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On the Formation of Cloudy Zones in Plagioclases

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Abstract

The occurrence of cloudy zones in the phenocrysts of plagioclase in certain volcanic rocks, especially in the Quaternary volcanic rocks of the Chaîne des Puys (France), is described in some detail. Related anomalies of plagioclases in these rocks are also dealt with. It is shown that the cores of these plagioclases are always of a more acid composition than their outer shell, the former corresponding in chemical composition to the calculated plagioclase of the norm. These two facts — it is stressed — form the clue to the genetical interpretation of this phenomenon. Attention is drawn to the difficulties encountered in attempting to explain the origin of these cloudy zones, as heretofore, by the mixing of two magmas of different chemical composition. Another theory is therefore proffered, according to which these plagioclases are formed by a process of autoresorption, during which the fluid magma breaks through the roof of the magma chamber, formed by a holocrystalline plutonic facies of the same magma. The bearing of this hypothesis on the study of the chronological order of the elaboration of different magmas from a common parent magma, as well as on the problem of the absence of wide-spread chemical and mechanical contamination of lavas by the country-rock, is discussed.

Introduction

On investigating the Quaternary volcanic rocks of the Chaîne des Puys (Massif Central Français), the observation was made that many crystals of plagioclase contained in these rocks show a special phenomenon known as cloudy zones. Since this feature is particularly well developed in these rocks, and is of more than local importance, it appeared worth while to study it more closely. The results of these investigations are of a more general character, bearing as they do upon the crystallization of plagioclases from rock-magma and upon some features of the mechanism of volcanic eruptions in general; they are therefore published here in a separate paper.

Observations

DESCRIPTION OF THE CLOUDY-ZONED CRYSTALS

The crystals exhibit a core of more or less homogeneous plagioclase, the composition of which ranges in the different rocks from acid oligoclase (An_{15}) to labradorite (An_{60}). This plagioclase is often faintly zoned, the arrangement of its zones being normal, i. e., the plagioclase becoming more acid from the centre outwards. These cores are always rounded, generally showing an almost ellipsoidal shape (Fig. 1). Sometimes, their outline is entirely irregular, showing deep embayments, doubtless due to corrosive action (Figs. 2 and 3). This core is surrounded by the cloudy zone, consisting of a plagioclase crowded with minute crystallites, particularly of pyroxenes, olivines and ore-minerals; inclusions of glass are sometimes present. All these inclusions are very small and do not exceed 1 μ. Frequently they are smaller still. In their arrangement they may or may not exhibit a fluidal structure. This cloudy zone is surrounded, in turn, by an outer shell of clear homogeneous plagioclase, showing no trace of any inclusions whatsoever. The outline of

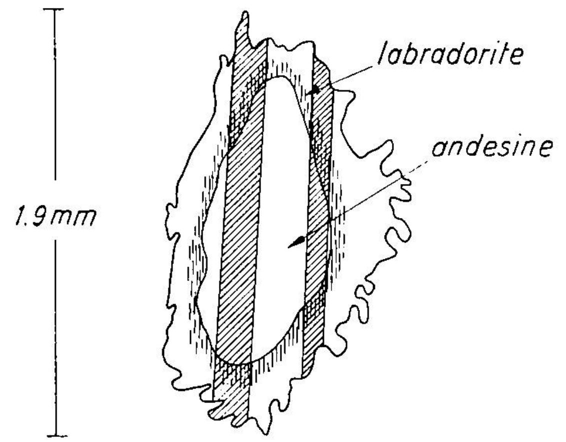

Fig. 1. Phenocryst of plagioclase, built up of andesinic core, small cloudy zone and outer rim of labradorite. Note the corroded ellipsoidal shape of the core, the fluidal texture of the microlites composing the cloudy zone and the crenellated outlines of the labradorite. The twinning passes, without deviation, through all three zones. Enlargement: 37×.

this outer shell is sometimes very irregular and crenellated (Fig. 1). In chemical composition this outer shell is invariably more basic than the core. The composition of the plagioclase of the cloudy zone itself, is generally intermediate between that of the core and that of the outer shell, but often tends to be very close to that of the latter. It is a remarkable fact that the chemical composition of the outer shell is closely related to that of the microlites of plagioclase in the same rock. These two plagioclases possess either exactly the same composition, or the outer shell of the phenocrysts is slightly more basic. These data, for a number of measured crystals from different rocks are given in table 1.

Table 1. *Chemical Composition of the Different Layers of Cloudy-zoned Plagioclases* (in % An).

core	shell	cloudy zone	microlites	rock
20—37	52—53	40—52	50—52	basic trachyandesite, lava flow
15—25	55	55	50—60	basic trachyandesite, lava flow
40	51—55	55	52	basic trachyandesite, lava flow
42—44	59	59	52	basic trachyandesite, lava flow
42—44	59	59	52	basic trachyandesite, ejection
40	53		50,5—56	basic trachyandesite, ejection
38—45	52		48—56	trachyandesitoid ejection
58	60	60	50—52	trachyandesite-basalt, lava flow
41	51		51—56	trachybasalt, lava flow
43	54		52—54	trachybasalt, lava flow
43	54		52—54	trachybasalt, ejection
54	73		55—62	essexite-basalt, lava flow
33	55		55	essexite-basalt, lava flow

The relative thickness of these three layers (core, cloudy zone, outer shell), varies greatly. In extreme cases, the cloudy zone may occupy almost $^{9}/_{10}$ of the whole crystal, whereas in other instances it is reduced to a single row of microlites.

