THE AMERICAN MINERALOGIST

JOURNAL OF THE MINERALOGICAL SOCIETY OF AMERICA

Vol. 44 MARCH–APRIL 1959 Nos. 3 and 4

SOME TEXTURAL FEATURES OF MAGMATIC AND METASOMATIC ROCKS*

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ABSTRACT

The textural features of magmatic rocks have been described with the emphasis placed upon their relationship to the crystallization sequence of the magma. Examples have been chosen from the basaltic and diabasic dikes in the vicinity of Cornucopia, Oregon, the shonkinite-granite porphyry sequence at Yogo Peak in the Little Belt Mountains of Central Montana, and a few other localities. The textural differences of the orthomagmatic as compared to the late magmatic or deuteric pattern of crystallization have been noted. Where it has appeared that the deuteric fraction had been involved in mass flowage the term deuteromagmatic is suggested.

For metasomatic rocks, textural features to illustrate various stages of crystal growth have been described, such as the development of porphyroblasts, glomeroblastic aggregates, and the final crystalloblastic pattern. Most of the examples are taken from occurrences near Cornucopia, Oregon, and Buffalo Hump, Idaho, with a few references to other localities.

The textural features resulting from the mobilization of metasomatized rocks, such as rheomorphic dikes and rheomorphic breccias have been briefly noted. These commonly show magmatic textures superposed on metasomatic ones. For many igneous rocks, however, later crystalloblastic textures are superposed on the earlier orthomagmatic textures. Textural features alone are not always adequate for petrogenetic interpretations but for some occurrences like granitic intrusions they may furnish clues as to whether the body has evolved from an orthomagma or from mobilized metasomatized material, namely a neomagma.

INTRODUCTION

The title of this address might suggest that textural features alone could form the basis for distinguishing a rock of magmatic descent from one of metasomatic lineage. Such an implication is not intended since many other features contribute toward adequate genetic interpretations. Chief among these is that of the geologic setting, including the more immediate field relations of the rock mass. Indeed the petrographic study of rocks in thin sections, and especially in large thin sections, may be

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* Address of the retiring President of the Mineralogical Society of America at the 39th meeting of the Society at St. Louis Missouri, November 7, 1958.

likened to a field study of a much contracted area but one which nevertheless may furnish many data of genetic importance.

Textural features of igneous or metamorphic rocks, as seen under the petrographic microscope, may be thought of as a pictorial record of the struggles of individual minerals to adapt themselves to the changes of their environment. Some textural patterns may resemble a naturalistic painting or design and these usually afford the basis for a ready explanation of origin. Other textural patterns, however, are more like modern art, and their interpretation from a genetic standpoint is influenced by the experience and imaginative ability of the viewer.

Many years ago Holmes (1921) stated: "Every texture and structure is a hallmark stamped on a rock by some process through which it has passed, and one of the most important objects of petrological study is the correlation of individual textures and structures with processes, and of the combinations of textures and structures with the succession of processes in time." More recently Barth (1952), in reference to metamorphic rocks, made this comment: "A great many textures can be interpreted in a variety of ways, depending upon the dominant belief of the observer." In a recent paper on the regional metamorphism and granitization in the Central Pyrenees, Zwart (1958) quite rightly points out that textural features are second order criteria. He states: "The occurrence of a so-called igneous texture versus a crystalloblastic texture says, of course, nothing directly about the mode of emplacement of the granite. Together with many other observations it may be important, but it will never have such a conclusive value as observations which are concerned with the emplacement itself."

Two contrasting environmental conditions must be considered; first, the growth of crystals from a liquid silicate melt or from a pasty, but mobile magma, and second, the development of minerals by metamorphic processes in a solid rock.

As a magma cools and crystallizes, the earlier minerals are formed in an environment conducive to the development of well-formed crystals, then as the initial fluidity dwindles, the later minerals are restricted by the earlier ones which are also subjected to magmatic reactions. In the final stages of consolidation minerals may form in a nearly solid medium. Many small igneous rock bodies such as diabase dikes display textural features which clearly indicate varying rates of cooling as well as the intersertal or intergranular textures which are good records of the magmatic stage of crystallization. Some of these occurrences also show textural features resulting from the crystallization of the late magmatic stage or of the deuteric fraction, and these commonly resemble the crystalloblastic textures of metasomatic rocks.

In metasomatic rocks, however, minerals are formed in an essentially solid medium by reactive penetrating solutions or emanations under conditions of rising temperature. This means that a growing crystal develops by pushing aside, surrounding, or replacing the original minerals of the metamorphic rock or by a combination of these processes. Hence, the initial crystalloblastic textures displayed by these growing crystals are quite different from those textural features resulting from the early stages of magmatic crystallization.

With continued increase in temperature, some metamorphic rocks may become mobile and their final stages of crystallization will be quite similar to that of some rocks formed from a fluid magma, so that their textural features will look like those of rocks of orthomagmatic descent. This convergence of textural features in rocks of diverse modes of origin means that it might be most difficult if not impossible to make adequate genetic interpretations based on textural features alone. Such is the case, unless the preservation of earlier formed minerals or relict textural features can furnish some clues pertinent to the genetic history of the rock. In other words, do the earlier formed minerals or relict textural features indicate crystallization from a magma or do they suggest an earlier period of metamorphism? The question as to whether or not the earlier minerals represent an earlier magmatic or metamorphic stage is further complicated by the fact that many minerals can be precipitated from a magma by a decrease in temperature or can be formed during metamorphism by increasing temperature. Mineral associations and their textural features may aid in such interpretations.

At present, textural features are largely descriptive, and genetic interpretations are much influenced by assumptions as to whether a particular rock is of magmatic or metasomatic origin. Neomagmatic rocks formed by rheomorphism have intrusive field relations and are properly classed as igneous, although their line of descent is through metasomatism rather than from an orthomagma.

In the future it is hoped that many textures of rock-forming minerals will be produced synthetically under known and controlled conditions of temperature and pressure, thus affording more accurate data for genetic interpretations.

TEXTURAL FEATURES OF THE TERTIARY BASALTIC AND DIABASIC DIKES AT CORNUCOPIA, OREGON

General field relations of the Tertiary dikes

One of the most conspicuous geologic features of the Wallowa Mountains of Northeastern Oregon are the numerous Tertiary basaltic and diabasic dikes which transect the older sedimentary, metamorphic and granitic rocks. In the vicinity of the old mining town of Cornucopia, which is in the southeastern portion of the Wallowas, the dikes stand out as dark brownish bands in vivid contrast to the light-colored granites.

In discussing the basalt dikes of the Blue Mountains of Oregon, Waldemar Lindgren wrote, "But in no place are they exposed on such a magnificent scale as in the Bonanza Basin near Cornucopia" (W. Lindgren, 1901). Not only are the dikes well exposed on the steep walls of glacial valleys and cirques, such as the Bonanza Basin, in this rugged area of nearly 5000 feet of relief, but they have been revealed in many of the underground mine workings including several long adits having a total length of over 18,000 feet. An area of about two square miles in the vicinity of Cornucopia is crossed by over forty basalt and diabase dikes with a prevailing northerly or northeasterly trend. At lower elevations most of the dikes have steep dips and transect the conjugate joints. At higher elevations many of the dikes follow these westerly or easterly dipping joints. The dikes range in width from 25 to 100 feet and usually have parallel walls, although local widening and changes in strike and dip are characteristic where they have intruded planes of weakness, such as some of the vein shear zones. The relation of the dikes to the veins were very accurately mapped by H. F. Anderson and J. P. Dunn in connection with their work for the Cornucopia Gold Mines Company and have been described by Fredrickson (1950).

It is apparent that there was more than one episode of dike injection; earlier diabasic dikes are transected by basaltic dikes which in turn are cut by later diabase dikes and then by basalt dikes. The fine-grained basaltic dikes commonly exhibit well defined columnar structure and are more resistant to weathering than the coarser grained diabasic dikes. Many of the dikes have narrow glassy selvages, usually only a fraction of an inch in width, others do not have these selvages but are finely crystalline at the actual contact with the wall rocks. The finer-grained borders of some of the dikes are, locally, two or three feet in width. There is also a marked contrast in grain size between the dense basalt dikes and the course-grained diabase dikes. The main mechanism of intrusion was one of dilation, and where the walls are parallel, earlier rock units and dikes transected at acute angles display appropriate offsets.

A few miles north of Cornucopia in a 200 square mile area of the Northern Wallowa Mountains, H. W. Smedes (1959) has recently mapped about 160 Tertiary basaltic and diabasic dikes, over 30 of which range from one to three miles in length with one nearly four miles long. Here, too, the dikes have a northerly trend, some northeasterly or northwesterly, and only four with an east-west strike. Almost all of these dikes are nearly vertical or have steep dips.

This display of Tertiary volcanism leaves little doubt that the dikes were originally feeders for some of the near-by extensive lava flows of the Columbia River Basalts. In an area two miles northeast of Cornucopia, H. F. Anderson mapped 22 flows averaging 40 to 50 feet thick forming a ridge having an elevation of about 7100 feet. He also noted 10 more flows on a higher ridge $\frac{1}{4}$ mile to the north. Although in the Cornucopia area no distinct exposures have been found to show the actual merging of a dike into a flow, such a one was described by Fuller (1927) in western Idaho on the canyon walls of Rock Creek, a tributary of the Salmon River. Here, some seventy miles northeast of Cornucopia, there is a remarkably good outcrop of a multiple dike which definitely extends upward and laterally into flows.

The general structural pattern of these Tertiary dikes as well as their association with extensive basaltic flows leaves little doubt that they were caused by fracturing so profound as to permit the upwelling of locally liquid sima. The fine-grained borders of the dikes probably represent the rapid chilling of the initial upward surge of magma and also served as insulators to retard heat losses as the dike fissures became conduits for the free-flowing magma. The coarse-grained central portions of the dikes represent the relatively slower cooling of the final phase of the magma.

With very few exceptions, the Cornucopia dikes are quite free from inclusions so that their crystallization was not complicated by the effects of contamination and assimilation. These effects, however, are very noticeable in one dike which is filled with inclusions for about 100 feet back from its wedge-shaped lateral termination. Some of the dikes do show deuteric features and a few contain later veinlets with low temperature minerals. None of the dikes have suffered from extraneous metamorphism.

Textural features of the magmatic stage of crystallization

The relatively simple mode of occurrence of these Tertiary dikes as well as their nearly uniform composition means that the textural features can furnish some clues, not only with regard to the initial physical state of the eruptive magmas, but also with respect to their crystallization sequence which in most of the dikes was uninterrupted by any addition of foreign material. The data for these textural features was obtained by the study of thin sections from several hundred specimens taken from surface and underground exposures and diamond drill cores.

