500	3500	3500
V.....			350	200	150	750
Y.....			35	20	20	35
Zr.....			350	350	350	350

\* Includes clinzoisite in vugs.

† Chiefly calcite, quartz, biotite, epidote, sphene, chlorite and microcrystalline sericite and limonite.

1. (HM 26A) Augite monzonite, 2½ miles northeast of Mt. Pennell.
2. (HM 26B) Augite monzonite, 2½ miles northeast of Mt. Pennell.
3. (HM 20D) Monzonite, Coyote Creek laccolith.
4. (HM 20F) Monzonite, Coyote Creek laccolith.
5. (HM 21) Monzonite, Coyote Creek laccolith.
6. (HM 23) Monzonite, Coyote Creek laccolith.



Trachyte Mesa laccoliths are sill-like bodies 80-100 feet thick with bulged roofs and leading edges. The form and interrelations as reconstructed by Hunt are shown in his Figure 51

TABLE 8.—VARIATIONS IN TRACE-ELEMENT COMPOSITION OF DIORITE AND MONZONITE PORPHYRIES

	Group I Diorite porphyry (54 samples)			Group II Monzonite porphyry (18 samples)		
	Mini- mum	Maxi- mum	Mean	Mini- mum	Maxi- mum	Mean
	(in parts per million)			(in parts per million)		
Ba....	750	1500	1100	1500	2000	1900
Co....	<10	15	<10	<10	10	<10
Cr....	<20	<20	<20	<20	<20	<20
Cu....	2	35	9	10	75	57
Mn....	500	3500	1500	1000	2000	1500
Ni....	<5	5	<5	<5	5	<5
Pb....	<10	75	15	10	150	59
Sn....	<10	10	<10	<10	<10	<10
Sr....	1500	3500	1600	1500	7500	4600
Ti....	1500	7500	2800	1500	5000	3300
V....	35	100	80	100	750	300
Y....	10	50	20	15	35	26
Zr....	100	500	340	200	500	360

Group I. Diorite porphyries from stocks, laccoliths, bysmaliths, dikes, and sills in the Mt. Ellen, Mt. Pennell, and Mt. Hillers complexes.

Group II. Monzonite porphyries from sills and laccoliths in the Mt. Pennell complex.

(1953, p. 126). All these rocks are diorite porphyry.

Samples from the North Sawtooth Ridge laccolith are the least altered diorite porphyries collected in this investigation. Both total rock (Table 3, column 4) and hornblende phenocrysts (Table 12, column 4) were analyzed. Most other specimens from the Mt. Hillers complex are moderately to highly altered. Modal analyses of porphyries from Mt. Hillers are shown in Table 9. Their primary mineral composition varies greatly, but the mean composition is approximately that of diorite porphyry throughout the Henry Mountains. There are no well-defined differences in composition between specimens of diorite porphyry collected in the Mt. Hillers complex and specimens collected in the northern part of the Mt. Ellen complex some 18 miles distant.

TABLE 9. MODAL AND SPECTROGRAPHIC ANALYSES OF DIORITE PORPHYRY FROM INTRUSIVE BODIES IN THE NORTHEAST PORTION OF THE MT. HILLERS COMPLEX

	1 (HM 48)*	2 (HM 17)	3 (HM 50)	4 (HM 51)	5 (HM 49)	6 (HM 52)
Modal Analyses						
Groundmass..	61.8	51.3	45.3	42.8	52.6	65.6
Plagioclase pheno- crysts.....	22.1	34.7	38.9	39.8	32.2	18.7
Hornblende..	13.1	13.2	9.9	12.5	5.5	11.4
Augite.....	...	tr	1.9	.8	...	.1
Quartz.....	...	...	.8	.8	...	...
Calcite.....	1.4	.3	.2	.3	3.3	1.2
Opaque min- erals.....	1.2	.3	2.3	1.9	3.0	.8
Others†.....	.4	.2	.7	1.1	3.4	2.2
Total.....	100.0	100.0	100.0	100.0	100.0	100.0
Trace-Element Analyses (ppm) (Analyst, U. Oda)						
Ba.....	1000	1500	1500	750	1500	750
Co.....	<10	<10	<10	<10	<10	<10
Cu.....	15	20	5	15	10	20
Mn.....	1500	1500	1500	1500	1500	1500
Ni.....	<5	<5	<5	<5	<5	<5
Pb.....	10	10	10	15	15	15
Sr.....	1500	1500	1500	1500	2000	1500
Ti.....	2000	2000	5000	3500	2000	3500
V.....	75	100	100	100	75	100
Y.....	15	35	35	20	20	15
Zr.....	100	200	350	350	350	350

\* For complete chemical analysis see column 4 of Table 3.

† Chiefly chlorite, apatite, epidote, sphene, zircon, and sericite.

1. (HM 48) North Sawtooth Ridge laccolith.
2. (HM 47) North Sawtooth Ridge laccolith.
3. (HM 50) Black Mesa bysmalith.
4. (HM 51) Black Mesa bysmalith.
5. (HM 49) Maiden Creek laccolith.
6. (HM 52) Trachyte Mesa laccolith.

The trace-element composition of rocks from the Mt. Hillers complex (Table 9) appears to be essentially like that of other diorite porphyries in the Henry Mountains. Any differences in trace-element content within the diorite porphyries can be demonstrated only with

much more precise sampling and analytical techniques.

#### PETROLOGY

Hunt concluded from stratigraphic and structural reconstructions in the Henry Moun-

porphyry from the Henry Mountains (Table 3, columns 9, 10) with an average diorite such as that tabulated by Osann, Washington, and Daly (Daly, 1914, p. 26) indicates the following differences: the diorite porphyry from the Henry Mountains contains more Si and Al and much more Na but is deficient in Fe and Mg

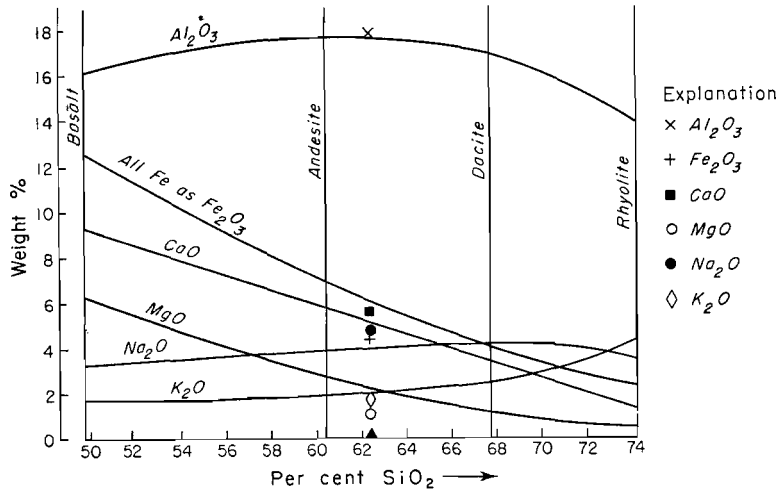


FIGURE 3.—COMPOSITION OF AVERAGE DIORITE PORPHYRY FROM THE HENRY MOUNTAINS PLOTTED ON A VARIATION DIAGRAM DERIVED FROM DALY'S AVERAGE BASALT, ANDESITE, DACITE, RHYOLITE (After Bowen, 1928, Fig. 37)

