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THE CONTRIBUTION OF DIFFERENTIAL PRESSURES TO MAGMATIC DIFFERENTIATION.

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ABSTRACT. Bowen has shown that during the crystallization of magmatic liquid the two phases, crystals and liquid, may have very different composition. At this stage differentiation is merely potential. Its realization requires the physical separation of these two phases. Among the processes already recorded in the literature, one is not receiving adequate attention. It is the separation of liquid from crystals through pressure differentials, created by fracturing of brittle wall rocks. This, I believe, is a leading process in separating granitic liquid from more basic crystals.

IT is the purpose of this paper to offer a simple explanation of the following field observations, based on the movement of magmatic mother liquor under structural control through pressure differentials. (1) The outstanding difference between pegmatites and aplites is textural. (2) The upper parts of most intrusive bodies are higher in mineralizers than the rest of the mass, despite the reasonable expectation that diffusion must be aiming at equalization. (3) Those zones, where stoping and assimilation are believed to have been active, in intrusive bodies of different kinds of rock, are commonly characterized by aplitic, granophyric, or micropegmatitic texture. (4) Field relations suggest that granite may produce syenite under the influence of quartzite. (5) Fenner and others have called attention to the observation that gabbro commonly has two kinds of pegmatite, one characterized by calcic plagioclase and the other by sodic plagioclase and even quartz. (6) Feldspars showing zoning and oscillatory zoning characterize dioritic rocks and especially hybrids.

It is anticipated that the following postulates will be acceptable to the reader and may serve as premises for further argument:—(1) Structural disturbance of both the intrusive and the containing rocks commonly accompanies intrusion. In the following discussion only those cases are in mind where this is true. (2) The residual magma accumulates first interstitially to the growing crystals in a cooling magma and from here may be collected in later formed, sizeable, openings. There is no other original "residual magma chamber." (3) By the time the cooling magmatic material has reached the stage where the term "residual magma" in its popular connotation, may be applied to the interstitial liquid, the igneous body is sufficiently crystallized to behave in many respects as a solid body—weak and mushy, but solid, in that crystals in contact offer resistance to shearing stresses and such stresses are a necessary concomitant of deformation. (4) It is not at all exceptional for diaschistic dikes to be multiple or in a very real sense composite. (5) The tension cracks that form near the margins of cooling intrusive bodies, and may become diaschistic dikes on proper filling, develop progressively and not simultaneously.

The Dilatancy Principle.[1]

Of fundamental importance to the development of the present topic is the realization that the fracturing or brecciation of a rock is accompanied by an increase in volume. This increase in volume is essentially to be measured by the voids created by the deformation. The newly created voids in a rock broken in air are of course filled by air, but such voids in a rock broken in a closed system become regions of relatively low pressure and to them will flow any mobile (fluid) material available, which is under higher pressure. Assuming the fluid pressure to have been hydrostatic prior to brecciation, then the voids in a brecciated rock become filled with available fluid *as they develop.*

The conditions set up above may be those of a rock which is brittle enough under its environment to yield to deformation *by fracture*, while being intruded by igneous material. In this way dikes or apophyses of the intrusive reach out or are drawn out from the intrusive into the walls and roof. The specific composition of such dikes and apophyses must depend greatly on the degree of crystallization of the parent body. In the early stages when the mass is largely liquid and yields as a fluid to deformation, the offshoots will necessarily have the same composition as the parent. But with advancing crystallization the fluidity of the mass changes as does the composition of the residual liquid. When the growing crystals engage each other the establishment of a differential pressure leads to the selective migration of the liquid phase to the region of lower pressure. *This is a physical separation of two magmatic substances of very different composition, from a common source.* Mead realized the importance of this process when he wrote,[1] "After this potentially dilatant condition of the magma has been reached it seems reasonable to suppose that any openings or fissures in the surrounding rocks will be filled not by movement of the magma as a whole but by the flowing out of the fluid phase under the fluid pressure of the liquid magma from the interior of the mass." Such physical separation of two magmatic phases is the complement of chemical differentiation. It may be seen in the field in all stages of development. Two stages, also mentioned by Mead,[1] are selected for field illustration. He says, "The potentially dilatant mass itself would also be capable of fracture under rapid deformation, and these fractures would be filled likewise by the fluid phase . . ." Such are the indefinite tabular masses which are most frequently seen perhaps in granite cupolas. The feldspar is commonly of the cleavelandite type, sericitized, the interstitial areas are graphic or myrmekitic and the boundaries are difficult to locate, in fact, more easily seen by standing back from the outcrop. In Plate I*, Figs. 1, 2, 3 and 4 these features are illustrated from exposures in Baxter Hollow of the Baraboo range, Wisconsin. The area shows an apparent granite cupola cutting the Baraboo quartzite and well crowded with inclusions of variously modified rock types. Vertical or nearly vertical channels through the inclusion-crowded granite may be found where the rising liquid has flowed. Some of these are filled with granite, clean and fresh and contrasting sharply with their walls. Those illustrated are interpreted as the beginning of such channels through partly assimilated material. They consist of fractures along which active solutions have initiated the crystallization of highly tabular feldspar and graphic quartz. Although the feldspar stands out prominently in the hand specimen it is seen under the microscope to be completely sericitized. Rather similar effects have reached into the wall rock. In outcrop, the "dike" stands out quite prominently. The most appealing in-

* Plate I. Figs. 2 and 3 are taken with "crossed nicols." Plate I, Fig. 6 is taken in ordinary light. All other photomicrographs are taken with "crossed nicols" and with the gypsum plate to reduce contrast caused by extinction. All magnifications are objective times ocular.

terpretation of such an occurrence is,—a fracture in the wall or roof of an advancing intrusive, which, being a region of lower pressure, was fed by solutions from the intrusive, such solutions being the still liquid part from interstitial areas, that is the residual liquor.

