Clouded felspars and thermal metamorphism.

By A. G. MacGregor, M.C., B.Sc.
Geological Survey of Scotland.

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THE present paper summarizes the facts at present known regarding a characteristic effect that is often produced in the fresh plagioclase felspars of igneous rocks by thermal metamorphism—namely the development of a special type of cloudiness caused by the appearance of minute inclusions. Reference is also made to certain well-known rocks in which the clouding of plagioclase felspars has been described without any suggestion that the peculiarity of the felspars is connected with thermal metamorphism.

Clouded Felspars in Contact-Metamorphosed Lavas and Minor Intrusions.

Teall seems to have been the first to connect with contact-metamorphism the presence in plagioclase phenocrysts of cloudiness of a peculiar and special type (1888, pp. 279, 280).[1] The cloudy appearance was caused by the presence of innumerable minute ininclusions. Teall studied their mode of occurrence in considerable detail, and pointed out their close resemblance to the minute inclusions in the clouded felspars of the Baltimore gabbro, described and figured by Williams (1886).

Eleven years later, in 1899, Kynaston read before the Edinburgh Geological Society a paper—not published until 1905—in which he showed that Teall's suggestion was correct (1905, pp. 18, 20, 24). He found that the same peculiar cloudiness was a characteristic feature produced by contact-metamorphism, due to the Cheviot granite, in the plagioclase phenocrysts of andesite lavas of Lower Old Red Sandstone age. Shortly afterwards Kynaston found that similar cloudiness had been produced in the plagioclase phenocrysts

[1] The references in brackets refer to the bibliography given on p. 537.

of andesite lavas in Glen Etive, as one effect of the intrusion of the Cruachan granite (1901, p. 83). Bailey (1916, pp. 204–209), besides confirming Kynaston's results, found that clouding of similar type in porphyritic plagioclase felspars is a feature of other lavas, and of various intrusions (mainly dikes), in the Glen Coe district, and is quite definitely due to contact-metamorphism. Tyrrell (1916, p. 544) appears to have observed the same phenomenon in the plagioclase phenocrysts of hornfelsed porphyries from Benguella. He made no comment, however, on the significance of the dust-like inclusions that gave the felspars a bluish tinge.

More recently, the writer has found that the development of this peculiar cloudiness in plagioclase felspars is a feature of certain contact-metamorphosed minor intrusions in Ayrshire (MacGregor, 1930, pp. 35–38, 50) and in Aberdeenshire (MacGregor, 1929, p. 553). It is convenient at this point to give a statement of the writer's Ayrshire results, for the account applies generally to all clouded plagioclase felspars that have been examined in the course of the preparation of this paper. It should be understood at the outset that the peculiar cloudiness of the felspars of contact-metamorphosed igneous rocks is in appearance quite different from any kind of turbidity due to decomposition.

In the Ayrshire dikes and sills the clouding is seen in plagioclase phenocrysts (andesine or labradorite) and sometimes in groundmass plagioclase laths as small as $0{\cdot}25 \times 0{\cdot}06$ mm. The contact-metamorphism may be severe enough to form hornblende and biotite from chlorite, and yet produce no effect on the plagioclase felspars (cf. p. 529). Cloudiness is not invariably found in the felspars of the more highly metamorphosed dikes. In fact in a single slice some crystals may show the feature well, and others poorly or not at all.

The phenomenon takes the form of faintly-brown patches due to almost ultra-microscopic specks, or of a general or localized (patchy) grey cloudiness due to the concentration of extremely minute opaque inclusions. The latter, under a $\frac{1}{4}$-inch objective or higher powers, may in some cases just be seen to consist of both (1) equidimensional specks, and (2) very short rod-like forms. The rods tend to occur in parallel sets (probably along crystallographic planes), and the equidimensional specks are interspersed among them. Sets of these minute inclusions occur at different levels even in the thickness of a normal rock section. Sometimes there is little apparent regularity in the distribution of the dark specks. Quite often, however, there

is a tendency to streaky development, especially along the junctions of multiple-twinning lamellae. Very occasionally longer hair-like rods (up to 0·05 mm.) accompany the very minute particles.

