ON CLOUDED PLAGIOCLASE

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ABSTRACT

Various theories to account for clouded plagioclase are reviewed. Observations indicate that the particles causing this effect may consist of different minerals, and that many minerals, besides plagioclase, may show clouding. It is suggested that in clouded minerals there are minute surfaces of physical discontinuity which provide adequate passages for diffusion of material into and out of the crystals. In intermediate plagioclases these surfaces may consist of internal phase boundaries in the unmixed feldspar. Slight clouding is probably due to exsolution of iron present in the feldspar lattice at the time of its formation, but more intense clouding is believed to be the result of the migration of iron and other elements into the crystal after its formation. The geological significance of clouded plagioclase is discussed and it is shown that such feldspars cannot be used as sole criteria for thermal metamorphism.

INTRODUCTION

There are many records in the literature of peculiarly clouded plagioclases. The phenomenon is due to the presence of numerous minute dark particles distributed throughout the crystals. These microlites consist of one or more minerals which sometimes can be recognized with difficulty (seldom with certainty) under the microscope. Clouding may be slight or very pronounced, rendering crystals nearly opaque. The particles are described as dust-like specks, short rods, or thin, hair-like growths and needles. They vary from sub-microscopic dimensions to one-tenth of a millimeter or more in diameter, but enclosures large enough to be identified with ease under medium powers of magnification are generally not included in the phenomenon of clouded feldspars.

Clouding of this type is different from the turbidity so frequently shown by feldspars upon weathering or hydrothermal alteration, and caused by the development of small flakes of kaolinite or sericite. It is also different from the phenomenon seen in so-called "gefüllte" feldspars in which the microlites consist of clinozoisite and sericite (Christa, 1931; Cornelius, 1935). The different types of turbidity are easily distinguished optically, and it would avoid confusion if the adjective "clouded" be reserved for the phenomenon described here.

The geological significance, origin, and nature of clouded feldspars has been the subject of speculation. Various opinions expressed in the literature are reviewed in the present paper, additional observations are made, and further suggestions offered concerning clouding in plagioclase and other minerals.

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PREVIOUS WORK

In an important contribution, MacGregor (1931) attributed clouding of plagioclase to thermal metamorphism. He thought that the minute particles which produce clouding probably consist of iron ore, and believed that later heating results in exsolution of iron originally contained in the plagioclase in solid solution. He noted that clouded plagioclase crystals often have clear margins which are also more sodic. Consequently he believed that the solubility of iron in plagioclase decreases rapidly towards the sodic end of the series. Feldspar analyses also show almost twice as much iron oxide in oligoclase-anorthite than in albite or potash feldspars. MacGregor considered that clouding of plagioclase marks low-grade thermal metamorphism of pre-existing feldspar, which with higher temperatures recrystallizes to clear plagioclase.

MacGregor's interpretation of clouded feldspars has been accepted by many petrologists; so much so that the occurrence of clouded plagioclase in a rock is now sometimes cited as "evidence" for the rock having been subjected to thermal metamorphism. Thus Bailey (1952, p. 303) remarks that "*all* the many Scourie dykes examined are metamorphosed, for *all* which have not suffered more obvious reconstruction have clouded feldspars."

However, the literature by no means shows general agreement with MacGregor's conclusions. Grout (1933, p. 1014) found clouded plagioclase in hornfels xenoliths in gabbros of Minnesota and pointed out that "in the Minnesota rocks the feldspars are newly generated from clay minerals, so that the cloudiness is not due to an attack upon old feldspars and certainly is not a sign that the unaltered rock was a feldspathic igneous rock."

Joplin (1935) criticized in particular MacGregor's opinion that clouding is an exsolution phenomenon. Anderson (1937, p. 65–7) found that "in the rocks of the northern Inyo Range, the potassic feldspars are as strongly clouded as are the plagioclase feldspars, and only the albite is relatively clear." He suggested that clouding may represent a forward migration of iron, sometimes of country-rock origin, through the pre-existing formations. Reynolds (1946, p. 435–6) noted that desilicated and basified rocks are commonly characterized by clouded lime-soda feldspars and concluded that "further investigation may show clouding of felspars, when present, to be a useful criterion in the recognition of rocks, produced by the basification of pre-existing types."

Williamson (1936, p. 149) pointed out that plagioclase crystals having a clouded core and clear rim do not always show a compositional change at the junction of interior and mantle. Shand (1945, p. 262) also found that the clear marginal parts of a plagioclase crystal may yet have the same composition as the dusty cores.