A crystallizing magmatic mass must yield to deforming stresses in a manner which depends very closely on the degree of crystallization. Early in its history it yields as a liquid, later it yields as a solid, but there is an intermediate stage in which the growing crystals have been able to establish only a loose bond. Deformation at such a time not only shatters the bond, but by disturbing the crystal arrangement results in a less closely packed condition. To such an area residual liquid flows, and as usual leads to a local concentration in quartz and the alkalies. Sericitized feldspars are typical. Since the introduced material is apt to impart a lighter color to the rock, the effect is especially well seen in a gabbro which is usually dark. An excellent illustration is to be found in the Duluth gabbro in the new rock cuts of the Skyline Parkway, in the City of Duluth. This is illustrated in Plate II, Figs. 5, 6 and 7. The sericitic alteration is evident in the photomicrograph. Mead conceived of this possibility when he said, "Zones of deformation not resulting in fracture of the partly solidified magma would conceivably produce zones of more open packing of the solid grains resulting in a greater proportion of the fluid phase . . ."

Five years earlier than Mead's paper quoted above, Bowen thought along similar lines, though at that time he preferred to stress the crushing and squeezing of a crystal mesh to force out interstitial liquid. Bowen[2] said "It is not difficult to conceive of a distribution of forces in the heterogeneous surroundings of an igneous mass, such that locally the liquid might be sucked out of a crystalline mesh which would acquire a miarolitic texture, temporarily at least."

Shannon[3] also employed the principle of pressure differentials for the same purpose four years after Bowen's paper when he said, "In larger intrusive masses, however, the volatile constituents seem to concentrate in centers whose location is determined by some unknown factor. Differential movements might result in local areas of lessened pressures and here gases would tend to concentrate and pegmatites might form."

Seemingly the mobility of the residual liquid of crystallizing magma during structural deformation is a recognized fact. Unknown, however, is the scale on which this principle operates. It is doubtless true, too, that we can explain more simply and directly on this basis some phenomena which are now the subject of controversy. Andersen has offered on this basis the first satisfactory explanation of the difference between aplites and pegmatites, as discussed below. I shall attempt to apply it also to certain other puzzling, selected occurrences to which I believe it is best suited.

The Genetic Difference between Aplite and Pegmatite.

In a given outcrop of granite showing diaschistic dikes, aplite and pegmatite may be seen to cut each other in a most confusing manner, such that the mutual age relationships are repeatedly reversed. If, according to the general beliefs, we regard both as the fillings of tension cracks, doubtless due to cooling, and if as postulated earlier we believe the cracks to have been formed progressively, then a given crack, filled by pegmatitic liquid and solidified may be cut by a later intersecting crack which may become either another pegmatite dike or an aplite. And a continuation of the process, easily and reliably accounts for the involved age relationships.

There remains to account for the textural difference. The most available liquid for the filling of these tension cracks as the granite crystallized is the liquid interstitial to the growing crystals from the immediate walls of the crack. The original filling of the cracks may quite safely be assumed to be wholly or largely liquid, from which crystals have been growing and which was therefore in essential crystallization equilibrium. It migrates from the interstices to the larger opening under the influence of the pressure differential which any new opening in such a closed system establishes. Such a crack, filled with rest magma, is a future pegmatite or aplite dike—the history of both must so far be the same. There seems to be rather general agreement that such a body, undisturbed especially with regard to its high mineralizer content, leads to the formation of a pegmatite dike. In agreement with that view let us turn to the possible influences that may modify the history of the crystallizing dike to produce an aplite.

The shape, distribution, composition and age relationships of aplite dikes leave little room for doubt that they were derived from the same rest magma as pegmatites, at the same general time as pegmatites and by the same means. But after accumulation their histories differ. Since the outstanding difference is textural then the modification must be one that affects the coarseness of crystallization. Since there is excellent laboratory and field evidence to indicate that rest magma is liquid mainly by virtue of its high mineralizer content then we may search for a cause for the removal of water. As Andersen points out,[4] the removal is most easily explained by the differential pressures established by the formation of new cooling cracks. This release of pressure he believes would permit gas bubbles to "run away from the magma." In this way he establishes a separation of pegmatitic magma substance and its volatiles, and he continues, "when the magma later had a chance to fill some of the openings it was impoverished in volatile constituents . . . and would form aplite." Such an explanation satisfies all the main requirements for the formation of aplites and may be complete as it stands. I believe, however, that the miarolitic nature of many aplite dikes indicates that the loss of gas followed emplacement rather than preceded it. This thought is supported in two ways. First, when there is special reason for an aplite not to have been crushed, such as that described below, it is apt to be more noticeably miarolitic. That is to say, these cavities indicate loss of gas in place and that ordinarily they *have* formed but have been closed by subsequent deformation. Second, the tenuous nature of aplites, comparable to that of pegmatites, indicates equally low viscosity and requires the presence of mineralizers at the time of emplacement.

Ordinarily the formation of each new cooling crack is facilitated by relative movement of the walls of one or more earlier formed dikes. Such movement crushes the rapidly crystallizing aplitic material and yields the textures most commonly seen. Johannsen[5] says, for instance, of the quartz of aplites "Undulatory extinction is common and there is frequently a cataclastic texture shown in fragmented border zones around the individual grains. This fragmentation may go so far that the original saccharoidal character disappears and the rock takes on a schistose appearance."