In his Descriptive Petrography of the Igneous Rocks, Johannson (1939) makes this statement with regard to basalt and diabase: "In the United States it is customary to call dikes or intruded sheets of basaltic composition 'diabase' since they usually have ophitic texture, but there is no reason why they should not be called basalt dikes, if desired, since the mineral composition is exactly the same, and there may be no difference in texture." Yet one of the most noticeable textural features of the Cornucopia dikes is the difference in grain size between the dense basaltic dikes and the coarse-grained diabase ones. For example, a thin section of a specimen from near the center of a dense basalt dike 30 feet wide discloses a mat-like aggregate of labradorite microlites (0.2 to 0.08 mm.) with numerous interstitial clouded grains of mafics (0.05 mm.) and magnetite with about three per cent of brown glass. An area of one square millimeter contains 490 mineral grains: 160 plagioclase microlites, 230 grains of mafics and 100 grains of magnetite. In contrast to this high concentration of centers of crystallization in basalt, a thin section from the central part of a coarse-grained diabase dike, 20 feet wide, shows on an average of 15 crystals or parts of crystals per square millimeter: i.e. 4 labradorite, 5 mafics, 6 magnetite.

Several years ago, H. F. Anderson (personal communication), who was at that time the resident geologist of the Cornucopia Gold Mines, came to the conclusion that the state of the magma in the underlying reservoir prior to injection was a determinative factor in reference to the final textural features of the basalt and diabase dikes. He pointed out that at Cornucopia some large dikes have a basaltic texture and others a coarse diabasic texture and also that some of the nearby Tertiary lava flows are fine-grained basalts and others coarse-grained diabases (Fig. 1).

As stated by Turner and Verhoogen (1951, p. 43), small crystal grains have a higher chemical potential than larger ones, so that for a slight degree of undercooling only large nuclei are stable. Hence, in a greatly undercooled magma the resulting rock would show many crystal grains representing crystallization centers which were unable to form larger individuals because of a rapid increase in viscosity. Under conditions of a slight degree of undercooling larger crystals will form at the expense of small ones.

Since it is probable that the Tertiary basaltic and diabase dikes of this region were successively intruded over a considerable length of time, it is reasonable to assume that there may have been some variation in the temperature of the source pockets of magma in the liquefied sima. Moreover this might also account for some slight differences in chemical composition of the successive dike intrusions.

Recently (1958) J. F. Lovering in a paper on the nature of the Mohorovicic discontinuity has suggested that "The eclogitic material which originally existed between the original and final levels of the discontinuity will transform to basaltic material with a volume increase of something like 15 per cent. It is the volume increase which then provides the mechanisms for raising the overlying crustal column relative to adjacent regions under which the Mohorovicic discontinuity has been unaffected." Under this hypothesis variations in composition of the eclogitic material would be reflected in the composition of the basaltic material which, also due to the 15 per cent increase in volume, would have a greater irruptive potentiality.

The fine-grained borders of the dikes represent the rapidly cooled initial magma, and they commonly contain a few euhedral crystals of labradorite and pyroxene in a glassy or very fine-grained groundmass. Most of the plagioclases are clear, twinned, and relatively free from fractures. Flow alignment shows that these crystals were originally free swimming in mobile liquid environment. Some narrow (3 to 4 inches) dike apophyses show skeleton crystals of the dominant minerals.

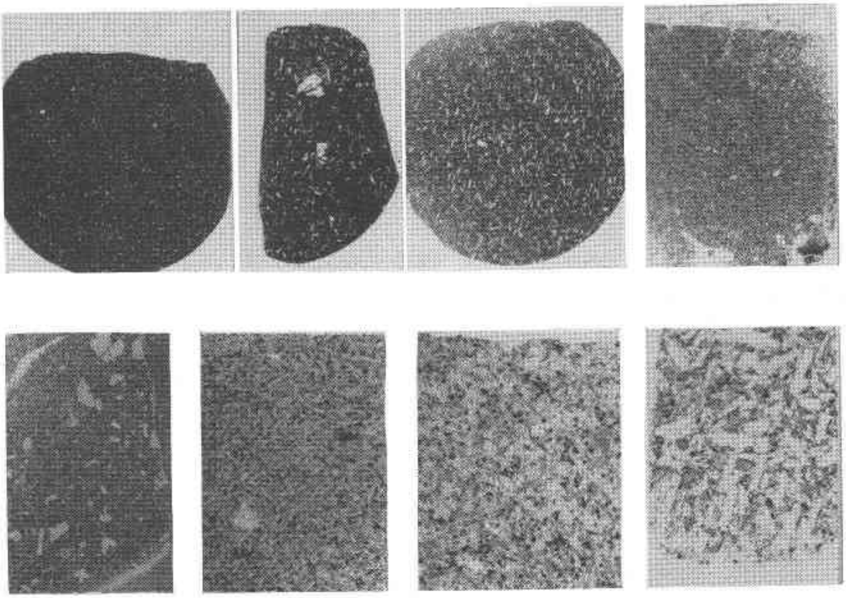

FIG. 1. Photographs (ordinary light) of four thin sections from diamond drill cores of basalt dikes (above) and of four thin sections from specimens of Cornucopia diabase dikes (below).

The textural features displayed in thin sections of specimens from the central parts of many of the dikes are the record of the consolidation of the final surge of magma at the cessation of the fissure eruption for which a particular dike was the feeder. The magma at that time may have been partially crystallized with numerous relatively large individual crystals; or it may have had, as in the case of the basaltic dikes, a great many very small crystals. The coarser-grained diabase dikes have intersertal, subophitic, or intergranular textures commonly modified by porphyritic textures.

Many of the porphyritic varieties show glomerophyric aggregates of large tabular labradorite crystals ranging from rather loosely grouped ones to very compact groups which approach the form of a single crystal. This suggests the possibility that feldspar crystals during a mobile stage of the magma preceding consolidation collided with one another and that some of them became stuck together in a haphazard arrangement. The material included in the triangular interstitial spaces of these aggregates depends upon the state of crystallization of the magma at the time and place of their formation.

Rectangular inclusions of glass or earlier pyrogenetic minerals are noticeable in many phenocrysts; and, in general, these inclusions are arranged parallel to the 010 faces of the labradorite phenocrysts. It seems quite probable that some of these crystals have been built up by the attachment and welding of smaller crystals. Where the weld is perfect, no material is included; if, however, two or more smaller crystals adhere to the tabular surface of the 010 face but fail to grow together, they will be separated by a rectangular re-entrant filled with the mesostasis (Fig. 2). Then if other crystals grow across this gap, the mesostasis is completely enclosed and becomes an inclusion which represents the state of the mesostasis at the time and place of the formation of the phenocrysts. In other words, a phenocryst of intratelluric origin would include material quite different from the mesostasis surrounding the phenocryst. Inclusions of glass are quite common; some consist of glass and pyrogenetic minerals or of pyrogenetic minerals alone. In some cases, as will be noted later, what look like inclusions may be the result of magmatic replacement.

The preference for growth along the 010 face of labradorite appears to be contingent upon its tabular habit when crystallized from a magma. Buerger (1947) in his paper on the relative importance of crystal faces states: "When a molecule lands on the crystal surface so as to continue the crystal structure, then the energy of the bond between the molecule and the crystal is (to first approximation) proportional to the area of the surface joining the molecule to the crystal. If several sites on the crystal are available, the preferred site (neglecting differential thermal effects) is the one with maximum bond strength. With the simplifying assumptions of this section, this is the site which offers the greatest area of attachment between crystal and molecule."

It should be pointed out that by no means all labradorite phenocrysts have a mode of growth as suggested above. Many, no doubt, develop as single crystals. Niggli (Parker translation, 1954) mentioned the effect that seed crystals have in promoting crystallization. He wrote: "It is a general rule that the formation of nuclei settling on a solid surface of any kind requires less work than does the formation of freely suspended nuclei" (p. 469).

Although most of the feldspars in the Tertiary dikes display sharp outlines, a few of them in some of the diabase dikes have ragged borders in contact with pyroxene. These outlines are apparently caused by magmatic corrosion. In some sections the paragenesis is clearly shown by the cusp-like borders of the mafics against the feldspars and also by the apparent penetration of mafics along the albite twinning planes. Where the apices of these cusps happen to be truncated by the plane of the thin section, the plagioclase looks as if it had included numerous small rounded mafic crystals; whereas, in reality, the final crystallization of the mafics is later than that of the feldspars. Some of these corroded plagioclases show thin delicate relics which extend into the mafic-rich groundmass, thus indicating that, at this stage of crystallization, the magma was in a rather static non-mobile state.

FIG. 2. Photomicrograph (plane light) of labradorite phenocrysts in basalt, Cornucopia, Oregon. Note: on the marked 1.7 mm. crystal the two smaller (0.2 mm.) attached crystals.

Another feature of most of the larger plagioclases is the presence of numerous irregular fractures which in some phenocrysts have an irregular veined-network pattern (Fig. 3). In some glomerophyric groups the fractures cut across the component feldspars and also penetrate glass and mafic mineral inclusions. Johannsen (1939) mentions fractures in plagioclase in basalt and states: "Cleavage on (010) and (001) often shows, and there may be cross-fractures along no special face, as well." In a more recent paper C. A. Zapffe, C. O. Worden, and Carl Zapffe (1951) have shown many interesting fractographs of minerals including the feldspars. Most of the small plagioclases, 0.1 to 0.2 mm. are devoid of fractures although some of them are slightly fractured. These fractures play an important role in the final stages of the crystallization history in that they provide minute channelways for late magmatic and deuteric alteration. In a few of the plagioclases the fractures form a pattern of closely spaced parallel lines and are perhaps similar to what has been described as lineage structure.

FIG. 3. Photomicrograph (ordinary light) of part of a thin section of the matrix of the contaminated dike. Note the inclusions in the glomerophyric aggregate of labradorite and the irregular fractures. ×30.

Several possibilities may be suggested to explain the origin of the fractures in the plagioclases:

(1) The crystal mesh of the cooling magma may have been subjected

to a uniform internal stress which was resisted by the criss-cross pattern of the feldspars characteristic of the diabases. A possible analogy is the decussate structure found in some metamorphic rocks.

(2) Crystallization of the pyroxenes pushing apart as well as partially replacing some of the earlier plagioclases may also have contributed to the internal stress of the almost completely crystallized magma.

(3) Some of the larger feldspars may have been of intratelluric origin and thus formed under conditions of considerable pressure. The sudden diminution of this pressure as the crystals were transported upward in the dikes to where a much lower pressure prevailed might cause an expansion in the crystals thus producing fractures.

(4) Some of the fractures may be similar to lineage structure. Based on evidence derived from artificial crystals, several interpretations regarding the origin of lineages have been advanced. Tuttle and Twenhofel (1946) suggest that crystals grown at higher temperatures, and hence under conditions of greater agitation and energy, have fewer structural defects than those grown at lower temperatures.

(5) Additional internal stress might be produced at the initial stage of the development of a deuteric fraction with its complement of less dense and hydrous minerals. At a slightly later stage deuteric products permeate the previously formed fractures in the plagioclase crystals and may cause more fracturing (Fig. 3).