tains that the porphyries were emplaced at a depth of about 1 mile (1953, p. 146). The total volume of the exposed intrusive igneous rocks is calculated by him (1953, p. 152) to be about 16 cubic miles. The textural features of the porphyries are consistent with this assumption of a hypabyssal environment. They are unquestionably igneous. There is no evidence of stoping or assimilation of wall rock; magma was forcefully intruded in those parts of the porphyry now exposed. Presumably the plagioclase and hornblende phenocrysts in the porphyries began to grow as intratelluric crystals in a deep-seated magma chamber from which the porphyries were derived. Later stages in the growth of these phenocrysts and the development of the groundmass occurred as the porphyries were emplaced in their present position.

The dominant rock type (95 per cent by volume) is referred to as diorite porphyry by most investigators, but this designation may be misleading. The name "diorite porphyry" for these rocks is derived from their mineralogical and textural features rather than from their bulk chemical composition. Comparison of the chemical composition of the average diorite

(Fig. 3). There the concentration of major elements in the "average" diorite porphyry from the Henry Mountains is plotted on a variation diagram based upon Daly's average basalt, andesite, dacite, and rhyolite. The diorite porphyry of the Henry Mountains is more felsic than Daly's average andesite, but its composition is not widely divergent from the curves drawn for Daly's average rocks. Assuming that the curves in Figure 3 represent a liquid line of descent during magmatic differentiation, the divergences that exist are of considerable interest. The Henry Mountain porphyries could have been derived by the tapping of the upper part of a deep magma chamber of andesitic composition in which the first-forming mafic crystals were slowly settling. A chamber of this type, at the onset of cooling, would contain crystals of plagioclase with either augite or hornblende. The density of the plagioclase crystals would be very close to that of the liquid, and the crystals would not sink rapidly to the base of the chamber. In contrast, the augite or hornblende crystals would tend to sink and be concentrated in the lower half of the reservoir. Even if they tended to be redissolved

or recirculated, a gradient in composition probably existed from bottom to top of the reservoir: the base relatively enriched in Fe and Mg, the top in Si, Na, and K, and (because of the suspended plagioclase) Ca and Al. The high Na content of the Henry Mountain rocks seems difficult to explain by a simple, reasonable hypothesis.

Tapping the upper portions of this magma reservoir would yield a magma analogous to that predominant in the intrusive forms (especially the laccoliths, bysmaliths, and dikes) of the Henry Mountains. This interpretation may be visualized from inspection of Table 10. In column 1 is the composition of the average diorite porphyry from the Henry Mountains which contains about 10 per cent hornblende. If another 10 volume per cent hornblende (13 per cent by weight) of composition HM 48 (Table 12) is added to this rock the result (Table 10, column 2) is a rock very similar in composition to Daly's average andesite (Table 10, column 3). These relations suggest that crystal settling of about half of the hornblende formed in a parental andesitic magma could have produced a rock like the porphyry of the Henry Mountains. Many andesitic flows in western North America contain about 20 per cent hornblende or hornblende and pyroxene. The abundance of hornblendite inclusions in the Henry Mountains porphyries may represent early formed hornblende crystals which have settled out of the magma.

The diorite porphyry of the Wickiup Ridge laccolith is slightly less siliceous and more mafic than the average diorite porphyry, and the included hornblendes are much more magnesian than the average. The ratio of Fe/Mg in the hornblende in the Wickiup Ridge laccolith is 1.5, whereas the average for hornblendes in most other porphyries is consistently about 2.5 (Table 12). Moreover, the hornblendes of the Wickiup Ridge laccolith are five times larger than most hornblendes in the Henry Mountains (Table 1). The high Mg content and the large size of the hornblende crystals suggest that they may have been some of the earliest hornblendes to crystallize or that the laccolith may have been derived from intermediate rather than upper parts of the parent magma reservoir.

Within the Mt. Ellen stock and shattered zone there are wide variations in the percentage of groundmass to coarse (largely intratelluric?) phenocrysts in the diorite porphyry. There the "porphyries" contain as little as 2 per cent

groundmass and more than 70 per cent plagioclase (Table 6, column 6). Other porphyries not far removed in space and transitional with the above type contain more than 56 per cent

TABLE 10.—AVERAGE DIORITE PORPHYRY FROM THE HENRY MOUNTAINS AND HYPOTHETICAL ROCK DERIVED BY ADDING 13 PER CENT HORNBLLENDE (BY WEIGHT)

Compared with Daly's average andesite

	1	2	3
SiO <sub>2</sub> .....	62.47	59.72	59.59
Al <sub>2</sub> O <sub>3</sub> .....	18.13	17.43	17.31
Fe <sub>2</sub> O <sub>3</sub> .....	1.68	2.19	3.33
FeO.....	2.45	3.31	3.13
MgO.....	1.28	2.70	2.75
CaO.....	5.73	6.51	5.80
Na <sub>2</sub> O.....	4.85	4.51	3.58
K <sub>2</sub> O.....	1.90	1.75	2.04
H <sub>2</sub> O.....	.77	.93	1.26
TiO <sub>2</sub> .....	.44	.64	.77
MnO.....	.15	.18	.18
P <sub>2</sub> O <sub>5</sub> .....	.21	.19	.26
Total.....	100.06	100.06	100.00

1. Average of five diorite porphyries from column 9 of Table 3.

2. Hypothetical rock derived by adding 13 per cent hornblende; hornblende analysis from column 5 of Table 12.

3. Average composition of 87 andesites from Daly (1914, p. 26).

groundmass and about 30 per cent plagioclase phenocrysts. These features are consistent with field relations that suggest that the porphyries richest in phenocrysts represent clusters of crystal-rich magma trapped in breccia pockets during the intrusion and cooling of the stock. The rocks impoverished in phenocrysts appear to represent liquid-rich magma filtered through breccias and crystal mats.

The rocks designated as monzonite also appear to have compositional peculiarities. If the specimens analyzed during this study are typical, the monzonite contains less Si than the diorite but more Al, Na, and K.