The crystallographic orientation of all three layers is uniform, twinning of the core passing through the cloudy zone into the outer shell (Figs. 1 and 3).

Finally we note that this complex crystal is frequently surrounded by a f o u r t h l a y e r, generally much thinner, consisting of anorthoclase (Fig. 3).

It can be seen from this description that the phenomenon of cloudy zones here discussed has nothing to do with that of the so-called „gefüllte"

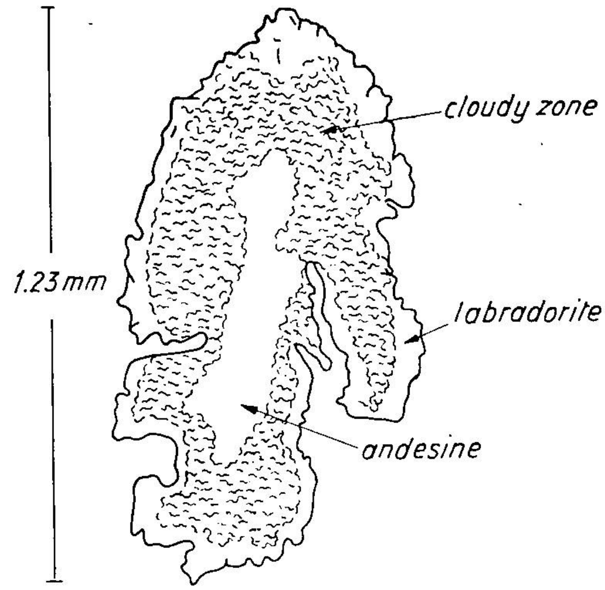

Fig. 2. Phenocryst of plagioclase, showing core of andesine, very large cloudy zone and outer rim of labradorite. Enlargement: 75×.

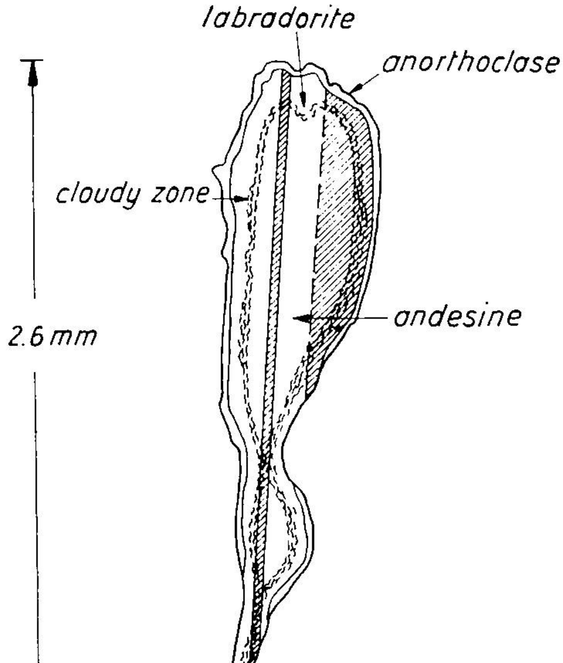

Fig. 3. Phenocryst of plagioclase, composed of four zones: andesine core, small cloudy zone, labradorite and outermost shell of anorthoclase. The twinning is common to the first three layers. Enlargement: 40×.

plagioclases dealt with, among others, by CORNELIUS[1]) and CHRISTA[2]). There too, the feldspars contain a multitude of small microlites interspersed more or less uniformly through the host crystal. However, stuffed plagioclases differ from cloudy-zoned ones in practically all other respects, and especially in the following:

1. Among the microlites of stuffed plagioclases two minerals are predominant: clinozoisite and muscovite. These minerals, as a rule, do not appear in these rocks outside these plagioclases.

The microlites of the cloudy-zoned plagioclases, on the contrary, are the typical constituents building up a good part of the ground mass of these rocks, such as: olivine, pyroxene and ore-minerals.

2. „Gefüllte" plagioclases are generally filled more or less uniformly, except for an occasional small outer rim of clear plagioclase. In cloudy-zoned plagioclases, on the contrary, the microlites are restricted in most cases to a well-defined zone, within the crystal, leaving a clear core as well as a noncontaminated outer shell.

3. For „gefüllte" plagioclases the uniformity of composition is stressed, whereas cloudy-zoned plagioclases invariably show a core richer in albite than the clear outer shell.

4. „Gefüllte" plagioclases were found only in plutonic rocks (including occasionally porphyritic varieties), whereas cloudy-zoned plagioclases are conspicuously restricted to volcanic rocks. We never found such crystals in the granites and associated plutonic rocks of the Massif Central, whereas the same crystals, torn from them and appearing as xenoliths within the volcanic rock, show the cloudy zones conspicuously. The formation of these cloudy zones is therefore certainly a volcanic phenomenon, whereas the „gefüllte" plagioclases appear preferentially, if not entirely, in plutonic rocks.