Not always is the crystallizing aplitic material crushed as, or after, the mineralizer content is removed. In Fig. I, Plate II, Fig. 8, Plate I, Figs. 5 and 6, are illustrated views of aplite dikes in which the first formed euhedral crystals and their interstitial voids, doubtless once filled by gas, have outlived such crushing and shearing. Miarolitic aplite dikes, of course, are not rare. This one is unique in two respects,—it is extensively miarolitic, and it represents the second filling of a crack, the first being a quartz vein. The quartz vein had become sufficiently resistant to shear that when shearing pressures were applied it merely brecciated coarsely and protected the aplite

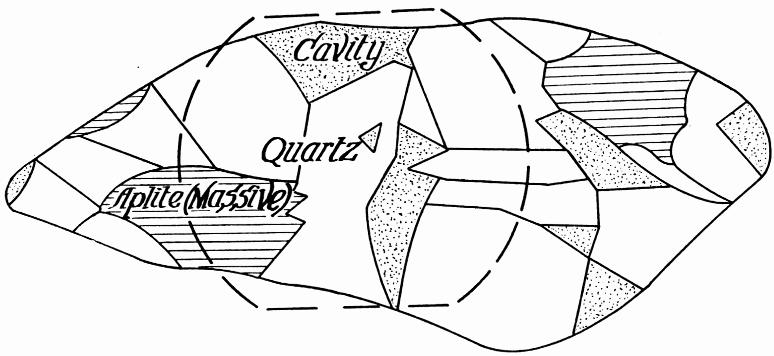

Fig. 1. Sketch of a specimen of an aplite dike showing brecciated quartz vein material filled interstitially by later aplitic material. From the "black granite" quarry one mile north of Mellen, Wisconsin. The portion shown by the dash line is illustrated photographically in Plate 2, Fig. 8.

filling from the crushing that ordinarily leads to true aplitic texture.

It is not intended that this suggested mode of origin is to be applied to all aplite dikes, but to a considerable proportion of them, and to virtually all that show miarolitic cavities. The sequence with the modifications listed, follows—A cooling crack is filled with residual magma. If this is undisturbed a pegmatite results. If, however, a subsequent cooling crack intersects, and therefore taps it, after partial crystallization, there is loss of gases and an arrest of crystallization. Cavities are formed. The remaining liquid, lacking mineralizers, crystallizes rapidly and finely. The later formed cooling cracks accompany crushing unless it is inhibited by special conditions. The crushing of new born crystals is most directly responsible for the recognized aplitic texture.

A crack filled with mother liquor may partly crystallize to a pegmatoid mass and the remainder lose its mineralizer content and become an aplite. Such mixed dikes are not at all uncommon. But these may sometimes have a different origin being actually multiple dikes, the first injection completing its history as a pegmatite before the second injection enters the reopened fissure.

The process outlined here explains, I believe, a common type of aplite dike rock. It may also explain the aplitic rock types which are to be found along the margins of sizeable igneous bodies such as the southeast margin of the intrusive granite area of Wisconsin, quarried in the Montello quarry and well exposed in Poppy's rock south of Shawano. This type of rock is aplite-appearing in the field but under the microscope is characterized by a considerable amount of vermicular quartz, myrmekite, and micrographic granite. The simplest explanation of the high quartz content of these marginal phases is to be found in the dilatant accumulation of residual magmatic material near and in the shattered, and perhaps assimilated wall rock (here a rhyolite). The aplitic texture is to be expected, since almost identical conditions prevail here as prevail in aplite dikes, namely, movement of the walls and the progressive drawing off of mineralizers as a consequence of such movement. This process will be discussed again below in connection with the origin of "red rock."

The Accumulation of Mineralizers Upward.

The concentration of vesicles and amygdules in the upper parts of flows is easily understood. But through sericitization and other deuteric effects in the upper parts of intrusive bodies, attributable to the action of at least some concentration of mineralizers, we are aware of the accumulation of these volatiles upward. Batholithic cupolas are characterized by deuteric minerals.

The well established principle of crystal settling does little to account for the upward migration of volatiles since only ferromagnesian minerals and some metallics are seriously involved. The feldspars which comprise the great bulk of our common intrusives apparently neither rise nor fall in magmatic liquid on a scale sufficiently large to lead to a concentration of residual magma.

Again the simplest explanation of this upward migration lies in the structural history of the intrusive and its roof. Earlier the structural disturbance of both the intrusive and its containing rocks was postulated. Our ability to read the history of the intrusive grows with its degree of crystallization, since the earlier history of such a mass is apt to be blurred or erased by later events. Especially, the structural disturbance of a magmatic mass which is dominantly liquid can lead only to better mixing and not to segregation. But when the degree of crystallization brings growing crystals in contact and prevents their free movement unhindered by each other then the body begins to assume the characteristics of a solid—it develops shear planes when deformed, and these shear planes, being regions of low pressure established through volume increase serve as spots of accumulation of mobile material. They serve also as solution channels for the further migration of the most mobile liquids. Since they originate from the walls they commonly lead to the walls at those points where deformation is most intense. In other words a cycle is established whereby faulting, brecciation or folding of the walls, especially of the roof as the weakest part, leads to the development of a means of transporting the most mobile part of the magmatic liquid to those points. Any deformation of the wall rock which is not purely plastic but creates openings, in turn creates additional differential pressure, all leading to further migration of liquid magma to this part. And to complete the cycle the concentration of mineralizers establishes the most favorable conditions for further stoping or assimilation. The essential point is then that structural deformation establishes a focal point of accumulation of rest magma. And since structural deformation is most manifest in the upper parts of a magma chamber the mineralizers gather here. There is ample field support for the view that the lower parts *by comparison* suffer less stoping and a deformation of a more plastic type, leading to fewer openings.