The monzonite variant in the central stock of Mt. Pennell may represent magma derived from the uppermost portions of the parent magma reservoir both during and after the emplacement of the diorite porphyry. This mon-

TABLE 11.—IGNEOUS ROCKS OF WESTERN UNITED STATES SIMILAR IN COMPOSITION TO DIORITE PORPHYRY OF THE HENRY MOUNTAINS

Column	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Location	Henry Mtns. Utah	Henry Mtns. Utah	Henry Mtns. Utah	Sierra el Late Colo.	La Plata Mtns., Colo.	Mt. Shasta, Calif.	Mt. Shasta, Calif.	Northern Calif.	Crater Lake, Ore.	Sierra Carriso, Ariz.	Yellowstone, Wyo.	Yellowstone, Wyo.	Absaroka Range, Wyo.	Southern Calif.	Sierra Nevada, Calif.	British Columbia, Canada
Rock	Porphyry	Porphyry	Porphyry	Porphyry	Porphyry	Andesite	Porphyry	Andesite	Andesite	Porphyry	Diorite	Porphyry	Andesite	Tonalite	Quartz diorite	Porphyry
Number of samples	5	7	3	1	1	3	1	3	4	1	2	2	3	3	1	1
SiO <sub>2</sub>	62.47	62.58	62.34	62.65	60.44	64.50	64.24	62.82	60.64	63.18	63.41	60.00	63.01	60.65	59.70	65.44
Al <sub>2</sub> O <sub>3</sub>	18.13	18.00	17.81	16.68	16.65	18.80	18.67	17.19	17.79	16.47	16.88	17.06	18.10	18.18	18.18	16.83
Fe <sub>2</sub> O <sub>3</sub>	1.68	2.27	2.02	2.35	2.31	1.15	1.40	2.01	2.01	2.36	1.98	4.26	2.71	.83	1.71	1.49
FeO	2.45	2.12	2.01	2.63	3.09	2.15	1.96	2.80	3.34	2.28	2.67	1.73	1.80	4.91	4.58	2.72
MgO	1.28	1.21	1.13	1.43	2.18	2.00	1.48	2.69	3.12	1.33	2.85	2.19	2.04	2.40	2.95	1.29
CaO	5.73	5.28	5.11	4.96	4.22	5.09	4.11	5.53	5.99	4.77	4.59	5.62	4.37	5.89	5.63	4.18
Na <sub>2</sub> O	4.85	4.91	5.30	4.45	5.18	4.53	4.14	3.94	4.21	4.40	4.42	3.73	4.05	3.77	3.57	4.14
K <sub>2</sub> O	1.90	2.11	2.54	2.75	2.71	1.19	1.71	1.76	1.43	2.93	2.16	1.44	2.40	1.54	2.16	1.88
H <sub>2</sub> O	.77	.84	.73	.93	1.43	.13	1.18	.80	.41	.87	.52	2.44	1.25	.65	.52	1.02
TiO <sub>2</sub>	.44	.39	.36	.42	.60	n.d.	.76	.40	.57	.66	.68	tr	.26	.75	.83	.50
P <sub>2</sub> O <sub>5</sub>	.21	n.d.	.16	.28	.29	n.d.	.08	.12	.20	.28	.21	1.15	.23	.08	.18	.22
MnO	.15	.09	.10	.16	.16	n.d.	tr	.10	tr	.15	tr	.12	.04	.07	.07	.06

1. Diorite porphyry (Table 3, column 9). Analyst, C. G. Engel.
2. Diorite porphyry (Table 3, column 10; data taken from Hunt, 1953, p. 154). Analysts, R. E. Stevens and F. G. Fairchild.
3. Diorite porphyry (Clarke, 1900, p. 165). Analyst, W. F. Hillebrand.
4. Hornblende porphyry. Contains hornblende, plagioclase, rare quartz and biotite (Cross, 1894, p. 227). Analyst, W. F. Hillebrand.
5. Diorite porphyry (Clarke, 1900, p. 161). Analyst, W. F. Hillebrand.
6. Hornblende-hypersthene andesite (Diller, 1898, p. 221, 227). Analyst, W. F. Hillebrand.
7. Dacite porphyry, contains phenocrysts of plagioclase, hornblende, biotite, quartz in fine-grained groundmass (Clarke, 1900, p. 177). Analyst, J. E. Whitfield.
8. Andesites (Clarke, 1900 p. 180-183). Analysts, J. E. Whitfield and W. F. Hillebrand.
9. Andesites, dikes and flows (Clarke, 1900, p. 222-223). Analyst, H. N. Stokes.
10. Hornblende porphyry, contains phenocrysts of hornblende and plagioclase in fine-grained groundmass (Cross, 1894, p. 227). Analyst, W. F. Hillebrand
11. Quartz, mica diorite (Iddings, 1891, p. 627). Analyst, W. H. Melville.
12. Hornblende, mica porphyry (Iddings, 1891, p. 627). Analyst, W. H. Melville.
13. Hornblende-andesite dikes (Clarke, 1900, p. 97-99). Analysts, H. N. Stokes and W. F. Hillebrand.
14. Tonalite, southern California Batholith (Larsen, 1948, p. 66, 73). Analyst, F. S. Gonyer.
15. Quartz diorite, contains feldspar, biotite, hornblende and quartz (unpublished). Analyst, C. G. Engel.
16. Biotite porphyrite, contains plagioclase, hornblende, biotite in microcrystalline groundmass (Phemister, 1945, p. 58). Analyst, W. H. Herdsman.

zonite contains phenocrysts of orthoclase, plagioclase, some augite, and minor amounts of altered hornblende. There is slightly less Fe and Mg and more Na and K than in the average diorite porphyry. The augite phenocrysts appear, from the geometry of textures in thin sections, to have formed late in the paragenetic sequence. The presence of augite suggests that water and halogens necessary for the formation of hornblende escaped through the thin roof of sedimentary rocks.

The field relations of the monzonite and diorite porphyry differ from place to place. Hunt noted (1953, p. 115) that many bodies of monzonite intrude the diorite with fairly sharp contacts. At other places noted during the present study contacts between the two rocks are gradational, suggesting a close genetic relationship.

Read (1948, p. 3-4) states that intrusive igneous rocks approximating diorite in composition are invariably of hybrid origin. This comment of Read's was prompted by the fact that both hypabyssal and plutonic diorite intrusives that presumably were derived from primary magmas are rare in the exposed Precambrian terranes and uncommon in younger terranes in most parts of the world. An important exception exists in the Cordilleran and Coast ranges of western North America. There both plutonic and hypabyssal diorites and quartz diorites are abundant. Plutonic diorites having a composition very close to that of the porphyries in the Henry Mountains occur from Alaska to Mexico. Perhaps the best known plutonic rocks analogous to the Henry Mountains porphyries are the quartz diorites (tonalities) described by Larsen (1948) from the Southern California batholith. (See Table 11, column 14.) Almost identical quartz diorites occur southward throughout Baja (Lower) California and northward into Alaska.

Hypabyssal porphyritic rocks analogous to those in the Henry Mountains are common in other laccolithic mountains throughout the Colorado Plateau. These are described by Hunt (1958) and by Eckel (1949). The great similarity in composition, mode of intrusion, and proximity of these intrusive rocks suggests that they are all derived from the same parent magma. Analogous porphyritic quartz diorites emplaced near the surface and erupted as flows are abundant also in the Yellowstone Plateau, the Absaroka Range of Wyoming, the volcanic centers of Mt. Lassen and Mt. Shasta in California, Crater Lake in Oregon, and

throughout the Sierran complex from Northern California to Baja California (Table 11).