The possibilities just listed are by no means mutually exclusive, but petrographic data are not sufficiently definitive to draw conclusions as to which play dominant roles. Future work on the textural features developed under known conditions from artificial melts would be of much aid in clarifying this problem.

Next to the plagioclases the most abundant minerals of these Tertiary dikes are pyroxenes. Of these augite and pigeonite are the most common varieties, with a few representatives of the enstatite-diopside series. Euhedral pyroxenes are characteristic of the finer-grained border zones of the dikes. In the central parts they occur either as interstitial anhedral grains or as larger anhedral individuals surrounding the net of earlier-formed feldspars.

The next most abundant mineral is magnetite which occurs in small discrete grains and also more conspicuously in the form of large irregular shaped grains molded around the plagioclases and other earlier formed minerals. Therefore, magnetite can be interpreted both as early magmatic and late magmatic in origin.

Several other minerals are present in minor amounts in a few of the dikes. Olivine occurs in its usual rounded shape and commonly shows some alteration along cleavage cracks. Brown hornblende, of rare occurrence, forms discontinuous zones around pyroxene and partially replaces pyroxene where it follows the original outline of this earlier formed mineral. Relict islands of pyroxene are noticeable in some of the hornblende. The hornblende is embayed by late magmatic magnetite. In a few sections incipient skeletal feldspars can be seen in pockets of glass-residium. Perhaps some of the very few quartz grains in some of the dikes can also be considered to be late magmatic since they exhibit sharp boundaries and appear to have crystallized before the rock became a solid crystalline aggregate.

Textural features of the deuteric products

In addition to the minerals of the magmatic sequence most of the Tertiary dikes contain paulopost alteration products which usually occur interstitially or as replacements of the earlier formed pyrogenetic minerals or the glass residuum. A few of the basalt dikes appear to be free from alteration but some contain about five per cent and the diabase dikes usually have about 10 per cent of deuteric alteration products. These products have a wide variation in composition; greenish chloritic or brownish chlorophaetic material are the most common; micropegmatitic and myrmekitic intergrowths are conspicuous in some of the diabases, as well as tremolite, zeolites, carbonate, hydromica, and rarely a reddish micaceous mineral.

The intergrowths also vary considerably in occurrence; some are associated with interstitial quartz grains and some appear to have replaced an originally glass residuum. As a rule the finer myrmekitic intergrowths have replaced some of the plagioclases, either partially or wholly, with the intergrowth following but preserving the forms of the earlier feldspars. These relict outlines indicate that the rock was essentially solid at the time of the myrmekitic replacement.

In several dikes the deuteric fraction is noticeable in the field in the form of narrow irregular light-colored veinlets which are usually nearly parallel to or coincide with the columnar jointing. The material in these veinlets is quite similar to the deuteric products which occur interstitially, although it usually has a slightly different textural pattern.

A 2×2 thin section taken from a specimen from the central part of a diabase dike 30 feet wide, exposed in the lower adit of the mine, shows one of these narrow (1 mm. in width) veinlets. The groundmass of this veinlet has a slightly pinkish tinge and is so fine-grained that under low power magnification it appears to be nearly isotopic. Under high power, however, it is seen to consist of an aggregate of minute grains of quartz, untwinned feldspar and a considerable amount of fine dust-like material which appears to be chiefly brown biotite. In this very fine grained groundmass are some relatively larger grains of quartz and feldspar and patches of micropegmatite. Some of these feldspars are albite and a few are orthoclase. Many of them are filled with minute inclusions of the very fine dust-like material of the groundmass. Some are quite anhedral, having amoeboid outlines with crenulated borders extending into the fine grained groundmass. A few of the albite crystals, however, are quite clear with sharp borders and have rectangular U-shaped outlines. The veinlet also contains a few crystals or fragments of labradorite crystals from the diabase. The pyrogenetic labradorite is commonly rimmed with albite and this also holds for those parts of the labradorite crystals which extend into the veinlet from the adjacent diabase.

Another noteworthy feature of this veinlet is the presence of a considerable amount of pinkish-brown mica which occurs in very small flakes with some suggestion of crystal faces. There are, however, several euhedral crystals of biotite, and some of these are included by the clear feldspars and by the albitic rims of the labradorite. Within the veinlet irregular patches of micropegmatite have formed late in the crystallization sequence since they not only surround the other minerals but also partially or wholly replace some of the late-forming feldspars as can be seen by the survival of the former outline of these crystals. Minor amounts of magnetite, chloritic material and carbonate are also present in the veinlet.

The textural features and the mineral composition of this veinlet are similar to those of some of the deuteric products of the diabasic magma. It consists of that part of the deuteric fraction which instead of remaining in the crystal mesh of the diabase become mobile enough to flow into a fracture, thus forming the veinlet. The crystallization sequence of the deuteric material in the veinlet seems to have ranged from a stage of initial mobility to that of crystallization in a nearly solid medium. Since this material apparently behaved like a magma, although clearly deuteric in origin, it is suggested that the term *deuteromagmatic* might be more appropriate than either magmatic or deuteric. The chloritic material and carbonate in this veinlet may be explained as local hydrothermal products formed during the final stage in the crystallization sequence of the deuteromagma.

Other minute veinlets consist of very low temperature minerals such as zeolites, carbonate, and chalcedonic quartz, and exhibit textural features indicative of hydrothermal deposition. They may have been formed during the closing stage of magmatic or deuteric crystallization. Another feature which may be accounted for by hydrothermal action are the minute vermiform quartz veinlets seen along the contacts of some of the dikes transecting granitic rock. These minute quartz veinlets extending from the dike into the granitic rock penetrate between and surround the constituent crystals thus producing a ring-like pattern. It is possible that some of the water for these hydrothermal solutions came from the wall rocks.

TEXTURAL FEATURES OF A CONTAMINATED DIABASE DIKE

Most of the Tertiary diabase dikes which cut across Cornucopia Mountain are through-going ones without lateral terminations and are essentially free from inclusions. One dike, however, is unique in that it does end abruptly and that it is filled with inclusions adjacent to its termination. This dike, exposed high up (7250′) on the steep walls of a glacial valley two miles west of the old townsite, has a width of 25 feet, a north-south trend and a 40° westerly dip. It transects quartz-dioritic country rock and is parallel to and locally in contact with one of the gold-quartz vein zones of the area. Fine grained chilled borders which are free from inclusions line both walls of the dike as well as its wedge-shaped northerly extremity. For a hundred feet south of here the central part of the dike contains so many angular xenoliths of granitic country rock, of silicified hornfels (which does not outcrop in the immediate vicinity) and xenocrysts of quartz and feldspar that it is lighter in color than the inclusion free main part of the dike to the south. Where the quartz xenocrysts are abundant the rock might easily be mistaken for a dacite were it not for the presence of reaction rims around the quartz grains.

Most of the xenoliths, which average four to five inches in size, are haphazard in their distribution in the central part of the dike, and show no preferred orientation. Some larger ($2 \times 1\frac{1}{2} \times \frac{1}{2}$ feet) granitic xenoliths are, however, roughly parallel to the walls of the dike. Thin sections of specimens taken along the borders of one of these slab-like granitic fragments show small (5 mm.) embayments of the diabasic matrix into the xenolith. Here small laths of plagioclase display a rough flow alignment. A few millimeters further into the xenolith the diabase forms a network of small veinlets which penetrate around the quartz and feldspar crystals of the granitic xenolith. About 10 mm. further into the xenolith these veinlets (0.1 to 0.5 mm. in width) show a gradual increase of secondary products with a concomitant decrease of pyrogenetic minerals, so that their composition is quite similar to that of the deuteric fraction locally abundant in the mesostasis of this dike. The secondary products are very fine grained in texture and consist chiefly of somewhat plumose aggregates of micropegmatitic intergrowths with numerous needle-like crystals of tremolite, some grains of magnetite, minute flakes of a pinkish mica, a little secondary quartz, a few clear untwinned feldspar crystals and indeterminable grains of mafics and brownish micaceous minerals.

Although the initial fractures which became the pathways for the network of veinlets may well have been caused by the heat of the diabasic magma, the dominant mechanism appears to be one of replacement. The evidence for this is especially clear with respect to those of the deuteric fraction. These veinlets show cusp-like indentations against the quartz grains with rather sharp contacts and no reaction rims, although along some parts of the boundaries the veinlets contain very minute disconnected lines of fine dust-like material. Along other parts of the boundaries, however, thin slivers of quartz protrude into the veinlets, and some grains of corroded quartz have bizarre shapes with two larger parts connected by a thin link. A few of the quartz grains are traversed by very minute (0.004 mm.) microveinlets of zeolite.

The plagioclase crystals of the xenolith also show similar replacement features where they are in contact with the veinlets, except that they are not as conspicuously embayed as the quartz grains and that most of them retain their rectangular shape but with rounded corners. Some of them show a penetration of the deuteric fraction along the albite twinning planes with thin relics of the lamellae extending into the veinlets. Adjacent to the veinlets several of the feldspars display rough irregular patches of a mosaic-like or fretwork-like structure and some of the smaller ones are completely matted by a very fine (0.004 mm.) fretwork. A few of these are replaced by clear secondary feldspars in the form of clear, minute (0.02 mm.) rectangular or hollow square crystals.

Quartz grains and plagioclase crystals detached from the deuterically altered granitic xenolith are engulfed as xenocrysts by the igneous matrix. These xenocrysts display superimposed textural features that are clearly indicative of magmatic reactions at relatively higher temperatures than those of the deuteric fractions. Similar features also occur with respect to xenocrysts of quartz and plagioclase distributed at random throughout the dike. The most noticeable of these features are the reactions rims of pyroxene around the quartz xenocrysts. The rims are from 0.1 to 0.2 mm. wide and the small, closely packed prisms of monoclinic pyroxene (probably diopside) are arranged radially, tangentially, or at other angles with respect to the quartz xenocrysts (Fig. 4). Most of these reaction rims include a few grains of magnetite and rarely minute euhedral crystals of a brown micaceous mineral. A few of the small pyroxene crystals penetrate slightly into the xenocrysts so that minute appendages of quartz extend into the reaction rims. In some thin sections there are roughly rounded aggregates of pyroxene crystals similar to those in the reaction rims. Some of these may represent the complete magmatic replacement of a quartz xenocryst and others merely the outer part of a reaction rim.

Reaction rims of pyroxene do not occur around plagioclase xenocrysts, but other features produced by the magma are quite noticeable. These include rounded and irregular borders, and a finely fretted texture (0.01 mm.) which is coarser than that produced by the deuteric fraction. The borders of some of these xenocrysts appear to have started to disintegrate into innumerable minute blocks (Fig. 4). Other plagioclase xenocrysts are partially or wholly covered by a fine fretwork; and where this occurs there is commonly a narrow (0.1 mm.) border of clear plagioclase similar in composition to the unaffected portions of the xenocrysts. Most of the plagioclases of the quartz-dioritic wall rock are in the oligoclase-andesine range of composition. The interstitital part of the fretwork in some of the plagioclase xenocrysts consists of extremely fine grains (0.002 to 0.06 mm.) of minerals of high refringence and birefringence with numerous small euhedral crystals of magnetite as well as some rod-like or staff-like forms of this mineral.

