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HEAVY MINERAL ASSEMBLAGES OF SOME OF THE PLUTONIC ROCKS OF EASTERN OREGON[1]

J. C. REED AND JAMES GILLULY

ABSTRACT

Plutonic igneous rocks constitute a large proportion of the pre-Tertiary terrane of the Blue Mountains of northeastern Oregon. Gabbro, hornblende-quartz diorite, biotite-quartz diorite, trondhjemite, and albite granite are abundant. The biotite-quartz diorite is notably less sheared than the other plutonic rocks and may belong to a later igneous cycle. On the other hand, it may belong to the same cycle as the other rocks and may be more massive because it was intruded near the close of the orogenic activity. Accordingly the correlation of the plutonic rocks is of major importance in the study of the regional geology.

The heavy residues of nineteen samples of plutonic rocks were examined by a method similar to that used by A. W. Groves for correlating some of the rocks of the Channel Islands.

The study has shown that the biotite-quartz diorite contains a suite of heavy minerals that is quite as diagnostic as the essential minerals. However, the heavy mineral suites of the more basic rocks are less trustworthy as a basis for classification, but if a number of slides of the heavy residue are studied it is generally possible to classify the rock. The fact that the distinction between the several suites is less definite than in the case of the biotite-quartz diorite may strengthen the field hypothesis of consanguinity of the gabbro, hornblende diorite, trondhjemite, and albite granite.

The fact that apatite is less abundant in the gabbro than in the diorite may mean that apatite does not always crystallize first, or that—because its crystals are usually small—the apatite is carried away from the larger separated crystals of augite and plagioclase by movements of the rest-magma.

The zircon and apatite crystals of the hornblende-quartz diorite and trondhjemite commonly appear to be corroded. This fact gives some reason to question the commonly accepted idea that these minerals, because they are among the first to crystallize, are stable throughout the later magmatic history.

[1] Published with permission of the Acting Director, U. S. Geological Survey.

CONTENTS

INTRODUCTION

Plutonic igneous rocks make up a large part of the pre-Tertiary terrane of the Blue Mountains of eastern Oregon. (See fig. 1.) The plutonic rocks recognized include gabbro with subordinate norite, peridotite, pyroxenite, and serpentine; basic diorite, hornblende-quartz diorite, biotite-quartz diorite, trondhjemite, and albite granite. Field work by the writers and their associates in the Baker City quadrangle and nearby areas in 1929 and 1930 resulted in the tentative assignment of these intrusive rocks to two igneous cycles, the earlier represented by the gabbro, norite, and other basic rocks, hornblende-quartz diorite, trondhjemite, and albite granite, the later by the biotite-quartz diorite and associated dikes. The principal criterion used in this division was structural, the rocks assigned to the earlier cycle being notably more sheared and even gneissic, while the biotite-quartz diorite shows only a faint mineral parallelism developed near the borders of the different masses. However, the fact that the schistosity of the country rock tends to follow the periphery of some of these biotite-quartz diorite masses seems to render this structural criterion of somewhat less value, as the biotite-quartz diorite might belong to the same magmatic cycle as the other rocks and owe its more massive structure to its intrusion almost at the close of the orogenic activity. Under this hypothesis, it would follow that even though the forcible intrusion of the biotite-quartz diorite masses may have induced peripheral schistosity in the country rocks, its final consolidation occurred under static conditions so that only the border facies show marked mineral parallelism.