## HORNBLENDES

### *Introduction*

The diorite porphyry of the Henry Mountains contains phenocrysts of hornblende and inclusions that are rich in hornblende. In the following discussion the phenocrysts are called hornblende phenocrysts, and hornblendes from inclusions are referred to as inclusion hornblendes.

Five samples of hornblende phenocrysts were extracted from various diorite porphyry intrusions. Ten samples of hornblende were obtained from inclusions. Brief descriptions of the inclusions appear in Table 14. All the hornblendes were analyzed spectrographically by U. Oda and E. F. Cooley in the Denver Laboratories of the U. S. Geological Survey. Six of these same samples were analyzed spectrographically by Elisabeth Godijn at the California Institute of Technology, to test the precision between the two laboratories. Wet chemical analyses were made of five hornblende phenocrysts and one inclusion hornblende. In addition, partial wet chemical analyses of Fe, Ti, and Mn were made on the remaining nine inclusion hornblendes. The wet chemical analyses and optical determinations were made by me.

The six hornblendes analyzed in detail fall into the femaghostingsite and magnesiohostingsite subdivisions of the hastingsite group, as defined by Billings (1928), on the basis of the molecular proportions of FeO/MgO: ferrohastingsite, FeO/MgO > 2; femaghostingsite, FeO/MgO < 2 but > .5; and magnesiohastingsite FeO/MgO < .5.

### *Sample Preparation*

Hornblendes were separated from the -100-mesh sample of porphyries and from hornblendite and amphibolite inclusions in the porphyries. Hornblende concentrates from inclusions were obtained from a -120-mesh and +150-mesh fraction. A single exception required crushing to -150- and +200-mesh size. Hornblendes from the porphyries were crushed to a -100 and +150 mesh. However, one sample required crushing to a -150- and +200-mesh fraction before a hornblende separation was possible. Hornblende concentrates were obtained by the combined use of heavy liquids

TABLE 12.—ANALYSES OF HORNBLLENDE

All chemical determinations made together with W-1 run as a reference (*See* Fairbairn, 1953, Table 1, p. 146.) (Analyst, C. G. Engel)

	1 (HM 9)	2 (HM 15)	3 (HM 22)	4 (HM 48)	5 (HM 2)	6 (HM 54)
SiO <sub>2</sub> .....	39.65	40.30	41.53	39.50	41.34	40.14
Al <sub>2</sub> O <sub>3</sub> .....	13.94	14.17	12.49	14.14	12.76	13.92
Fe <sub>2</sub> O <sub>3</sub> .....	4.60	5.86	5.63	6.98	5.65	6.49
FeO.....	15.46	13.24	13.22	13.66	9.12	9.56
MgO.....	7.68	8.48	9.30	7.33	12.27	10.94
CaO.....	11.19	10.93	11.07	11.04	11.68	11.93
Na <sub>2</sub> O*.....	2.19	1.83	1.79	2.06	2.20	2.01
K <sub>2</sub> O†.....	.98	.95	.96	1.02	.77	.79
H <sub>2</sub> O+.....	1.68	1.86	1.88	1.40	1.86	1.83
H <sub>2</sub> O-.....	.08	.05	.00	.05	.00	.01
TiO <sub>2</sub> **.....	1.57	1.32	1.40	1.52	1.99	1.98
P <sub>2</sub> O <sub>5</sub> .....	.17	.16	.13	.12	.10	.16
MnO††.....	.59	.53	.63	.55	.36	.26
F.....	.32	.21	.20	n.d.	.20	.22
Less O for F	100.10 .13	99.89 .09	100.23 .08	99.37	100.30 .08	100.24 .09
	99.97	99.80	100.15		100.22	100.15
FeO/MgO (Mol. prop.).....	1.13	.88	.80	1.04	.42	.49
Nx.....	1.682	1.677	1.669	1.675	1.666	1.675
Ny.....	1.693	1.688	1.686	1.690	1.679	1.688
Nz.....	1.700	1.696	1.693	1.698	1.686	1.694
Nz - Nx.....	.018	.019	.024	.023	.020	.019

Hornblende from	Pleochroism		
	X	Y	Z
1. Horseshoe Ridge laccolith, diorite porphyry, Mt. Ellen complex	pale yellow green	green	blue green
2. Shattered zone, diorite porphyry, Mt. Ellen complex	pale greenish yellow	yellow green	bluish green
3. Horn laccolith, diorite porphyry, Mt. Pennell complex	yellow green	green	blue green
4. North Sawtooth Ridge laccolith, diorite porphyry, Mt. Hillers complex, 15 miles SE of No. 1	pale greenish yellow	green	bluish green
5. Wickiup Ridge laccolith, diorite porphyry, Mt. Ellen complex	pale greenish yellow	pale brownish yellow	green
6. Hornblende inclusion in No. 4	yellow green	green	blue green

\* Na<sub>2</sub>O determined for W-1, 2.27 per cent. Adjusted mean for W-1, 2.00 per cent.

† K<sub>2</sub>O determined for W-1, 0.69 per cent. Adjusted mean for W-1, 0.63 per cent.

\*\* TiO<sub>2</sub> determined for W-1, 1.09 per cent. Adjusted mean for W-1, 1.10 per cent.

†† MnO determined for W-1, 0.16 per cent. Adjusted mean for W-1, 0.165 per cent.

and the Frantz isodynamic separator. Samples were first run through bromoform, tetrabromoethane, and diiodomethane, and final cleaning was made with the magnetic separator. The

hornblende concentrates used for analysis ranged from 96 to more than 99 per cent pure. The contaminants are chiefly feldspar and pyroxene with very minor amounts of apatite

and biotite (Table 14). The feldspar occurs as tiny grains that have not broken free from the hornblende. Most of the pyroxene occurs as free grains but has about the same density and

(Table 12) are those of fragments crushed from numerous crystals. The indices were determined in sodium light and also in white light in oils graduated on .002 intervals. The determinations

TABLE 13.—STRUCTURAL FORMULAE OF HORNBLENDES\*

	1 (HM 9)		2 (HM 15)		3 (HM 22)		4 (HM 48)		5 (HM 2)		6 (HM 54)	
K	.18		.18		.18		.20		.14		.14	
(W) Na	.64	2.64	.54	2.49	.52	2.48	.61	2.62	.62	2.61	.62	2.61
Ca	1.82		1.77		1.78		1.81		1.85		1.85	
Mg	1.73		1.91		2.09		1.67		2.70		2.39	
(X) Fe <sup>++</sup>	1.96	3.76	1.67	3.64	1.66	3.83	1.75	3.49	1.13	3.87	1.17	3.60
Mn	.07		.06		.08		.07		.04		.04	
Al	.50		.61		.47		.66		.35		.47	
(Y) Fe <sup>+++</sup>	.53	1.21	.67	1.43	.63	1.26	.81	1.64	.62	1.19	.72	1.41
Ti	.18		.15		.16		.17		.22		.22	
(Z) Si	6.01	8.00	6.09	8.00	6.25	8.00	6.05	8.00	6.12	8.00	6.06	8.00
Al	1.99		1.91		1.75		1.95		1.88		1.94	
OH	1.69		1.87		1.88		1.43		1.83		1.80	
F	.15	1.84	.10	1.97	.10	1.98	n.d.		.10	1.93	.11	1.91

\* The structural type is taken as  $W_{2-3} (XY)_5 (Z_4O_{11})_2 (OH, F, Cl)_2$ .