The Red Rock Problem.

In logical sequence with the foregoing, which is concerned with the upward movement and accumulation of residual magma and late exudates, is a consideration of the common granophyric masses which overlie more basic rocks and intrude them.

These, frequently discussed as "red rock," still present enough difficulties that opinions on their origin differ. An extreme view was presented recently by Bastin,[6] in a study of the classic Pigeon Point area. In July of 1939 I visited Pigeon Point with the ideas already outlined in mind. As a result of this study I should like to support the view of Grout[7] and Daly[8] that the granite is a differentiation product of the gabbro, and I should like to outline my reasons for so doing.

The numerous published descriptions of the geology of the Point make a review unnecessary. The later papers agree on the general picture of a gabbro, grading upward into an intermediate rock having some red feldspars, and this in turn passing up into a red rock which is granite in places, and almost a syenite in other places. In some outcrops the granite cuts the other igneous rocks. Above all is a quartzite, much modified by contact action and cut by apophyses of granitic material, much of which is highly miarolitic. Some inclusions of quartzite in the intermediate rock are surrounded by rims of granite which are regarded by Grout as a reaction product between the gabbroic material and the quartzite. Bastin has adequately stressed the prevalence of hydrothermal alteration, but he concluded with reservations that the granite is a separate intrusive.

Assuming familiarity with the literature on Pigeon Point, for brevity, I shall offer my interpretation as a suggested sequence of events—Into the quartzite was intruded a gabbro liquid, after which there was sufficient disturbance of the overlying quartzite to cause the extensive shattering of the roof. Into these fractures, which continued to develop as the sill crystallized, was drawn the available residual liquor much of which crystallized as granite and pegmatite apophyses, as a network around the quartzite blocks. This process continued as the sill crystallized until the last apophyses were frozen in place and can now be seen. In the earlier stages some of these were also frozen but with continued disturbance were again ruptured along the old breaks as the lines of greatest weakness, and these blocks became incorporated in the intrusive. Some may have been wholly assimilated, others with their enveloping granite rims constitute the blocks now seen. The granite rims on this basis represent remnants of earlier apophyses rather than reaction rims produced by the immediate influence of gabbro on quartzite. Also on this basis much or even most of the hydrothermal alteration of the quartzite inclusions is to be attributed to the earlier influence of the volatile-bearing apophyses rather than to the gabbro in which the inclusions are now found. In fact such alteration by the gabbro must first penetrate the granite envelope to which the gabbro (intermediate rock) is now remotely related.

The influence of the quartzite, if this interpretation is correct, is only in part chemical, and is in large part mechanical or structural. It served in this way to draw constantly upward in the sill the more mobile constituents, causing the granitic liquid to accumulate at the top of the sill, a direct derivative of the gabbro, modified to an unknown extent by the assimilation of quartzite. The granite thus segregated is free to intrude the gabbro which would be the first to solidify. The crystallizing granite is also subject to the same structural influence as the crystallizing gabbro, and locally lost its own rest magma, largely quartz, to produce the areas of syenite.

Some very pertinent statements by Grout merit repetition. He shows that the Pigeon Point red rock contains about twice as much alkali as *either* the gabbro or the sediments, and uses this forceful argument in support of the differentiation hypothesis. He terms this concentration of alkali an "unanswered question." He says,[7] "How an inclusion might cause or modify a differentiation in a magma without making any notable contribution to the magma is obviously a puzzling question." Does not this mechanical influence of the quartzite roof drawing off the high alkali residue of the crystallizing gabbro answer Grout's question?

Comparing the Pigeon Point red rock with similar occurrences elsewhere would seem to stress the structural factor in the realization of a granite differentiate from a gabbro. On the north shore are many other sills cutting other types of rock, and showing less striking differentiation. In the city of Duluth, Minnesota, is a locally well known sill between basalt lava flows, rather than in quartzite. Differentiation is much less marked. Moore, in his study of the Cobalt district, says,[9] "It may be observed also that in the Cobalt district the granophyre (red rock) and aplite are most extensively developed in those areas where sediments of the Cobalt series are widespread and not where the diabase is directly in contact with the Keewatin rocks." Bastin recently said of the Cobalt district red rock,[10] "In some cases a distinctly dike-like mass of red rock in diabase can be traced along its trend into continuity with the red portions of an irregular body of mottled red and green rock." His description of the mottled red and green rock shows a strong similarity to the intermediate rock of Bayley[11] on Pigeon Point.

New rock cuts made during the summer of 1939 in connection with the widening of the Sky Line Parkway of Duluth show granite apophyses cutting the gabbro. Bowen made similar observations in the Duluth gabbro ten years ago and said in this connection in his paper on the *Deformation of Crystallizing Magma*,[12] "The down-warping of the tabular mass of crystallizing magma would seem to necessitate the development of fracturing—This action opens the possibility of the filling of . . . 'fissures' with liquid from the interstices of that portion of the adjacent mesh that happens to be weakest and of developing layers that have approximately the degree of contrast shown between crystals and residual liquid at the time the action takes place. . . local crushing of the mesh, formation of 'fissures' and their filling with liquid are absolutely synchronous."

Syenite from Granite and Quartzite.