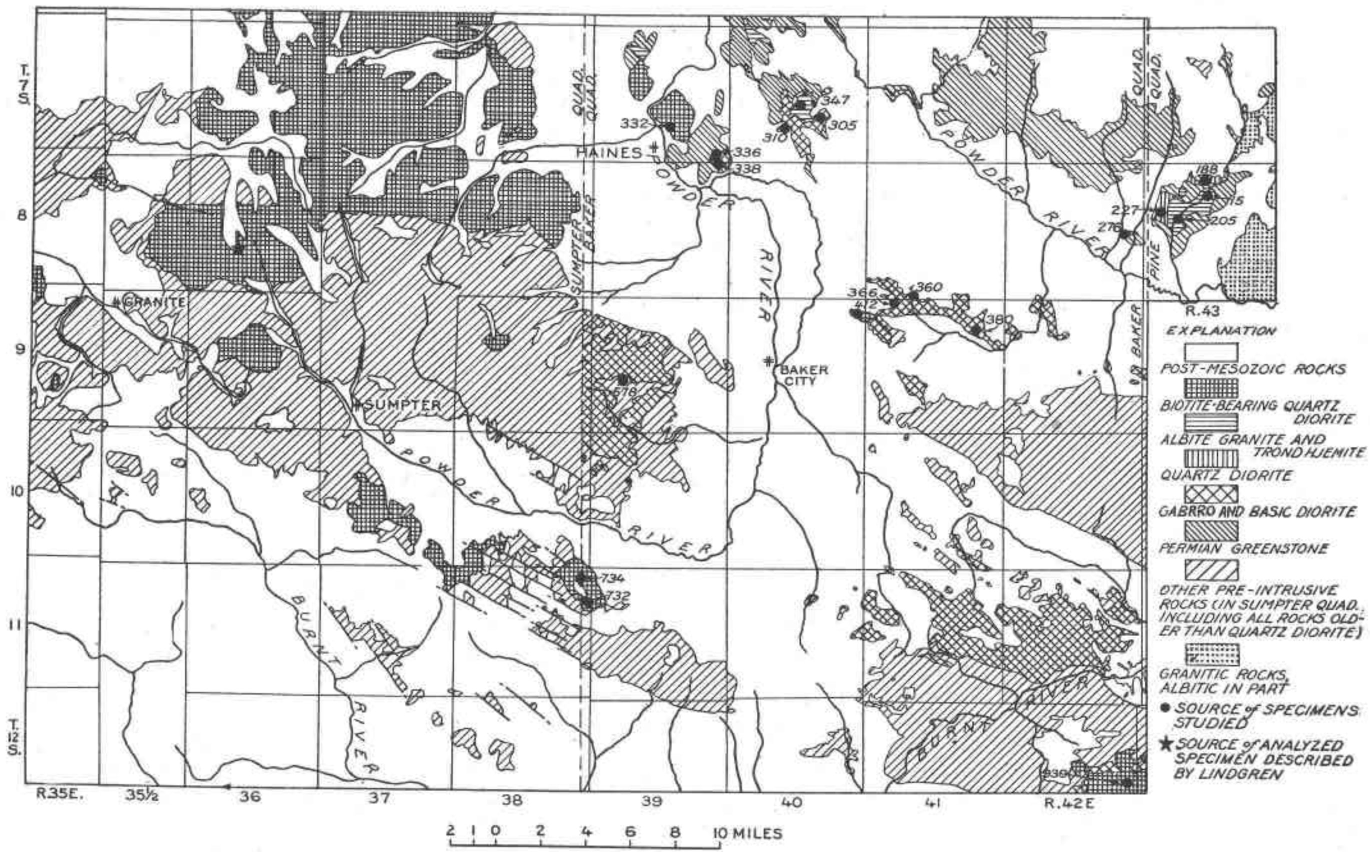

FIG. 1. Generalized geologic map of the Sumpter, Baker City, and part of the Pine quadrangles.
Geology of the Sumpter Quadrangle by J. T. Pardee and D. F. Hewett, Baker Quadrangle by James Gilluly, J. C. Reed, C. F. Park, Jr., and R. E. Stewart.

Independent evidence for the existence of more than one magmatic cycle in the region is supplied by the presence of volcanic rocks in the representatives of the Mississippian (?), Permian, and Triassic in the Blue Mountains, and by the fact that some at least of the intrusive rocks cut the Triassic. Correlation of the earlier plutonic rocks with any of these surficial lavas has not yet proved feasible however, if indeed, any of the plutonic rocks now exposed are so related. Accordingly the problem of correlation of the plutonic rocks assumes major proportions in a study of the regional geology. Presumably, detailed areal studies of more of the area will throw much light on the matter; pending these, however, it seems desirable to attack the problem as thoroughly as is permitted by the evidence at hand. In this connection our attention was drawn to the recent work of Groves[2] on the correlation of plutonic rocks by means of the suites of heavy minerals they contain and it was decided to see what light a study of these minerals would throw upon the correlation of the rocks in question.

Abstract of Groves' work. Groves worked with specimens between a quarter of a pound and one and one-half pounds in weight. These he prepared as follows: The specimen was crushed in a mortar, taking precautions to minimize the formation of rock dust. After the powder was passed through a thirty mesh sieve it was washed, dried, and then separated by means of bromoform. The heavy residues of those specimens yielding large quantities of biotite were subjected to special treatment. They were divided into two parts, one of which was boiled in concentrated hydrochloric acid (baueritized) to leach the mica so it could be removed, and the other retained to study the minerals destroyed by the acid in the first part. The heavy residues in which hornblende was plentiful were passed under an electro-magnet. Some residues were further separated with methylene iodide.

In Groves' later paper[3] he makes certain claims for, and points out certain limitations of the method. He also answers several criticisms which have been made regarding it. The following quotations present some of his main points.

[2] Groves, A. W., The heavy minerals of the plutonic rocks of the Channel Islands: *Geol. Mag.*, vol. **LXIV**, pp. 241–51 and 457–73, 1927.

The heavy mineral suites and correlation of the granites of Northern Brittany, the Channel Islands, and the Cotentin: *Geol. Mag.*, vol. **LXVII**, pp. 218–240, 1930.

[3] The heavy mineral suites and correlation of the granites of Northern Brittany, the Channel Islands, and the Cotentin: *Geol. Mag.*, vol. **LXVII**, pp. 224–239, 1930.

The basic idea which prompted this work has been as follows:—Neighboring granites, if comagmatic, should reflect their relationship in possessing heavy mineral suites with many points in common and this for the reason that such minerals as zircon, apatite, monazite, rutile, iron ore, and sphene, generally crystallize from the magma at an early stage of cooling and thus, in their colour, inclusions, habits and peculiarities, give valuable characteristics dependent on the original composition and early cooling history of the magma. . . .

Merely to enumerate the minerals present and to attempt correlation by means of the names of the mineral species is as futile as to attempt accurate stratigraphical zonal correlation when the generic names only of the fossils involved are known. The colour, dimensions, habits, nature of inclusions and any other peculiarities of each mineral have to be carefully noted and compared with those in other specimens. . . .

Attention should be focussed principally on the primary stable minerals such as zircon, apatite, monazite, rutile, sphene, muscovite, biotite, hornblende, iron ores, etc. Next in importance came the pneumatolytic minerals such as tourmaline, fluor, topaz, cassiterite, etc. . . .

Less attention need be paid to minerals of the epidote and chlorite groups, these being mostly secondary. Orthite is however an exception, as it indicates the presence of cerium in the magma. . . .

The index figure or percentage weight of the rock exceeding bromoform in density (about 2.8) should be determined in the case of every sample. It is useful for comparison and in this way differentiation and contamination by assimilation are readily detected—even when the worker has not visited the outcrop in the field. . . .

Upon theoretical grounds various objections to the method have been raised, among which the following are perhaps the most important:

(1) The heavy minerals of a granite are dependent not only on the original composition of the magma itself, but also on the rocks into which it is intruded.

(2) The habits and characters of minerals such as zircon, etc., are known to be dependent on the physical and chemical environment at the time of crystallization. Big differences in habit might therefore be expected between a zircon which crystallized near the roof and another in much greater depth.

(3) Why bother with the heavy and accessory minerals at all: are not the characters of the essential minerals more important? . . .