Little is known of the solubility of iron in plagioclase, and neither iron-albite nor iron-anorthite has been synthesized. However, experimental work has been done on iron-bearing potash feldspars (Faust, 1936; Rosenqvist, 1951). It is now generally believed that to a limited extent Fe^{+3} may substitute for Al^{+3} in the feldspar lattice, and that the iron would probably exsolve upon slow cooling as hematite or magnetite lamellae. Ramberg (1949, p. 30) in a footnote stated that the greenish brown color of plagioclase in the granulite facies "is due to absorption of about 0.5 per cent FeO and Fe_2O_3 in the feldspar lattice"—"probably the high P-T conditions of the granulite facies enable iron to enter the feldspar lattice provided that the chemical potential or vapor tension of Fe in the rocks is high enough." Finally, Herz (1951, p. 985) found that finely crushed plagioclase with clouded cores and clear margins from the Baltimore gabbro, Maryland, could be separated with a Franz separator into a least magnetic fraction of sodic plagioclase free from inclusions, and a more magnetic fraction of calcic, clouded plagioclase.

Examples of clouding in plagioclase of volcanic rocks have also been found. Cloudy zones in plagioclase phenocrysts of pyroxene-andesites from Hakone volcano were observed by Kuno (1936; 1950) and attributed by him to mixing of two different magmas. Bentor (1951, p. 535) found similar plagioclase phenocrysts in the Quaternary volcanics of the Chaîne des Puys and believed the phenocrysts "formed by a process of auto-resorption, during which the fluid magma breaks through the roof of the magma chamber, formed by a holocrystalline plutonic facies of the same magma." In both cases the particles producing the cloudy zones consist of glass and of minerals other than plagioclase found also as constituent minerals of the rocks. It is therefore believed that this type of clouding is produced by the incorporation of foreign particles through rapid growth of the plagioclase. Consequently the cloudy zones in plagioclase phenocrysts of volcanic rocks are different from the clouded plagioclase described in the present paper.

Present Observations

The writers studied a large number of different examples of clouded feldspars and as a result are able to confirm and add to observations made by previous workers. The relations of clouded plagioclase are here summarized.

1. Plagioclase of large gabbroic intrusions, such as the Bushveld, Namaqualand, Stillwater, Sudbury, Baltimore, and Cortlandt plutons is frequently slightly and sometimes even strongly clouded. The particles causing this effect may be extremely small and clouding may be so slight as to escape notice in cursory examinations of thin sections.

2. Plagioclase may show slight or medium clouding, even when there is no evidence of subsequent thermal metamorphism. Several authors have given examples of older rocks with clouded plagioclase occurring in regions where there are no younger intrusives (e.g., Wiseman, 1934; Poldervaart and von Backström, 1949). The conclusion drawn from equivalent examples by MacGregor (1931) is that the presence of clouded feldspar indicates later regional heating of the rocks, even when no younger intrusions can be found in the area. At Khale (Bechuanaland Protectorate) Poldervaart (1952) found a Karroo diabase sheet which shows clouded plagioclase near the chilled upper contact, although the feldspar of both the central diabase and the granitic country rock at the contact is clear. There are again no younger intrusives in this area. An assumption of post-Karroo regional heating of the rocks is extremely unlikely and does not explain the observed variations in clouding of plagioclase in different parts of the sheet.

3. Feldspar-bearing coronites invariably contain clouded plagioclase (Shand, 1945, p. 262). Feldspar-bearing meteorites, likewise, contain clouded plagiocalse (H. H. Hess, personal communication). Members of the charnockitic suite of rocks often, but not invariably, contain clouded feldspar, as well as blue quartz (Quensel, 1951). Basic dikes cutting charnockites and other Basement rocks of southern Mysore *all* contain clouded plagioclase, although probably several ages of dike-intrusion are involved. The equivalent dikes of northern Mysore contain clear feldspar (Ch. Pichamuthu, personal communication).

4. Clouding is not confined to plagioclase only, but has been observed in apatite, spinel, olivine, rhombic and monoclinic pyroxene, potash feldspars, quartz, biotite, hornblende, garnet, and even in calcite and serpentine. Platy or needle-like opaque inclusions of a larger size (schiller, sagenite, etc.) are more common in ferromagnesian minerals, but the dust-like particles which cause clouding can also be found and exactly reproduce the features of clouded plagioclase described here. In thin sections of blue quartz clouding appears as a yellow turbidity, believed by Jayaraman (1938; 1939) to be due to the presence of colloidal TiO_2.