FIG. 4. Photomicrograph (plane light) showing xenocrysts of quartz and plagioclase from a thin section of a specimen from the contaminated dike. The 3 mm. quartz xenocryst (center) has a reaction rim of prisms of pyroxene. The xenocrystic plagioclase shows various stages of disintegration. Note the fretwork developed in one of the xenocrysts of plagioclase.

Some of the plagioclase xenocrysts show recrystallization effects such as the development of ragged porphyroblasts of monoclinic pyroxene, irregular interlocking patches which have a faint birefringence suggestive of feldspathic recrystallization, and the transformation of a few of the xenocrysts into a fine mosaic of clouded feldspar crystals. In contrast to this type of recrystallization, some small xenocrysts are changed into a checkerboard aggregate of several hundred subhedral, blocky, clear, twinned andesine (An35) crystals averaging about 0.02 mm. square. Some of these are oriented at right angles to the extinction position of the original xenocryst, but most of them have an over-all conformity to the original crystal. Some of these checkerboard aggregates show a zigzag penetration of pyroxene in and around some of the small compact crystals. Where these small plagioclase crystals break away from the irregular borders of the aggregate, they merge into and become a part of the igneous matrix of the dike thus indicating assimilation without melting into a glass. In some of the plagioclase xenocrysts, however, the interstitial part of the fretwork contains several very small (0.1 to 0.01 mm.) irregular drop-like forms of a brown, isotropic, nearly opaque material which corrode the feldspar in minute cusps. They appear to be glass, and if so, represent a local incipient melting of the xenocrysts.

In addition to these effects of recrystallization, disintegration and assimilation of xenocrystic material, this dike displays many noteworthy features with respect to its conspicuous deuteric fraction. Deuteric products are not only noticeable in the mesotatis, but also occur in irregular segregations, veinlets, and amygdules. The relationship of the mesostasis to an amygdule is well shown in one thin section where a small (2 mm.) round aggregate contains numerous thin (0.7 mm. long) crystals of clear oligoclase and monoclinic pyroxene. Some of these pyroxenes are almost wholly replaced by granular magnetite. The material between these larger crystals is light brown in color and is peppered by innumerable minute mineral grains of high refringence and birefringence and magnetite in small crystals of dust-like or rod-like forms. Numerous microlites of oligoclase, some grains of pyroxene, minute plumose clusters of zeolites, patches showing faint ill-defined extinction are also present. One-half of the border of this round aggregate is clearly defined against the igneous matrix by several curved crystals of oligoclase (0.2 to 0.4 mm. long) whereas the other half, not as well marked, shows locally a merging of the deuteric fraction of the igneous matrix into the aggregate.

Another larger (5 mm.) round amygdule is well shown in a large thin section cut from an inclusion rich specimen taken near the hanging wall of the dike. The deuteric fraction filling this amygdule consists chiefly of a plexus of incipient feldspar microlites (0.3 mm. long) with some interstitial zeolites and brown mesostasis which has a very faint birefringence and is filled with extremely minute opaque dust-like material. Within this amygdule is a smaller one (3 mm. in diameter) consisting of zeolites, and there are also several small (0.2 mm.) similar amygdules along part of the periphery of the host amygdule and some small irregular veinlets of zeolite. This section also contains a few small amygdules consisting chiefly of zeolites (Fig. 5).

FIG. 5. Photograph (ordinary light) of a 6×7 cm. thin section of a specimen from the hanging wall of a contaminated diabasic dike. Note the irregular xenoliths of quartz granulite and siliceous hornfels which are recrystallized and partly disintegrated, and a few quartz xenocrysts surrounded by a narrow (0.1 mm.) reaction rim of pyroxene. Scattered through the section are numerous rounded or irregular patches of xenocrystic plagioclase in various stages of assimilation. In contrast are the sharp rectangular crystals of pyrogenetic labradorite. Note also the two round (light colored) amygdules of zeolites surrounded by an outer amygdule of the dark colored deuteric fraction.

These features suggest that the deuteric fraction was not only able to seep into a vesicle but was also locally capable of forming a vesicle which became filled with the final products of its crystallization sequence. At this late stage of crystallization the deuteric material appears to have changed into a local hydrothermal solution. This is suggested by several other features such as the previously described vermicular veinlets, and the alteration of the pyrogenetic labradorite phenocrysts. Many of these crystals show the penetration of zeolites along minute irregular fractures and cleavage cracks accompanied by varying degrees of replacement (Fig. 3).

Some Textural Features of Magmatic Rocks from Various Localities

In the Cornucopia diabase dikes the textural features of the orthomagmatic sequence of crystallization is, in general, quite distinct from that of the deuteric fraction. In many other basic igneous rocks which occur in much larger bodies, and, therefore, have a longer consolidation period, it is not always a simple matter to distinguish strictly magmatic textures from those of the crystallized deuteric fraction. Moreover, in some igneous masses, later extraneous metamorphism may impose quite different textural features and so make the textural pattern more complicated.

Sudbury, Ontario.

For example, many thin sections from specimens of the noritic part of the Sudbury, Ontario, intrusive show alteration to such an extent that only a few relics of the original mafics remain and even the plagioclases are partly seritized. The amount of micropegmatitic intergrowths as seen in some of these sections is far greater than that which might be expected from a normal crystallization sequence of a gabbroid magma. The normal sequence of crystallization is, however, illustrated by the textural features and mineral composition in a few specimens from certain localities near Sudbury. One of these specimens taken about 500 feet from the footwall of the intrusive body north of the Murry mine is a good example of the unaltered norite. It is a dark gray, medium grained crystalline rock consisting chiefly of clear tabular plagioclases (with a maximum length of 5 mm.) with interstitial mafics and a few flakes of brown biotite. In thin section it is seen to consist of about 58 per cent labradorite An51, 23 per cent pyroxene and a little hornblende, 9 per cent alkalic feldspar, 6 per cent biotite, 3 per cent quartz, and 1 per cent opaques. The labradorite laths average 1 to 2 mm. in size, have a haphazard arrangement, and some of the larger ones show a few irregular fractures. Pigeonite (0.4 ×0.6×1 mm.) is the dominant pyroxene although some hypersthene is present. Some of the pyroxene is interstitial to the labradorite, some includes labradorite crystals showing a subaphetic texture, and some embays the plagioclase along cleavage cracks. Green hornblende forms rims around some of the hypersthene and also shows replacement textures against the pigeonite. Brown biotite mostly in solid patches exhibits boundaries indicating that it has partially replaced some of the hornblende, pyroxene, and plagioclase. A few flakes of biotite are embayed by quartz and a small one (0.2 mm.) showing some crystal faces is surrounded by quartz. The clear untwinned alkalic feldspar which has a small (−) 2v and is probably sanidine, looks like the quartz which, however, is optically positive. Both of these minerals occupy interstitial positions with respect to the other minerals. In contrast to most of the Sudbury "norite" this specimen contains only an extremely small amount of micropegmatitic and myrmekitic intergrowth: one very small crystal of plagioclase is partially replaced by a myrmekitic intergrowth and is surrounded by clear alkalic feldspar which is in an interstitial position to labradorite. The opaques are magnetite, pyrrhotite, and pyrite. One irregular aggregate of pyrrhotite (2 mm. in size) shows replacement cusps against the labradorite and also penetrates between some of the labradorite crystals. This aggregate of pyrrhotite is transected by a few minute (0.01 mm.) veinlets of micaceous minerals and is also partially rimmed by them. Another irregular aggregate (1.0×1.5 mm.) is entirely enclosed by biotite, but the borders between these minerals indicate that the biotite has been partially replaced by the sulphide. A few small grains of pyrite are rimmed with magnetite, and magnetite has partially replaced both biotite and hornblende developing the usual replacement textures.

The textural pattern of the earlier magmatic minerals of the Sudbury norite, namely, the labradorite and the pyroxenes, bears a close resemblance to that of some gabbros and many diabases especially with respect to the random orientation of the feldspars and the intergranular and in part subophitic texture (Fig. 6). Although some of the pyroxenes show small irregular penetrations into the labradorite, on the whole the boundaries between these minerals are clear cut and sharp. In contrast to this, some of the later formed minerals show distinct replacement textures against the earlier formed ones and the minerals last to form, namely the alkali feldspar; the quartz and the sulphides occupy interstitial positions comparable to that of the deuteric fraction as seen in some diabases. This feature suggests that these minerals crystallized at a time when the rock was a close-knitted net of earlier formed magmatic minerals and that they represent the final stage of consolidation.

Yogo Peak, Little Belt Mountains, Montana

The textural features of the later consolidation products of a basic magma are well shown in some of the shonkinitic rocks of central Montana. At the classical locality of Shonkin Sag, shonkinite occurs both above and below a relatively narrow band of microsyenite and a narrower one of syenite pegmatite. The upper shonkinite consists chiefly of euhedral augite (up to 5 mm. in size) in a random arrangement and a few crystals of euhedral to subhedral olivine some of which are enclosed by the pyroxene, numerous block-like forms of biotite with some showing crystal faces and some surrounding the earlier formed minerals. The mesostasis consists for the most part of a partly altered confused aggregate of micropegmatitic intergrowth, alkalic feldspars, some nephelite and a little fibrous stilbite. Embayment of biotite by the mesostasis and cusp-like indentations into the biotite are indicative of replacement by the mesostasis. The mineral association as well as the textural pattern of the mesotstasis suggest that it formed at a very late stage in the consolidation of the rock. It is of interest to note that in this shonkinite the mafics, particularly the augites, display marked euhedralism, whereas the interstitial feldspathic material is mostly quite anhedral.

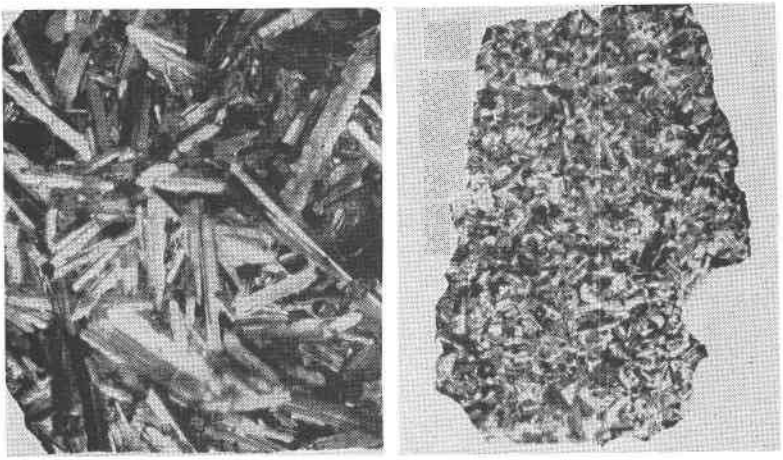

FIG. 6. Photographs (crossed polarized light) of a 4×4.5 cm. thin section of Duluth gabbro and a 3×4 thin section of the Sudbury, Ontario, norite. Note the criss-cross pattern of the labradorite crystals.

