THE WALLOWA BATHOLITH.

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ABSTRACT. The Wallowa batholith is a relatively simple intrusive, consisting chiefly of uniform biotite-hornblende quartz-diorite. Its contacts are vertical or outwardly flaring, generally concordant but in places discordant, for the most part sharp but locally gradational. Planar foliation, limited to the border zone, parallels the main trends of the contact. Linear foliation is conspicuous at only one locality. Dikes and xenoliths are abundant locally near the contact, scarce elsewhere.

The chief intruded rocks are hornfels, greenstone, quartzite, and marble. Contact metamorphism is superposed on dynamic metamorphism, the intensity of both increasing toward intrusive contacts. Well foliated schists and gneisses appear in only one place. Additive metamorphism is locally prominent, especially at marble contacts. Along much of the contact medium-grade metamorphic rocks are sharply separated from quartz-diorite of normal texture. Locally alteration is more intense and the various kinds of metamorphic rock appear to grade into quartz-diorite.

Although the batholith is a simple one, its internal structures, contact structures, contact metamorphic effects, dikes, and xenoliths are conspicuously variable from place to place. These different features show little correlation among themselves, and their extreme variability makes difficult a comparison of this batholith with others.

Although parts of the contact show good evidence for the formation of quartz-diorite by the making over of metamorphic rocks in place, some movement of the batholith as a whole seems necessary to explain its simple structural pattern, its prevalingly sharp contacts, and its petrographic uniformity.

INTRODUCTION.

In the highest and most rugged part of the Wallowa Mountains of northeastern Oregon (Fig. 1) is an island of old intrusive and metamorphic rocks nearly surrounded by Columbia River basalt. High altitude, considerable relief, and deep erosion by Pleistocene glaciers have combined to give excellent exposures of the batholith that occupies the central part of the “island”. Not only the interior of the intrusive but long stretches of its contacts are visible in three dimensions. Hence the region is admirably suited for a study of batholithic structures and contact relations.

This report is primarily a detailed description of all easily mappable features of the Wallowa batholith—variations in composition, internal structures, contact structures, contact metamorphic effects, associated dikes, and mineral deposits. Attention is concentrated on the intrusive as a geologic unit,
to be examined in all parts as completely as exposures permit. Such a compilation of data has three chief purposes: (1) to show the amount of variability to be expected in a relatively simple batholith, (2) to establish a valid means of comparing and correlating the batholith with other intrusives, and (3) to furnish evidence regarding hypotheses of emplacement of the batholith. A similar study of batholiths in north central Washington was undertaken in a previous paper.\textsuperscript{1} The Wallowa batholith, much better suited for this kind of investigation because of its better exposures and simpler structure, has shown that some conclusions from the earlier paper need modification.

Field work for this report occupied ten weeks in the summer of 1941. Subsequent laboratory work consisted chiefly in the examination of ninety-odd thin sections.

A general description of the geology and geography of the

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region, together with an excellent geologic map and a complete bibliography of earlier publications, has been prepared recently by Smith and Allen.² Formation boundaries on Fig. 2 have been copied from Smith and Allen’s map, with only a few minor

changes. The detailed geology of a small district near Cornucopia has been discussed in several papers by Goodspeed.3

GENERAL GEOLOGY.

The triangular area of granitic rock shown on Fig. 2 includes most of the exposed part of the batholith. Westward for a few miles from the map area granitic rock is visible in valley bottoms, the basalt cover dropping lower and lower until it finally conceals the older rocks altogether. Since the western area is difficult of access and since there seemed little chance of finding anything but uniform quartz diorite, the batholith was not followed beyond the limits of Fig. 2. Rocks probably related to the main intrusive form two large outliers east of Lostine River ("Lostine outlier") and west of Cornucopia ("Cornucopia outlier"), and a few small outliers on the ridge southwest of Wallowa Lake.

The intruded rocks include a series of old lavas and pyroclastics, which Smith and Allen correlate with the Clover Creek greenstone of Permian age, and a sequence of metasedimentary rocks which contain rare Upper Triassic marine fossils. Smith and Allen distinguish three formations in the Triassic rocks, the middle one largely metalimestone and the other two chiefly fine clastic material. The stratigraphy is not altogether clear, since fossils are rare, the limestone beds are not persistent, and the clastic material shows rapid changes of facies. A few minor changes in the boundaries of the three formations as mapped by Smith and Allen are suggested on Fig. 2—notably the inclusion of some clastic material in the Martin Bridge formation and a lowering of the Triassic-Permian boundary on the ridge west of Wallowa Lake. These changes were suggested by detailed mapping on airplane photographs, which were not available when Smith and Allen’s report was prepared.