Let us next consider the dilatant effect of different rock types on rising magma. Since the operation of the principle of dilatancy is dependent upon the creation of openings in a closed system, it is evident that the dilatant accumulation of rest magma will not be realized in rocks which yield in a plastic manner. In other words, we may look for the most effective accumulation and migration of rest magma in brittle rock types. Let us take a theoretical case and then illustrate it with actual field examples.

Perhaps the most brittle of the common rocks is quartzite, and the most "juicy" of the common magmatic materials is granite. When a granite intrudes a quartzite, accompanied by deformation, then we may expect a maximum of the dilatant effect and a variety of rock types. An advancing granite magma on encountering a quartzite meets a refractory barrier as has been described and observed too often for further discussion. The progress of the granite without structural assistance is virtually arrested if the quartzite is at all pure. If, however, we assume movement in the roof, producing brecciation of the quartzite an ideal condition for the present purpose is established. Between the quartzite blocks, regions of low pressure are established; and these regions are filled with the most mobile material which the granite magma contains, namely, the rest magma. If movement stops at this point then a section would show granitic material, above which are apophyses, including pegmatite and aplite, cutting the quartzite. And according to the purity of the quartzite, these apophyses being the most active part of the intrusive will react more or less with the quartzite. To carry this theoretical process one step further, if the movement which gave rise to the brecciation of the quartzite were sufficiently vigorous and prolonged the draining of the interstitial rest magma from the granite would produce a modification of the granite as well as a more profound modification of the quartzite. A crystallizing granite, deprived of its rest magma at the proper stage of its crystallization yields a syenite. A quartzite impregnated with granitic rest magma may yield a variety of rock types ranging from alkaline to siliceous.

Near Wausau, Wisconsin, in Rib Hill State Park, is a considerable body of quartzite, underlain by syenite. The syenite is in turn surrounded by granite, well exposed except to the southeast. In the theoretical description given above, this particular occurrence was in mind. There is no known limestone within many miles which could have desilicated the granite. Outcrops of granite, on the southwest approach to the syenite, apparently show a progressive decrease in quartz content, though more numerous exposures might change this observation. Although the association of granite, syenite, and quartzite may be merely coincidental, there is some evidence to support the interpretation offered.

The genetic relationship between the granite and the syenite is supported by the apparent gradation between them already referred to. It is also supported by the similarity between their heavy mineral suites and especially by the presence in both of traces of molybdenite. The most critical question then is—Did the quartzite drain quartz from the granite? With this idea in mind the writer assisted by Messrs. R. M. Gates and Dan Turner searched Rib Hill for evidence of vein quartz. Rib Hill quartzite is a pure white quartzite—lithologically indistinguishable in the field from the Lorraine quartzite of the original Huronian area. Vein quartz cutting this is no more evident than a white rabbit in a snowstorm. Exposures are good, however. We found innumerable possibilities parallel to the bedding but these I have always mapped as "cherty quartzite beds" according to the custom of geologists of the Canadian Pre-Cambrian. We found one very instructive exposure about one hundred feet north of Sunset Point on Rib Hill, sketched in Fig. 2. Since this cuts the bedding sharply it is un-

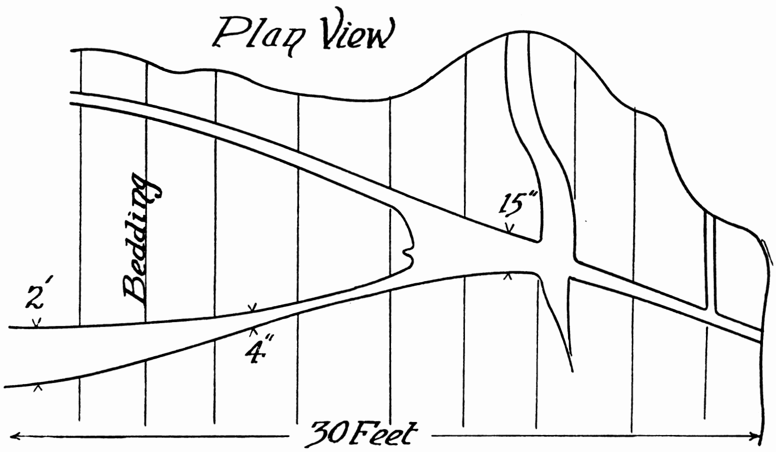

Fig. 2. A field sketch of vein quartz cutting Rib Hill quartzite both across and parallel to the bedding. This exposure is on the trail, about 100 feet north of Sunset Point. See Plate 1, Figs. 7 and 8 showing the identical nature of the two rocks.

questionably vein quartz. But, as shown in the figure, the true vein is continuous with "cherty quartzite beds." I do not believe the vein could be contemporaneous with the quartzite and am forced to the conclusion that at least *these* "cherty quartzite beds" are vein quartz. We estimated the cherty quartzite beds to be three-five per cent of the quartzite where best exposed. If this is vein quartz, deposited from the granite, then the disposition of the quartz on the desilication of the granite is no mystery. Plate I, Figs. 7 and 8 are two photomicrographs illustrating the difficulty of recognizing the vein quartz in quartzite. No distinction is apparent.

A diligent search failed to reveal the base of the quartzite.