Thus, „gefüllte" plagioclases differ from cloudy-zoned ones in the character of their microlites as well as in the form and distribution of the phenomenon. The different theories, endeavouring to explain the origin of the former plagioclases (diaphtoresis according to CORNELIUS, intramagmatic crystallization under special conditions of hydrostatic pressure caused by orogenetic movements according to CHRISTA) are therefore not applicable to the genesis of cloudy-zoned plagioclases, which represent quite a different phenomenon.

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1) H. P. CORNELIUS: Zur Deutung gefüllter Feldspäte. Schweiz. Min. Petr. Mitt., 15, 1935, pp. 4—30.

2) E. CHRISTA: Das Gebiet des oberen Zemmgrundes in den Zillertaler Alpen. Jb. Geol. Bundesanst. Wien. 81, 1931, p. 533.

OTHER ANOMALIES

These cloudy-zoned crystals are usually accompanied in a given rock by others exhibiting a series of additional anomalies. These may be classified as follows (see Fig. 4):

1. Plagioclases with a more acid core (mostly andesine) surrounded by an outer shell of more basic character (mostly labradorite), without exhibiting any intermediate cloudy zone. The boundary between core and margin is very sharp, showing no trace of a gradual transition. The crystallographic orientation of the two parts of these crystals is the same (Fig. 4a).

2. Crystals of strictly idiomorphic plagioclase (mostly labradorite), showing an entirely resorbed core. The centre of these crystals is constituted in one of the following ways:

a) A filling of material identical with that of the ground-mass of the rock, but lacking the fluidal structure characterising the latter. (Fig. 4b).

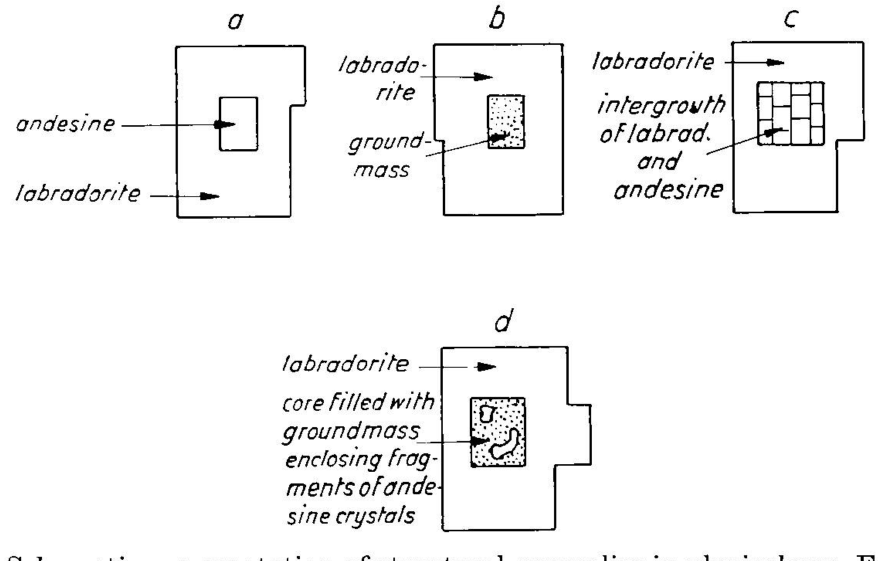

Fig. 4. Schematic representation of structural anomalies in plagioclases. For fuller explanation see text.

b) The core is constituted by an intergrowth of two different plagioclases, one possessing the chemical composition of the outer shell (labradorite), the other being distinctly more acid. These two plagioclases have a checker-board arrangement, each type forming prisms bordered by planes parallel to the cleavage planes. All these prisms run parallel, and show the same crystallographic orientations as the plagioclase of the surrounding shell (Fig. 4c).

c) The filling of the core may simultaneously show features pertaining to the types described under a) and b). In this case the core is made up of the material of the ground-mass enclosing fragments of a more acid plagioclase (Fig. 4d).

One or more of these anomalous plagioclases frequently accompany the cloudy-zoned crystals in the same rock. That all these anomalies of the plagioclase crystals are genetically inter-related is shown by the fact that the chemical composition of the plagioclase forming the surrounding shell of all the anomalous crystals, including the cloudy-zoned ones, is identical for all the individual cases. The same applies to the composition of the more acid plagioclase occurring in the core.

DISTRIBUTION OF CLOUDY-ZONED CRYSTALS

Cloudy zones occur only in plagioclases and were never found in orthoclase or other feldspars. The cloudy-zoned plagioclases, including those showing the other anomalies described above, occur in different types of rocks. Generally their development is more marked in the rocks of the lava flows than in the ejecta. A comparative study further shows that with reference to the chemical character of the rocks their occurrence is restricted to the more basic types (basic trachyandesites, trachybasalts and essexite-basalts), whereas in the more acid rocks (intermediate and acid trachyandesites, trachytes and leucotrachytes), this phenomenon is conspicuously absent. About half of the lava flows at the Chaîne des Puys, in so far as they consist of these basic rock varieties, show plagioclases with cloudy zones. Within this group of rocks the cloudy-zoned plagioclases are in no way restricted to rocks of a special chemical or mineralogical composition; moreover, two different lava flows are frequently identical in all respects except for the occurrence of cloudy-zoned plagioclases in one of them. This fact suggests that the formation of this zone is not a direct consequence of the chemical composition of the magma, but depends on the prevalence of special circumstances during the period of crystallization.