The inclusions occur in perfectly fresh plagioclase in which the original twinning and very marked zoning appear quite unaffected. Where part of a felspar was decomposed before metamorphism the clouding is only seen clearly in the originally fresh and limpid felspar substance. The originally decomposed portions remain clearly distinguishable, even in the most severely metamorphosed rocks. The least basic (outermost) parts of zoned crystals do not as a rule become clouded, nor do those portions of the more basic interior that may have been replaced by albitic felspar before metamorphism.

The cloudiness is not seen in any of the numerous sliced minor intrusions that occur outside the metamorphic aureole of the Ayrshire granodiorite-diorite complex, and within the aureole it appears only in the more intensely altered rocks.

The inclusions look more like iron-ore than anything else, for even with a high-power objective they appear to be opaque in most cases (cf. Rosenbusch, 1907, pp. 323, 324). In some cases, however, it is not quite certain whether this is because the particles and hair-like rods are too small for the resolving power of the microscope.[1] The writer was unable to decide whether the inclusions owe their origin to pneumatolytic effects, or to purely thermal effects within the felspars. It is clear, however, that these inclusions arise in perfectly fresh plagioclase; that soda-rich plagioclase is unfavourable to their formation; and that apart from the cloudiness due to their presence the zoned and twinned felspar crystals appear quite unchanged after the inclusions have developed. The felspar phenocrysts are stable even in rocks that are found at a plutonic contact and that have suffered groundmass granulitization.

Kynaston found at Cheviot and in Glen Etive that clouded felspars in the lavas show a marked stability and usually maintain their individuality as phenocrysts[2] even at the actual granite contact, although outer margins against the recrystallized groundmass may become ragged (cf. Thomas and Bailey, 1924, p. 154). Bailey made

[1] Dr. T. Robertson and the writer have recently found evidence suggesting that rutile needles are present in certain clouded felspars.

[2] The writer has confirmed this. In the Survey Collection from Glen Coe no fresh phenocryst is recrystallized.

the suggestion that the cloudy felspars of the Glen Etive and Glen Coe region had been partly decomposed to albite with minute inclusions of zoisite and epidote before the intrusion of the granite, and that the heat of the intrusion regenerated basic plagioclase, with indefinable residual products, from the mixture (1916, pp. 205, 208, 209). After reconsidering the whole question in the light of the Ayrshire evidence Bailey[1] has come to the conclusion that the hypothesis of the Glen Coe Memoir must be abandoned. He agrees that the peculiar cloudiness is produced in perfectly fresh felspars by contact-metamorphism, and that the phenomenon is not a sign of the regeneration of decomposed felspar.

Clouded Felspars in Certain Odenwald Dike-Rocks: *e.g.* Malchite.

While dealing with the significance of clouded felspars in porphyritic rocks it seems desirable to discuss briefly a well-known rock-type from the Odenwald in Germany.

When working out a classification for the north Ayrshire dikes, the writer, along with Prof. E. B. Bailey, examined a suite of slices of Odenwald dikes for comparative purposes. Prof. Bailey, who was familiar with the contact-metamorphosed dikes and lavas of the Glen Coe region, pointed out that the slice representing malchite showed many of the peculiarities of the baked Scottish rocks. This was also found to apply to others, such as alsbachite. One of these features was the characteristic clouding of larger plagioclase felspars in the malchite. The writer agreed with Prof. Bailey that the evidence for the thermal metamorphism of the malchite dike (the type rock from Melibocus) appeared to be quite conclusive. In consequence, it appeared undesirable to continue to apply the name 'malchite' to unmetamorphosed dike-rocks of similar chemical and mineralogical composition, but of normal igneous structure.

More recently the writer has examined a number of other slices of Odenwald dikes sent to this country at various dates by Krantz, or Voigt and Hochgesang. Plagioclase felspars showing the clouding typical of contact-metamorphism are present in slices labelled 'Malchite, middle of dike, Zwingenberg, Bergstrasse,' and 'Orbite, summit of Melibocus, Odenwald'; moreover there has been considerable recrystallization in the groundmass of both specimens.

[1] Personal communication.