For lack of data to the contrary, it seems reasonable to assign the deformation and metamorphism of the older rocks

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(b) ———: 1937a, Development of plagioclase porphyroblasts. American Mineralogist, Vol. 22, pp. 1133-1138.
(c) ———: 1937b, Hornfels-granodiorite transitional facies at Cornucopia, Oregon. Proceedings Geological Society of America, pp. 74-75.
and intrusion of the batholith to the Nevadan revolution in late Jurassic or Cretaceous time.

**PETROGRAPHY.**

**Intrusive rocks.** The most striking single characteristic of the rocks in the Wallowa batholith is their uniformity. Except for the eastern part of the Cornucopia outlier, there are no notable differences in color, composition, texture, or grain size from one end of the mass to the other. Even near contacts the rock commonly differs little from the normal variety, although patches of aplitic or unusually mafic material appear locally.

The average rock is biotite-hornblende quartz-diorite, with about 55 per cent plagioclase, 25 per cent quartz, less than five per cent potash feldspar, ten per cent biotite, and five per cent hornblende. Potash feldspar varies enough from specimen to specimen so that some of the rock can more properly be called granodiorite. Percentages of the mafic minerals have a considerable range, hornblende sometimes exceeding biotite in quantity. Quartz is seldom less than 20 per cent or more than 30 per cent of the rock.

Texturally and mineralogically the rock is so common a type that it needs only brief description. Megascopically it is light gray, uniform-grained, with average size of the more conspicuous grains ranging from 3 to 6 mm. Microscopically it shows normal granitic texture, with only occasional signs of minor cataclasis and deuteric alteration. Plagioclase is normally zoned over a range of ten to fifteen per cent, the calcic cores in different specimens varying from An₃₄ to An₄₄. Usually a few crystals in a thin section show oscillatory zoning also, sometimes conspicuously. In a few slides a little of the plagioclase is surrounded and invaded by late albite. Potash feldspar usually shows microcline twinning in part of a slide. Myrmekite is often present at boundaries between plagioclase and potash feldspar. Biotite and hornblende appear in undeformed subhedral and anhedral crystals, often with a little chlorite; in foliated specimens the mafic minerals show rude orientation. Epidote (or clinozoisite) is usually present as separate grains, sometimes also scattered through plagioclase crystals. Accessories are the usual magnetite, apatite, sphene, and zircon.

To provide a further test of the apparent uniformity of rocks in different parts of the batholith, the heavy minerals in samples from several specimens were separated with acetylene
tetramethyl. This made possible a more reliable estimate of relative amounts of accessory minerals than can be made from thin sections alone. No accessories were found in any specimen except magnetite, apatite, sphene, zircon, and epidote; of these magnetite and apatite are usually relatively abundant while zircon and epidote are relatively scarce. Sphene is the most abundant accessory in some specimens, practically absent in others. Except for the variation in sphene there are no notable differences in the accessory minerals, even in specimens of unusual texture and composition from near contacts.

The eastern part of the Cornucopia outlier differs somewhat from the rest of the batholith. Here the rock is chiefly biotite quartz-diorite, with about 60 per cent plagioclase, 35 per cent quartz, five per cent feldspar, variable but small amounts of orthoclase. A little muscovite is present in some specimens. Hornblende and sphene are practically absent except near contacts. Plagioclase shows conspicuous zoning, both normal and oscillatory; composition of the calcic cores ranges from An$_{26}$ to An$_{34}$.

Variants of the quartz-diorite found along contacts include abnormally mafic and felsic types, as well as types of normal composition but relatively fine grain. Mafic variants differ from the average rock in greater amounts of hornblende or biotite or both, smaller amounts of quartz and orthoclase, and often a more calcic plagioclase. The grain size is usually normal but sometimes fairly fine. Felsic variants include fine-grained aplite rocks and alaskites with normal granitic texture, usually with abundant quartz and a relatively sodic plagioclase. Some of the felsic rocks have peculiar fine intergrowth textures and an abundance of chlorite and sericite, suggesting deuteritic alteration. Prominent areas of mafic and felsic rocks are shown in the right-hand map of Fig. 3.

Dikes associated with the batholith were not given detailed petrographic study. Aschistic dikes include dikes of normal granitic or microgranitic texture, quartz-diorite and granodiorite porphyries, and occasional larger sheets of unusual texture within the batholith. The aplites are the usual sugary quartz-feldspar rocks. Pegmatites include normal coarse quartz-feldspar rocks, others consisting chiefly of microcline and micropegmatite, and a third type characterized by large biotite crystals in thin laminae and elongated laths. The relatively scarce dikes more mafic than the normal quartz-diorite
were grouped together as lamprophyres, although they include a considerable variety of textures and compositions; the commonest ones are hornblende-plagioclase and biotite-plagioclase rocks. Places where diachistic dikes are relatively abundant are indicated by letters on the right-hand map of Fig. 3.