The questions raised are answered in the following paragraphs. . . .

(1) . . . If intrusion is accomplished entirely by stopping and assimilation then the heavy mineral suite must depend as much on the nature of the country rocks as on the original composition of the magma. . . . That assimilation of country rocks has taken place is acknowledged but this appears to be merely that which might be expected by reason of the excess of heat possessed by the magma after it had come into position. . . . Therefore, the heavy minerals of the normal uncontaminated granite give a very fair representation of the content of minor constituents in the original magma irrespective of the nature of the country rock. . . . Numerous specially selected specimens have been examined to test the effects of contamination and these have been found to be as follows:

(a) The zircons of the assimilated rock in some cases appear to survive as xenocrysts.

(b) Where granite is intrusive into gabbro it may contain hornblende. . . .

(c) Assimilation of argillaceous sediments increases the production of biotite and sphene in most cases . . . . Andalusite appears to demand special conditions for its formation. . . .

(2) Dr. A. Brammall has informed the writer that in the case of the Dartmoor granite there is some slight difference in habit between the zircons of the highest and lowest types of granite exposed. It is already quite clear, however, that this is not a serious factor; nevertheless it should not be entirely overlooked.

(3) The importance of the essential minerals is in no way belittled. The heavy minerals, however, reflect the presence of the minor constituents, which, for correlation purposes, are quite as important as the major constituents. Moreover, the heavy minerals serve as an important index to the early cooling history. . . .

Method of Procedure

We adopted the method of Groves to free the accessory minerals, but owing to finer grain of our rocks, used smaller screens. The best material was that which passed a 100 mesh and was retained by a 200 mesh screen. The only heavy liquid used in our work was bromoform, sp. gr. 2.84. The biotite-rich residues were baueritized for ease of study.

The residues were passed under a horse-shoe magnet. The only minerals removed in this way were magnetite and pyrrhotite. Following the suggestion of Rastall and Wilcockson,[4] the magnetic separate of each specimen was treated with a few drops of water in a watch glass for several hours. Pyrrhotite is completely decomposed by this treatment while magnetite is unaltered and the two minerals are by this method readily discriminated. The non-magnetic residue was examined under a binocular to distinguish ilmenite and pyrite. The non-opaque minerals were examined by the usual immersion methods.

Determination of the Index Figure

Groves terms the amount of heavy mineral in a sample expressed as weight per cent of the total sample the "*index figure.*" In this paper the term, although subject to objection, is retained.

The index figure was determined by weighing the light fraction and the heavy fraction of a sample and calculating the weight per cent of the heavy fraction. Several of the sized samples were weighed before separation and the results compared with the sums of the weights of the heavy and the light fractions. The loss was found to be negligible, less than 2 per cent.

[4] Rastall, R. H., and Wilcockson, W. H., The accessory minerals of the granitic rocks of the English Lake District: *Quart. Jour. Geol. Soc. London*, vol. **71,** p. 617, 1915.

A consideration of the methods employed shows that the recorded index figure commonly differs considerably from the true index figure which would be almost impossible to determine with great accuracy. Despite care in crushing we never succeeded in effecting clean separations of the entire rocks into individual grains.

In most separations there is an intermediate zone in the funnel between the heavy and light fractions in which are suspended particles of nearly the same density as the separating medium and of particles made up of two or more minerals whose average density is about the same as the medium. It is often a question just where to draw the dividing line between heavy and light fractions.

These difficulties depend in large part on the grain size of the rock and the relative grain sizes of the heavy and light minerals. For instance, the feldspars of one of the border facies examined contain myriads of minute sillimanite fibers which could not be freed except by crushing to a degree that would entail great difficulties in making gravity separations.

In brief: The finer the sample the more difficult the gravity separation. The finer the sample the more complete division into particles consisting of a single mineral. The finer the sample, after a certain point, the greater breakage of the small crystals used in crystallographic study.

Chemical analyses were available for three of the specimens, 188, 205, and 15. The modal mineral compositions were caluculated for these specimens from their analyses on the basis of the microscopic study of the rocks, and their theoretical index figures were in this way, found to be 36, 24, and 8, respectively. The corresponding indices as measured were 32, 8, and 1. These figures clearly show that the index figures obtained in our work are very crude and of little value in classifying the rocks.

Examination of the Residues

At least half a dozen mounts were made from each sample and in many instances several times that number. Figure 2 shows how the results were tabulated so as to indicate the presence or absence of a particular mineral in a sample, the relative amount of a mineral in the heavy residue, and the index figure. The spaces indicating mineral frequencies are to be read in fifths, corresponding to the following order of abundance: very rare, rare, common, very common, abundant.