There is little in the present interpretation of the geological history of the Odenwald[1] to account for the postulated contact-metamorphism of the Melibocus malchite. It seems possible, however, that the complicated igneous and metamorphic history of the Odenwald is not yet fully known. For many years it was believed that the beerbachites, gabbro-porphyrites, and gabbro-pegmatites of Chelius were, as he asserted, dike-rocks cutting the Odenwald gabbro. It is only recently that Klemm has shown that these rocks are in reality hornfelsed inclusions in the gabbro.[2]

The Clouded Felspars of the Scourie Dikes and of Certain Metadolerites.

The illustrations of the micro-sections of the metamorphosed dikes of the Scourie district in Sutherland, published in Teall's 'British Petrography' (1888, plates XIX, XX) and in the Geological Survey Memoir on the north-west Highlands (1907, plate XLVII, fig. 2), suggested to the writer that the plagioclase felspars of these rocks contain clouds of inclusions similar to those that have been under consideration. On examining slices mentioned by number in the north-west Highland Memoir, it was found that clouding of the same type is to be seen in the Ayrshire contact-metamorphosed dikes.

In several of the Scourie slices clouding is of the ultra-fine brown variety. This is often accompanied by grey clouding due to very minute rods and specks, or in many cases to specks and longer hair-like rods (rarely exceeding 0·05 mm. as seen in rock slices).

In one of the unsheared Scourie slices (3043)[3] anhedral quartz, wedged between the felspar laths, locally shows ultra-fine brown clouding as well as part of the plagioclase. The latter has, in addition, grey clouding due in part to delicate hair-like rods. Several of these hairs cross the felspar-quartz junction, one half being embedded in felspar and the other half in quartz. This seems to show that the delicate hair-like inclusions developed after the

[1] G. Klemm, Notizblatt des Vereins für Erdkunde und der Grossherz. Landesanstalt zu Darmstadt, 1910, IV Folge, Heft 31, pp. 21, 25; and op. cit., 1926, V Folge, Heft 9, pp. 104, 107–111; also G. Klemm, Führer bei geologischen Excursionen im Odenwald, Berlin, 1910, pp. 11–67; and G. Klemm, Geologische Übersichtskarte des Odenwaldes, second edition, 1929; and Beda Sandkühler, Abhandl. der Grossherz. Hessischen Geol. Landesanstalt zu Darmstadt, 1913, Band V, Heft 3, pp. 201–211, 214–219, 222.

[2] G. Klemm, op. cit., 1926, pp. 111–115.

[3] No. of slice in Scottish Collection of H.M. Geological Survey.

consolidation of the felspar and quartz. Very sparse short little rods are wholly embedded in quartz. The quartz seems free from clouding or inclusions in a number of the slices with well-clouded felspar.

Teall originally considered that the dikes had been metamorphosed under high pressure at ordinary temperature (1885, p. 141). In later years, however, he thought that the temperature may have been not far below that of actual fusion (1918, p. 6). The peculiar clouding of the plagioclase felspars of the massive portions of the dikes did not escape the notice of Teall (1888, p. 198, and *explanation of plate XIX; also* 1907, p. 90). He also recorded similar inclusions in the olivines and augites of the dikes, but not in all three minerals in one and the same rock, and expressed the opinion that possibly they are original products of the magma.

Teall made important observations in those parts of the dikes showing incipient alteration to hornblende-schist. In these rocks he found that the plagioclase is partly cloudy and partly colourless. The cloudy portions often preserve more or less the form of the original felspars, whereas the newly crystallized felspar developed under dynamic metamorphism is quite clear. In the thoroughly schistose rocks, in which recrystallization is complete, the felspar no longer shows the peculiar clouding (Teall, 1888, pp. 199, 200, and explanations of plates XIX, XX, XXI). Teall's observations also show that parts of the Scourie dikes have been converted by metamorphism into hornblende-plagioclase-rocks *without foliation*. Where original igneous structure is still recognizable in such rocks clouding of the relict labradorite laths, as Teall pointed out, is still to be seen. Where complete recrystallization has obliterated igneous structure Teall observed, however, that the recrystallized felspar is not clouded and tends to be more albitic.