Metamorphic rocks. Among the metamorphic derivatives of clastic sediments, a common type is a fine grained biotite-quartz-feldspar hornfels with textures ranging locally to coarse, well-foliated mica schist. Feldspar is usually abundant, and plagioclase (most often oligoclase) greatly exceeds orthoclase. Muscovite is present only rarely. Sphene, magnetite, clinzoisite, and blue tourmaline often appear in minor amounts. Even in well-foliated specimens many of the mica flakes show random orientation. Where bedding is visible it parallels the foliation.

Much of the biotite hornfels contains a little amphibole, pleochroic from colorless to pale brown. With increase in this mineral, the hornfelses grade into a peculiar type of fine amphibolite, composed chiefly of andesine or oligoclase and nearly colorless amphibole, with or without biotite. In hand specimen the amphibolites are purplish-gray to purplish-brown rocks, very similar to the hornfelses. The great abundance of amphibole rocks in the metasedimentary sequence suggests derivation from tuffaceous shales.

Coarser, quartz-rich rocks interbedded with the hornfels are probably derivatives of original sandy layers. Some of these are typical quartzites, but most have considerable amounts of feldspar or mica.

The Paleozoic greenstones are chiefly fine, unfoliated oligoclase amphibolites. Some layers have large plagioclase phenocrysts, often in aggregates of several crystals. Most of these rocks are probably derivatives of intermediate or mafic lava flows, although some coarser ones are doubtless old dikes and sills. Interbedded with the lavas are volcanic breccias, graywackes, and coarse conglomerates containing abundant material not of volcanic origin.

The calcareous rocks range in texture from fine, almost unaltered limestone to coarse marble with crystals several centimeters in diameter. In composition the least-altered rocks show all gradations from pure calcite limestone to limy hornfels. Where metamorphism is more intense the impure varieties have
been converted into garnet-diopside and diopside-plagioclase rocks. Near intrusive contacts additive metamorphism has produced calcium-silicate rocks in great variety, with such typical contact-metamorphic minerals as deep brown garnet, idocrase, epidote, diopside, wollastonite, plagioclase, and tremolite. Some of the rocks rich in tremolite and diopside probably contained a good deal of magnesia originally, but no dolomite marbles were found.

The high-grade metamorphic rocks found in small quantity near contacts and as xenoliths will be described later.

STRUCTURE.

*Structures in the intrusive.* Mappable foliation, only locally conspicuous, is limited to the borders of the batholith. The left-hand drawing in Fig. 3 is a map of the planar structures, the weight and spacing of the lines suggesting roughly the prominence of these structures in different parts of the intrusive. Linear structure is well developed only at one locality, the contact on Hummingbird Mountain just southeast of upper Eagle Creek. This structure, not shown on the map, lies in the plane of foliation and trends N60°W—roughly perpendicular to the contact and to the strike of the planar structure.

Both planar and linear structures are defined principally by orientation of mafic minerals. Schlieren sometimes give the orientation and xenoliths locally show rough alignment. Banding of light and dark material is seldom evident. Dragging out of crushed material on minor shear surfaces occasionally gives a suggestion of linear structure at contacts other than that on Hummingbird Mountain, but shear surfaces are so uncommon that these readings have little significance.

As Fig. 3 shows, the planar structures in general parallel major trends of the intrusive contacts but often cut across minor irregularities. A rough arch is outlined by the planar structures in the eastern projection of the batholith. The Cornucopia outlier has faint gneissic structures in its western part, but almost none in the biotite quartz-diorite to the east. Very little structure is visible in the Lostine outlier, even at its contacts.

A curious superposition of two planar structures appears near the northernmost tip of the intrusive and again near the large xenolith eight miles to the south. Here successive outcrops show first one direction more prominent, then the other;
probably at both localities the northeast-southwest structure is the younger.

A map on the scale of Fig. 3 perhaps gives a false impression of extreme simplicity and uniformity in the structural pattern. At several localities the indicated trend is an average of highly variable readings. For several hundred feet from a contact, especially where the general trend is turning and where xenoliths are abundant, the structure is often so contorted as to make any average unreliable. Also at the inner border of the foliated zone, where structures are faint and readings difficult, trends are frequently too erratic for mapping.

Although the interior of the batholith for the most part completely lacks directional structures, sporadic small areas show complex swirls in vaguely defined bands of light and dark material. These patches are too small to be indicated on the map.

The larger dikes associated with the batholith are most commonly parallel to contacts or to foliation or to bedding in the metamorphic rocks, but there are many exceptions. The small aplite dikes show no consistent orientation either within or outside of the intrusive.

