COMPOSITION AND DISTRIBUTION OF FELDSPARS IN MAGMATIC AND METAMORPHIC ROCKS

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With the aid of modern methods of rapid analysis it is possible to investigate the composition of feldspars statistically, using a great number of rock samples. Distribution patterns can be established by means of isochemical or isomodal lines revealing the internal structure of the rock body. Quantitative chemical and mineralogical determinations concerning the feldspar content of magmatic, metamorphic and anatectic rocks recently published are summarized and the results are confronted with the problems of feldspar formation generally discussed in the symposium.

Introduction

Since classification and nomenclature of magmatic and metamorphic rocks are based on the composition of feldspars, it is necessary to have an extensive review of all available quantitative data concerning the feldspar group of a rock body. In recent time much progress has been made in the development of rapid analyses of rocks, both chemical and mineralogical, whereby it is possible to analyse a great number of rock samples and to collect them according to statistical principles. Some problems can even be approximated by mathematical conceptions or with the aid of computers (see Krumbein (1959) and Whitten (1959–61)). Some critical remarks on this subject have recently been published by Chayes (1961).

Magmatic rocks

A rather simple case of this seems to lie in the investigation of an apparently homogenous batholithic rock body, e.g. of granite or granodiorite etc. Therefore in former times it often seemed sufficient to analyse one or some few samples of a massif, taken from "typical" outcrops, and if there was no great difference between the values so obtained, an average composition of the rock mass had been computed from them. In this manner "magmatypes" or differentiation trends have sometimes been established from only a few single values, whose areal distribution might well give quite another aspect of the relations so deduced.

It is therefore necessary to fill out the missing data and to analyse granite batholiths on a statistical basis. Some massifs have already been analysed in such a manner, usually by using 1 or 2 samples per km^2. With a hundred or more values in massifs that are not too complicated, lines of equal composition ("isopleths") can be established, showing a distribution pattern in more or less detail, depending on the number of samples available per km^2.

However, there are still some difficulties to mention which have already appeared in some recent papers on this subject. The patterns of course are based on the rock samples in their present state, i.e. as a result of a series of petrogenetic reactions whose influence on the composition of the rock sample differs considerably. Only seldom has a rock originated in a single act of formation which gives a plain uniform distribution pattern. All others show more or less telescoping effects not easily explained and grouped into the individual phases of evolution.

This must be borne in mind when collecting samples. It is therefore not recommended just to collect samples simply according to a theoretical, statistical conception. This, in itself, would require an extremely high number of stations in order to eliminate the telescoping effects. The best way is to collect samples according to principles determined by previous petrographic work based on the distinction and correlation of already well known rock types.

The first example demonstrating some of the principles of the composition and distribution of the feldspar group in granitic rocks has been taken from two recent papers (Rein (1961), Mehnert and Willgallis (1961)) dealing with the Malsburg Granite, Southern Schwarzwald, Germany. These investigations have been made in order to check the comparison between the chemical determinations of alkalies and the mineralogical mode of the rocks, using ca. 200 samples from the same localities.

The main part of the granitic body shows the classic form of a batholith with concentric "isopleths", representing the shells of an updoming pluton. The central part has a slightly higher content of both alkalies, Na and K, than the outer part, and accordingly a higher content of sodic plagioclase and of K-feldspar. Obviously this central part was formed in a somewhat later stage by the continuous uplifting of the domeshaped body. This main part of the massif shows a relatively plain and uniform variation pattern. This is in accordance with the assumption of an emplacement by intrusion of a coherent mass, presumably of a magma, followed by slightly differentiated parts of the same magma, enriched in alkalies, mainly in the central part of the pluton.

The border zones, on the contrary, show a much more complicated variation pattern. On all sides of the pluton, especially in the north-eastern part, where the contact is well exposed and dips not so steeply as in the western part, both alkalies decrease owing to a lower content of K-feldspar (not compensated by a higher content of biotite) and the formation of intermediate plagioclase (besides hornblende). This change of rock composition can be explained by an assimilation of Ca-rich and low-alkali country rocks. But, locally, this evolution has been overcome by another important process taking place especially at the northwestern and and southeastern border zone of the pluton, i.e. the extensive formation of K-feldspar porphyroblasts. Of course the K-content of these rocks is rather high and, accordingly, the Na-content is only low. This may be explained by the feldspar genetic relations: plagioclase and other minerals are strongly replaced by K-feldspar. The determinations concerning the balance of matter, especially of the alkalies, show that K-feldspar was not simply added to the granite (increasing the volume) but crystallized by replacing the other minerals. Even the Na-content of plagioclase must have been partially removed from the system. So it is most likely to assume transports in solution, i.e. complete dissolution of the older minerals and new crystallization of those replacing them.