In this connexion attention must be called to certain general results of the writer's work on the metamorphism of igneous rocks in normal contact-aureoles. When contact-metamorphism has been so severe as to render original plagioclase unstable, so that it loses its original form and recrystallizes, *such newly formed felspar is not clouded.* Recrystallization of original *fresh* labradorite usually takes place in contact-aureoles under physico-chemical conditions that result in the formation of pyroxenes at the expense of hornblende. In contact-aureoles, plagioclase-clouding represents a grade of metamorphism lower than that at which original fresh labradorite

becomes unstable and recrystallizes; and under these lower grade conditions biotite or hornblende, not pyroxene, is often formed (MacGregor, 1930, pp. 35–38). *Large* fresh plagioclase felspars, however, often remain stable in rocks in which very advanced or complete granulitization has taken place at the expense of the groundmass constituents.

The writer would suggest that the peculiar clouding of the felspars of the Scourie dikes is due to the fact that after—probably long after —the intrusions had completely consolidated, they were very considerably heated up again. This reheating of the dikes was followed at a later stage by metamorphism under different physico-chemical conditions. Earth movements were going on during the recrystallization produced by this phase of metamorphism, and brought about local foliation. The felspars became clouded, but remained stable, during the preliminary phase of thermal metamorphism unaccompanied by appreciable shearing stress. The subsequent dynamo-thermal metamorphism, in which water in some form perhaps played an important part, gradually broke down the original minerals, and the felspar that recrystallized was unclouded. Whether the thermal metamorphism that produced the clouding was caused by regional heating connected with depth, or was brought about mainly by the heat of neighbouring igneous magma, is not a matter on which the writer cares to express an opinion at the present time.

It may be mentioned here that during research work on the Dalradian schists in Glen Clunie, Aberdeenshire, the writer has recently found a small fine-grained epidiorite sill or sills that show phenomena closely similar to those of the Scourie dikes, and on which he puts a similar interpretation. In places the original fresh felspar-plexus of the dolerite is preserved, although all original pyroxenes have disappeared and are now represented by aggregates consisting mainly of pale green hornblende. These relict felspars are zoned labradorite, and under low powers show greyish clouding. Under high powers the cloudy effect is seen to be partly, perhaps largely, produced by minute apparently opaque specks and tiny rods, but in addition there are present in some instances numerous larger, but still very minute, needles, prisms, and grains of a transparent mineral with a refractive index that is high with relation to the enclosing felspar. As far as optical properties can be made out in such minute crystals they seem identical with those of the very pale hornblende that in places extends into the felspar laths along cracks. The minute

doubly-refracting needles and prisms are often arranged in parallelism. In other slices, dynamic metamorphism has completely obliterated igneous structures and the felspar is recrystallized. The granular recrystallized felspar is unclouded.

This epidiorite is mentioned because the doubly-refracting nature of some of the inclusions make possible a comparison with Australian metadolerites described by Tilley (1921, pp. 75–131). The latter are probably dike-rocks entangled in later acid gneisses, and thermally metamorphosed by them. The zoned labradorite crystals are crowded with minute black or dark dust that renders them semi-transparent. These minute inclusions were regarded by Tilley as probably composed of pyroxene, and he apparently thought they were an original feature of the felspars. To the writer it seems more probable that the clouding was caused by thermal metamorphism.

Clouded Felspars in Certain Plutonic Rocks.

Clouding of plagioclase in plutonic rocks—notably gabbros and hyperites—has often been described, but until recently no definite suggestion has been put forward that the phenomenon is a result of thermal metamorphism.

Last year the writer brought forward evidence to show that clouding in the felspars of certain dioritic rocks of north Ayrshire has been produced by contact-metamorphism due to a later intrusion (MacGregor, 1930, pp. 39–52). Some of these north Ayrshire rocks are indistinguishable from 'hyperites' described by Teall from the Southern Uplands of Scotland (Teall, 1899, pp. 612–615), and the writer suggested that the latter are also contact-metamorphosed, having been thermally altered by the adjacent granodioritic rocks.

In the Geological Survey Memoir on Ardnamurchan, Richey and Thomas deal with the clouded felspars of gabbros, eucrites, and dolerites, and they have come independently to much the same conclusions as those at which the writer arrived in Ayrshire.