5. The particles producing clouding may vary greatly in size, sometimes within the same host. When large enough to be identified, it is frequently noted that they consist of other minerals such as biotite (Groves, 1935), spinel (Shand, 1945), rutile (MacGregor, 1931), hornblende, or garnet, as well as opaque ore.

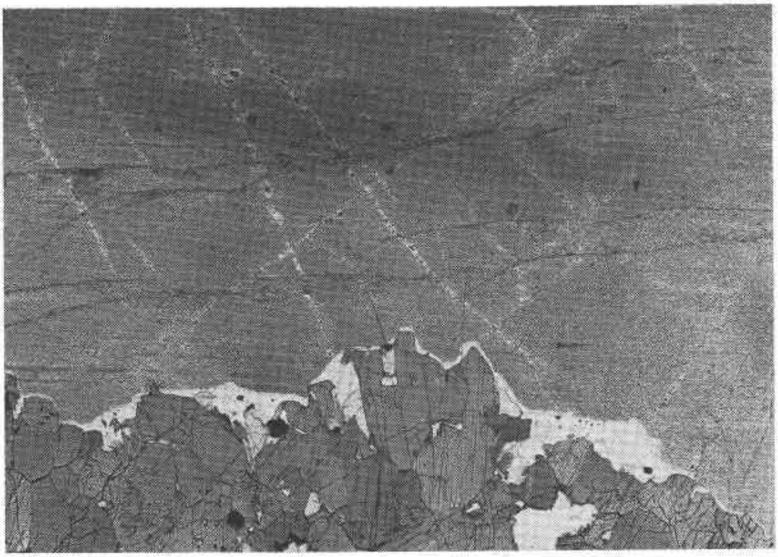

FIG. 1. Magnetite-ilmenite ore, Sanford Lake, Adirondack Mountains, New York. Clouded plagioclase crystal with irregular trails. ×15.

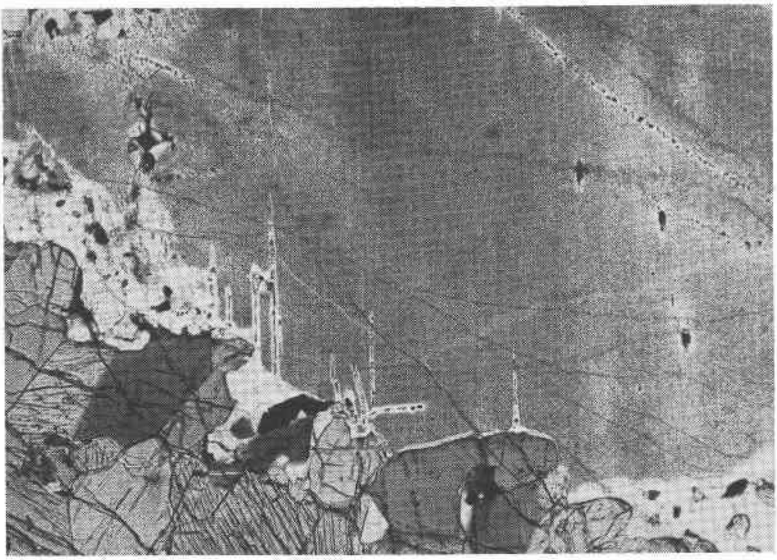

FIG. 2. Magnetite-ilmenite ore, Sanford Lake, Adirondack Mountains, New York. Clouded plagioclase crystal with trails. Note cleared incursions with larger microlites extending inward from unclouded periphery. ×25.

6. The particles appear to be rod-shaped rather than spherical, and small specks are probably cross sections of rods. Even the smallest particles seem to be elongated when viewed with high magnifications.

7. The orientation of the rods is somewhat variable. The smallest particles are apparently randomly distributed throughout the host-crystal, but their seeming lack of orientation may be the result of their smaller size. Larger particles are oriented either parallel to albite composition planes (Reynolds, 1936, p. 341), or are aligned in at least three, and probably four sets which intersect the albite twin planes (Williamson, 1936, p. 149). Apparently both types of orientation have not been found in the same rock.