1. (HM 9) Horseshoe Ridge laccolith, diorite porphyry.
2. (HM 15) Shattered zone, Mt. Ellen, diorite porphyry.
3. (HM 22) Horn laccolith, diorite porphyry.
4. (HM 48) North Sawtooth Ridge laccolith, diorite porphyry.
5. (HM 2) Wickiup Ridge laccolith, diorite porphyry.
6. (HM 54) Hornblendite inclusion in North Sawtooth Ridge laccolith (HM 48 above).

magnetic properties as the hornblende and could not be completely separated from it. Some workers claim 99.5–99.9 per cent purity for hornblendes extracted from equigranular rocks although no evidence is offered to demonstrate this purity. In the diorite porphyries a sample with less than 0.5 per cent impurity is rarely possible even after exhaustive hand picking. This is due to the fact that crystals are partly altered or replaced by calcite, chlorite, and epidote, and some contain clouds or clusters of minute inclusions. I found that about 60 hours of hand picking under the microscope was required to purify only 2 grams of a sample of approximately 99 per cent pure hornblende.

*Optical Properties*

All the hornblendes are green, and all show faint to well-developed zonal growth. The indices of refraction determined on each sample

made in sodium light and white light were in fair agreement (usually .002), and I believe that white light is the better medium for deeply colored minerals with high absorption, such as hornblende. There seems to be no simple correlation between chemical composition and optical properties of hornblendes. A lack of obvious correlations of optics and composition of hornblende is implicit in most modern studies (Deer, 1938; Buddington and Leonard, 1953; Larsen and Draisin, 1950) although there is little discussion of the fact, and Winchell's elaborate diagrams (1951, p. 434, Fig. 325) suggest precise, sympathetic relations between optics and composition that cannot be demonstrated.

*Chemical Composition*

*Wet chemical analyses.*—The chemical analyses of five hornblende phenocrysts and one

inclusion hornblende appear in Table 12. These analyses are computed to the structural formula in Table 13. The inclusion hornblende HM 54 was extracted from an inclusion at the locality from which phenocrysts HM 48 was obtained. The inclusion was collected about 5 feet from the sample of porphyry HM 48 and hornblende phenocryst HM 48. This is the only instance where it was possible to obtain fresh phenocryst and inclusion hornblendes from the same intrusive body and locality.

The compositions of porphyries from which these hornblendes were obtained appear in Table 3. Rocks and phenocrysts have the same sample numbers. The hornblendite inclusion from which hornblende HM 54 was obtained was not analyzed. The textural and mineralogical composition of the hornblendite and amphibolite inclusions is given in Table 14. Locations of rock and hornblende samples are shown in Figure 1.

Four of the 5 hornblende phenocrysts analyzed (HM 9, HM 15, HM 22, HM 48) are very similar in composition even though two (HM 9 and HM 48) are from localities 15 miles apart in separate intrusive complexes. The hornblende phenocrysts, HM 9 and HM 2, that are from adjacent laccoliths of approximately the same composition, showing striking differences especially in the molecular proportions of FeO/MgO (Table 12). Hornblende HM 2, the "aberrant" hornblende phenocryst, is 5 times larger than other phenocrysts in the Henry Mountains (Hunt, 1953, p. 155). The rock in which it occurs is much coarser-grained than the average porphyry and contains much less groundmass. Phenocryst HM 2 is almost identical in composition to the inclusion hornblende HM 54 but is unlike the hornblende phenocryst HM 48 from which the inclusion came.

Billings' study (1928) of hornblendes from the Paleozoic igneous intrusive complex of northeastern United States and southeastern Canada led him to suggest that the molecular proportions of the ratio FeO/MgO increases with decreasing temperature of crystallization of the parent rock. If this generalization is valid for hornblende phenocrysts and inclusion hornblendes in the Henry Mountains, then the coarsely crystalline phenocryst HM 2 and the inclusion hornblende HM 54 were crystallized at higher temperatures than the rest of the hornblende in Table 12. In an effort to determine whether other inclusion hornblendes were enriched in Mg relative to Fe, analyses were made of total Fe on nine other inclusion horn-

blendes (Table 14). These analyses were undertaken on the assumption that the total Fe content of the hornblendes would offer an approximate index of its Mg content. As a further test of this assumption, the approximate Mg content of each hornblende was determined spectrographically (Table 14). The data show that hornblendes relatively enriched in total Fe contain about 50,000 ppm Mg (5 per cent); hornblendes relatively low in Fe contain about 70,000 ppm Mg (7 per cent). Most of the inclusion hornblendes are what Billings classified as magnesiohastingsite and may reflect a more mafic environment and higher temperature of crystallization than most hornblende phenocrysts in the diorite porphyry. The inclusions are probably not formed by the clustering of crystals formed in equilibrium with porphyry enclosing the inclusion. Presumably the inclusions are either xenoliths or crystal aggregates formed in another part of the magma or at an earlier stage in its differentiation. These problems are considered in the succeeding section on origin of the hornblendes.

*Spectrographic analyses.*—The concentrations of elements obtained spectrographically by Oda and Cooley are listed in Table 14, which also contains data on Fe, Mn, and Ti obtained using wet methods. All analyses of a given type were done at the same time to limit the errors in precision as much as possible. Elisabeth Godijn repeated trace-element analyses of six of the same samples of hornblende at the California Institute of Technology, and the results of independent analyses of the two laboratories are listed in Table 15. Studies of analyses of masked replicate samples show variations up to 50 per cent from the posted values for most elements. This error increases appreciably if the analyses are made at different times, even in the same laboratory by the same analyst.