No detailed mapping of joints in the quartz-diorite was attempted. In the foliated zones one prominent joint set usually parallels the foliation, especially where the foliation has low or moderate dips. The structural arch rudely suggested by foliation in the eastern prong of the batholith is continued across the unfoliated interior by joints of this sort. A locally prominent vertical set trending about N10°W, parallel to many dikes of Columbia River basalt, is probably a result of Cenozoic deformation rather than an original structure of the quartz-diorite.

In and near the quartz veins at Cornucopia, Goodspeed finds evidence of recurrent fracture and microbrecciation during the formation of the veins. The veins have a general strike of N40°E and an average dip of 40°W. Grooves in slickensided surfaces suggest an earlier movement in the direction of the dip, while later grooves have a rake to the south. Similar evidence of cataclastic deformation and movement on shear surfaces was found only rarely and locally in the rest of the batholith.

*Structures in the metamorphic rocks.* In general, structures

*Op. cit., reference 3 (d).*
in the intruded rocks are characterized by open folds, with complexity of folding and steepness of dips increasing toward intrusive contacts. As Smith and Allen⁵ have pointed out, the principal structure north of the batholith is a northwest-plunging syncline, while south of the batholith are a number of small folds trending northeast-southwest.

The different formations show widely varying degrees of deformation. The greenstone shows little distortion, although an accurate estimate is difficult since recognizable bedding planes are seldom visible. The major structures are outlined by the competent hornfelses, amphibolites, and quartzites of the Hurwal and Lower Sedimentary formations. The meta-limestone beds show the undecipherable contortions and the rapid thinning and thickening of highly incompetent material. Some lensing out of limestone bodies is doubtless due to original uneven deposition, but much of it is more probably a result of intense squeezing between stronger layers. The curious appearance of abundant dike material in small, rounded masses strung along bedding planes of the marble seems most reasonably explained, as Allen has suggested, by flow of the marble during or shortly after intrusion of the dikes.

The greater complexity of structure near contacts is shown by generally steeper dips, by more intricate minor crenulations in both hornfels and marble, by increased schistosity only partly obliterated by later baking, and at two localities by stretched congiomerates. Foliation and bedding in the metamorphic rocks are for the most part roughly parallel to intrusive contacts, although locally they are cut off abruptly.

No certain evidence of pre-Cenozoic faulting was found, although small faults might easily have been made unrecognizable by later recrystallization.

Contacts. The intrusive contacts are mostly concordant on a large scale, but nearly everywhere discordant in detail. Seldom does the contact follow a given bed for more than a few hundred feet without cutting across it.

Reliable readings on the attitude of the contact can only be made where vertical exposures of several hundred feet are available; otherwise minor irregularities may give a completely false impression. Figures obtained where the contact is well exposed are shown in the right-hand drawing of Fig. 3. Nearly everywhere the contact is either vertical or outwardly dipping.

Contacts along the south border are conspicuously less steep than most of the contacts on the north border.

The contact in general is sharp. In places neither quartz-diorite nor intruded rock shows any observable change up to the actual contact. More commonly, quartz veinlets and tiny apophyses from the intrusive form an injection gneiss or intrusive breccia on a minute scale within a few centimeters of the contact, although the actual line of separation can still be located within a centimeter or so. At some places, however, the contact is more indefinite, either because of a large-scale intrusive breccia or because recrystallization and addition of material have so changed the metamorphic rock that it resembles the adjacent intrusive. The best localities for observing gradational relations are (1) the ridge two miles southeast of the point where Lostine River crosses the contact, (2) on the next ridge to the east, seven miles southeast of the same point, where the foliation makes a nearly right-angled bend, (3) the small exposure of the contact beneath the basalt at the south side of the eastern prong of the batholith, and (4) on Hummingbird Mountain southeast of upper Eagle Creek.

The nature of the contact depends in part on the character of the metamorphic rock. Contacts with biotite schist or hornfels are often gradational, at least on a minute scale. Contacts with quartzite and limestone are often clean-cut. Perhaps the chief reason that contacts are prevailing sharp is that the metamorphic rock at the contact is so frequently a meralimestone or a quartz-rich clastic rock. Locally, however, even these rocks have gradational contacts.

**METAMORPHISM.**

**General features.** The mica-rich intruded rocks show the effects of dynamic metamorphism in their schistosity, and the effects of thermal metamorphism in the partial or complete destruction of schistosity by the growth of mica flakes and amphibole needles across foliation planes. Rocks without abundant mica show no more than rudimentary schistosity. The intensity of both dynamic and thermal alterations increases toward the intrusive contacts. The assemblage of coarse biotite-feldspar schists, biotite-andesine amphibolites and complex calcium-silicate rocks suggests a fairly high grade of metamorphism near the contacts. Thermal effects are later, or were continued longer, than the dynamic alteration, but probably
both belong to the same period of diastrophic and igneous activity in which the batholith was emplaced.