8. The distribution of the particles is also irregular. Clouding may be evenly distributed throughout the host crystal. Frequently narrow irregular trails of clear or less turbid feldspar may be seen in the clouded crystals (Figs. 1, 2). These trails pursue a course entirely unrelated to the morphological directions of the host mineral, branch and bifurcate freely, and coalesce in slightly larger, clear patches. Sometimes the trails are studded at irregular intervals with larger enclosures of various minerals (Fig. 2), but this is not always the case. In other instances, different densities of clouding within the same crystal may form a highly irregular pattern (Fig. 3).

9. Clouded feldspars do not invariably have clear margins. The "clear"

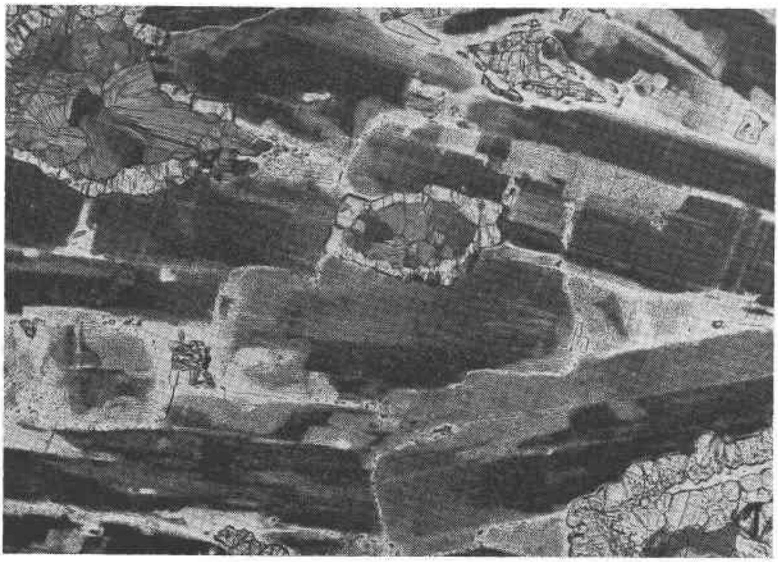

FIG. 3. Metagabbro, Adirondack Mountains, New York. Densely and irregularly clouded plagioclase mostly with narrow, clear rims. ×25.

FIG. 4. Metagabbro, Gore Mountain, New York. Plagioclase clouded with spinel and garnet particles, larger in the marginal portions than in the cores. ×70.

mantles, when present, may actually be devoid of inclusions, or may contain fewer and larger enclosures than the clouded cores (Fig. 4), thus creating an impression of greater purity, although probably containing the same total amount of foreign material as the clouded cores. In some cases clouding actually increases in density toward the margin, despite a narrow, clear outer zone. In coronites clouded plagioclase crystals often show corroded outlines and are surrounded by olive green, greenish brown, or brown hornblende. The outer portions of the plagioclase may be clear, or clouding may persist to the periphery, or it may actually extend some distance into the surrounding hornblende (Fig. 5); all three instances having been observed in the same rock, and even in different marginal portions of the same crystal. Where clouding extends into the surrounding hornblende the particles are often slightly larger in the hornblende than in the plagioclase. Moreover, the rods maintain the same orientation in the hornblende coronas as in the enclosed plagioclase, regardless of the disposition of the former in relation to the latter mineral.

10. Demarcations between clouded and clear portions of crystals are not confined to planes of chemical discontinuity in the host mineral. Such demarcations may occur at twin composition planes, or along boundaries which mark a temporary halt in the crystallization of the host mineral. The latter boundaries often coincide with sudden variations in composi-

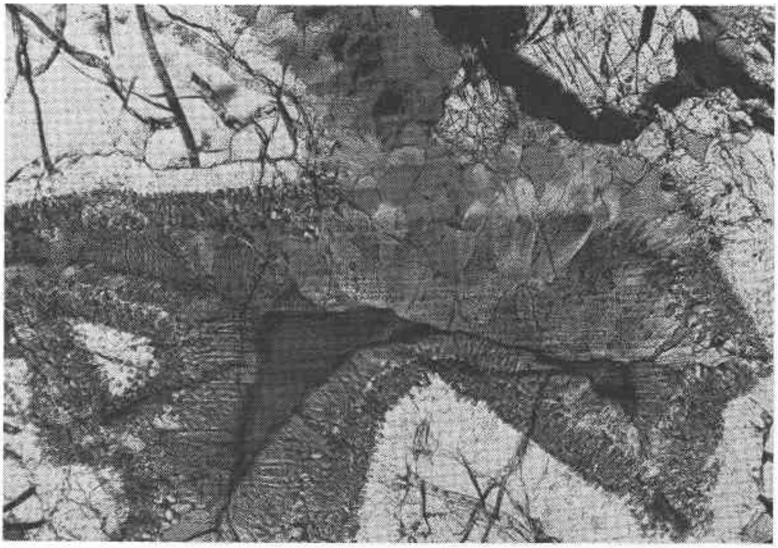

Fig. 5. Coronite, eastern Quebec. Corroded plagioclase crystal with spinel and opaque ore particles which extend into the surrounding hornblendic corona. ×30.