In Table 14 the spectrographic analyses of hornblende phenocrysts constitute Group I; analyses of inclusion hornblendes form Group II. Arithmetic means for the concentrations of each element in each group are listed in the right-hand column of Table 14. The analyses of trace elements in the two types of hornblendes corroborate the general conclusion drawn from the data on major elements; both hornblende phenocrysts and inclusion hornblendes show moderate variations in composition with essentially complete compositional overlap. Eight of the inclusion hornblendes are magnesiohastingsite with more Cr, Ni, and Mg and possibly less Ti and Mn than four of the five hornblende phenocrysts. In the inclusion horn-



TABLE 14.—SPECTROGRAPHIC AND PARTIAL CHEMICAL ANALYSES OF HORNBLENDE FROM DIORITE PORPHYRIES AND INCLUSIONS

	Group I Hornblende phenocrysts from diorite porphyry					Group II Hornblende from inclusions in diorite porphyry										Group I Mean	Group II Mean	
	HM 9	HM 15	HM 22	HM 48	HM 2	Hornblende from inclusions that consist of very coarse-grained, randomly oriented crystals of hornblende with minor amounts of feldspar, pyroxene, and magnetite					Hornblendes from inclusions that consist of about equal amounts of hornblende and feldspar. This type of inclusion has a crude layering and orientation of crystals.							Hornblende from amphibolite gneiss with alternate feldspar-and hornblende-rich layers
						HM 54	HM 13	HM 16	HM 7	HM 14A	HM 1	HM 3	HM 6	HM 4	HM 2A			
ppm*																		
Ba.....	150	150	300	200	150	150	150	150	150	150	150	150	100	100	100	200	150	Ba
Co.....	20	50	50	30	50	50	50	50	70	50	70	30	70	50	70	40	50	Co
Cr.....	50	50	30	20	<20	150	20	150	20	1000	100	700	300	1000	300	~30	400	Cr
Cu.....	5	7	7	30	7	150	20	5	300	7	7	5	5	5	10	10	20	Cu
Mn.....	3000	3000	3000	3000	3000	1500	3000	2000	2000	3000	3000	3000	3000	3000	3000	3000	3000	Mn
Ni.....	30	15	20	20	20	70	20	50	70	300	50	100	100	300	70	20	120	Ni
Sc.....	50	70	70	50	70	70	70	100	100	50	150	50	70	50	100	70	70	Sc
Sr.....	150	150	300	200	300	150	100	300	300	100	<50	200	50	100	<50	200	~150	Sr
Ti.....	7000	5000	5000	7000	7000	7000	5000	7000	7000	3000	7000	5000	3000	3000	7000	7000	5000	Ti
V.....	300	300	500	500	300	500	300	300	500	300	500	300	300	300	500	300	300	V
Y.....	30	30	30	50	30	20	30	20	15	50	30	30	15	30	30	30	30	Y
Zn.....	300	200	200	200	<200	<200	200	<200	<200	<200	<200	<200	<200	<200	<200	~200	<200	Zn
Zr.....	150	200	200	150	100	100	100	70	50	100	100	70	50	70	70	150	70	Zr
Mg.....	50,000	50,000	50,000	30,000	70,000	70,000	50,000	70,000	70,000	70,000	70,000	70,000	70,000	70,000	50,000	50,000	70,000	Mg
Weight per cent †																		
Fe.....	15.22	14.38	14.20	15.49	11.04	11.97	13.73	11.92	11.11	8.80	13.60	12.40	12.84	9.60	14.81	14.1	12.1	Fe
Mn.....	.46	.41	.49	.43	.28	.20	.39	.21	.25	.40	.25	.28	.32	.25	.29	.41	.28	Mn
Ti.....	.94	.79	.84	.91	1.19	1.19	.74	.91	.87	.40	.97	.91	.41	.53	.90	.93	.78	Ti
Mg.....	4.63	5.12	5.61	4.42	7.40	6.60	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	5.44	n.d.	Mg
Estimated purity of sample (%)	99	97	98	98+	99	99+	98	96	97	97	99	98	98	99+	98			
Impurities**.....	f	f	f	f, p	f	f, a	f, a	f, p	f, p	o	f, a	f, a	f, b	o	f, p			

\* Semiquantitative spectrographic analyses by U. Oda and E. F. Cooley, U. S. Geological Survey.

† Wet chemical analyses by C. G. Engel.

\*\* f = feldspar, p = pyroxene, a = apatite, o = opaque inclusions, b = biotite.

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blends Zn may be less abundant but this is not positively demonstrated. The differences in Ba and Sr probably reflect the unequal distribution of feldspar impurities but may be intrinsic

ences are not apparent. The two inclusion hornblendes that show the highest concentrations of Cr and Ni have a "bleached" appearance and contain numerous oriented opaque

TABLE 15.—SPECTROGRAPHIC ANALYSES OF IDENTICAL HORNBLENDE SAMPLES, MADE IN DIFFERENT LABORATORIES  
(In parts per million)

	HM 9		HM 15		HM 22		HM 48		HM 2		HM 54	
Ba.....	150	160	150	170	300	330	200	280	150	185	150	290
Co.....	20	25	50	26	50	33	30	26	50	36	50	29
Cr.....	50	33	50	47	30	45	20	40	<20	6	150	245
Cu.....	5	17	7	17	7	29	30	28	7	17	150	56
Mn.....	3000	3200	3000	2000	3000	2300	3000	2400	3000	2100	1500	830
Ni.....	30	16	15	15	20	20	20	15	20	14	70	48
Sc.....	50	39	70	42	70	41	50	41	70	65	70	46
Sr.....	150	330	150	310	300	330	200	320	300	410	150	310
Ti.....	7000	6300	5000	4800	5000	4800	7000	6900	7000	7700	7000	5100
V.....	300	440	300	420	500	610	500	550	300	320	500	470
Y.....	30	69	30	77	30	43	50	63	30	52	20	pt
Zr.....	150	108	200	135	200	145	150	114	100	51	100	28
Analyst.....	A	B	A	B	A	B	A	B	A	B	A	B

Analyst A. Analyses run independently by U. Oda and E. F. Cooley, U. S. Geological Survey. The figures reported are an average of the two runs.

Analyst B. Analyses by Elisabeth Godijn, California Institute of Technology.

HM 9. Horseshoe Ridge laccolith, diorite porphyry, Mt. Ellen complex.

HM 15. Shattered zone, diorite porphyry, Mt. Ellen complex.

HM 22. Horn laccolith, diorite porphyry, Mt. Pennell complex.

HM 48. North Sawtooth Ridge laccolith, diorite porphyry, Mt. Hillers complex.

HM 2. Wickiup Ridge laccolith, diorite porphyry, Mt. Ellen complex.

HM 54. Hornblendite inclusion in HM 48, Mt. Hillers complex.

differences in the amounts of these elements in hornblendes.

The enrichment of Cr and Ni in the more magnesian inclusion hornblendes is established; Cr shows a maximum enrichment—by a factor of 5—as the molecular proportions of FeO/MgO are halved (decreasing from 1 to about 0.5). The enrichment of Cr is accompanied by a fivefold increase in Ni. There is little or no increase in Co.

The absence of adequate data on Fe<sup>++</sup> and Mg in the inclusion hornblendes prevents a more rigorous correlation between the concentrations of Co, Cr, and Ni with these major elements.