Even with the excellent exposures available, no contact was found where the progression from low-grade to high-grade metamorphic rocks could be traced in individual beds. Well-exposed contacts at a high angle to bedding are not common; and the distribution of rocks showing different kinds of metamorphism at such contacts seems always erratic. In part this is due to the thinness and variability in composition of individual beds; in part to discontinuities produced by small gullies and talus slides in even the best-exposed contacts; and in part to the complicating effects of additive metamorphism near the contact and of large dikes even at considerable distances.

The general increase in metamorphic intensity toward the intrusive contacts, however, is clearly evident. Biotite schists and hornfelses show proximity to contacts chiefly by an increase in grain size. Fine actinolite-plagioclase rocks at a distance from the contact are probably equivalents of the high-grade amphibolites and biotite amphibolites near the contact. The coarse clastic rocks of the Lower Sedimentary formation on the mountain just west of Wallowa Lake, several miles from the nearest contact, show no sign of alteration except a little chlorite. Limestone and limy shale at the same locality are not visibly altered and locally contain well preserved fossils. Impure limestone nearer the contact is a fine marble with scattered tremolite metacrysts; close to the intrusive pure limestones become coarse marbles and shaly limestones become diopside and garnet hornfelses.

Additive metamorphism is seldom observable more than a few feet from the intrusive. In hornfelses and amphibolites it is evident in the appearance of abundant quartz and potash feldspar and in the development of feldspar, biotite, or hornblende metacrysts. Calcareous material is particularly susceptible to additive metamorphism, changing to a rock conspicuous because of its deep-brown garnets. In addition to garnet, the usual constituents are epidote, quartz, calcite, diopside, and one or more sulfides; of more local occurrence are idocrase, wollastonite, tremolite, phlogopite, scapolite, and plagioclase, the latter ranging from albite to calcic labradorite in different specimens.

The intensity of contact metamorphism, as measured roughly by grain size, by width of the zone of conspicuous metamor-
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...phism, and by the extent of additive alteration, varies markedly along the contact. The principal localities where contact alteration is especially prominent, as shown on Fig. 3, are the south edge of the Lostine outlier, several points a few miles southwest of Wallowa Lake, and three areas along the southern contact. In general these are localities either where the contact dips outward at low angles, or where it cuts the metamorphic foliation abruptly.

The large zone of intense alteration southeast of upper Eagle Creek includes a number of rock types not found elsewhere in the area. In contrast to the prevailing slight development of schistosity, these rocks are conspicuously foliated and banded. Near the contact they are chiefly fine biotite gneiss, hornblende gneiss, and coarse quartzite; a few hundred feet from the contact they are schists with various mixtures of biotite, actinolite, and chlorite. Their composition suggests that the original rocks were the same sequence of shale, limy shale, and tuff found elsewhere but that here dynamic metamorphism was more intense than usual.

Evidences of assimilation. Despite the prevailingly sharp intrusive contacts, nearly all of the different kinds of metamorphic rock locally show evidence of being made over into igneous-appearing material and of being incorporated into the intrusive rock.

With all kinds of rock the process of assimilation is in part mechanical. Where intrusive breccias are well developed, the larger blocks are penetrated by dikes and stringers of granitic or pegmatitic material, so that corners and edges appear to be undergoing intimate fragmentation. Penetration of igneous material along bedding planes of a block produces thin laminae which may be curved and contorted; in places gradations can be traced between blocks having outlines still preserved and others that evidently have lost their form in vaguely defined swirls and streaks of dark material. In general, however, evidence of swirling movements near present contacts is rare, blocks most often retaining their angular outlines.

Accompanying the mechanical fragmentation are chemical and mineralogical changes which ultimately give the metamorphic rocks a composition similar to that of the intrusive. Biotite schist and hornfels first develop small bands of quartz and potash feldspar, probably in part introduced from the intrusive, perhaps to some extent formed by partial melting of
the metamorphic rock. Metacrysts of feldspar, biotite, and hornblende appear, hornblende growing at the expense of some of the biotite. The rock increases in grain size and loses all trace of schistosity, at length gaining a composition and general appearance much like that of the surrounding intrusive, except for a slightly higher percentage of mafic minerals. This complete sequence of changes was never observed at an actual contact, but at several localities is beautifully shown in xenoliths near a contact. Perhaps the best place is on the ridge two miles southeast of the point where Lostine River crosses the contact.

Contacts where quartz-rich rocks are demonstrably undergoing assimilation are much more rare. Usually a contact against quartzite is perfectly sharp, even most xenoliths retaining sharp boundaries and showing no change in texture or composition. The clearest example of extreme alteration of a quartzite is a series of xenoliths about one and one-half miles west of the point where Lostine River crosses the intrusive contact. Here successive blocks of gray quartzite show mechanical breaking up by aplite and granite dikes into smaller and smaller fragments, coupled with the growth of tiny feldspar, biotite, and hornblende crystals all through the rock, until in some spots quartzite is just recognizable as thin bands and lenses of finer material in the quartz-diorite.