tion, but the former do not. The demarcations appear sharp with low or medium magnifications, but with high magnifications they can be seen to consist of narrow zones in which there is a rapid, but gradational decrease in concentration of the minute enclosures. Whether or not there is a compositional difference, clouded crystals frequently show a decrease in clouding intensity towards their margins, and this peripheral clearing does not appear to be related to either chemical or physical differences in the plagioclase of the turbid and clear portions.

11. Larger inclusions of foreign minerals (e.g., quartz) or of newly-formed minerals (e.g., garnet) in clouded plagioclase may or may not be surrounded by narrow, clear rims. In the case of newly-generated garnet in plagioclase of a coronite (Fig. 6), it may be noted that there is a concentration of minute opaque particles immediately surrounding the garnet enclosure, though a narrow clear strip may be present between the garnet and the nearly opaque plagioclase. Similar features may be observed in enclosures of opaque ore in pyroxenes or other ferromagnesian minerals. Here too there is no evidence of any physical or chemical discontinuity between the clear and the clouded portions of the host mineral.

12. Time appears to play a major role in the production of clouded feldspars. Country rocks at the immediate contact of diabase intrusions are heated to a higher temperature than those occurring at contacts of granitic plutons, yet the authors know of no case of small diabase intru-

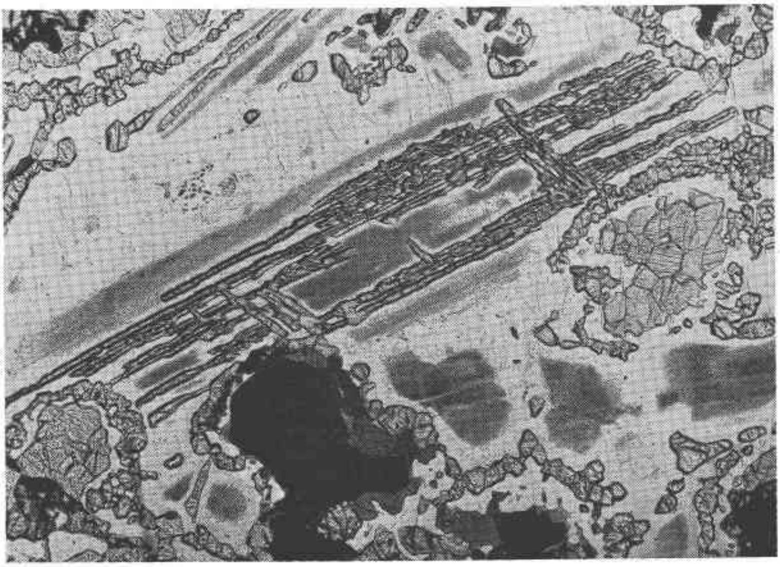

FIG. 6. Coronite, Essex County, New York. Newly-generated garnet in partly clouded plagioclase crystal. Clouding is concentrated around the garnet, but generally there is a narrow, cleared zone between the garnet and the clouded feldspar. ×25.

sions having produced clouding in the plagioclase of the adjacent rocks by thermal metamorphism only. This appears to hold no matter what the composition is of the plagioclase. However, assimilation of argillaceous material by diabase magmas produced hypersthenic rocks which frequently contain newly-generated, clouded plagioclase (cf. Walker and Poldervaart, 1941).

ORIGIN OF CLOUDING MATERIAL

There appear to be two contrasting views with regard to the origin of the particles producing clouding in plagioclase and other minerals. According to one view the material composing these particles was incorporated in the crystal at the time of its formation, while the second theory holds that the material was introduced into the crystal some time after its formation. It may be stated here that in the opinion of the present writers both theories are probably correct and supplement one another.