An abundance of float, however, suggests the nature of the rocks at this horizon. They are in the freshest specimens arkosic, and in the most altered specimens virtually pure perthite. Intermediate types predominate in the specimens collected from the southwest flank of the hill. The three stages are illustrated in Plate II, Figs. 1, 2 and 3. The mutual field relationships are not revealed. It seems, however, that alkalies have been contributed to the rocks at the base of the quartzite and that the silica continued farther up to be deposited in the quartzite as quartz veins. Or, stated interpretatively, the base of the quartzite, some of which is arkose, was intruded by granitic magma, which as it crystallized and as the quartzite above was deformed lost its residual liquor to regions of lower pressure above. As this residual liquor streamed upward through growing feldspar crystals the alkalies were filtered out to convert the feldspar to perthite and the remaining silica-bearing liquid continued into the quartzite to deposit quartz veins.*

This mode of origin of the syenite on Pigeon Point under the influence of quartzite has already been mentioned above. The relationships appear to be entirely analogous.

The granitic cupola of Baxter Hollow,† in the Baraboo range of Wisconsin, referred to earlier, contains among its numerous interesting rock types a high-feldspar rock, found in several outcrops. These masses are irregular in shape, and apparently fill large spaces between inclusions. This rock is regarded in point. I can conceive of no other cause of the segregation of feldspar in this environment and from a granite. To be specific —I believe this feldspar to be trapped from flowing magmatic liquid—liquid in which feldspar was virtually the only crystal

* These rocks, which are here interpreted as basal to the quartzite on account of the lack of outcrops may be viewed in another light. Lithologically they are lestiwarite[5], (Vol. 3, p. 25) an uncommon hypabyssal rock of the alkali syenite family. Such an interpretation is better suited to the views being offered here but until outcrops are discovered which reveal a dike-like occurrence I prefer the simpler explanation of a modified arkose. But especially any occurrence of an alkaline rock type between granite and quartzite has significance in this discussion.

† Stark[13] draws no conclusion relative to the age of the granite or its intrusive relationship to the quartzite. Geo. Field, in an unpublished thesis (University of Wisconsin) believes the quartzite to rest on the granite. I believe there is good evidence that the granite is an intrusive cupola, younger than the quartzite. In any case, for the present purpose, the granite is crowded with inclusions and heavily modified by their influence. These rocks are being re-studied in detail by R. M. Gates. His report should appear shortly.

growing, and in which feldspar units were numerous enough for mutual interference of free movement. At a favorable constriction in the solution channel, such moving crystals are apt to bridge and thus form their own filter. Continued flow of rest magma through the voids, interstitial to the crystals, leads to sericitization. Plate II, Fig. 4.

To repeat, the essential requirement for the best operation of this process is the structural disturbance of *a brittle rock which is being intruded.* Quartzite is not the only brittle rock which is apparently capable of creating an adequate dilatant effect on an intrusive. On highway "State 32," two miles south of Mountain, Wisconsin, exposed in a road cut a younger granite may be seen cutting an older granite. This observation has been checked also in the laboratory by Dr. S. A. Tyler, employing his newly developed heavy mineral technique. The younger granite follows a trend slightly north of east along which much syenitic material may be found, together with an abundance of pegmatite. Since the distinction is between two granites, the field evidence is not so clean cut but the principle of dilatancy seems clearly to have been operative to produce the syenite. And granite as a rock type is second only to quartzite in refractoriness and brittleness.

PLATE I.

Fig. 1. Two dike-like masses cutting the contact zone in the roof of the Baxter Hollow granite.

Fig. 2. Another view of the same showing the right-hand dike more clearly.

Fig. 3. Photomicrograph (X45) of the wall rock of Figures 1 and 2, a few inches from the dike. Note especially the high quartz content and its granular appearance.

Fig. 4. Photomicrograph (X45) of the dike rock of Figures 1 and 2, showing the tabular feldspars highly sericitized and the myrmekitic texture.

Fig. 5. Photograph (X2.5) of a specimen of aplite from a dike in the first quarry north of Mellen, Wisconsin. Note the extremely high pore space.

Fig. 6. Photomicrograph (X6) of a thick section of the rock shown in Figure 5. These openings are interpreted as gas bubbles formed by the release of pressure after partial crystallization. This loss of mineralizers arrested further crystal enlargement.

Fig. 7. Photomicrograph (X30) of vein quartz on Rib Hill (see text Fig. 2).

Fig. 8. Photomicrograph (X30) of adjacent quartzite to that of Fig. 7. Note the similarity between Figs. 7 and 8. This illustrates the difficulty of recognizing vein quartz in Rib Hill.