As to the different generations of the plagioclases, the occurrence of cloudy zones is definitely restricted to the phenocrysts and is never found in the microlitic generation. If a given rock possesses cloudy-zoned plagioclases, they appear in all its phenocrysts. An exception occurs only in a small number of crystals which differ clearly from the cloudy-zoned crystals in other respects as well, such as their chemical composition and morphological appearance.

Interpretation

It is clear from the outset that the cores of these plagioclases cannot be true phenocrysts, being of a more acid composition than would result from normal crystallization, as indicated by the inversions of zones between core and shell. It has therefore been repeatedly suggested[3]), that these cores may be xenocrysts resulting from the mixture of two magmas of different acidity, each plagioclase being stable in its respective magma. This explanation however, cannot be regarded as satisfactory for the following reasons:

1. Among the cores of these plagioclases, there are many of a fairly acid composition. Interpreting them as true phenocrysts of a volcanic rock, we must assume the existence among these lavas of some magmas of a very acid character, much more acid indeed, than any volcanic rock encountered. Thus, the essexite-basaltic flow of the Puy de Bleymas, for instance, bears cores of plagioclase of An_{33}, whereas the most acid true phenocrysts in any of the known rocks of this volcano are labradorites of An_{51}. In the trachyandesites of the Puy de Barme, cores of plagioclases as acid as An_{15} were found whereas the phenocrysts in the trachytes, the most acid rocks of this volcano, are oligoclases of An_{24-27}. There is no rock at all in this entire magmatic province carrying true phenocrysts of plagioclase as acid as An_{15}.

2. It is surprising that, except for the occurrence of cloudy-zoned plagioclases, these rocks, which are supposed to be the result of a mixture of two different magmas, show no other traces of this process, such as resorption, corrosion or irregularities in the distribution of minerals, patchy development of the matrix, peculiarities in chemical composition etc.

3. The mixture of two magmas of such different composition must result in a notable change in the chemical composition of the mixture as compared with that of either of the original magmas. However, there are rocks, which, while carrying ordinary plagioclase, nevertheless do not differ in any other respect, neither mineralogically nor in chemical composition, from the rocks carrying plagioclases with cloudy zones. This fact is in striking contrast to the hypothesis of magma mixture. Moreover, the

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[3]) Kuno: Petrological Notes on some Pyroxene-Andesites from Hakone Volcano with special reference to some types with Pigeonitic Phenocrysts. Jap. Journ. of Geology and Geography, XIII, 1936, p. 107. — Lehmann: Das Vulkangebiet am Nordende des Nyassa als magmatische Provinz. Z. f. Vulkanologie. Erg. Bd. IV, 1924, p. 95.

rocks containing cloudy-zoned crystals fit well into the diagrams of magmatic differentiation, into that of the single volcano as well as that of the region as a whole.

4. The hypothesis does not explain the noteworthy fact that plagioclases with cloudy zones were never encountered in acid rocks.

5. Furthermore, there is nothing to explain the observation that the cores of these plagioclases — despite their being heavily corroded — are frequently of very large size, exceeding 2 or 3 cm; crystals of this size were never encountered among the true phenocrysts of plagioclase in the volcanic rocks of the region studied.

6. Finally, there is a temporal problem, difficult to solve on the basis of that theory. The existence of these plagioclases depends on a very delicate state of equilibrium. The cores of plagioclase, having crystallized in the first magma, must, according to the theory of magma mixture, have been in contact with the second magma long enough to enable the formation of the cloudy zone, but, on the other hand, not too long to prevent their total resorption. It is difficult to imagine how a series of such highly spezialized circumstances happened to occur so often in one single volcanic province. All this points to the conclusion, that there must be a causal relationship between the capture of these plagioclases and the time of the final eruption of the lava.

We must therefore try to evolve another hypothesis capable of explaining the above-mentioned features which at first glance appear to be of a contradictory nature. The theory must account for the occurrence of crystals of unusual size, which were certainly brought in from without, but which did not change the chemical composition of the magma; moreover, they were always seized at a definite moment, i.e. just before the eruption of the magma. The following explanation is therefore suggested: There was a mixture of magmas. Not of two essentially fluid magmas of different chemical composition, but of two magmas which, while possessing the same chemical composition were in a different stage of crystallization. The essential fact to support this view lies in the following:

There is an obvious relationship between the chemical composition of the plagioclase cores and the normative composition of the plagioclase as calculated from the analysis of the rock[4]). In fact, in the great majority of cases, the composition of these two plagioclases is virtually the same, allowance being made for that part (generally very small in these

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[4]) See P. NIGGLI: Über Molekularnormen zur Gesteinsberechnung. Schweiz. Min. Petr. Mitt., 16, 1936, p. 295—317.