Slight clouding of plagioclase, such as observed in many gabbroic intrusives, is probably caused by exsolution of foreign ions in the plagioclase lattice upon slow cooling. Most likely a large proportion of these foreign ions consists of Fe^{+3} substituting for Al^{+3} in the lattice, but undoubtedly other ions such as Fe^{+2} and Mg^{+2} are also present. However, it appears to the writers somewhat unreasonable to assume that intense clouding of plagioclase which renders crystals almost opaque, is due to exsolution of iron and other ions originally contained in the lattice. Whatever the solubility of iron in plagioclase, it is not likely to be more than a fraction of a per cent. Reliable analyses of clear plagioclase from volcanic rocks, in which the foreign ions are presumably not exsolved, also do not show more than at most 0.5 per cent total iron.

Bowen (1948) has ably summarized the case against diffusion through crystals in noting that (1) the threshold temperature for appreciable diffusion is approximately 0.8–0.9 T (Eitel, 1929), where T is the absolute melting temperature of the silicate, (2) the crystallization temperature of minerals in polycomponent systems such as magmas is far below that of the individual phases, and hence probably also below the diffusion threshold temperature, (3) the coefficient of diffusion for solid silicates is of the order 10^{-9}–10^{-10} cm^2/sec., while that of "dry" silicate melts is roughly 10^{-6}–10^{-7} cm^2/sec., and the temperature diffusion coefficient is about 10^{-2} cm^2/sec.; hence heat dissipation would normally prevent any appreciable diffusion in crystals and (4) zoned crystals should become uniform upon diffusion of ions through their lattice; the presence of zoning therefore indicates that diffusion through the lattice of the zoned crystal did not occur.

Objections could probably be raised against these arguments (Goldsmith, 1952), but the weight of the evidence does not favor diffusion of extraneous ions through the feldspar lattice as being the cause for intense clouding of plagioclase. On the other hand, the evidence does indicate that the material which produces clouding in plagioclase is extraneous and only migrated into the crystals after their formation. Other examples, such as the replacement of plagioclase by almandine garnet starting in the feldspar core (Fig. 6), also indicate that extraneous material can and does diffuse into already-formed crystals. This is the main conclusion of the present writers, but in seeking to explain how this material migrated into the plagioclase crystals they can only offer suggestions, in the hope that this will stimulate further experimental work.

Cleavage planes probably provide openings of relatively large size which freely permit outside solutions to penetrate the crystal. Deposition of and replacement by other minerals along cleavage planes prove that solutions do penetrate crystals along these passages. Subboundaries have been observed in metals (Guinier, 1950, pp. 402–440) and similar phenomena may be present also in silicates, representing potential passages for diffusion of slightly smaller separation than cleavage planes. If present in silicates, block structures (Freudenthal, 1950) may provide potential passages for diffusion of comparable or smaller separation.

Transformations of the so-called disordering type (Buerger, 1948) result in the production of innumerable small surfaces of physical discontinuity, each the size of a few unit cell surfaces. Intermediate plagioclases are at low temperatures mixtures of low-albite and anorthite; two phases which are evenly, and probably more or less symmetrically distributed throughout the crystal in layers a few unit cells large (Cole, Sörum, and Taylor, 1951). Along the mutual boundaries of these two phases there probably exists a state of high disorder, and such "internal phase boundaries" may provide a great many potential passages for diffusion, allowing for extremely intimate penetration of the crystal. Owing to this high degree of disorder, the internal phase boundaries may show features comparable to the surface boundaries of the crystal, rather than the bulk material.

Surface effects are still very imperfectly understood, yet present evidence indicates that they may play a major role in such important geological processes as diagenesis, metasomatism, metamorphism, and weathering (Verhoogen, 1948). Experiments show that "monomolecular films" have properties different from those of the corresponding solids and more nearly like those of the liquids. Lichtenecker (1942) found that surface melting of metal layers 10^{-4} cm. thick occurs at temperatures much lower than the true melting temperature. Adam (1941) noted that melting of thin films is rarely sharp but occurs gradually over a melting interval. Most significant to the present discussion, Beischer (1950) found that surface diffusion coefficients of stearic acid on mica are "greater than the values normally found for volume diffusion coefficients of substances in solids. They are of the magnitude of diffusion coefficients in liquid diffusion media" (1952, p. 683).