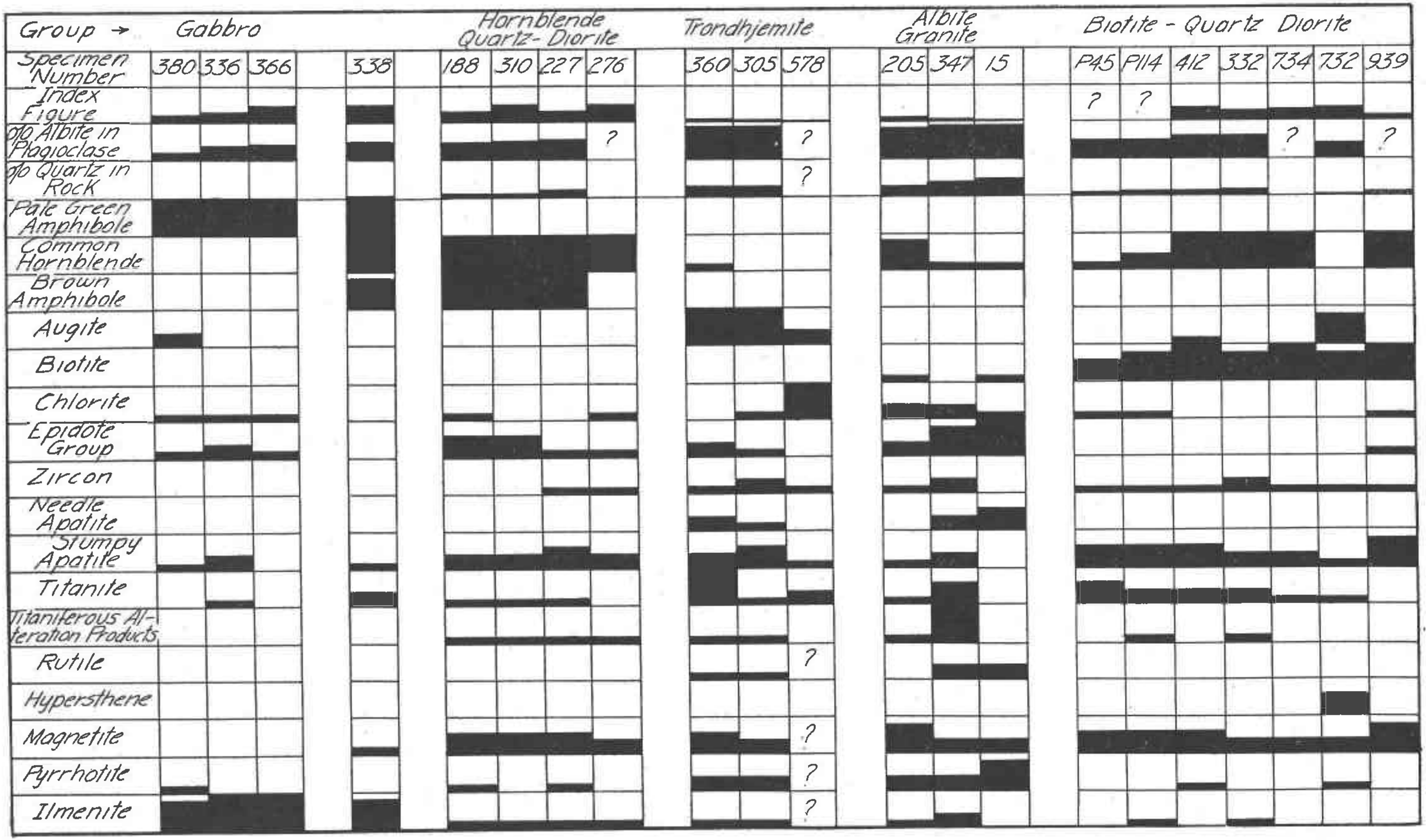

FIG. 2. Mineral frequencies in heavy residues of rock suites studied. Data for columns shown under P45 and P114 and all feldspar determinations and quartz percentages based on thin section studies.

No attempt was made to identify and count all the grains in any particular mount or even field; the figures representing relative quantities are estimates only.

More important than the above criteria for grouping rocks together are the varietal characters[5] of some of the heavy accessories.

The dimensions of typical minerals were taken. The proportions, such as the ratio of length to breadth, appear to be more important, however. In many of the crops of heavy minerals such measurements can be made on the smaller accessories only, as the dimensions of the larger ones have been destroyed during crushing.

The color and the presence or absence of inclusions was noted. Where present the identity, number, arrangement, and other peculiarities of the inclusions seem to be characteristic of the individual rock bodies.

The bounding surfaces of a mineral are among the most important features. A mineral may be bounded by fracture surfaces, cleavage planes, crystal faces, corrosion surfaces, or any combination of these. If bounded by crystal faces, the typical habits of crystals of the mineral in a sample were observed. Corrosion obscures the habits of some minerals, sometimes obliterating small faces, but the degree of corrosion seems of itself to be characteristic.

Biotite-quartz Diorite

The residues of several samples (numbers 332, 412, 734, and 939) of the biotite-bearing quartz diorite were studied. These were from widely separated localities as shown in figure 1. In addition the residues of a rock believed to present a finer grained border facies of the quartz diorite, number 732, and thin sections of all these together with two other specimens were studied. No examination was made of the residues of any of the numerous darker segregations in the quartz diorite.

Lindgren[6] gives an analysis made by Dr. W. F. Hillebrand of a "granodiorite" from the northern base of Bald Mountain (Sumpter quadrangle). Study of thin sections of the rock from which the

[5] The use of the term "varietal characters" is continued in this paper following Groves' usage. It is not used in the sense alone of the characters defining a particular variety of a mineral group such as the amphiboles, but includes all the characters that are observed that may help to distinguish one mineral from a corresponding mineral from a different sample.

[6] Lindgren, Waldemar; The gold belt of the Blue Mountains of Oregon: *U. S. Geol. Survey*, Twenty-second Ann. Rept., pt. **2**, p. 587, 1900–1901.

analyzed specimen was taken shows that it is undoubtedly similar to the masses from which the four samples we examined were collected. The theoretical index figure of the rock as calculated from the norm given in Washington's Tables, page 257, is 7.00. The index figures of the rocks crushed varied from 11 to 31, the border facies, No. 732, reaching 34.

The following paragraphs list the minerals seen in the residues and describe their varietal characters.

Hypersthene. Hypersthene, pleochroic in light green and light red, was found only in sample 732, in association with augite.

Titanite. Titanite occurs in small amounts in all specimens except 939. It was seen only as fracture fragments.

Magnetite. Magnetite occurs more or less abundantly in all the samples. It was most often seen as irregular black splotches from a few hundredths to a few tenths of a mm. across. In most samples a few grains were seen showing crystal outlines. This was particularly true of sample 939.

Sillimanite. The determination of sillimanite was doubtful. It was seen only in number 732, a specimen selected as representing a contact facies and which gives evidence of endomorphism in its contained hypersthene. It occurs as very fine needles impregnating feldspar crystals. The needles were all too fine to permit accurate determination of the optical properties.