The present discussion will be limited to the Ayrshire dioritic rocks, the Tertiary Igneous Complex of Ardnamurchan, and the Baltimore gabbro and Swedish hyperites cited by Teall as directly comparable with rocks which, according to the writer, show evidence of thermal metamorphism.

Dioritic rocks of north Ayrshire.

The writer's Ayrshire results may be summarized as follows. The cloudiness in the plagioclase felspars of some of the dioritic rocks is

exactly similar to that found in the more highly contact-metamorphosed dikes and sills (p. 525). Other evidence (e.g. the presence of a contact-metamorphosed dike cutting one exposure of dioritic rocks; the occurrence of hornblende-filled veinlets traversing the felspars) shows that these plutonic rocks have been affected by thermal metamorphism after their consolidation. The plutonic rocks cut and bake sandstones of Downtonian and Lower Old Red Sandstone age. It was therefore concluded that the clouding in their felspars is due to contact-metamorphism produced by the local granodiorite.

Pronounced grey cloudiness in the plagioclase felspars of other slices of the contact-altered dioritic rocks is, however, seen to be due to the presence of innumerable inclusions which, though very minute, are individually larger than those which produce the grey cloudiness in the dikes and sills. These relatively larger inclusions also consist of little apparently opaque grains and relatively short rods, and occasionally of longer hair-like rods arranged in parallel sets. The latter type of clouding is also seen in some of the slices of the granodiorite that is supposed to have effected the thermal metamorphism of the dioritic rocks.

As there seems to be every transition from the ultra-fine clouding due to indeterminate specks, through cloudiness due to minute specks and tiny rods, to that due to longer hair-like rods, the conclusion was arrived at that all varieties of clouding owe their origin to thermal or pneumatolytic metamorphic effects.

The cloudiness in those granodiorite slices that show it is much less pronounced than in most of the dioritic rocks or in the dikes and sills. It was suggested that in the granodiorite the phenomenon may be due to late auto-pneumatolytic effects, or more probably to a later intrusion of granodiorite having affected an earlier one. There is some local evidence to support the latter hypothesis.

In the last paragraph we come to the main difficulty in dealing with the significance of clouded felspars in plutonic rocks. If we have evidence to show that the felspar-clouding is not an original feature of the crystallization period, can we decide whether it is (1) the result of late auto-pneumatolytic, or deuteric, effects, or (2) the result of post-consolidation thermal metamorphism due to an external cause? The observations of Richey and Thomas in Ardnamurchan throw a good deal of light on this problem, and will now be considered.

The Tertiary gabbroic rocks of Ardnamurchan.

The phenomenon described in this paper as 'cloudiness' in felspars is the same as that referred to in the Ardnamurchan Memoir in some places as 'cloudiness' but usually as 'turbidity and schillerization'. The writer has examined the slices mentioned in the memoir as containing 'turbid and schillerized' felspars, and there is no doubt about the identity with the peculiarities of the clouded felspars of Ayrshire and elsewhere.

Richey has found that the clouding of the felspars of the gabbros gives to the rocks concerned a remarkable black or bluish-black hue that is very conspicuous in the field (Richey, 1930, p. 238).

There is abundant evidence that clouding is not an original feature of the plagioclase dating from the crystallization period. It is found, for instance, in quartz-dolerites that show other evidence of having been baked, and is not seen in similar rocks that are known to be unaffected by contact-metamorphism (Thomas, 1930, pp. 193, 277, 280). Again in many cases the clouding of gabbro felspars can be definitely ascribed to re-heating due to the later emplacement of a neighbouring intrusion (Richey and Thomas, 1930, pp. 225, 238, 239, 253, 273, 314). In one or two instances the felspar-clouding in the gabbro is recognizable in the field as a localized effect connected with part of the margin of the later intrusion that cuts it. Where the whole of a rock-body shows the phenomenon there is evidence in more than one instance to show that it has been subjected to intense contact-metamorphism by a number of later intrusions in turn (e.g. Richey, 1930, pp. 238, 314).