It would seem from these observations that (1) in unmixed minerals, such as intermediate plagioclases, there are innumerable surfaces of physical discontinuity present, more or less regularly distributed throughout the crystals, (2) the material along these boundaries is probably highly disordered and may show effects comparable to crystal surfaces rather than bulk material, (3) surface properties are different from those of bulk material and more nearly like those of the corresponding liquids, (4) surface melting occurs at lower temperatures than the true melting of the equivalent bulk material, while measured coefficients of surface diffusion are appreciably higher than those of the corresponding solids. Thus it seems at least plausible for material to diffuse into crystals along these potential passages, in preference to diffusion through the crystal lattice. Nor is it necessary for zoned crystals to become uniform when diffusion takes place along internal phase boundaries. Whether these passages are large enough to accommodate water molecules, or diffusion is in the "solid state" is not known, but the solution of this problem is not essential to the present discussion.

Experimental work carried out so far has been mainly concerned with solid diffusion of ions through crystal lattices, in the absence of water (cf., Rosenqvist, 1951; Verhoogen, 1952; Jensen, 1952). These experiments have shown that ionic diffusion in crystals is controlled by both ionic size and electrostatic charge. The influence of electrostatic charge appears to be especially marked and Verhoogen found that large K^{+1} ions diffuse more rapidly through quartz plates than small bivalent or trivalent ions such as Mg^{+2}, Fe^{+2}, Al^{+3}, or Fe^{+3}. On the other hand, in clouded feldspars it is apparent that diffusion affected especially these smaller ions of high valency. Coefficients of diffusion found experimentally so far also seem too low to account for clouded feldspars. The present writers suggest that possibly higher values might be obtained if the experiments were repeated under high water vapor pressures. It may be significant that Bowen and Tuttle (1950, p. 500) found that unmixing in K-Na feldspars at elevated temperatures is accelerated when the crystals are maintained under high water vapor pressures.

The size of the particles in clouded plagioclase is clearly many times that of the suggested internal phase boundaries. Possibly upon crystallization of the introduced material along the larger conduits ions were drawn from the smaller passages, or perhaps the growing microlites enlarged the smaller passages.

Replacement of one mineral by another from the core outwards, instead of from the periphery inwards (Fig. 6), and the intimate penetration achieved in associations of synantectic minerals in symplektites may also be explained by the occurrence of minute division surfaces within unmixed crystals and migration of extraneous ions along these potential passages.

PETROLOGY OF CLOUDED PLAGIOCLASE

Given a sufficiently high temperature level for diffusion, ions will migrate principally down concentration gradients, but other effects, notably thermal convection-diffusion (Wahl, 1946) may also prevail. Temperature probably also governs which ions are predominant in the solutions at any particular time. Iron apparently migrates at rather low temperatures, while the predominance of Fe^{+2} or Fe^{+3} is probably determined by such factors as temperature, initial rock-composition, hydrogen ion concentration at any particular stage, etc. With an adequate temperature level, sufficient time, and in the presence of water, a fluid phase relatively rich in iron will be developed in the rocks.

In any particular crystal of intermediate plagioclase the iron concentration along the internal phase boundaries and other surfaces of greater separation will be lower than that of the surrounding pore fluid, hence iron will tend to migrate along these potential passages into the crystal, and will continue to do so until some degree of equilibrium has been attained in the iron concentration of the pore fluid of the rock and that existing within the division surfaces of the crystal. Other ions will also tend to establish equilibrium by migrations into and from the crystal, but it is assumed that iron is the principal migratory constituent under the postulated conditions.

With a subsequent decrease in temperature, iron will crystallize from the pore fluid, perhaps as magnetite. The iron present along the internal phase boundaries and other surfaces of greater separation within the plagioclase crystal also crystallizes as magnetite, since there is equilibrium between the interior and exterior of the crystal. Likewise, hematite, spinel, garnet, biotite, rutile, or hornblende are formed *inside* the crystal if they happen to crystallize at the same time from the pore fluid *exterior* to the crystal. The fact that enclosures of clouded plagioclase, when large enough to be recognized, invariably are the same as minerals occurring outside the plagioclase crystals indicates some degree of equilibrium between exterior and interior of the crystals, and would seem to militate against the formation of the clouding particles by exsolution.

Within the minute division planes of the plagioclase crystal the iron ions are used up in the formation of numerous magnetite rods. The relatively rapid decrease in iron concentration of the pore fluid upon crystallization of magnetite may result in iron again diffusing out of the plagioclase crystal, but both the time factor and the interior crystallization of magnetite inhibit complete clearing of the plagioclase. Thus only the peripheral parts of the crystal become clear, while the larger part remains clouded. The above explanation assumes that concentration gradient is the dominant driving force for ionic diffusion. Other factors may also be important, and chemical potential, especially, may play a role, as suggested by Jensen (1952).