Most of the hornblendes contain about 6 ppm Cu. The much higher values in several specimens (up to 160 ppm) are probably correct, although the reasons for the abrupt differ-

ences are not apparent. The two inclusion hornblendes that show the highest concentrations of Cr and Ni have a "bleached" appearance and contain numerous oriented opaque

#### Comparisons with Other Hornblendes

Hornblendes from igneous rocks compositionally like the diorite porphyry of the Henry Mountains have been described by Larsen and Draisen (1950), Deer (1938), and others. Analyses of similar hornblendes from metamorphosed granitic rocks have been published by Buddington and Leonard (1953). Older analyses of hornblendes from dioritic rocks are discussed by Hallimond (1943). Hornblendes from inclusions like those in the porphyry are discussed by Deer (1938) and Hurlbut (1935). Hornblendes similar in composition to inclusion

TABLE 16.—CHEMICAL ANALYSES OF HORNBLENDENES FROM OTHER IGNEOUS ROCKS, INCLUSIONS, AND AMPHIBOLITES, COMPARED WITH COMPOSITION OF HORNBLLENDE FROM THE HENRY MOUNTAINS, UTAH

	1	2	3	4	5	6	7
SiO <sub>2</sub> .....	40.30	43.72	42.11	38.92	39.78	41.25	40.14
Al <sub>2</sub> O <sub>3</sub> .....	14.17	12.40	10.05	12.68	11.39	13.26	13.92
Fe <sub>2</sub> O <sub>3</sub> .....	5.86	3.32	2.82	7.42	5.93	3.56	6.49
FeO.....	13.24	14.22	15.14	14.64	14.21	13.50	9.56
MgO.....	8.48	9.86	11.48	7.86	9.62	10.27	10.94
CaO.....	10.93	11.64	11.34	11.24	9.68	10.22	11.93
Na <sub>2</sub> O.....	1.83	.86	1.01	2.38	1.57	1.82	2.01
K <sub>2</sub> O.....	.95	.77	1.43	1.58	1.60	.83	.79
H <sub>2</sub> O+.....	1.86	1.69	2.02	.93	2.59	1.48	1.83
H <sub>2</sub> O-.....	.05	n.d.	.06	n.d.	.25	.06	.01
TiO <sub>2</sub> .....	1.32	1.44	2.76	1.51	1.47	2.96	1.98
P <sub>2</sub> O <sub>5</sub> .....	.16	n.d.	n.d.	n.d.	n.d.	n.d.	.16
MnO.....	.53	.08	.24	.09	.68	.47	.26
F.....	.21	.18	n.d.	1.20	1.29	.11	.22
Less O for F.....	99.89 .09	100.18 .08	100.46	100.45 .51	100.64* .67	99.79 .05	100.24 .09
	99.80	100.10		99.94	99.97	99.74	100.15
FeO/MgO (Mol. prop).....	.88	.80	.74	1.04	.83	.75	.49
MRM/MRR†.....	.93	.96					
N <sub>x</sub> .....	1.677	1.667	1.662	1.690	1.666	1.666	1.675
N <sub>y</sub> .....	1.688	1.680	1.673	1.702	1.689		1.688
N <sub>z</sub> .....	1.696	1.685	1.680	1.705	1.693	1.689	1.694

\* The original analysis published by Buddington and Leonard (1953) contains 0.58 Cl. The Cl is deleted from this table but is included in the total.

† Ratio  $\frac{\text{FeO} + \text{MnO} + \text{Fe}_2\text{O}_3}{\text{FeO} + \text{MnO} + \text{Fe}_2\text{O}_3 + \text{MgO}}$  in hornblende to  $\frac{\text{FeO} + \text{MnO} + \text{Fe}_2\text{O}_3}{\text{FeO} + \text{MnO} + \text{Fe}_2\text{O}_3 + \text{MgO}}$  in rock.

1. Hornblende phenocryst from diorite porphyry, Mt. Ellen shattered zone. Analyst, C. G. Engel.
2. Hornblende from Lakeview Mountain tonalite, southern California batholith (Larsen and Draisén, 1950, p. 71, Table 3, column 8). Analyst, F. A. Gonyer.
3. Hornblende from Glen Tilt diorite, Scotland (Deer, 1938, p. 58, Table 1, column 1). Analyst, W. A. Deer.
4. Hornblende in vug (miarolitic cavity) in monzonite dike, Bearpaw Mountains, Montana (Pecora and Fisher, 1946, p. 379). Analyst, F. A. Gonyer.
5. Hornblende from microcline granite gneiss, northwest Adirondack Mountains, New York (Buddington and Leonard, 1953, p. 894, Table 1, column 1). Analyst, E. K. Oslund.
6. Hornblende from garnet-bearing amphibolite, northwest Adirondack Mountains, New York (Buddington, 1952, p. 42, Table 3, column 7), Analyst, Lee C. Peck.
7. Hornblende from, hornblende inclusion in diorite porphyry, North Sawtooth Ridge laccolith, Henry Mountains, Utah. Analyst C. G. Engel.

hornblendes occur in metagabbro of the Adirondack Mountains (Buddington, 1952).

The similarities in composition between the plutonic tonalites from the southern California batholith (Larsen, 1948, p. 67, columns 3, 4, 7) and the diorite porphyry made comparisons of their constituent hornblendes especially inter-

esting. Hornblende is the most widespread femic mineral in the southern California batholith and is the chief dark mineral in the tonalite. Analysis of one of the hornblendes from the Lakeview Mountain tonalite (Larsen and Draisén, 1950, p. 71) is given in column 2 of Table 16. Analyses of hornblendes from the

Henry Mountains, the Glen Tilt complex of Scotland, a monzonite dike in the Bearpaw Mountains, and the Adirondack Mountains are also given in Table 16.

The hornblendes in the Lakeview Mountain tonalite and in the diorite porphyry are alike in composition. Larsen and Draisen (1950, p. 74-75) note that the ratio of  $\text{FeO} + \text{MnO} + \text{Fe}_2\text{O}_3 / \text{FeO} + \text{MnO} + \text{Fe}_2\text{O}_3 + \text{MgO}$  is about the same for the rock as for the mafic minerals (*e.g.*, hornblende). This is also true for the hornblende phenocrysts and enclosing porphyry of the Henry Mountains (Table 16, columns 1, 2). The hornblendes in the southern California batholith appear to have concentrations of the oxides  $\text{Fe}_2\text{O}_3$ ,  $\text{MgO}$ , and  $\text{FeO} + \text{MnO}$  systematically related to the composition of the parent rock. As plotted against  $\frac{1}{3} \text{SiO}_2 + \text{K}_2\text{O} - \text{FeO} - \text{MgO} - \text{CaO}$  in the rock,  $\text{Fe}_2\text{O}_3$  and  $\text{FeO} + \text{MnO}$  in the constituent hornblendes seems to increase, whereas  $\text{MgO}$  decreases (Larsen and Draisen, 1950, Fig. 2).

Hornblende-rich inclusions are abundant in the tonalites of the southern California batholith. Hurlbut (1935, p. 609) interprets these inclusions to be xenoliths of associated gabbro, variously modified by interaction with the tonalite. There are no chemical analyses of the inclusion hornblendes, but Hurlbut states (1935, p. 622) that their optical properties ( $N_x$  1.64-1.664,  $N_z$  1.662-1.682) "indicate that the hornblendes of the inclusions are higher in Mg and lower in Fe than those of the tonalite." If the optical data are diagnostic, there are obvious analogies between the hornblendes of the Henry Mountains and those in the tonalites of the batholith.