Somewhat similar textural features are present in the shonkonitic border phases of the Yogo Peak chonolithic intrusive mass in the Little Belt Mountains of north central Montana. As described by Weed and Pirsson (1898), this mass is some five miles long and about one mile wide, the western end making the peak. Here the rock is a shonkinite which, as one proceeds eastward, changes into rocks of dioritic, monzonitic, syenitic character, to what has been termed a porphyritic granite (Fig. 7). A similar gradation from shonkinite to granite is noticeable from the eastern border westward. In the summer of 1949 the writer collected specimens one-tenth of a mile apart from the West peak of Yogo Mountain to the central part of the intrusive mass.

At the western border the rock is nearly black, coarse-grained, and

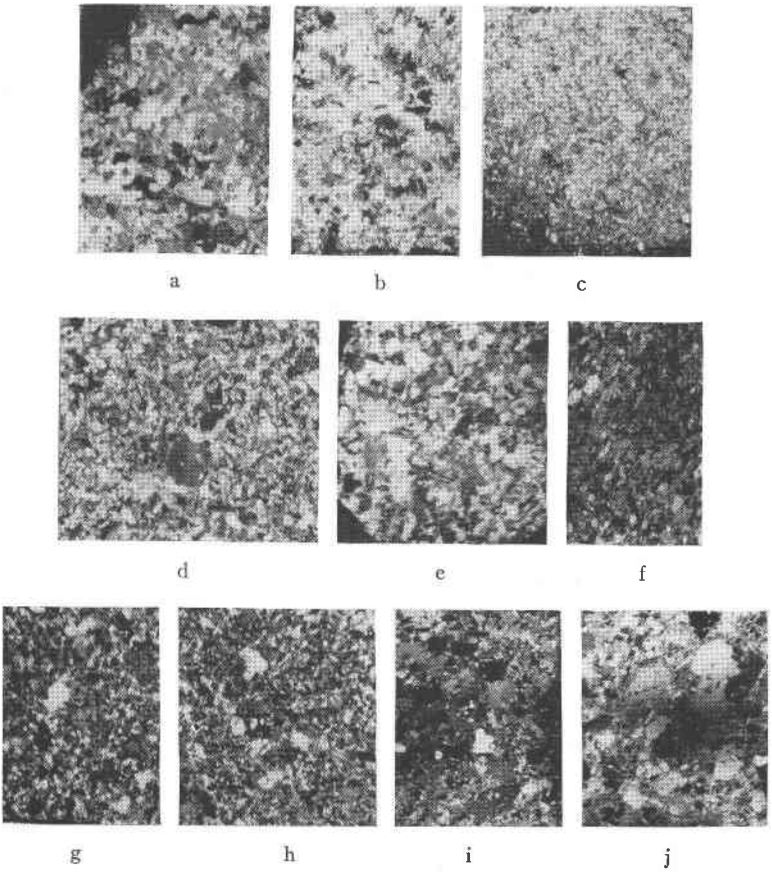

FIG. 7. Photographs (crossed polarized light) of ordinary thin sections from Yogo Peak to illustrate the gradual change from shonkinite to granite porphyry, as follows: a) Yogo West Peak; b) 0.3 Mile East; c) 0.4 Mile East; d) 0.5 Mile East; e) 0.6 Mile East; f) 0.7 Mile East; g) 0.9 Mile East; h) 1.1 Mile East; i) 1.3 Mile East; j) 1.4 Mile East.

consists chiefly of numerous plates of biotite (5 to 10 mm.) showing a poikilitic texture, pyroxene, a few grains of which are euhedral, some greenish rounded grains of olivine and some interstitial feldspar. As seen in thin section, euhedral to subhedral pyroxenes (2 to 5 mm. in size) with an occasional remnant of olivine are included poikilitically by subhedral to anhedral blocky brown biotite. All these minerals are included by large (10 to 15 mm.) clear anhedral plates of feldspar mostly orthoclase with a little andesine, and oriented at random. Magnetite in small irregular grains or rod-like forms is for the most part scattered through the mafics but some is concentrated in altered relics of what was probably originally olivine. In one part of a large thin section from this rock there is an irregular cluster (10×5 mm.) of prismatic hornblende crystals arranged haphazardly with interstitial carbonate. A few of the pyroxenes are embayed by biotite, some of them show the penetration of biotite along minute fractures, and others contain minute flakes of biotite. Some of the altered mafics are rimmed with green biotite and a few of the feldspars are slightly clouded by sericitic material. Although this shonkinite from the western peak of Yogo Mountain is characterized by euhedral pyroxenes like the one from Shonkin Sag, it differs in that instead of a confused aggregate of interstitital feldspathic material, large plates of feldspar, mostly orthoclase, enclose the earlier-formed minerals.

The igneous rock three-tenths of a mile east of West Peak is slightly finer-grained than that at the western border and similar although slightly different textural features are revealed in the thin sections. The mafics are not as large, most of the pyroxenes averaging 1 mm., with a few olivine crystals of the same size. The large plates of orthoclase also include several small crystals of oligoclase, some of which show ragged borders and embayments indicative of replacement by the alkalic feldspar.

At four-tenths of a mile to the east the igneous rock is finer-grained and not quite as dark in color as that to the west. Several altered mafics (5 mm. in size), probably originally olivine, are noticeable and on exposed surfaces these have weathered out giving a pseudovesicular appearance to the rock. Interstitial feldspathic material is more conspicuous than it is in the previous specimens. Thin sections show that the mafics, with the exception of the olivine, are smaller, ranging in size from 0.1 to 1.0 mm. Most of the mafics have ragged borders and embayments indicative of replacement by the feldspathic mesostasis which is an aggregate of small (0.1 to 0.3 mm.) subhedral oligoclase enclosed in an interlocking aggregate of anhedral alkalic feldspar. A few of the mafics, especially the olivines, are rimmed by small flakes of green mica and contain numerous grains of released magnetite.

At a half mile east of the western border, the igneous rocks become finer-grained and gray in color. Interspaced with the mafics are numerous clear subhedral crystals of feldspar. Biotite is the most noticeable of the mafics, but some hornblende and pyroxene are recognizable in the hand specimen. As seen in a large thin section under a wide field microscope, clear subhedral plagioclase with rectangular outlines or groups of plagioclase crystals are in part surrounded by smaller, earlier-formed mafic crystals which appear to have been pushed aside by the growing feldspar. It is clear that the mafics formed earlier than the plagioclases because they are embayed by the feldspars which also contain a few inclusions of mafics. The mafics are hornblende, pyroxene, (diopsidic augite) and biotite, and the plagioclase is oligoclase An27. A late-forming mineral, occurring interstitially, is anhedral alkalic feldspar which appears to have partly replaced all the other minerals including the oligoclase. Instead of being clear like the plagioclase, this feldspar is turbid, being filled with dust-like inclusions of minute mafic crystals and a few euhedral crystals of apatite. There is also a little interstitial quartz with replacement borders against the other minerals. Some interstitial magnetite which embays the earlier minerals is in turn embayed by the alkalic feldspar.

The igneous rock for the next two-tenths of a mile is similar both megascopically and microscopically to that just described except that the plagioclases, instead of having a random orientation, show some degree of parallelism. This preferred orientation of the plagioclases is quite evident on large cut surfaces of the rock or in large-sized thin sections. It is probably the record of late stage magmatic flowage. This rock also contains a few small (5–15 mm.) irregular inclusions consisting chiefly of an aggregate of biotite with interstitial plagioclase liberally sprinkled with grains of magnetite. In the central part of one of these inclusions is a small segregation of pyrite.

At nine-tenths to one and one-tenth of a mile east of the western border of the Yogo intrusive mass, the igneous rock does not show any flow structure, becomes lighter in color due to the diminution of mafics, and has about the same grain size. Thin sections reveal that orthoclase is the dominant mineral with subordinate oligoclase, some crystals of which are partly or almost wholly replaced by orthoclase. Some of the larger (up to 3 mm.) crystals of orthoclase are composite ones consisting of several interlocking anhedra. These usually contain inclusions of oligoclase or phantom relics of this mineral. Some microperthite is also present. The mafics constitute about ten per cent of the rock and consist of hornblende, pyroxene, and biotite. A few relic pyroxenes are heavily mantled with hornblende. Some of the mafics are embayed by the feldspar, but a few of the hornblendes show some crystal faces against them. Most of the mafics contain grains of magnetite, and a few of them include flakes of brown biotite and occasional grains of sphene. This rock also contains from three to five per cent of interstitial quartz which also penetrates and partly replaces the earlier minerals. Although the overall texture of this rock could be described as hypidiomorphic granular, the irregular interlocking boundaries of the feldspars as well as the prevalence of replacement textures strongly suggests a crystalloblastic growth in the deuteric fraction of an originally basic magma. Relics of pyrogenetic minerals such as the pyroxenes confirm the magmatic lineage of the rock as shown by the field evidence.

Less than one-half mile farther to the east the igneous rock has changed into what has been called a porphyritic granite. At a distance of 1.3 miles from the western border of the intrusive mass, it has a light cream color and numerous conspicuous crystals of orthoclase (5 to 7 mm.) in a finer-grained matrix of feldspar, grains of quartz, and a few mafics consisting of biotite and hornblende. In thin section the texture of this rock is seen to be very different from those in the western part of the Yogo intrusive mass. Large (3 to 7 mm.) crystals of alkalic (orthoclase) feldspar, some of which are slightly microperthitic, compose about 50 per cent of the rock. A few of these larger feldspars are compound crystals where several anhedra with different orientations and irregular boundaries form one crystal. There are also a few conspicuous anhedra of quartz ranging in size from 1.3 to 2.2 mm. Interstitial to the larger alkalic feldspars are numerous anhedra (0.5 mm.) of alkalic feldspar, subhedral oligoclase 1–2 mm., perthitic anhedra (1.5 mm.), ragged relict hornblende (2 mm.) partly replaced by biotite, blocky biotite (1 mm.), anhedral quartz (1 mm.) a few relics of augite and an occasional crystal of sphene, zoisite, and magnetite. The mesostasis of this matrix consists of a mosaic-like aggregate of anhedral quartz (0.2 mm.) in rounded or polygonal forms, and anhedral feldspar (0.2 mm.) orthoclase and oligoclase. The mesostasis embays a few of the larger quartz anhedra which are also traversed by minute (0.01 mm.) veinlets of alkali feldspar. The larger alkalic feldspars include some of the small subhedral oligoclase and partly replaced oligoclase crystals. These larger crystals in turn appear to have been invaded by the small quartz grains of the mesostasis which appear along their borders as advanced islands of replacement. Many of these rather complex textural features are suggestive of crystalloblastic growth. The field relations as well as the relics of pyrogenetic minerals, however, clearly indicate that this granitic rock is of a magmatic lineage.