Table 2. *Comparison between the composition of the core of the cloudy-zoned plagioclases and the composition of the plagioclase of the norm*

rock	calculated (normative)	observed (core)
trachyandesite, Puy de Côme, lava flow	40	42—44
trachyandesite, Puy de Côme, ejection	40	41—43
trachyandesite, Puy de Louchadière, ejection	38,5	40
essexite-basalt, Puy de Côme, lava flow	53	54
andesite, Hakone volcano, Japan, lava flow	57	59
essexite-basalt, Kiwira Nyassa	52,7	40—60
trachybasalt, Puy de Bleymas, lava flow	53	41
trachybasalt, Puy de Bleymas, other flow	53,5	43

rocks) of anorthite entering the pyroxenes. This relationship is shown in table 2.

In order to show that the rule applies generally, we have included in the above table in addition to some examples of the French volcanoes, two rocks from other regions: one andesite from HAKONE volcano, Japan, calculated from the paper by KUNO[5]), the other an essexite-basalt from Nyassa, the data for which are taken from BEHRENDT[6]). Apart from the last two examples of our table, which represent a special case to be dealt with below, the agreement between normative and modal composition is striking. Throughout, the composition of the core is that of the normative plagioclase of the rock[7]). Yet, the conditions causing the crystallization of a plagioclase out of a rock magma in accordance with its normative composition, are those of a plutonic rock. This leads to the following deduction: A part of the magma crystallizes under intratelluric conditions into a holocrystalline plutonic rock. This rock may form the roof and the

[5]) KUNO, loc. cit.

[6]) BEHRENDT, loc. cit.

[7]) It may be mentioned that the same holds true for certain phenocrysts of pyroxene accompanying the cloudy-zoned plagioclases, for instance in the above quoted Japanese rock. There are crystals of orthorhombic pyroxene, showing an inverse arrangement of zones, the core being richer in Fe and poorer in Mg than the surrounding shell. Calculation shows that the composition of the core corresponds very closely to that of the normative pyroxene, as calculated from the analysis of the rock (observed En_{55}, calculated En_{57}). The cores of these crystals, therefore, have the chemical composition to be expected on the assumption of a crystallization of this magma under plutonic conditions.

walls of the magmatic chamber. Later, that part of the magma not yet crystallized, on its way to the surface, breaks through this plutonic rock of its own; in the course of the process, some of the plagioclase crystals are recaptured from the solid rock. If, as will generally be the case, these crystals are too acid in composition for the magma in this less advanced stage of its crystallization, they will be resorbed.

Then, during the dissolution of the plagioclase, the magma, from which at the same time a more basic plagioclase is crystallizing out, becomes, in the immediate neighbourhood of the corroded crystals, supersaturated with feldspathic matter. Therefore, another plagioclase will crystallize here very rapidly. It will have the composition of the plagioclase crystallizing in equilibrium with the magma at this time, or it will be only slightly more acid. As its crystallization proceeds very rapidly a large number of finely divided droplets of the fluid magma are enclosed in this newly formed shell of plagioclase, which later, during the final cooling of the rock, crystallize into the fine crystallites characteristic of the cloudy zone. Since this process of the inclusion of finely divided droplets of fluid magma into a quickly-formed shell of plagioclase proceeds in a magma having an ascending motion, it is not surprising that a fluidal arrangement is so often exhibited. The development of this cloudy zone continues until the original core is entirely surrounded. At that point the contact between the acid core and the fluid magma is interrupted, so that the formation of the cloudy zone ceases. From then on, the further growth of the plagioclase proceeds normally, and leads to the formation of the clean outer shell of these crystals.

As regards the phenocrysts of the same rock, showing no cloudy zones, we note that they are generally much smaller and more lath-shaped, and are always more basic in composition; more so even than the outer shell of the cloudy-zoned crystals. It is obvious that they represent those phenocrysts which had already begun to crystallize out prior to the recapture of the more acid plagioclase of the roof rock. They are the ordinary phenocrysts of these rocks which have not crystallized round a foreign core of a more acid composition.

The same hypothesis, developed to explain the origin of the cloudy-zoned plagioclases, automatically explains the abnormal features of the other plagioclases accompanying the cloudy-zoned crystals. They can be explained as the result of the different relative velocities of the two opposing processes involved: the corrosion of the acid core and the contemporaneous crystallization of the basic outer shell. If the second process proceeds rapidly, the core is surrounded by the outer shell before it comes to the formation of the cloudy zone; in this case we have the type cited on p. 540 under Fig. 4a. On the other hand, if the process of corrosion is more rapid than that of crystallization, the core may be entirely resorbed before the cloudy zone is able to interrupt contact with the fluid magma outside. The central hollow is then filled with fluid magma, and we thus have case 4b, c, d, a crystal built up of a core formed by the groundmass of the rock (naturally without its fluidal structure) surrounded by an outer shell of clear plagioclase with or without an intervening cloudy zone. In case 4b, the core is partially resorbed and in the spaces of the corroded parts the same plagioclase crystallizes out which also forms the outer shell. Finally, in case 4d, the destruction of the core is complete, except for the remains of the original plagioclase which are still preserved in the fluid magma, filling the central cavity; these survive the final cooling of the rock. The same process of autoresorption therefore automatically explains all the different abnormal features of these plagioclases.