Limestone contacts also are prevalingly sharp, the contact layer of garnet-diopside-epidote rock usually showing clean-cut separations from quartz-diorite on one side and marble on the other. But locally contact relations suggest assimilation in progress; the best localities are near the two small outliers about five miles west and four miles southwest of Wallowa Lake, and the contact above the headwaters of Wallowa River. At these contacts, and often near xenoliths elsewhere, garnet-diopside rock grades into plagioclase-diopside rock, often with an intervening zone rich in clinozoisite or epidote, and this in turn passes into hornblende-plagioclase rock with or without biotite. Sometimes the whole series of changes takes place on so small a scale that a single thin section will show a garnet-diopside mixture at one end and at the other a hornblende diorite with relic diopside grains surrounded by hornblende. Structural relations of the garnet rock and its hornblende-plagioclase derivative may be extremely complex, the latter penetrating and surrounding blocks of the former in
intricate patterns, sometimes minutely banded and swirled, sometimes containing patches of large hornblende crystals. Often the intrusive for a considerable distance from one of these contacts has less quartz and a higher hornblende-biotite ratio than normal.

Incorporation of the metamorphic material into the igneous rock may seemingly take place at any of the later stages of the making-over process, perhaps depending on such local factors as temperature, amount of movement, and concentration of mineralizers. At several places where the present contact is sharp and conspicuous xenoliths are scarce, careful examination of the intrusive shows distinct outlines of large angular blocks of material very slightly more mafic than the rock that separates them, suggesting that here the alteration was a static metasomatic process with the metamorphic fragments remaining distinct from the intrusive even when their compositions and textures were practically identical. At other places xenoliths show gradational boundaries against quartz-diorite, although their interiors are still considerably more mafic than the intrusive. Some even have gradational margins on one side and sharp boundaries on the other. On Hummingbird Mountain (southeast of Eagle Creek) and to a lesser extent elsewhere, the dragging out of partly made-over xenoliths into dark streaks and intricate swirls suggests incorporation of metamorphic material by movement of the intrusive rock before alteration had progressed far toward completion.

Xenoliths. Xenoliths are abundant near some parts of the contact, practically absent near other parts. Inclusions of recognizably metamorphic origin appear sporadically elsewhere in the batholith, and small, dark bodies of uncertain origin occur in minor amounts all through the mass. Areas where inclusions of any kind are particularly numerous, whether they are known to be true xenoliths or not, are indicated by X’s on Fig. 3.

The small inclusions of uncertain antecedents have a considerable variety of textures and compositions, although the greater number are mafic diorite or quartz-diorite with a slightly porphyritic (or porphyroblastic) texture. Not many have diameters greater than a few centimeters; most have irregular shapes and are unoriented, but some are elongated with the foliation. A few, especially the larger ones, are themselves vaguely foliated and banded. Boundaries of the finer grained ones are sharp, but some of the coarse ones grade into the sur-
rounding rock. The intrusive adjacent to the inclusions is sometimes abnormally felsic or mafic, but usually retains its normal composition. Since many of these inclusions resemble rocks found near contacts as alteration products of metamorphic rocks, it seems most reasonable to interpret them as true xenoliths.

In addition to these well-defined small bodies, the interior of the batholith has sporadic small areas where relatively mafic material forms larger ill-defined angular blocks, vague irregular patches, and contorted streaks and bands. The origin of this material is obscure, but it could conceivably represent one-time metamorphic rock in the final stages of assimilation.

MINERAL DEPOSITS.

Pyrite is disseminated through much of the garnet-epidote-diopside rock at intrusive contacts against marble, locally accompanied by chalcopyrite and molybdenite. Sphalerite is prominent at one locality and traces have been found elsewhere. Galena is said to be a minor constituent of several deposits. Scheelite has been reported from two places. Assays of the contact metamorphic rock are said to show small amounts of gold and silver. The contact metamorphic deposits have been extensively prospected, but none has proved commercially valuable.

Quartz veins in the intrusive near Cornucopia have produced a total of approximately $15,000,000 worth of gold, in addition to considerable copper and silver. Goodspeed lists pyrite, chalcopyrite, tetrahedrite, tellurides, and native gold as the principal metallic minerals, with smaller amounts of sphalerite and galena. Quartz and pegmatite veins elsewhere in the batholith show sufficient copper staining to encourage prospecting, but no deposits of any size have come to light.

The principal mineralized areas are indicated on Fig. 3 by the symbols of the important metallic elements found in the deposits.

CORRELATIONS.