The Yogo Mountain intrusive mass is transected by numerous aplitic dikes. One of these cutting the shonkinitic rock near the western border is 2 cm. wide and contains a few small xenoliths which, aside from being elongated not quite parallel to the walls of the dike, do not appear to have been changed by the aplitic magma. In thin section this small dike is seen to consist chiefly of anhedral to subhedral alkalic feldspar (1 mm.) some of which is perthitic, a few small (0.7 mm.) crystals of oligoclase many of which are partly replaced by alkalic feldspar. Minor constituents are interstitial quartz which has replaced some of the feldspars; relict hornblende usually with a little magnetite, a few flakes of biotite some of which show some crystal faces, and a few interstitial grains of sphene. This rock is similar texturally to some of the dioritic facies, but does not have nearly as many mafics.

Osgood Mountains of Northeastern Nevada

Some thirty miles to the east of Winnemucca, Nevada, in the Osgood Mountains, is a small granodioritic intrusive body described by Hobbs and Clabaugh. This intrusion has an outcrop form of a figure eight with a north-south dimension of six miles, a width of two miles in the bulges and only 1000 feet in the narrow connection between the wider parts. The country rock consisting of interbedded argillites and limestone dips away from the igneous body, with dips of 40° to 60° on the eastern side and nearly vertical on the western side. The contact aureole is relatively narrow and irregular, and most of it is characterized by the usual lime silicate minerals. Locally small parts of the contact aureole have been granitized.

The intrusive rock is light-colored, medium to coarse grained with a few large (1 cm.) plagioclase crystals showing rectangular outlines in a matrix of smaller feldspars, mafics, and interstitial quartz anhedra. Hornblende and biotite are recognizable, and some of the biotite shows nearly euhedral basal sections. Under the microscope the larger plagioclases are seen to be oligoclase (An27) and to include numerous smaller (2 cm.) plagioclase crystals. There are a few ragged remnants of pyroxene and hornblende. Hornblende also occurs as small euhedral crystals (0.1+ to 0.7 mm.). Brown biotite is in a blocky rather than a shredded form, and there are a few larger (2.5 mm.) euhedral basal sections of biotite, some of which include small (0.5 to 1.0 mm.) plagioclase crystals. Platelike forms of anhedral alkalic feldspar (sanidine) surround the smaller crystals of plagioclase, biotite, and hornblende. Interstitial quartz anhedra range from 1 to 2 mm. in size. There is no question as to the intrusive nature of this igneous rock, and its magmatic lineage is clearly shown by the relict mafics. Mobility of the final stage of consolidation is indicated by the euhedralism of the late-forming biotite.

SOME TEXTURAL FEATURES OF METASOMATIC ROCKS

The textural features of magmatic rocks are, in general, the result of a crystallization sequence from an initially fluid magma to a nearly solid medium. The magma is usually limited by the boundaries of the intrusion and with falling temperature solidification and crystallization proceed from the borders inward. In the late magmatic or deuteric stage of crystallization the residual magmatic solutions may replace some of the earlier formed pyrogenetic minerals thus producing textural features somewhat similar to those found in metasomatic rocks.

Crystallization by metamorphism takes place in an essentially solid medium with first rising, then falling, temperatures or even under conditions of undulating temperature. It also takes place progressively from one part to another of a pre-existing rock mass rather than throughout the whole mass at one time. This mass may consist of any kind of rock and therefore will present a variety of physical and chemical properties which, in part, are accountable for the diversified results of metamorphism. Another factor, which is sometimes most significant, is the effect of stress not only previous to, but during metamorphism.

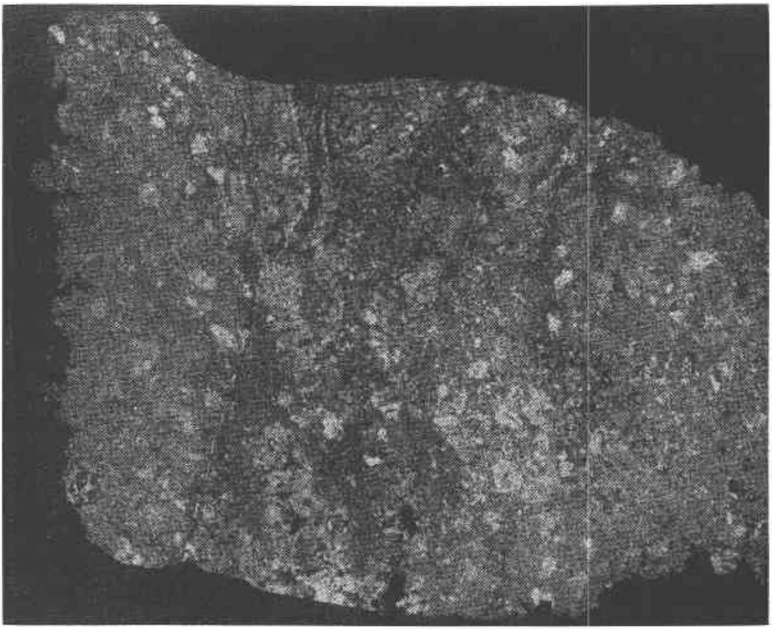

FIG. 8. Photograph (crossed polarized light) of a 5×7 cm. thin section from a specimen of hornblende granulite from the lowest adit, Cornucopia, Oregon. Note plagioclase porphyroblasts in an early stage of development.

Metasomatic rocks are those metamorphic rocks which have been formed by the addition of material carried by emanations or solutions through minute fractures or permeable zones. This material aided by a rising temperature reacts with the constituents of the rocks and new minerals are formed. Unlike the crystallization of a magma, no orderly sequence obtains and individual minerals commonly show various stages of crystalloblastic development. Within the area of a single section, porphyroblasts of the same mineral species may be displayed in several stages of development from initial amoeboid forms through those with ragged crystal outlines with pronounced sieve structure to nearly euhedral crystals which are practically free from inclusions (Fig. 8).

The character of the inclusions seen in these crystals depends upon the nature of the original material, or the stage of metamorphism preceding the development of the porphyroblasts. In contrast to inclusions in minerals in igneous rock, they are not governed by a definite crystallization sequence as is illustrated by included round grains of quartz in calcic plagioclase or hornblende. Relics of a former schistosity; i.e., helicitic structure or bands of platy or acicular minerals in porphyroblasts are cogent proof of metamorphic origin. Some plagioclase porphyroblasts occurring in a hornblendic granulitic rock in the vicinity of Cornucopia, Oregon, show rings of inclusions which have apparently been pushed outward by the growing crystal. In some of these porphyroblasts zonal structure coincides with the disconnected rings of inclusions. This suggests that the absorption of mafic inclusions has had some influence on the chemical composition of the plagioclase, and may be one of the causes of the oscillatory zonal structure. In other feldspathized rocks from this area it is not uncommon to see plagioclase porphyroblasts partially rimmed by the finer-grained schistose groundmass, thus indicating the effect of crystal pressure so commonly seen with respect to garnet porphyroblasts.

Where porphyroblasts are grouped together, the terms *glomeroblastic* for crystals of the same mineral or *cumuloblastic* for groups of different minerals were suggested by the writer some twenty years ago (Goodspeed, 1937). Some glomeroblastic aggregates seem to represent an intermediate stage in the formation of larger porphyroblasts. In the earlier stages of crystalloblastic growth, these groups are merely aggregates of crystals; then with further development the individual crystals coalesce to form a single larger crystal. The outline of this crystal is apt to be quite irregular with sharp re-entrant angles resulting from the growing together of several individual crystals. With continued development, this irregular outline may be modified or may disappear with the result that it becomes a single crystal. In this crystal, however, the twinning and other structures of the smaller individual crystals may persist and thus reveal its composite nature. In the later stages of development these features may be nearly obliterated so that only a hazy mottling gives a clue as to its former composite character. Although glomeroblastic aggregates are superficially similar to glomerophyric aggregates in igneous rocks, their metasomatic origin is evident where they occur in rocks of unquestionable metamorphic origin (Fig. 9).

For example, near Buffalo Hump, Idaho (Goodspeed, 1942), glomeroblastic aggregates of plagioclase occur in a fine-grained biotite schist. Most of the smaller aggregates (1 cm.) have irregular, ragged gradational boundaries with the schist, and some show helicitic structure. Others are

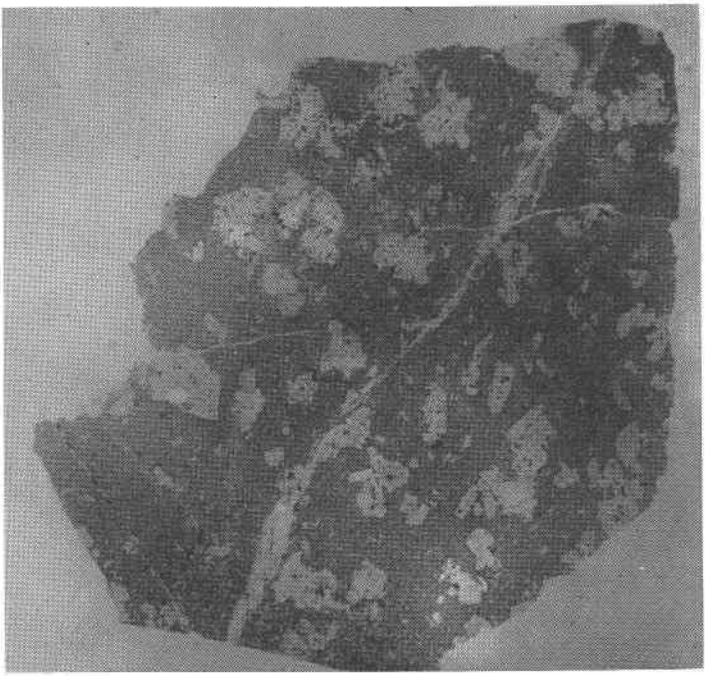

FIG. 9. Photograph (ordinary light) of a 5×6 cm. thin section of hornblende granulite, Cornucopia, Oregon. Note the glomeroblastic plagioclase with inclusions.

grouped in a radial fashion, have rounded outlines like miniature incipient orbicules, and display transitions from glomeroblastic aggregates to small but fully formed orbicules in the schist. Some of these appear to have developed around a core of schist.