This hypothesis implies the existence in depth of a holocrystalline plutonic facies of the magma giving rise to the volcanic phenomena. This plutonic rock must meet certain requirements as regards size and composition of its constituent minerals. And indeed, this assumed rock with its postulated properties was actually observed in the field. We found in the trachyandesite lava-flow of the Puy de Côme (cited in table 2) xenoliths of huge blocks — up to $^1/_2$ m^3 — of a plutonic rock belonging to the gröbaïtes. They have the same chemical composition as the lava-flow and represent the holocrystalline facies of this trachyandesitic magma. All three plagioclases, that of the norm, that of the cores of the cloudy-zoned crystals in the flow and that of the gröbaïte, have in fact the same composition (An_{40-44}). Furthermore, these xenoliths have undergone an interesting magmatic alteration. The melanocratic minerals have disappeared altogether and are replaced by iron ore. The orthoclases are strongly decomposed, whereas the plagioclases are quite fresh or but slightly saussuritized. It is therefore obvious, that in the course of the magmatic resorption of this rock, the plagioclases may easily be detached and will be but slightly corroded, whereas the bulk of the other minerals is bound to disappear more or less completely.

As we have seen, it is a necessary condition for the formation of a cloudy zone, that the plagioclase of the outer shell should posses a more basic composition than that of the core. Since in the normal process of crystallization the evolution of the plagioclase goes from a more basic to a more acid composition, special conditions must prevail in order to enable the formation of the cloudy zones. Therefore, the occurrence of cloudy-zoned plagioclases can only be an exceptional case. This result is in harmony with the fact that, after all, cloudy-zoned plagioclases are much rarer than normally formed crystals. Plagioclases, normally crystallized from a molten magma, can never develop cloudy zones.

But even if the above-mentioned process of autoresorption is taking, place, i. e., if the crystalline roof-rock of the magma chamber is partly remelted by the ascending magma, the conditions for the formation of the cloudy zones are not always fulfilled; or rather, even here, their formation constitutes the exception, for the time of crystallization of the outer shell is nearly the same or only slightly less than that of the first microlites, as indicated by the fact that the outer shell possesses the same chemical

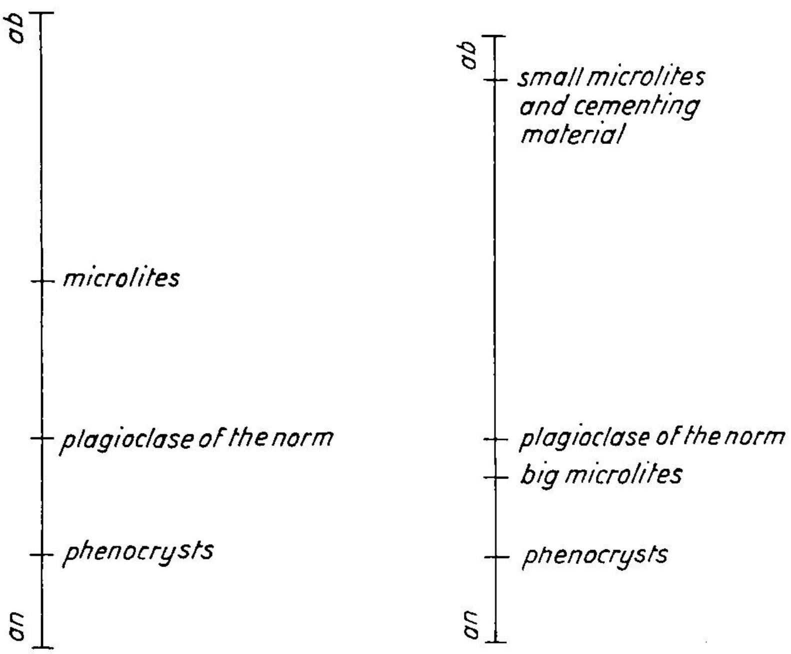


Fig. 5/6. Acidity of the different generations of plagioclases. For explanation see text.

composition as the microlites (see table 1). However, in an ordinary volcanic rock, the plagioclase appears in two generations: there are phenocrysts, of a composition more basic than the plagioclase of the norm, and microlites, showing a composition more acid than the plagioclase of the norm (see diagram Fig. 5). Since, as we have demonstrated, the composition of the core of the cloudy-zoned plagioclases is that of the plagioclase of the norm, obviously in all these rocks the primary condition for the formation of the cloudy zone does not exist.

If a cloudy zone is to be formed, a part at least of the plagioclase microlites must show a composition more basic than the plagioclase of the norm. But this is only possible if the microlitic generation is split up into two types of plagioclases, one more basic than the norm, the other markedly more acid (see diagram Fig. 6). The latter is, even in highly basic rocks, akin to albite. Yet, in the majority of cases, this albite is combined with the orthoclase molecule with the resulting formation of an anorthoclase. This is born out by the fact that all the rocks quoted in table 1 (the French as well as the Japanese and African examples) carry a considerable amount of albite, or much more frequently of anorthoclase, cementing the other microlites of the ground-mass. The splitting up of the microlitic plagioclase into two kinds of crystals of a different chemical composition is thus a necessary primary condition for the formation of the cloudy zones.