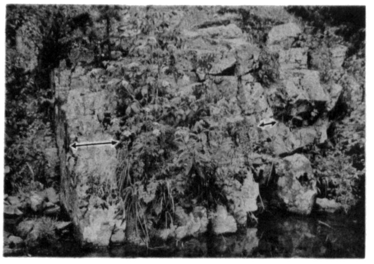

FIG. 1

FIG. 2

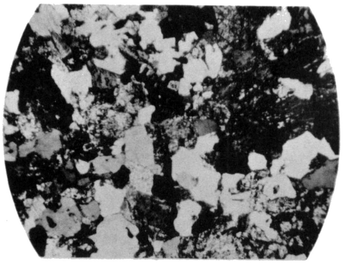

FIG. 3

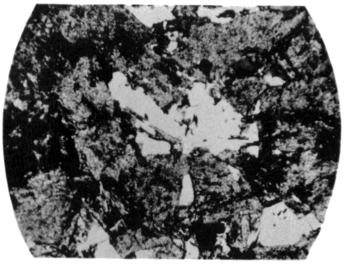

FIG. 4

FIG. 5

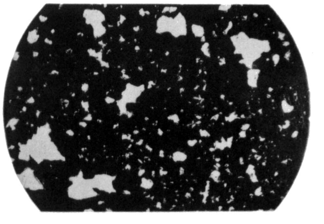

FIG. 6

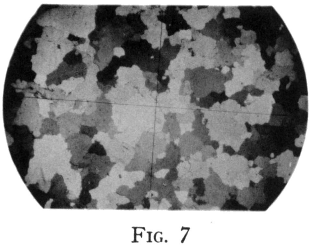

FIG. 7

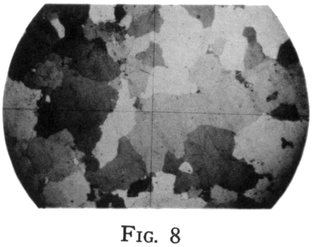

FIG. 8

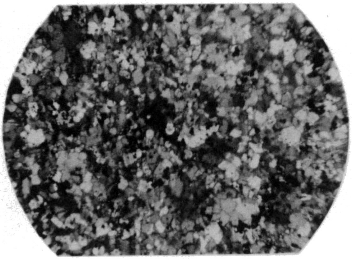

FIG. 1

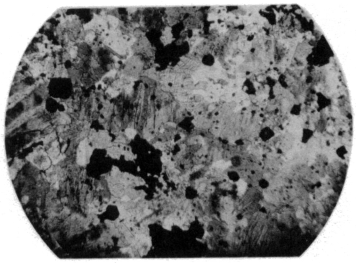

FIG. 2

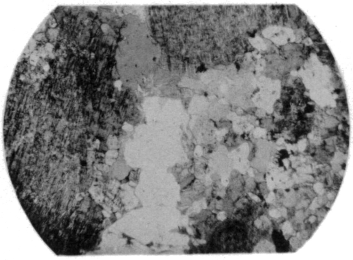

FIG. 3

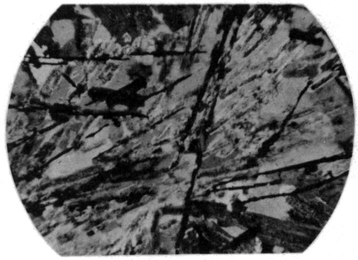

FIG. 4

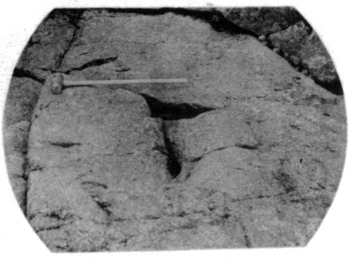

FIG. 5

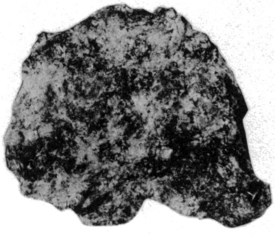

FIG. 6

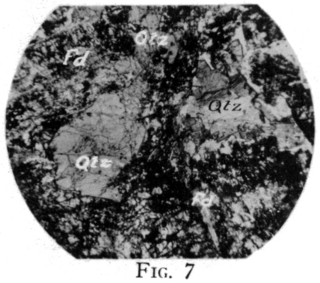

FIG. 7

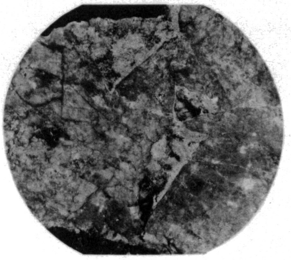

FIG. 8

The Association of Calcic and Sodic Pegmatite in one Rock.

Fenner[14] appropriately calls attention to the occurrence of calcic and sodic pegmatite in one rock with special reference to the work of Shannon[3] on the Goose Creek diabase. He points out that such an occurrence requires more adequate consideration since it apparently "would mean that the magma was differentiating simultaneously in two very different directions." The Duluth gabbro as exposed in the vicinity of Mellen, Wisconsin, shows entirely similar features, namely, coarse calcic pegmatite in tabular masses and granitic aplite and pegmatite dikes of light color cutting the dark gabbro. As Shannon states for the Goose Creek diabase, so here, the calcic pegmatite is made up of the identical minerals as the gabbro it cuts, but differing in the much coarser crystals. Any acceptable explanation must account for the lack of gradational or intermediate material to satisfy Fenner's query. If we search for the most logical sources of liquid to fill the constantly opening fractures in a crystallizing gabbroic mass these two types of pegmatoid material seem to be the normal result. A fracture which taps the still liquid source of magma which is producing the gabbro must be filled with gabbroic liquid. The rate with

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PLATE II.

Fig. 1. Photomicrograph (X90) of possible arkosic material, found in float only, in lieu of outcrops at the point where the base of the Rib Hill quartzite is expected to be.

Fig. 2. Photomicrograph (X90) of perthitic material (contact effect?) from the same locality as that of Figure 1. Also float.

Fig. 3. Photomicrograph (X90) of intermediate (partly altered?) material from the same locality. Also float. Compare these three (Figs. 1, 2, 3) with Johannsen's description and illustrations of lestiwarite.

Fig. 4. Photomicrograph (X90). High feldspar rock from Baxter Hollow, Wisconsin. This rock occurs irregularly as a filling between large inclusions, in relatively small masses. It is regarded as a filtration product.

Fig. 5. Patchy gabbro, city of Duluth. The patches are sericitized feldspar and quartz, believed to be introduced from adjacent gabbro as a result of local deformation.

Fig. 6. Hand specimen from the outcrop of Figure 5. The thumb tack serves as a scale.

Fig. 7. Photomicrograph (X30) of the patchy gabbro of Figures 5 and 6.