In a number of cases the available evidence is said to suggest that felspar-clouding in quartz-gabbro and eucrite has been brought about by the permeation of the rock-mass by granophyric material that consolidated partly as mesostasis and partly as veins. In some cases this granophyric material appears to be of external origin, and to have been injected after the shattering of the rock by explosion (Richey and Thomas, 1930, pp. 101, 102, 267, 268). In other cases the granophyric material appears to belong to the rock itself; the clouding would in this case be a deuteric effect (Richey and Thomas, 1930, pp. 101, 102, 278).

In Ardnamurchan, however, it is in many cases impossible to refer the clouding *definitely* to one particular agency. Some of the intrusive masses have been proved to be more or less granulitized by re-

heating although there is no intrusion now exposed at the surface that can reasonably be supposed to have effected that re-heating (e.g. Richey and Thomas, 1930, pp. 280, 281). · Again, in more than one case, the chilled edge of an intrusion has been partly granulitized by re-heating apparently consequent on fresh influx of magma *from the same source* (Richey and Thomas, 1930, pp. 230, 333, 334). In these cases it should be noted that the re-heating is not deduced from the presence of clouded felspars, but from other, or additional, evidence of contact-metamorphism (partial granulitization, &c.).

Under these circumstances the writer does not consider that Ardnamurchan provides *definite* proof that permeation by residual acid magma has produced clouding of plagioclase felspar, though admittedly such may actually be the case: it is, however, quite clear that in many cases clouding has been produced by contact-metamorphism due to a known later member of the plutonic complex. All the evidence is against the plagioclase-clouding being an original feature of the felspar crystallization period.

In discussing the clouded felspars of the gabbroic rocks of Ardnamurchan one cannot pass over Judd's references to them, and the part they played in his 'theory of schillerization' (Judd, 1885, pp. 375–387; 1886, pp. 82, 83; 1889, p. 244). Some of the phenomena exhibited by the basic felspars of the plutonic rocks of Ardnamurchan and elsewhere, that were described by Judd as 'schillerized', are undoubtedly the same as those referred to by the writer as 'clouding' of various types. Judd was of course not fully aware of the diversity of the rock-masses he studied, nor of their complex time-relationships. We shall therefore not analyse his conclusions; nor have we space to follow up the literature of schillerization.

The writer has not been able to come to any conclusion regarding the origin of schiller inclusions in the pyroxenes and olivines of plutonic rocks (gabbros, hyperites, &c.) or of the Scourie dikes. In such rocks clouding of the felspar is frequently accompanied by schillerization of pyroxenes and olivines. But it is also a fact that contact-metamorphism produces clouding in the felspars of lavas and minor intrusions in which ferromagnesian minerals are not schillerized.

The Baltimore gabbro, and Swedish hyperites.

The petrography of the gabbro—gabbro-diorite (massive epidiorite)—hornblende-schist complex of Baltimore, Maryland, U.S.A., presents many points of similarity to that of the Scourie dikes discussed

above. These rocks were described by Williams in 1886. Further work has been published quite recently (Insley, 1928, pp. 289–332; Knopf and Jonas, 1929, pp. 102–137). Williams pointed out the close resemblances between these American gabbroic rocks and the hyperites and allied types of Sweden. He describes and illustrates fine dust-like inclusions in the felspars of both gabbro and gabbro-diorite (Williams, 1886, p. 21 and plates); but, like Insley, Knopf, and Jonas, regards them as original features of the plagioclase. There is no doubt that he was dealing with felspars clouded by inclusions in the same way as those discussed in the present paper. Knopf and Jonas consider the inclusions to be ilmenite or magnetite (1929, p. 110). Williams records too the presence of schiller inclusions in the augite and hypersthene of the gabbro. The hornblendic rocks (gabbro-diorites) are stated to pass laterally into hornblende-schists, perhaps most commonly near the junction of the gabbroic rocks with the adjacent schists and gneisses. Insley, Knopf and Jonas ascribe the alteration of the hypersthene-gabbro to regional dynamic metamorphism.

Törnebohm, in his paper on the Swedish hyperites (1877, pp. 379–393), describes the brownish clouding of the plagioclase felspars, but he regards it as an original feature. He also refers to schiller inclusions in the augite, hypersthene, and olivine. The hyperite is said to be changed into a diorite-like rock (hyperite-diorite), often rich in garnet, both in the neighbourhood of the surrounding rocks and in the vicinity of quartz-veins in the middle of the rock-mass.