As has been stressed above, an important point in all these reflections is the identity of composition between the plagioclase of the cores and that of the norm. Yet although this identity is observed in the great majority of cases, there are occasional exceptions, as the two shown at the end of table 1, which obviously behave in a different manner. The most conspicuous among the cases studied is that of the Puy de Bleymas. This volcano has produced seven lava flows of different chemical composition, five of them carrying cloudy-zoned phenocrysts of plagioclase. Table 3 shows, in chronological order, the succession of these flows, together with the chemical composition of the core, of the outer shell and of the microlites of their plagioclases.

These figures may be interpreted as follows: The chemical composition of the rocks varies widely and with it the composition of the normative

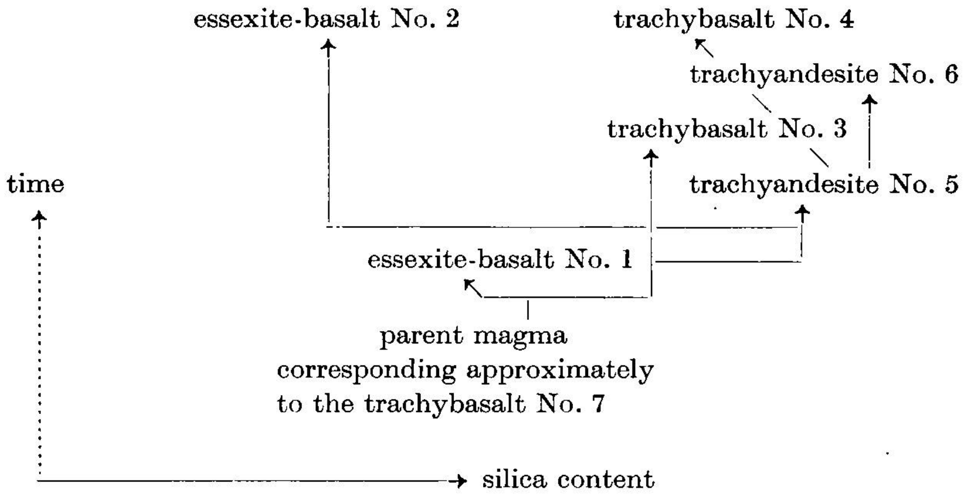
Table 3. *The lava flows of Puy de Bleymas and the chemical composition of their plagioclases* (in An%).

character of rock	plagioclase of the norm	core	outer shell	big microlites
1 essexite-basalt	54	no cloudy zones		53—55
2 essexite-basalt	55	37	55	52—68
3 trachybasalt	53	41	51	51—56
4 trachybasalt	53	no phenocrysts		51—52
5 basic trachyandesite	38	40	55	52
6 basic trachyandesite	40	40	52—55	52
7 trachybasalt	53,5	42	54	52—54

plagioclases, which lies between An_{38} and An_{55}. The cores of the plagioclases on the contrary show a quite constant chemical composition always near to An_{40}. As to the relation between the composition of the outer shell and of the large microlites, it is the usual one, the two plagioclases having practically the same composition.

Doubtless the cores of all these plagioclases derive from the trachyandesitic magmas Nos. 5 and 6. Not only are the cores and the plagioclase of the norm here of identical composition, as required, but also — petrographically speaking — it is in the trachyandesitic rocks that the cloudy-zoned crystals are by far the best developed; moreover they are here particularly abundant, accounting for up to 11% of the whole mass of the rock. For these flows the explanation given above must therefore hold true. As regards the other flows, which behave exceptionally, it is evident from table 3 that their magmas reached the surface by breaking through a roof not formed by their own magma but by the holocrystalline plutonic variety of the trachyandesitic magma of flows 5 and 6. It is from this foreign roof-rock that they obtained by resorption a certain amount — generally quite small — of plagioclases, now represented by the cores of their cloudy-zoned crystals. It is only these magmas, therefore, that are chemically contaminated by the resorption of a certain amount of a rock of different, though consanguine, chemical composition. Yet this contamination is not sufficiently important to make major changes in the over-all chemical composition of the rock, although minor changes, especially in the amounts of Fe and Mg are clearly recognizable in their chemical analysis. The reason why the trachyandesitic magma alone forms the roof of the magma chamber is obvious. For this magma, as the lightest of all, was most likely to be located in the uppermost part of the chamber.

If we have interpreted the facts correctly, this theory enables us to determine more closely the chronological order of the differentiation of the various partial magmas from the common parent magma. In the example discussed above (Puy de Bleymas) the order must have been quite different from that of the eruption. The first magma extruded does not contain cores of andesitic plagioclase. We may assume, therefore, that it is older than the trachyandesitic magma. But the second essexitic flow, although its eruption largely precedes that of the trachyandesitic flows, already contains these crystals. Therefore, at least the first of the two trachyandesitic magmas must be older than the second essexite-basaltic magma. This reflection leads to the following diagram regarding the chronological order of the genesis of the magmas for this volcano.