On the two maps of Fig. 3 are shown qualitatively the more important features of the batholith and the intruded rocks—the structure pattern, the areas of abnormally felsic and mafic intrusive rock, the distribution of dikes and xenoliths, the mineral deposits, and the areas of most extensive contact metamorphism.

Fig. 3. Sketch maps of the Wallowa batholith. Left-hand map shows principal structures in intrusive and metamorphic rocks. Right-hand map shows attitudes of contact, petrographic facies, type of mineralization, intensity of metamorphism, and areas of abundant dikes and xenoliths.
Inspection of the maps shows surprisingly little correlation among these various features. Abundant xenoliths often occur together with numerous pegmatite dikes. Mineral deposits near the contact and mafic areas in the intrusive are often associated with abundant xenoliths and pegmatites. The important copper-molybdenum deposits are all found in areas of extensive contact alteration. On Hummingbird Mountain a large area of high-grade foliated metamorphic rocks is adjacent to a part of the intrusive showing conspicuous linear structure. These appear to be the only valid generalizations that can be read from the maps.

Perhaps the almost complete lack of correlation is the most significant fact revealed by the maps. Planar foliation in the border zone of the quartz-diorite is prominent in some areas, faint in others. Mafic and aplitic zones appear haphazardly along the contacts, with no apparent relation to structure. Dikes are fairly common near parts of the contact, scarce elsewhere; especially striking is the concentration of lamprophyres at the northern tip of the Lostine outlier, in contrast to the small number of these dikes elsewhere. Although it is true that the areas of extensive metamorphism are all either above gently-dipping contacts or at vertical contacts that cut across bedding planes, nevertheless metamorphism is slight at many places where these conditions are fulfilled. Mineral deposits occur at both concordant and discordant contacts, and show no evident relation to structures in the intrusive. On Hummingbird Mountain the linear structure in the intrusive and the conspicuous foliation in the metamorphic rocks contrast strongly with structures elsewhere along the contact.

DISCUSSION.

The petrographic homogeneity and the simple structure pattern of the batholith leave little doubt that it is nearly all part of a single intrusive, in the sense that all of its material was formed and emplaced at approximately the same time. The eastern part of the Cornucopia outlier differs from the rest of the intrusive in its more felsic composition, in the absence of hornblende and sphene except near contacts, in its complete lack of directional structure, and in its associated mineralization; its contact relations with the normal biotite-hornblende quartz-diorite in the western part of the outlier suggest that it is a slightly later facies of the intrusive. Rock in the Lostine
outlier resembles that of the main batholith in all respects except for its nearly complete lack of foliation.

Petrographically the intrusive is characterized by the usual presence of both hornblende and biotite, by fairly abundant quartz and low potash feldspar, by moderately zoned andesine as the usual plagioclase, and by lack of any but the common accessories. Aside from its uniformity in these petrographic features, the batholith is surprisingly variable for so simple an intrusive. Its contacts are in part sharp and in part gradational, in part concordant and in part discordant, in part accompanied by extensive thermal and additive metamorphism and in part by minor baking. At one spot on the contact well-foliated gneisses grade into quartz-diorite through a zone of injection and streaking out of xenoliths; contact rocks at other points are poorly foliated schists and hornfelses that have sharp borders or grade into the intrusive by the making over of angular xenoliths. Foliation near the border of the intrusive is mostly faint but locally prominent, and at one locality shows linear elements in addition to the prevailing platy structure. Dikes have similar compositions in different parts of the batholith, but in some places are rare and in others abundant. The number of xenoliths varies erratically. The type of mineralization associated with the intrusive is fairly uniform, but the size of the mineral deposits shows little relation to structures of the intrusive or its contacts.

Thus to characterize the batholith in simple terms for comparison with other intrusives is a difficult matter. The petrographic features, although uniform over the batholith, are not very distinctive. Other characteristics are so variable that a description would be misleading without a complete statement as to their range of variation. Complex batholiths must be expected to have even greater variability when studied as a whole, and adequate descriptions would accordingly be still more difficult. This conclusion makes perhaps too optimistic the suggestion of an earlier paper that long distance correlation of batholiths might be possible by cataloging their more prominent characteristics. At least such correlations can have value only if each mass is well exposed and is studied at all available points, so that its possible variations are adequately taken into account.

The question of the rôle of replacement and granitization
processes in the formation of large intrusive bodies has a particular interest for the Wallowa batholith, since Goodspeed\(^6\) has described in minute detail the making over of hornfels into granodiorite at Cornucopia. The perfect exposures available in the Cornucopia mines show all stages of the alteration—the development of plagioclase porphyroblasts, the growth of hornblende from biotite, the change in texture to that of a granodiorite porphyry and finally to normal granodiorite. Aplite and granodiorite dikes form by replacement of hornfels along minor shear zones, and angular granodiorite blocks develop within brecciated hornfels. Goodspeed pictures the process as a "recrystallization replacement" brought about by solutions; recurrent fracturing aids the solutions, but no large-scale movement is involved. Having demonstrated this granitization process at many places near Cornucopia, even deep within the intrusives, Goodspeed suggests that the entire batholith may have been emplaced by a similar mechanism—by slow, progressive metamorphic alteration of metamorphic material that remained essentially solid and approximately in place during the transformation.