Zircon. Zircon has been detected in all the samples. It commonly, but not exclusively, occurs in the biotite, where it is surrounded by moderately intense pleochroic halos. The lengths of the crystals usually fall within the limits. .03 mm. and .15 mm. while the thicknesses lie typically somewhere between .01 mm. and .06 mm.

The zircons are always euhedral and doubly terminated except when broken. No sign of corrosion was seen except in specimen 332 where one zircon is slightly corroded.

Plate I shows several typical crystals. The first and the second order prisms or the ditetragonal prism were present on all the crystals examined. The corresponding pyramid faces were also developed and in many crystals a myriad of faces may be made out, notably on some of the crystals of specimen 939. All of the crystals seen were clear and colorless. A few rounded indeterminable inclusions, probably gas or liquid filled cavities, were noticed in a few crystals.

Apatite. Apatite, like zircon, was definitely established in all samples.

Two varieties of apatite crystals have been distinguished, a long slender variety, and a much stouter variety.

The slender apatites range in length from .05 mm. to .03 mm., and in thickness from .015 mm. to .008 mm. The apatites of the stout variety are of much greater average size ranging in length between .20 mm. and .10 mm. and in width between .18 mm. and .08 mm.

Typical apatites of the stout variety have been represented in Plate I. The crystals are characteristically developed with sharp edges. Exceptional ones are slightly corroded. The crystals are as a rule simple, consisting of combinations of the prism, pyramid, and base. In many crystals the base is not conspicuously developed

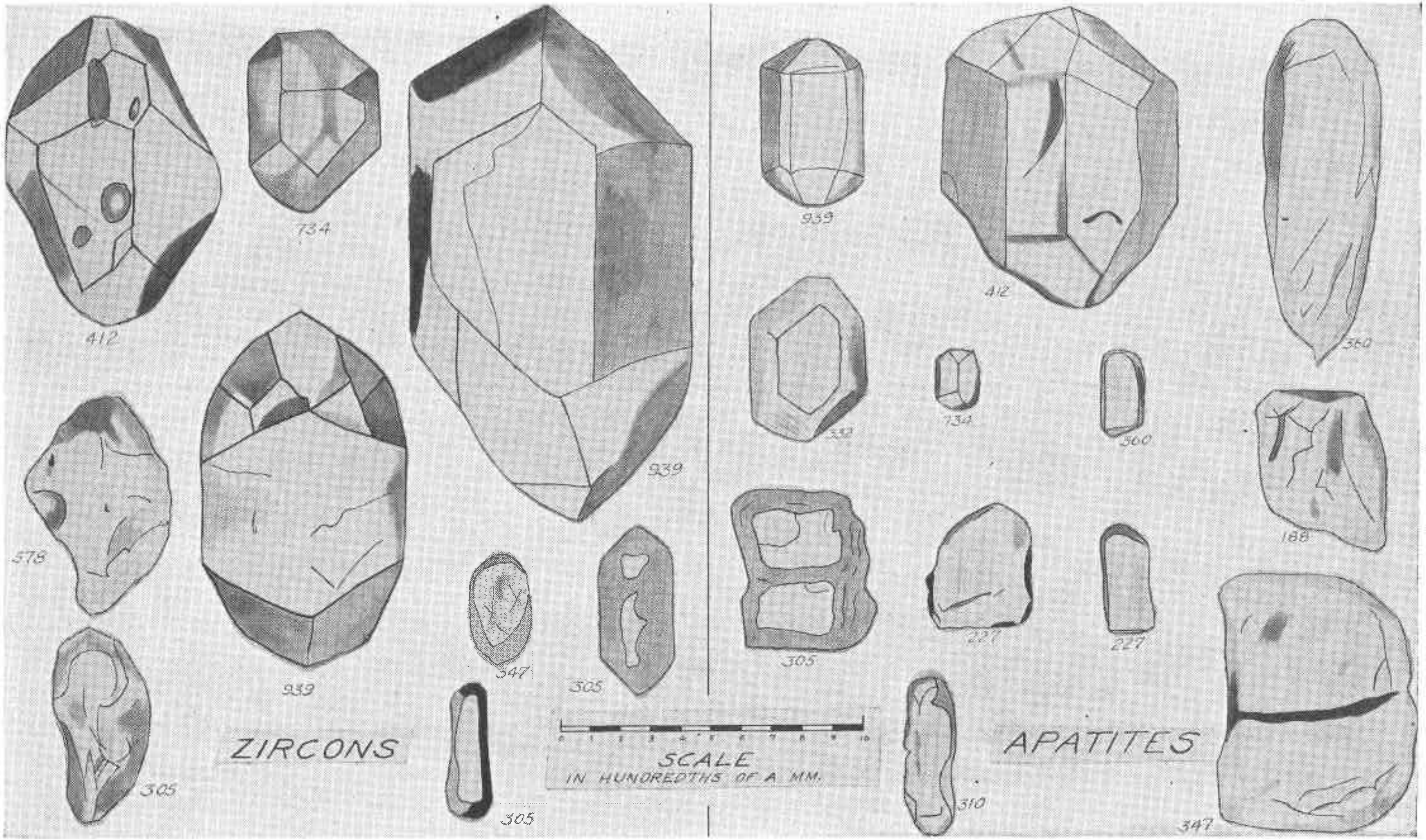

Plate I. Zircons and apatites. Reference to figure 2 will show in what group various individuals belong.

probably because of breakage in crushing, but at least as many are doubly terminated.

The crystals are clear and colorless with few exceptions. Small inclusions, which appear reddish under high powers and are probably gas cavities, are nearly always present.

The foregoing features conform to the hypothesis, based upon field studies and examination of thin sections, that all the specimens examined in this set are closely related and probably represent intrusive masses which may be directly correlated and which may be continuous in depth.

The megascopically observable heavy minerals appear to be identical in all the specimens.