The numbers indicate sequence of eruption. The arrows indicate sequence of differentiation.

It seems that the phenomenon of the partial resorption of the consolidated holocrystalline plutonic facies of a magma by the still fluid part of it, just before the eruption of the latter, is much more frequent than the appearance of the cloudy-zoned crystals may suggest. A special relationship between heat and the time factor is required in order to enable the magma to partially melt down the holocrystalline rock, but to prevent the total resorption of the thus recaptured plagioclases. The existence of a holocrystalline cover, never itself erupted, surrounding the still fluid magma, may largely contribute to the surprising fact that chemical contamination by, or mechanical inclusion of, the country-rock, is so seldom encountered in volcanic rocks. This is especially true in the case of volcanoes like those in Central France. There the differentiation took place not in a great deep-seated basin, but in a secondary magma chamber situated higher, each belonging to only one of the numerous geographically adjoining volcanoes.

Summary and Conclusion

The hypothesis of autoresorption put forward in order to explain the formation of cloudy-zoned plagioclases and related phenomena may be summarized as follows: the inversion of the zonal arrangement of the cores as compared with the outer shell of the same crystals, as well as the peculiar character of the cloudy zone itself, indicate that the cloudy-zoned crystals are not formed in the course of normal crystallization. The source of the plagioclases forming the cores must be sought for out-side. The lack of any changes in the chemical composition of the rock accompanying the formation of cloudy-zoned plagioclases as well as other facts, exclude the possibility of two fluid magmas of different chemical composition having become mixed. The fact that there is identity in composition between the core and the plagioclase of the norm of the rock leads, consequently, to the assumption of the existence of a plutonic facies of the same magma, which is partly liquefied by the still fluid magma in the course of its ascension towards eruption. Blocks of this plutonic rock, showing the required properties in regard to mineralogical composition and behaviour under the influence of the attacking fluid magma, have actually been found in the form of big xenoliths within the lava-flow. From this rock, large crystals of plagioclase are recaptured. If they are, as it sometimes happens, more acid than the plagioclase crystallizing out of the magma under the given circumstances, they are more or less resorbed, this process accounting for the ellipsoidal or irregular shape of the nucleus. The resorbing magma being in this stage generally saturated with feldspathic molecules, becomes in the neighbourhood of the corroded crystals supersaturated with feldspathic matter. This leads to a hasty precipitation of a new layer of plagioclase of a more basic composition, including many drops of the magmatic liquid within its lattice. Thus is formed the cloudy zone. Resorption of the core and crystallization of the cloudy zone are therefore contemporaneous processes. As soon as the cloudy zone completely envelops the corroded core, contact with the resorbing magma is interrupted, the formation of the cloudy zone ceases and a new outer shell, consisting of a clear homogeneous plagioclase, is formed. Differences in the relative speed of the resorption of the core on the one hand, and of the formation of the cloudy zone on the other, account for a series of other closely-related anomalies of these plagioclases.

This hypothesis further automatically explains the other supplementary observations, otherwise difficult to understand:

1. The cores of the cloudy-zoned crystals are sometimes of exceptionally large size, unusual in volcanic rocks, but not exceeding that of plutonic rocks.

2. The plagioclases of the core are often much more acid in composition than the true phenocrysts of plagioclase in any of the accompanying normal rocks, but never more acid than the plagioclase of the norm of the rock carrying the cloudy-zoned crystals, i. e., the plagioclase which would be formed under plutonic conditions.

3. Cloudy-zoned plagioclases are entirely absent in more acid rocks. In view of their higher viscosity and their generally lower temperature at the time of eruption, their magmas are incapable of isolating the plagioclases out of the holocrystalline rock by resorption. Instead, as a rule, they carry this rock in the form of fragmentary xenoliths.

4. The mineralogical evidence makes it clear that the incorporation of the plagioclase core into the fluid magma must always have taken place just before eruption. The capture of these plagioclases and the eruption of the lava must therefore be causally linked, as set out in the theory of autoresorption, but not satisfactorily explained by the theory of mixture of magmas.

5. It is established that the rocks containing cloudy-zoned phenocrysts of plagioclases always carry anorthoclase (or albite-oligoclase) in their ground-mass as products of the last phase of crystallization. As demonstrated, this is a necessary consequence of the theory.

6. Cloudy-zoned plagioclases are often markedly more frequent and better developed in the rocks of a lava flow than in the corresponding volcanic ejecta. In the latter case the ascension of the magma was frequently so rapid as to restrict the development of cloudy zones or even to prevent it altogether.

7. Cloudy zones are markedly absent among the microlites in all the rocks studied. This cannot be otherwise, as their crystallization dates from a period well after the piercing of the roof-rock.

8. Sometimes magmas of different composition, evolved in one single magma chamber by the normal process of differentiation from a common parent magma, are forced successively through the same roof-rock belonging to only one of the many differentiated magmas. In this case, a whole series of different lava flows may carry cloudy-zoned plagioclases all possessing cores of the same chemical composition. The presence or absence of these anomalous plagioclases in the different flows provides a valuable clue for determining the relative age of the different magmas, as distinct from the chronological order of their eruption.

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