From later accounts (Högbom, 1910, p. 30; 1913, p. 18) we learn that the hyperites are lenticular bodies or sills. In their interiors they have original igneous structure well preserved. At their boundaries they pass over into garnetiferous amphibolites, generally with a well-developed schistosity conforming to the foliation of the adjacent gneiss. According to Högbom's 1910 paper the hyperites have been subjected to the high-grade metamorphism, connected with tectonic movements, that produced the neighbouring gneisses. But in his later account (1913) he argues, from the fact that the hyperites have locally retained primary igneous structure, that they are *younger* than the far-reaching metamorphism that has produced the neighbouring gneisses.

From the above accounts it is obvious that both the Baltimore gabbro and the Swedish hyperites have been subjected to metamorphism involving the action of shearing stress. The writer would

suggest that the sequence of events that affected the gabbro and the hyperites is much the same as that postulated at Scourie (p. 530). First thermal metamorphism without shearing stress re-heated the rocks long after their consolidation, and brought about the clouding of their felspars. Later on, under different physico-chemical conditions in which stress and probably circulating water in some form played an important part, the rocks were converted into epidiorites and hornblende-schists. In both America and Sweden the gabbros and hyperites are now known to be cut by granitic intrusions in some localities. The presence *in depth* of the granitic magma-reservoir, from which the acid intrusions were later injected, may have been an important or dominant factor in the first phase of thermal metamorphism without appreciable shearing stress.

Summary and Conclusions.

In the intermediate and inner zones of contact-aureoles thermal metamorphism has often, but not invariably, produced in the fresh plagioclase felspars of lavas and minor intrusions a peculiar and easily recognized type of clouding due to the development of minute inclusions. When, in the highest grades of such contact-metamorphism, original plagioclase crystals have been recrystallized, the newly-formed felspar is unclouded. Clouded phenocrysts have, however, often remained stable although the felspar of the finer-grained groundmass is completely granulitized by recrystallization. This is because, under contact-metamorphic conditions, large fresh crystals are more stable than aggregates of small crystals.

The minute inclusions are very often restricted to the more basic portions of plagioclase crystals, and are absent from the more albite-rich parts. This fact suggests that the original nature of the felspar controls the formation of the inclusions.

There may be some significance in a fact that can be ascertained by looking through a large number of analyses of felspars. A certain amount of iron oxide is a fairly constant feature, but in the series oligoclase-anorthite the percentages are often almost twice as great as most of the higher values recorded in albite or in potash-felspars. It therefore seems possible that the preferential clouding of basic plagioclase is due to its having an original iron-content higher than that of albitic or potassic felspar. In this case the clouding is caused by the appearance of iron oxide as such, or by its concentration to some extent by migration. Clouding due to minute ferromagnesian

particles could be accounted for in a similar way, for some percentage of magnesia is also a feature of felspar analyses.

Partly on the evidence of clouded felspars, the suggestion is made in one section of this paper that certain malchite dikes in the Odenwald, Germany, have been affected by contact-metamorphism.

Observations in Ayrshire and Ardnamurchan have shown that one effect produced in dioritic and gabbroic rocks by a later plutonic intrusion is the development in their plagioclase felspars of a peculiar cloudiness like that found in the contact-metamorphosed lavas and minor intrusions already mentioned.

Clouded felspars are also found in certain gabbros, 'hyperites', and metadolerites known to have undergone regional metamorphism. In a number of such rocks cited above (Scourie, Baltimore, Sweden) the presence of clouded felspars, like those in contact-metamorphosed igneous rocks, has led the writer to postulate a high degree of heating, comparable to that in granitic contact-aureoles, at an early stage in their metamorphism.

The evidence set out above shows that in the case of *any* igneous rock with clouded felspars it seems necessary to prove that such a rock-body can never have been subjected to regional- or contact-thermal metamorphism, before the clouding can be regarded either as an original feature of the felspars, or as a deuteric effect that arose at a late stage in the consolidation period.

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(An asterisk indicates literature in which clouding of felspars in igneous rocks is shown to be the result of thermal metamorphism.)

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