Fig. 8. Photograph of a portion of the specimen sketched in text Figure 1. The thumb tack serves as a scale. The miarolitic cavities were protected from crushing by the brecciated, earlier vein quartz filling.

which it opens must be a dominant factor in deciding the crystal size. A rapidly opened fracture would be filled rapidly and lose its identity on crystallizing whereas a slowly opened fracture, feeding growing crystals, as it lessened crystal interference by increasing the available space for their growth, would normally lead to coarser texture but no great change in mineral composition. Furthermore, and perhaps worthy of special note is the characteristic presence of curved cleavage faces in the crystals composing these pegmatites. This is stressed by Shannon and is true of the occurrences mentioned in the Duluth gabbro. Does not slow movement during crystal growth most easily explain these curved faces—the same movement postulated to feed the crystals?

On the other hand a fracture similarly developed in the crystallizing magma but not tapping the still liquid source of magmatic material must draw its supply of liquid from the interstitial spaces between crystals, even from the immediate walls. Such material being rest magma must be comparatively granitic in composition. There is no source of liquid of intermediate composition since at such time as such liquid exists the proportion of crystals is too low to lead to fracturing on deformation. Calcic, and sodic pegmatites as found in the field, are, then, theoretically to be expected and quite in accord with Bowen's view. Local concentrations of micropegmatite, or quartzose material found interstitially to larger crystals (Plate II, Figs. 5, 6 and 7) are discussed elsewhere. Perhaps legitimate objection can be raised to applying the term pegmatite to the coarse-grained calcic feldspar dikes, but that is largely a matter of definition. If the explanation offered here is correct they are not true pegmatites. In the field, however, they have the earmarks of a pegmatite, since the identical nature of their mineral composition with the wall rock is less apparent than their difference in texture.

Oscillatory Zoning of Plagioclase.

The most frequent occurrence of zoned feldspars is in the diorites. Here Johannsen[15] says the range of zone composition is commonly from labradorite to oligoclase. Homma[16] records a similar range. The origin of progressive zones in plagioclase is not believed to be due necessarily to one process; but many petrologists are satisfied that rapid cooling, relative to the establishment of feldspar equilibrium, is adequate to produce this kind of zoning. Oscillatory zoning has not been completely explained. The remaining problem is to account for the variation in composition of magmatic liquid. To the many excellent suggestions already recorded in the literature the following thought may be added.

In the dioritic hybrids, presumably due to the digestion by granitic magma of mafic material, conditions may be ideal for the establishment of differential pressures, as structural disturbance accompanying intrusion affects the walls and more especially the stoped blocks near the walls. This disturbance means the shifting of mobile magmatic material in the contact zone. It also means, as Mead has pointed out, the surging of mobile material from the intrusive itself also. Considering any one spot in the contact zone, then, we may expect a given growing feldspar crystal to be fed by liquid which is by no means constant in composition. And continued growth necessarily means layers of different composition. In this sense then an oscillatorily zoned feldspar may be regarded as a record of a complex structural history as well as a complex chemical history. The same history, of course, given more time for the establishment of equilibrium, would simply not be recorded. The absence of zoning does not necessarily mean then the absence of such a history.

The Shortage of Rocks of Intermediate Composition.

I should like for a moment to throw caution aside and venture an opinion on this attractive but highly speculative subject. It is a fact, as pointed out by Daly,[17] that "The igneous rocks of the globe belong chiefly to two types, granite and basalt." Although one is extrusive and the other intrusive it is doubtless true that the diorite class is not represented in the earth's crust as abundantly as the modern theories of igneous rock differentiation would lead us, *at first*, to expect. Does it not seem reasonable, however, if we combine crystal fractionation with the deformation of crystallizing magmas, thereby bringing about the separation, mechanically, according to the thesis of this paper, that basaltic magma, though unaffected by deformation in its early history will, when crystallization has reached favorable advancement, suffer the removal of its rest magma to form granite? We apparently see it on a small scale in sills and laccoliths, and it is only a change of scale to apply it to larger provinces. In other words, the answer to this question, which is really the origin of granite, is to be found in Bowen's feldspar studies according to which calcic crystals separate from alkaline liquid. Eskola[18] recently made a somewhat similar suggestion, but employed a different mechanism—squeezing. If this is not true then we are faced with a difficult question—in what larger size of magmatic body does this broad principle cease to operate? As seen in smaller bodies, the tendency is for the granitic fraction to rise—hence its prevalence at the surface on a regional scale, leaving the plutonic calcic equivalent too deeply buried for exposure. It is not intended to imply a belief that such a process is operative alone or even dominantly. As Fenner[19] once pointed out ". . . it is impossible to say what is the quantitative importance of any one of (the processes) in volcanism, or whether there may not be still other important processes."

Conclusion.

There is nothing in this picture which seems to explain the melanocratic dikes that accompany intrusions of the type we have been discussing—the lamprophyres, or the basic dikes of Pigeon Point. Their ultimate understanding may do much to modify the interpretation offered. One further observation relative to these dikes seems worth recording. They seemingly increase in numbers with the development of the red-rock granophyres. This suggests a genetic connection which is easy to believe. It does seem patent that they are in some way complementary differentiates of the granophyres in some instances, but that adds little to our understanding of them. They are and doubtless will continue to be somewhat neglected in routine field work.

The term "magmatic material" has been used here in a broad sense to include hydrothermal solutions accompanying intrusive activity. This is done in the belief that there is a complete gradation between the magma and quartz-depositing solutions.

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ERRATUM

January 1940 issue of the AMERICAN JOURNAL OF SCIENCE, Vol. 238. Line 13 on page 8 should read New London for Shawano.