From these considerations the geological implications of clouded plagioclase may be postulated. Clouding occurs in unmixed plagioclases of intermediate composition, and intense clouding has not been observed in either albite or anorthite.* Conditions for clouding of plagioclase in a rock are (1) the existence of an adequately high temperature for a sufficient length of time, (2) the presence of an aqueous pore fluid, and (3) the presence of iron-bearing minerals in the original rock. These conditions are often realized in thermal metamorphism, but both the time factor and the amount of iron present in the original rock may be insufficient,

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* Slight clouding in the end-members of the series is probably due to exsolution.

while there may also be insufficient water available for the formation of a medium for diffusion. It should also be noted that an "excess" of water would promote recrystallization of plagioclase in preference to clouding. In such cases thermal metamorphism does not produce clouded feldspars in the rocks. Regional metamorphism may likewise result in clouding of plagioclase if the requisite conditions are fulfilled. Clouding of plagioclase in the basic dikes of the north-west Highlands and southern Mysore is probably due to regional, rather than thermal metamorphism. A prolonged iron-rich deuteric phase in basic intrusives, as might result from magmatic incorporation of water and pelitic material upon emplacement, may also produce clouding of pre-existing or newly-formed plagioclase which cannot then be attributed to later thermal or regional metamorphism. The writers believe that the absence of strongly clouded plagioclase from basic intrusives not affected by later metamorphism is primarily due to a combination of unfavorable factors such as relatively rapid crystallization of iron ore, slow unmixing of plagioclase, and relative brevity of the deuteric stages. Clouded plagioclase clearly cannot form the sole criterion for thermal or regional metamorphism

CONCLUSIONS

Clouded feldspars are often found in thermal metamorphic aureoles, but plagioclase of thermally metamorphosed rocks is not invariably clouded, even when crystals are of original feldspar, nor is clouding of plagioclase confined to rocks subjected to thermal metamorphism. It follows that clouding of plagioclase cannot be used as a criterion for thermal metamorphism.

Slight clouding may be the result of exsolution of iron dissolved in the plagioclase crystal at the time of its formation. More intense clouding cannot reasonably be expected to be due to exsolution. The evidence indicates that such clouding is produced by diffusion of extraneous material into the crystal after its formation. Strong clouding is only observed in intermediate plagioclases, and crystals of this composition are at low temperatures extremely fine-grained mixtures of low-albite and anorthite.

Unmixing of a uniform plagioclase is considered to produce innumerable minute surfaces of physical discontinuity throughout the crystal, and these surfaces are believed to provide potential passsages for diffusion of material. The properties of the internal division surfaces are regarded as comparable to those of monomolecular films, for which experimental evidence indicates much higher coefficients of diffusion than are estimated for the bulk material. Thus the rate of diffusion along these passages is probably considerably higher than experimentally determined diffusion rates through crystal lattices.

Clouding is most common in plagioclase, but the same effects may be encountered in apatite, spinel, olivine, pyroxenes, amphiboles, micas, quartz, potash feldspars, garnet, calcite, and serpentine. The particles which produce clouding generally consist of opaque ore, but other minerals such as spinel, garnet, biotite, hornblende, and rutile may also be present in clouded minerals.

The requisites for plagioclase clouding are (1) elevated temperature for a prolonged period, (2) presence of water, and (3) supply of iron from the original rock. These conditions may or may not be realized in thermal or regional metamorphism. Frequently they are met, especially when basic rocks, normally of high iron content, are metamorphosed, but clouded feldspars are rarely found in metamorphosed arkoses poor in iron. Clouding of plagioclase may also be caused by extended iron-rich deuteric activity in basic intrusives, which often results from earlier assimilation of pelitic material and water by the magma.

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"MR. ARTHUR K. GILKEY died August 10, 1953, in the unsuccessful attempt of the Third American Alpine Club Karakoram Expedition to climb K-2 in the Himalayas. It was a great shock to all who were privileged to know him to hear of his tragic death. As a student of geology Art Gilkey showed exceptional promise. He had completed a brilliant study on the Zuni uplift in New Mexico under the sponsorship of Professor Walter H. Bucher for his Ph.D. thesis, which he was to defend after his return from the Himalayan Expedition. His keen interest in and awareness of geologic problems was also manifest throughout the work for the present paper. All of us here at Columbia University had the highest regard for him, both as a man and as a geologist. His death leaves us with a deep sense of loss. He was a good friend and a fine man, whom I am proud to have known.

Arie Poldervaart"