Sillimanite and hypersthene are present in the border sample only and are not considered as furnishing criteria of correlation. Neither is augite, which, though vestigial, altering to hornblende in No. 412, is an essential mineral only in the same border specimen.

Small significance is attached to the titanite, which, although seen in all the samples, is present in other plutonic rocks of eastern Oregon in apparently identical grains.

Magnetite is common in all the plutonic rocks of eastern Oregon and it therefore furnishes no criteria. This suite is notably lower in pyrrhotite and ilmenite than any of the other suites collected.

Zircon and apatite are the two heavy minerals whose presence, relative amounts, and varietal characters are considered the most characteristic. Zircon is always subordinate to apatite.

The Gabbro, Hornblende-quartz Diorite, Albite Granite Series

Inasmuch as one of the objects of this paper is to test the postulated consanguineous nature of the great series of intrusions occurring in eastern Oregon and ranging from gabbro to quartz diorite and trondhjemite, and from quartz diorite to albite granite as proposed by one of the authors,[7] the residues of fourteen members of the series have been examined. Figure 1 shows the sources of the samples. Thin sections of most of the specimens were available as were three chemical analyses.

Study of thin sections and of the residues resulted in the collection of the samples into four groups: the gabbros, the horn-

[7] Gilluly, James, Origin of the albite granite near Sparta, Oregon: *U. S. Geol. Survey Prof. Paper* 175-C, (in preparation).

blende-quartz diorites, the trondhjemites, and the albite granites.

GABBRO. Four specimens were selected as representing the gabbro, numbers 338, 366, 336, 380. The textures are widely divergent. Number 336 is exceedingly coarse grained with hornblende crystals up to 1.5 cm. in length. The feldspar crystals are also large, up to .5 cm. across. Number 380 is a dark colored specimen. Its texture is also coarse with hornblende and feldspar crystals having dimensions of several millimeters. Number 338 is medium grained while 366 is fine grained and bounded by chlorite-covered joint planes. Thin section studies show that specimen 338 has a calcic andesine and a little quartz, and probably should be classed with the hornblende-quartz diorites. As will be noted in the table, its heavy mineral assemblage is intermediate between the two groups. It will, however, be discussed with the gabbro group.

The index figures as determined range from 23 to 53. Two determinations were made on each sample but on material crushed to different grain size. Estimates of the volume percentages of the various minerals in specimens 338, and 336 were made from thin sections. A recalculation of the results to weight percents gives theoretical index figures of 57 and 41 respectively, contrasting with the weighed figures of 53. and 28. Varietal characters of the minerals are as follows:

Ilmenite. The relative proportions of ilmenite in the residues differ only slightly. It occurs as irregular or rounded opaque blebs or as fragments having sharp edges some of which appear to be crystal boundaries. In size they range from very minute to .1 mm. across.

Magnetite. Magnetite is present in small amounts in No. 338 which thereby shows similarity to the hornblende-quartz diorites.

Among the alteration minerals, chlorite, zoisite and epidote occur. They are not considered diagnostic.

The heavy mineral residues of the four specimens have the following characters in common: (1) The most conspicuous mineral in the residues is a light green amphibole not here described, seen in the residues of no other rocks of the region. (2) Zircon was not seen in any of the residues. (3) The dominant opaque mineral they contain is ilmenite. (4) They contain little apatite and such as they do have is badly corroded.

HORNBLENDE-QUARTZ DIORITE. The residues of four specimens of hornblende-quartz diorite were studied, numbers 310, 276, 188, and 227. Specimen 338, described with the gabbros, also has some characters in common with these.

Number 310 is a greenish gray, medium grained, equigranular rock, in which hornblende and plagioclase are visible to the unaided eye. The specimen is veined with calcite.

Number 276 is a dark colored, gneissic rock. The ground mass is fine grained but phenocrysts of hornblende and plagioclase are numerous.

Specimen No. 188 is grayish, coarse grained, and exhibits macroscopically hornblende, feldspar, and quartz.

Number 227 is similar to 188 but is darker, more altered, and does not show as much quartz.

The determined index figures of the four specimens is as follows: number 310, 51; number 276, 51; number 188, 32; and number 277, 31.

Thin section estimates of volume per cents of the various minerals recalculated to weight per cents gives theoretical index figures of 57 for number 310 and 36 for number 188.

The heavy minerals found and their varietal characters are as follows:

Magnetite. Magnetite occurs as inclusions in hornblende and as liberated fragments and rounded irregular masses usually of small dimensions.

Apatite. Apatite is rare in all specimens but 227 in which it is common. Plate I shows typical apatites of this group. Most of the apatites of 310 are small, slender, broken, and corroded prisms, averaging about .05 mm. long and .016 mm. in thickness. However, some larger ones .3 mm. long and .2 thick also occur.

The typical apatites of 188 are somewhat thicker. All of them are corroded but a few show indications of the terminating pyramid. They range in dimensions up to .4 mm. in length by .1 mm. in thickness. Some of the thin prisms like those in 310 were also seen in 188. Most of the crystals show very few inclusions but some are dark in patches and cloudy throughout.

In addition to the types seen in 310 and 188 there occur in specimen 227 small apatite crystals (about .04 mm. by .02 mm.) having a fairly sharp crystal outline.

Zircon. Zircon is very rare in 227 and 276. The few grains seen were small and corroded and showed no crystal terminations. None were found in the other specimens.

Neglecting the nearly ubiquitous and presumably insignificant epidote, chlorite, and leucoxene, the hornblende-quartz diorites are characterized by the presence of apatite, magnetite, and ilmenite in all and of small amounts of zircon and pyrrhotite in some specimens.

Contrasted with the gabbro suite, these rocks show relatively more apatite and much magnetite; contrasted with the biotite-quartz diorite, they show no biotite, relatively less apatite, which is, however, in larger crystals and much more corroded, less zircon which is also more corroded, and more ilmenite.