These orbicules occur in zones about 50 feet wide and parallel to the schistosity. They range in size from less than an inch to several inches in diameter. Most of them are fairly regular ovoids with their major axes up to three inches in length. Although most of the orbicules are closely clustered, some are scattered in the adjacent fine-grained quartz biotite schist (Fig. 10). Around these scattered orbicules is a secondary schistosity which suggests that the growing orbicule pushed aside the minerals of the schist in a manner similar to a garnet porphyroblast. Where the orbicules are closely clustered, they are in the form of rounded polygons apparently due to mutual interference at the time of crystalloblastic growth. Some orbicules actually merge with one another. Where the orbicules are close together, the matrix loses its schistosity, becomes slightly coarser grained, and shows a marked increase in crystalloblastic feldspar. Even here, however, thin tabular relics of schist grade into the coarser grained matrix which otherwise has the appearance of a fine-grained granitic rock. Thin sections, especially large sections, of this orbicular rock reveal some of the complex textural features of glomeroblastic growth. In general the orbicules are plagioclase porphyroblasts or sheaf-like aggregates of andesine (An34) arranged in cross section something like a four-leaf clover with the intervening spaces occupied by crystals or aggregates of different orientation. The larger plagioclases commonly include other small plagioclases in various positions and irregular patches of unstriated feldspar. In some orbicules later formed oligoclase-andesine (An28–30) transects and embays the earlier andesine (An36–37) thus partly replacing it. Some of these earlier plagioclases have distinct outlines and may show rough zonal structures where the central part is more calcic than the outer zone. In other orbicules the plagioclase has a mottled appearance suggesting that it originally consisted of many individuals. Polished specimens of some of the orbicules display minute vugs which show crystal faces of the constituent minerals. It is clear from both the field and petrographic evidence that these orbicules are the result of crystalloblastic growth rather than magmatic crystallization.

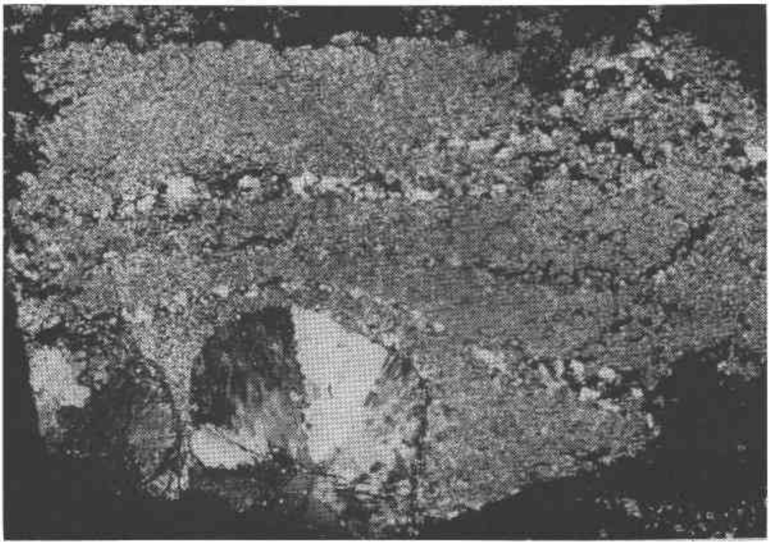

FIG. 10. Photograph (crossed polarized light) of a 6×9 cm. thin section of a biotite schist from Buffalo Hump, Idaho. Note the glomeroblastic plagioclase in the form of a 25 mm. orbicule.

Hornblende in rocks of magmatic derivation is commonly seen to have surrounded and replaced earlier pyrogenetic pyroxene. In rocks of metasomatic origin hornblendes may be seen in various stages of development: First, several small separate hornblende crystals have an over-all similar orientation as is shown by their extinction position; then a larger, very ragged inclusion-filled hornblende apparently is the result of a partial coalescence of the small crystals; finally, a more compact homogeneous crystal is formed. Although these hornblendes display a few crystal forms, some ragged borders and inclusions which persist give a clue as to their mode of origin.

Large biotite porphyroblasts may also develop from glomeroblastic aggregates of small flakes of biotite which appear to have coalesced into a larger individual with fairly definite crystallographic outlines. Such a large biotite porphyroblast will commonly have a poikiloblastic texture and crenulated border and show thin extensions into the surrounding groundmass.

Where porphyroblasts in any stage of development are fairly evenly distributed throughout a rock, it is an indication of either isochemical recrystallization or widespread permeability with respect to additive emanations or solutions. As the porphyroblasts develop, and as their number increases, the original material of the rock is either absorbed or pushed aside by them so that under favorable conditions they finally form a dominant part of the rock. Although the textural features of feldspathized rocks bear a superficial resemblance to those of magmatic rocks, they differ in that the later-formed feldspars are usually more euhedral than the earlier ones and the relict material consists of metamorphic minerals which commonly show some vestige of earlier metamorphic structures.

Later structural features such as fractures, fracture and shear zones, and brecciated zones are commonly a controlling factor with respect to subsequent feldspathization. This relationship is quite prominent in the Cornucopia hornfelses and is well shown in many places along the low level 6400-foot adit. Here zones of complex fracturing display varying degrees of feldspathization from single fractures lined with porphyroblasts to areas of feldspathization bounded by fracture and shear planes.

Where fracture planes are closely spaced the feldspathized body has a tabular dike-like form. These have been termed replacement dikes, and in the Cornucopia area they can be seen in various stages of development; namely, (1) the initial stage where closely spaced parallel fracture surfaces form a zone along which incipient mineralization has taken place; (2) partial replacement of the intervening screens of wall rock by appropriate minerals; and (3) finally, a complete recrystallization replacement with the obliteration of nearly all traces of the wall rock material. In some replacement dikes these traces of wall rock material are merely thin trains of relict minerals which retain their original orientation; in others, septa of the country rock extend from wall to wall or are in the form of projections into the dike (Fig. 11).

Replacement dikes have a wide range in mineral composition depending upon the character of the wall rock and the penetrative solutions. Where permeable zones are a controlling factor, they are likely to have gradational borders whereas control by two distinct parallel fractures or shears commonly produces sharp borders. In his study of aplite and pegmatite dikes in Nigeria, King (1948) gave an excellent description of non-dilation dikes with sharp borders. In contrast to igneous dikes, replacement dikes do not show field evidence of dilation such as appropriate offsets of wall rock units. Chilled borders are lacking, and there is no progressive change in grain size from the borders inward. There may, however, be local changes in grain size within the dike resulting in in uneven crystalloblastic texture with some minerals or aggregates of mineral much larger than others. These larger crystals lack the regularity in size that is usually seen in the phenocrysts of a porphyritic igneous rock.

FIG. 11. Photograph (ordinary light) of a 6×9 cm. thin section showing a contact of a replacement dike with a hornblende biotite schist. Note the thin lines of mafics extending from the schist into the dike, which also contains streaks of mafics having, in general, the same orientation as the mafics in the schist.

Some replacement dikes contain inclusions which look like xenoliths, but the lack of magmatic reaction products, the presence of schistosity similar in attitude to that of the wall rock as well as the textural and structural features of the dike do not favor a magmatic interpretation. As these inclusions become feldspathized with the development of porphyroblasts similar to the feldspars of the dike, they assume a shadowy appearance showing but little contrast to their crystalloblastic matrix and for this reason have been termed skialiths (Goodspeed, 1948).

Where initial fracturing of the country rock has been in roughly parallel planes, elongated relict fragments are the rule; whereas in cataclastic zones unoriented blocky relics are common. In the latter case, relict pieces of country rock may be seen in various stages of transformation from well defined fragments to hazy skialiths hardly discernible from the crystalloblastic matrix. It is also not uncommon to see two relatively large parts of a fragment connected by a thin link, thus negating the possibility of magmatic flowage of the matrix. Such fractures coupled with the crystalloblastic textures of the matrix warrants the term replacement breccias for these occurrences.

Replacement breccias are common along many of the granitic hornfels contacts where there are also much larger inclusions of hornfels in the granitic rocks. These large included blocks could, of course, be interpreted as remnants of roof pendants or as the result of magmatic stoping. Many field and petrographic data however do not favor this interpretation. Detailed plane table maps of several critical areas in the vicinity of Cornucopia, on a scale of 200 feet to the inch, show several large inclusions some of which are in two parts connected by a relatively thin link of hornfels. Another significant feature of some of these inclusions is the preservation of structural features such as remnants of plunging folds. These structures might be interpreted as the result of forceful magmatic intrusion, but such an explanation is very doubtful since the strike of these folds is nearly at right angles to the main granitic mass and some of them are truncated by the granitic rocks, and others appear to be undisturbed relics surrounded by the granitic rock.

Most of these larger blocks of hornfels have gradational borders with the granitic rock, and some have been changed to a migmatite consisting of numerous smaller irregular relict fragments interspersed with granitic rock. These fragments usually range from two to ten cm. in size and display the schistose texture which has an over-all general alignment despite the separation of the fragment. This alignment is, no doubt, inherited from the attitude of the original schistosity in the hornfels. In thin sections, the fragments exhibit typical crystalloblastic textures with hornblende and biotite in a parallel arrangement. There are also some porphyroblasts of plagioclase and hornblende and narrow bands of anhedral aggregates of quartz. In the granitic parts of the thin sections there are trains of mafics, hornblende, and shreds of biotite and elongated narrow aggregates of quartz anhedra (0.02 to 0.3 mm.) which retain the same general direction that they have in the hornfels fragments. Biotite has been partly replaced by feldspars as is shown by selective embayments along cleavages and minute linear inclusions of biotite in the feldspars. Many of the hornblendes can be seen to have been derived from the fragments, and as they extend further into granitic matrix, some are bent around the plagioclase crystals in the matrix. Here the feldspars range in size from 0.5 to 3.0 mm. and consist mostly of subhedral to anhedral oligoclase-andesine (An31) with a few anhedral crystals of orthoclase. Many of the plagioclases show various kinds of zoning and are quite complex, as though made up of several individual crystals grown together. Minute grains of metamorphic minerals, zoisite, garnet, and epidote are included in some of the plagioclases and also occur interstitially with grains of magnetite and sphene.

Other exposures along the numerous hornfels-granitic contacts at Cornucopia show similar textural features, and a few show a complete gradation from schistose hornfels into a gneissic rock which, in turn, grades into a granitic rock with a directionless texture. Locally, the granitic rocks display variations in texture and composition ranging from dioritic types to leucocratic and aplitic varieties. In general, however, as seen in hundreds of thin sections of specimens from all parts of the area, the granitic rock is a quartz-diorite with a seriate crystalloblastic fabric of anhedral to subhedral oligoclase-andesine (2+4 mm.) with interstial anhedral quartz, feldspar, and ragged flakes and shreds of brown or green biotite. This mineral as seen in most thin sections is positioned around the larger plagioclase crystals in such a way as to suggest that it had been pushed aside by the growing feldspar (Fig. 12).