The evidence presented in this paper corroborates Goodspeed's conclusion that granitization has taken place on a considerable scale near the present borders of the batholith. Not only hornfels, but all varieties of metamorphic rock which make direct contact with the batholith, can be shown to undergo locally an extreme alteration that gives them a texture and composition similar to the intrusive. Nevertheless, some features of the batholith seem difficult to reconcile with Goodspeed's extreme view of emplacement wholly by static metasomatism.

One difficulty is the sharpness of the intrusive contact over considerable distances. If granitization in place were the sole means of emplacement of the batholith, some evidence of assimilation might reasonably be expected at all contacts. Local sharp contacts could perhaps arise from limitation of the replacing solutions by joints and zones of shear, but jointing would be an extreme hypothesis for the juxtaposition of normal quartz-diorite and medium-grade metamorphic rocks over distances of thousands of feet. Some movement of the intrusive with respect to its present walls would seem a more reasonable assumption.

A second difficulty is the simple structural pattern of the intrusive. Static alteration of metamorphic rocks would seemingly produce structures, if any, which would mimic the pattern of structures originally present. Now admittedly foliation in the intrusive usually parallels the metamorphic foliation, even at discordant contacts, which suggests that foliation in the batholith might indeed be a relic of original metamorphic structures. Nevertheless, the pattern of foliation in the intrusive is much simpler than the pattern in adjacent metamorphic rocks, and in general it faithfully parallels the major trends of the contact. Since the pattern shows closer relation to the form of the intrusive than to metamorphic structures, it again suggests movement of the batholith as a whole as the most likely explanation.

Perhaps the most serious argument against emplacement by metasomatism without movement is the remarkable uniformity of the batholith in texture and composition. The metamorphic rocks now visible are a most heterogeneous assortment; surely some trace of this heterogeneity would be preserved even after profound alteration.

Thus it seems probable that the Wallowa batholith, whatever its origin, has behaved to some extent like an orthodox intrusive: it has moved, in the manner of a viscous fluid, sufficiently to produce sharp contacts, to give its borders a distinct foliation, and to obliterate initial heterogeneities of material.

The ultimate origin of the quartz-diorite is an elusive question to which data at present available cannot provide an answer. Perhaps the bulk of the material rose as a silicate melt from far below, as batholiths are traditionally supposed to do; no conclusive evidence can be cited against such a view. Since the borders of the intrusive show good evidence for widespread granitization, a more attractive hypothesis would be formation of the quartz-diorite by metasomatic alteration of metamorphic rock accompanied by some movement of the mass as a whole—essentially Goodspeed’s idea, modified to eliminate its chief difficulties.

With no thought of urging this conception as more than a working hypothesis, the possible stages in the development of the batholith may be outlined: (1) The metamorphic rocks in an area of extreme diastrophic disturbance are permeated by solutions and vapors, in part from deeper levels and in part from the partial melting (“differential anatexit”) of the rocks
themselves. In this manner is created a viscous body of partly fluid, partly crystalline material, which undergoes sufficient internal movement to iron out initial differences in composition. Perhaps the patches of vaguely outlined inclusions and swirled dark material occasionally found in the interior of the batholith are preserved from this stage. (2) As diastrophic movement slackens and the temperature falls, the mass becomes more viscous and movement grows sluggish. Granitization of metamorphic rock continues at a reduced rate along the borders of the mass, its extent at any point depending on the kind of metamorphic rock and the local concentration of solutions. To this stage belong the initiation of sharp contacts along parts of the border, and the production of foliation by slow movement in the predominantly crystalline outer portion of the batholith. (3) Movement ceases while the interior and parts of the border still contain interstitial fluid, and before the permeating solutions have completed their work. In this quiescent stage foliation and swirling in the interior are largely obliterated, angular xenoliths are slowly granitized with no alteration of form, marginal assimilation goes forward only at the few points where solutions are concentrated. In one locality, on Hummingbird Mountain, enough diastrophic movement persists to create strongly foliated metamorphic rocks and a banded hybrid rock at the contact. Final freezing catches these various processes at the stage shown by present exposures.

Whether or not this sequence of events has any historical reality, it is at least consistent with the salient features of the Wallowa batholith: its petrographic uniformity, its simple marginal foliation, its local gradational contacts and widespread sharp contacts, and its xenoliths that show transitions from metamorphic to igneous rock.

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