TRONDHJEMITE. Three specimens, Nos. 360, 305, and 578 were, because of their dominant sodic oligoclase feldspars, classed as trondhjemites (oligoclase-quartz diorite). From field studies they were regarded as belonging to the hornblende-quartz diorite suite but are distinguished from these rocks in several respects.

All are very light colored medium grained rocks, highly quartzose, with macroscopic plagioclase and few mafic minerals. Their index figures were all determined as less than 5.

Varietal characters of the accessory minerals are as follows:

Zircon. All the specimens carry zircon, ranging between .04 mm. and .10 mm. in length and .015 and .03 mm. in thickness. They are barrel-shaped, free from inclusions and notably corroded.

Apatite. Two varieties of apatite are present, one needle-like, the other stumpy. The needle-like variety ranges between .04 and .20 mm. in length and from .003 to .006 mm. in thickness. The stumpy apatite is about .30 mm. long and .15 mm. thick. Both varieties are notably corroded.

Titanite, although especially prominent in specimen 360 is poorly formed, and shows corroded outlines. None of the entire suite of specimens examined shows titanite whose characters were recognized as distinctive, however.

Rutile. This suite of specimens is the first included in our study in which rutile is present. It is in notable association with quartz, in which it occurs as very elongate, fine needles.

Magnetite and pyrrhotite are about equally conspicuous in the two specimens examined. This marks a notable relative increase in the pyrrhotite over its proportion in the quartz diorites. Ilmenite is present, but not abundant, in all the specimens.

The heavy mineral suites of the trondhjemite specimens are distinguished by the presence of augite (which is noteworthy in rock so silicic), two varieties of apatite, rutile, zircon, magnetite, pyrrhotite, and ilmenite, as well as the almost ubiquitous chlorite, epidote, titanite, and leucoxene. Common hornblende is a very minor constituent and biotite is lacking. The suite shows relationships with that of the albite granites, next to be described, in the presence of "needle" apatites, rutilated quartz, and considerable pyrrhotite along with magnetite. It shows relationships with the hornblende-quartz diorite suite in the common presence of corroded apatite and zircon crystals of similar proportions, except that the "needle" apatites do not occur in the diorites.

The suite is also distinguished by the relatively very low index figures, from all but the albite granites.

ALBITE GRANITE. The specimens representing the albite granite group are all light gray or slightly iron stained. They are medium grained with macroscopic quartz, plagioclase, and a little dark mineral. All have the appearance of altered rocks. The index figures of all are less than 10.

The heavy minerals found are as follows:

Magnetite. This mineral is common in all the residues of this group. It appears most frequently as irregular blebs and blotches from very small to several tenths of a mm. across. Much of the magnetite occurs as inclusions in chlorite or augite and some is even included in apatite crystals.

Ilmenite. Although more abundant in this suite than in the biotite-quartz diorites, ilmenite is not an important accessory in the albite granites.

Pyrrhotite. This suite of rocks is characterized by a very much higher proportion of pyrrhotite relative to the other opaque minerals than any of the other rocks except the trondhjemites. It is present in each of the albite granites and in No. 15 is more abundant than magnetite.

Apatite. Although apatite is present in each residue its proportions have a considerable range.

The apatite crystals are all much corroded. Usually the elongation is still parallel to the axis but seldom do any of the pyramidal terminations remain. In spite of the degree of corrosion the apatites appear to fall into two groups according to size and shape.

Epidote. Although not present in every specimen, epidote is, on the whole, far more abundant in this suite than in any other.

Zircon. Zircon is not conspicuous in this suite of rocks, although it was detected in all except No. 15. Most crystals are small, the dimensions of an average crystal being about .01 mm. by .004 mm.

The zircons are either clear and colorless or very slightly yellow. Zircon crystals are commonly included in chlorite.

Titanite. Titanite is plentiful in the residues of No. 347 but is absent from those of No. 15. It occurs in the residues in broken grains. The thin sections show the typical acute rhombic shape.

All the members of this group have determined index figures below 10.

Zircon was observed in two of the three specimens. The mineral is corroded, as in the hornblende diorites and trondhjemites. Apatites of this group, like those of the trondhjemites, fall into two groups. This suite also resembles the trondhjemites in the possession of rutilated quartz and much pyrrhotite. It carries no pyroxene, however, and does have a little biotite.

Specimen 205, although classed with the albite granites, is interpreted from other evidence[8] as a product of partial albitization

[8] Gilluly, James, The origin of the albite granite near Sparta, Oregon: *U. S. Geol. Survey Prof. Paper* 175-C, (in preparation).

of the hornblende-quartz diorite. It will be observed that the heavy mineral assemblage of this specimen shows characters intermediate between the diorite and the albite granites, perhaps resembling those of the diorites somewhat more than those of the granites. In this connection it is considered significant that the corrosion of the zircon and apatite mildly shown by the hornblende diorites is very conspicuous in this specimen and is extreme in the albite granites, a result which might be expected if the albitization hypothesis is sound.

Summary and Discussion

The heavy residues of nineteen samples of plutonic rocks from eastern Oregon were examined following in general the method used by A. W. Groves for similar work in the Channel Islands. Xenotime, monazite, brookite, and anatase, commonly occurring as accessories in other granitic rocks were searched for but not found.

The study has shown that the biotite-quartz diorites represented by specimens collected over an area about thirty miles long are characterized by accessory minerals whose similarities are as striking as those of the essential minerals. The apatites and zircons in particular have similar development in size, proportions, and degree of perfection of crystal forms. The similarities are so marked that a single mount of the residues almost suffices to place the specimen in or out of this group. Exception to this rule is found in the one contaminated rock examined. In this specimen the similarities with others of the group are very tenuous and in default of field evidence would by no means enable the rock to be placed with confidence. However, the same criticism could be made against a classification based solely on study of the essential minerals, for these, too, are aberrant in this specimen.