Many of the plagioclases are complex crystals and some show oscillating zoning. In G.S.A. Memoir 52, R. C. Emmons (Chapter 9, p. 111) states: "Oscillatory zoning in plagioclase of an igneous rock is interpreted in Chapter 4 to reflect the role of liquid in crystallization. However, thin sections, especially large ones, may show the percentage of oscillatorily zoned plagioclase to be low enough to suggest that liquid has played a locally prominent but generally minor role. This irregular distribution of significant zoning has been observed in metamorphic rocks and in those which show brecciation. It is interpreted as a dilatant effect characteristic of metasomatic granites." Not only is there an irregular distribution of oscillatory zoned plagioclase in the Cornucopia granites but this feature is also noticeable in some of the porphyroblasts of feldspathized schistose hornfelses.

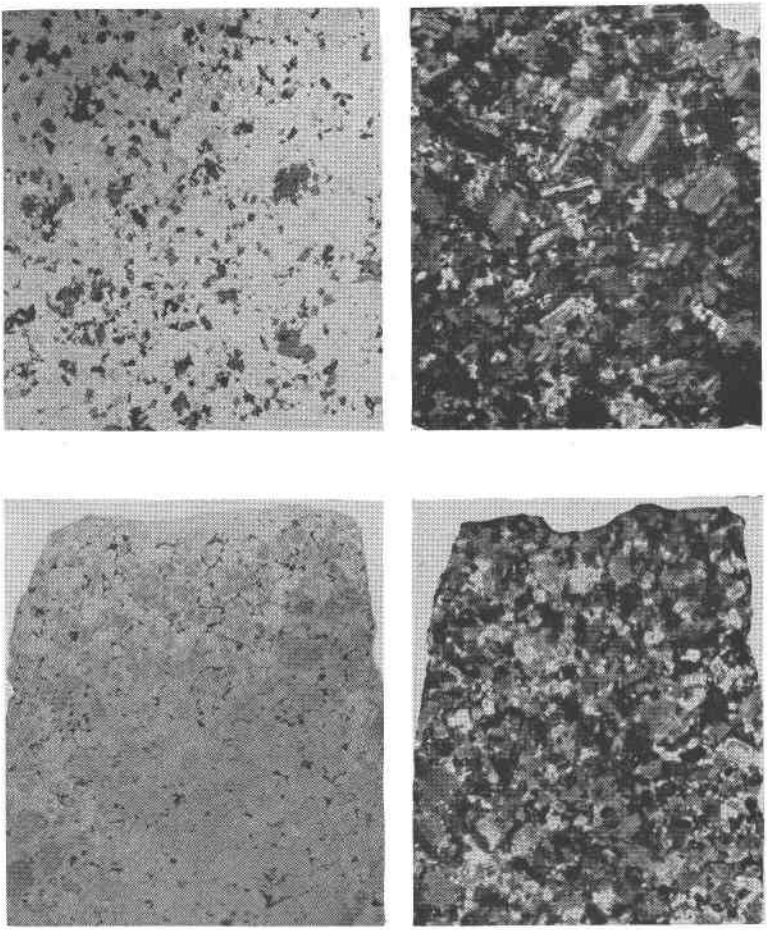

FIG. 12. Photographs (in ordinary light and crossed polarized light) of granitic rock; (1—above) 4×4 cm. thin section of a specimen from Boulder, Montana; (2—below) 3×4 cm. thin section from the lowest adit at Cornucopia, Oregon. Note that in (1) the early formed plagioclase is subhedral to euhedral, the quartz fills spaces between the other minerals, and the biotite is blocky. In (2) the later plagioclase is subhedral, most of the quartz is in rounded grains and the shredded biotite surrounds the plagioclase.

The preceding descriptions have had reference, in general, to metasomatized rocks where there has been a considerable change in grain size and mineral composition from the original material to the final product. If, however, the pre-existing rock happened to be an arkose, which already has a mineral composition and grains size comparable to a granite, the degree of transformation is much less. All stages of the transformation of an arkose to a granite have been well described by Coombs (1950) in a paper entitled "Granitization in the Swauk Arkose near Wenatchee, Washington."

Most of the examples of metasomatic rocks just described have been taken from relatively small rock bodies. Some large-size granitic masses occur in the central parts of metamorphic terranes. They usually grade into adjacent gneisses and schists which in turn blend into less metamorphosed rocks. Such features have been described by P. Misch (1949) in three papers entitled "Metasomatic Granitization of Batholithic Dimensions," in which he demonstrates the relationship of high-grade regional metamorphism to synkinematic granitization and its relation to static granitization. Since many kinds of metamorphic rocks are involved, wide variations in textural features are to be expected although the dominant pattern is a crystalloblastic one. In synkinematically granitized rock the minerals, especially the mafics, usually display a preferred orientation.

RELICT DIKES AND RELICT PSEUDODIKES

In some parts of the Cornucopia area are small dike-like bodies which can be seen to be definitely pre-granitic in age, because they are cut by granitic veinlets or penetrated by crystalloblastic extensions of the granitic rock. Their irregular or shadow-like borders and locally gradational contacts are indicative of partial replacement by the surrounding granitic rock. They also have attitudes nearly the same as the replacement dikes in the nearby hornfels, and this feature, coupled with their petrographic similarity to some of the replacement dikes, suggests that they were originally replacement dikes in the hornfels before it was transformed into granitic rock and that already having been changed from hornfels into a more granitic-like rock, they were able to resist further change and remain as relict dikes (Goodspeed, 1955). Similar relics of long thin tabular masses of schistose hornfels surrounded by the granitic rock also occur in this area. Since these are merely dike-like remnants of metamorphic rock, they are termed relict pseudodikes. The presence of relict dikes or relict pseudodikes suggest that the granitic rock was emplaced by a gradual transformation of the country rock because it is difficult to see how such thin tabular bodies could have escaped being disturbed by magmatic intrusion.

MOBILIZATION--RHEOMORPHISM—NEOMAGMAS

The textural features of rocks from some occurrences in the vicinity of Cornucopia are somewhat paradoxical in that they display crystalloblastic features common to metamorphic and metasomatic rock and yet have some features, including fluxion textures, which are characteristic of magmatic rocks (Goodspeed 1952). For example, a small leucocratic dike well exposed in the bed of Pine Creek, two miles west of Cornucopia, reveals features indicative of both replacement and mass flowage. A coarse gneissic rock is transected by this dike, and at one place near one wall delicate remnants of mafic minerals extend from the gneiss into the dike and retain their original alignment which is nearly at right angles to the dike. Along the opposite border, however, these mafic remnants appear to have swirled away from the wall and tend to become parallel to it. This occurrence is called a mobilized replacement dike. In other somewhat similar dikes, metasomatized material has apparently flowed as a neomagma into a dilated fissure. These are called rheomorphic dikes.

The textural features of some breccias also, like those of rheomorphic dikes, present the apparently contradictory evidence of a crystalloblastic pattern and fluxion textures. Some breccias in the Cornucopia area show, in part, the characteristics of a replacement breccia and also locally a flow alignment of mafic minerals in the matrix. Others also show a flow alignment of the fragments. Likewise, breccias in other localities; i.e., in the northern Cascade Mountains of Washington or at Sudbury, Ontario, the textural evidence of flowage is not only confined to the matrix but is emphasized by the rounded or drawn-out elongated character of the fragments. These have been termed rheomorphic breccias so as to differentiate them from static replacement breccias or from those of orthomagmatic origin, and to emphasize the interpretation that they represent the mobilization of a partly metasomatized rock mass (Goodspeed 1953).

CONCLUSIONS

Some rocks display field relations and textural features which present a clear picture as to whether they have resulted from the crystallization of a magma or from the transformation of pre-existing material. For other rocks where the textural features emphasize only the final stages of crystallization, detailed field evidence is of primary importance for petrogenetic interpretations.

The textural features of the rocks from some basic intrusive bodies delineate the changes in crystallization from a fluid magma to an essentially solid medium. Although different conditions modify the textural patterns, the sequence of crystallization is mainly an orderly one, as, for example: (1) High temperature minerals such as olivine, pyroxene, and calcic plagioclase are early in the sequence, and if plagioclase happens to form earlier than the pyroxene a characteristic criss-cross pattern is the usual result. (2) Although initially these minerals may be quite euhedral they will, if a slow rate of cooling prevails, be transformed in accordance with Bowen's reaction principle so that they become merely relics. (3) In the later stages of crystallization, minerals lower down in the reaction series may replace, surround, or form interstitially to, the earlier minerals. Some of these later minerals may be euhedral and others anhedral, dependent upon immediate environmental conditions. (4) The very late magmatic or deuteric stage is characterized by low temperature minerals which commonly show crystalloblastic and replacement textures. (5) Finally, hydrous minerals like the zeolites may appear. Some intrusions such as the Yogo Peak body in the Little Belt Mountains of Montana show a range of crystallization of an orthomagma from a shonkinite to granite porphyry.

The textural features of metasomatic rocks are similar to those of metamorphic rock, in that crystalloblastic textures are dominant and show a crystallization sequence which is not an orderly one like that of a magmatic rock. Minerals, such as feldspars, which may in part be due to the addition of material, can be seen in a single thin section, in forms indicative of their development from initial amoeboid ones to nearly euhedral crystals. The recrystallization of a pre-existing rock is indicated by helicitic structures, the presence of rounded grains of quartz or relics of typical metamorphic minerals like kyanite. Another indication that crystallization took place in an essentially solid medium is where earlier minerals seem to have been pushed aside by later ones. For example, in some granitic rocks ragged shred-like flakes of biotite surround large plagioclase crystals somewhat similar to the way they enclose garnet porphyroblasts in a metamorphic rock. In the field, metasomatic rock masses commonly show widespread gradations into the surrounding metamorphic rocks, in contrast to the limited extent of metamorphic aureoles around intrusive bodies.

Intrusive field relations, however, do not necessarily mean that the rock body has been formed by the crystallization of an orthomagma or that it is of orthomagmatic lineage. This holds for some granitic bodies which are clearly intrusive and which are commonly termed igneous. Their textural features, however, may indicate one of three possibilities with regard to their mode of origin, namely: (1) Direct crystallization or differentiation from an orthomagma; (2) Mass flowage of a late magmatic or deuteric fraction; that is, a deuteromagmatic origin; (3) Mobilization or mass flowage of metasomatized material, namely, a neomagmatic origin. This last possibility is perhaps the most difficult to recognize because it depends in part upon the presence of relics of metamorphic minerals.

With respect to some relict minerals, the question arises as to whether they are of metamorphic or of magmatic origin. For example some intrusive granitic bodies contain relics of pyroxene, and since this mineral is common to magmatic rocks the interpretation of a magmatic line of descent is usually proposed. Pyroxene, however, is also found in some metamorphic rocks. Therefore the mere presence of pyroxene does not furnish a definitive answer to this question. What is needed are data to show, if possible, whether a particular mineral was originally crystallized from a magma or was formed by rising temperature in a solid rock. Perhaps laboratory experiments in the future will disclose whether there are any slight but significant differences in artificial rock-forming silicates produced from melts as compared with similar ones formed by heating material that is essentially solid.

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