The hornblende-bearing diorites of the Glen Tilt complex, Scotland, also contain hornblende-rich inclusions derived from the Perthshire Series of the Dalradian (Precambrian). Hornblendes from both rock types have been analyzed by Deer (1938, p. 58). He reports that the intrusive diorites (appinites) commonly contain two hornblendes. One, the first formed, is brown; the later generation is green. Neither hornblende is interpreted by Deer as having formed in equilibrium with magma. The hornblende from "typical Glen Tilt diorite" (Table 16, column 3) is much richer in Ti and Mg and much poorer in  $\text{Fe}_2\text{O}_3$  than the hornblende phenocrysts in the Henry Mountains (Table 16, column 1).

The hornblendes analyzed by Deer (1938) from the xenoliths have a higher content of silica (44.2-49.0 per cent  $\text{SiO}_2$ ) than those from the diorites. The molecular proportions of  $\text{FeO}/\text{MgO}$  in the xenolithic hornblendes range

from 0.29 to 0.49, as compared to 0.49 for the inclusion hornblende HM 54 in the Henry Mountains.

The constituent hornblendes in metamorphosed granitic rocks of the northwest Adirondack Mountains are of interest in that several of them are very like the hornblende phenocrysts in the Henry Mountains. An analysis of hornblende from microcline granite gneiss as reported by Buddington and Leonard (1953) is listed in column 5 of Table 16. It differs from the hornblende phenocrysts from Mt. Pennell only in its slightly lower Al and Ca content and very high F content.

The hornblendes described by Buddington (1952) from metamorphosed and granitized gabbros of the Adirondack Mountains also are noteworthy because of their similarity to the inclusion hornblendes from the Henry Mountains (Table 16, columns 6, 7). Except for the differences in F and in the oxidation state of Fe, these hornblendes are remarkably alike. Buddington suggested a correlation between Ca content of the hornblendes and that of the enclosing rocks. This relationship does not seem to exist, however, for the rocks and constituent hornblendes in the southern California batholith (Larsen and Draisen, 1950; this report, Table 16). The ratio of CaO in parent rock to CaO in the constituent hornblende decreases markedly with decreasing basicity of the rocks in the calc-alkaline line of descent.

Another hornblende essentially like the phenocryst hornblendes has been described by Pecora and Fisher (1946). The analysis is listed in column 4 of Table 16. This hornblende occurs in vugs in a monzonite dike in the Bearpaw Mountains, Montana.

Most analyses of hornblendes published before 1943 are tabulated by Hallimond (1943). He attempted to correlate their Si content and "excess" (more than 2 atoms of Na + K + Ca with the origin and composition of the host rock. Both phenocrysts and inclusion hornblendes from the Henry Mountains fall in the field of "diorite" hornblendes, near its mutual boundary with hornblendes from basalts (Fig. 4). Hallimond's elaborate diagram is liable to criticism if only because of the probable lack of precision between many of the analysts involved and the impurities of the samples analyzed.

#### *Origin*

The similarity in composition of four of the five hornblende phenocrysts is expectable in view of the constancy in composition of the

parent diorite porphyry. The one hornblende phenocryst from the Wickiup Ridge laccolith is compositionally unlike the others, and its parent rock is abnormally coarse-grained. This

portion of the magma chamber and intruded with more initial heat or volatiles, these conditions would enable hornblende crystals to grow larger, to acquire a higher ratio of Mg/Fe,

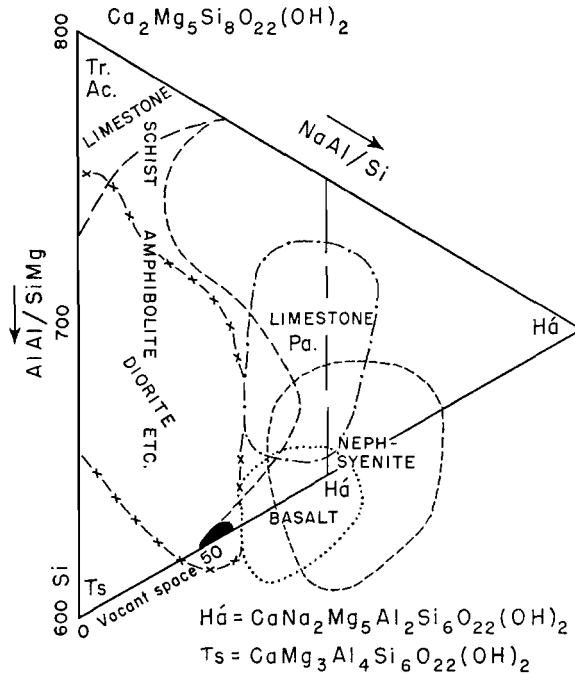


FIGURE 4.—RELATIONS OF HORNBLENDES FROM THE HENRY MOUNTAINS (SOLID AREA) TO HORNBLENDES FROM VARIOUS ROCK TYPES

(After Hallimond, 1943) Total Si content of the hornblendes is plotted against "excess" (more than 2 atoms) of Na + K + Ca.

hornblende also replaces pyroxene. Elsewhere, pyroxene replaces hornblende. Both the textural and paragenetic differences at Wickiup Ridge are stated by Hunt (1953, p. 105) to be unique in the Henry Mountains. One possible explanation of the paragenetic, textural, and compositional differences is that the Wickiup Ridge hornblende and associated plagioclase began growth in the parent magma before most of the phenocrysts in the exposed porphyries. If the Wickiup Ridge type phenocrysts were crystals formed early in the paragenetic sequence they may have settled to a different level in the magma chamber than that supplying most of the intrusive rocks in the Henry Mountains. This implies that part of the Wickiup Ridge laccolith with very coarse-grained crystals was tapped from deeper levels of the parent magma than the rest of the exposed porphyry. If the coarse-grained porphyry at Wickiup Ridge was derived from a deeper, hotter, and more mafic

and to prevent late pyroxenes from forming at the expense of hornblendes.

The origin of the inclusion hornblendes is obscure because of the enigmatic nature of the inclusions themselves. Hunt (1953, p. 164) suggested that "... the inclusions may be altered fragments of diverse wall rock floated from great depths, or rock fragments from early differentiates in the magma reservoir or fragments of marginal unfused layers of the substratum from which the magma was derived." The possibility that these inclusions represent early hornblende-rich segregations is appealing because this would readily explain (1) the overlap in composition of phenocrysts and inclusion hornblendes, (2) the relative enrichment of Mg, Cr, and Ni in most of the inclusion hornblendes, and (3) the constancy of mineralogy in the inclusions, and (4) their abnormally high hornblende content (80-95 per cent in many inclusions). Inclusions of other rock types are

extremely rare in the porphyries of the Henry Mountains (Hunt, 1953, p. 164), whereas hornblendite and amphibolite inclusions are numerous.

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