In the other, more basic rocks the heavy mineral suites give less ground for confident classification, although we believe it possible to determine from study of a number of slides of a residue in what group the rock should be placed. Perhaps the very fact that the distinction between the several suites is less definite is some ground for additional confidence in the field hypothesis of consanguinity of these rocks.

Nevertheless there are differences in the accessory minerals of these rocks such that the residues alone are hardly a safe basis for correlating them. For instance one of the gabbro specimens contains neither titanite nor apatite (or at least diligent search failed to reveal any), yet apatite is present in all the other rocks, and titanite was found in all but two others. To the writers, this and smaller differences of the same kind found in other rocks of the suite examined are not grounds for postulating different intensities of foliation the rocks have undergone, yet the accessories of the cataclastic diorites are not broken and it is difficult to see how crushing could eliminate them completely from any rock. More probable causes are assimilation or differences in the depth beneath the roof of the intrusive.

The fact that apatite is less abundant in the gabbros than in the diorites, a feature that the average analyses of Daly[9] shows in general, may indicate that this mineral either does not always crystallize first,[10] or that due to the usual small size of its crystals it is carried off by movements of the rest-magma with respect to the larger separated crystals of augite and plagioclase. In either case it loses much value as a diagnostic mineral in the correlation of the more basic rocks. Zircon is useless in the same rocks. Of course, Groves has never urged the application of the method to these rocks, but if the implicit postulate underlying Groves' work is sound, that is that magmas of a given age have characteristic chemical peculiarities which are necessarily reflected in the mineralogic peculiarities, such idiosyncrasies should be recognizable in the parental gabbros as well as in the granites. Indeed, as Wells[11] has pointed out, such characteristics in so far as they are original, should be less subject to masking by contamination in the gabbros than in the granites.

Wells' criticism appears to be, in the main, well-founded. In summary, he points out that, even assuming a common composition for parental magma of a given age, many factors affect the total composition of satellitic magma bodies. Among these are contamination, depth of cover and consequent effects upon volatile content, and structural history involving such matters as sinking

[9] Daly, R. A., Igneous rocks and their origin: pp. 19–36, *New York*, **1914.**

[10] Apatite is clearly enriched in the late magmatic or hydrothermal stage in many rocks in the Ardnamurchan volcanic center. See Thomas, H. H., in *Geol. Survey Scotland Ardnamurchan Memoir*, pp. 147, 227, 306 and many others. See also Gillson, J. L., Contact metamorphism of the rocks in the Pend Oreille district, northern Idaho: *U. S. Geol. Survey Prof. Paper* **158-F,** pp. 118–119, 1929.

[11] Wells, A. K., The heavy mineral correlation of intrusive igneous rocks: *Geol. Mag.*, vol. **68,** pp. 255–262, 1931.

of minerals under gravity and filter pressing. Consequent upon such factors it is a priori unlikely that all granites of a given age, even in the same orogenic zone, would yield identical heavy mineral suites. Accordingly, most of the accessories are more apt to reflect differences in intrusive history than in original magmatic composition. On this basis he excludes such minerals as tourmaline, fluorite, topaz, cassiterite, and much rutile, anatase, and brookite, which are likely to be variable due to volatile content, and hence to vary with depth in one and the same granite mass. Cordierite, silimanite, andalusite, spinel, and garnet are excluded by Wells because they are very likely to be contamination products, while chlorite, serpentine, and epidote, reflecting hydrothermal processes, are likewise rejected as insignificant. Accordingly Wells regards only zircon, monazite, and apatite as likely to reflect original characters of the magma, and only very striking differences in these minerals are justifiably used as a basis of correlation.

Wells' comments seem to us somewhat too pessimistic. It is no doubt true that structural influences on the mineral characters may be expected to be great. To the writers this seems a much more cogent reason for anticipating recognizable mineralogic peculiarities of age significance than the unproved assumption of original chemical peculiarities of each magmatic cycle. The structural and orogenic influences are in any given igneous cycle much more likely to be similar than they are in different cycles. In fact, if, as modern petrology has tended to accept, crystallization differentiation is the fundamental cause of rock variation, it is difficult to see how the features we loosely regard as characterizing one petrographic province as distinct from another can arise except through differing structural histories during the magmatic cycles.[12] Hence, granting Wells' contention, we still believe it theoretically possible to effect correlations even on the basis of pneumatolytic and secondary accessories, although, of course, considerable caution is required.

The similarities shown in the heavy mineral suites we have examined (aside from the biotite-quartz diorite suite already discussed) are so tenuous and largely subjective that we would decline to extend our correlations widely without other evidence;

[12] In this connection see especially Goldschmidt, V. M., Stammestypen der Eruptivgesteine: *Vidensk. Skrifter I, Mat-Naturv. Klasse*, No. **10**, 1922.

however, the method seems to furnish some worth-while clues and can be used to supplement other methods.

The common apparent corrosion of the zircon and apatite crystals of the quartz hornblende diorites and trondhjemites gives some reason to question the commonly accepted idea that these minerals, being among the earliest to crystallize, are stable throughout the later magmatic history. If they are, indeed, partly corroded and not merely imperfectly grown crystals this change may well be sufficiently variable from place to place in the same magma body to invalidate the method of correlation by degree of "corrosion." However, the specimens examined were not numerous enough to throw light on this possibility. It seems, however, worth while to suggest that these minerals may not always survive unaltered through the entire magmatic history.

The work of Rastall and Wilcockson[13] has shown that some dikes in undoubted connection with the main mass of the Shap granite body have accessory minerals widely different from those of the main body. In conjunction with the differences shown by the endomorphic diorite we examined, this result is an additional reason for regarding the method cautiously. Nevertheless, we believe it worthy of further trial, even though not yet convinced that the possibilities of the method are very great.

[13] Rastall, R. H., and Wilcockson, W. H., *op. cit.*, p. 616.