It appears that the source of feldspathization fluids must lie in the magmatic body itself, for there is a continuous development from the late-magmatic K-feldspar formation (in the inner core of the body) to the post-magmatic regional feldspathization in the border zones. The replacement of the older minerals by the feldspar-forming solutions can be explained by the Bowen principle. Late magmatic processes in the granitic differentiation series certainly tend towards complete equilibrium but are nearly always preserved in numerous disequilibrium stages. Consequently, the general distribution of feldspars in a granitic body is not the result of a single process but is, instead, the result of a highly telescoped sequence of reactions.

It is, therefore, not surprising that various conclusions, based on other granitic massifs, differ from this conception. The changing conditions of the emplacement, mainly governed by tectonic events, and of the crystallization process could result in very different patterns of feldspar distribution. Normally, cooling begins at the border and from there extends to the inner parts. Therefore, the outer parts are usually richer in plagioclase with a higher An-content (andesine to oligoclase) and the core is poorer; having a low An-content (oligoclase to albite) but a higher content of K-feldspar. A comprehensive statistical compilation covering these granite data is given by Whitfield, Rogers and McEwen (1959). This sequence certainly corresponds to the normal course of differentiation (Compton (1955), Taubeneck (1957), Larsen and Poldervaart (1961)). However, there are massifs with the same sequence, running in the opposite direction, i.e. from the core to the border (Hutchinson (1956), Saha (1959)) or massifs comprising a more or less complicated series of shells of different composition (Saha (1958)). These examples at the present time are perhaps too intricate for an investigation of the history of feldspar formation. They certainly need much more quantitative data for explanation, as Whitten (1961a, b) pointed out, when using various computing methods in order to assess the distribution laws in granitic bodies.

The difficulties become even greater, when metamorphic transformations and granitization phenomena have to be assumed. It seems appropriate, therefore, to consider some of the most simple cases of metamorphic and anatectic evolution.

Metamorphic rocks

In a quantitative manner, metamorphic processes are investigated to a lesser degree than magmatic processes. It is difficult to determine even simple metamorphic reactions statistically by a great number of rock samples, because of the heterogeneity of the parent rocks and the far more complicated series of the rock forming parameters. Despite numerous investigations on individual reactions, little is still known about the quantitative metamorphic evolution of rocks on a larger scale.

The lower ranks of metamorphism are still relatively well known, since the petrographical character of the parent rock is usually well preserved. Recently, special attention was drawn to the series of plagioclases during the course of early metamorphism (de Waard (1959), Rutland (1961), Wenk (1958, 1962), Christie (1962), Noble (1962)). The classical view holding that the An-content of plagioclases grows with rising pt-conditions of metamorphism has been confirmed on the whole. But in certain important respects it had to be modified.

Plagioclase of low *pt*-conditions (epizone) is nearly always pure albite, regardless of the bulk composition of the rock. But, as demonstrated by Wenk in an extensive series of determinations in the western Alps, plagioclase of higher *pt*-conditions varies with the bulk composition of the rock. This correlation of plagioclase composition with chemical variations of the parent rock is often so clear that it may be assumed that the reactions took place in an essentially closed system (with regard to the plagioclase formation). Thus, plagioclase can only serve as a geothermometer in rocks of equal bulk composition.

However, the series of plagioclases in low range metamorphic rocks is discontinuous. Frequency diagrams show high values of albite 0–5% An, but distinctly lower values of An-contents of about 5–20% (de Waard (1959)), 10–20% (Lyons (1955)), 12–15% (Compton (1958)), 8–17% (Wenk (1958)). These "peristerites" seem to be unstable under low grade metamorphic conditions but occur in pegmatoidal mobilisates and similar rocks (s.p. 462). On the other hand, plagioclases of 20–30% An are very frequent in metamorphic rocks. At about 30% An there is obviously another discontinuity in the frequency curve, but this is not so sharp as that of the peristerite discontinuity, and, furthermore, its petrological explanation as a facies boundary between the greenschist and amphibolite facies remains still somewhat controversial. De Waard has demonstrated how the boundary at An_{5-10} can be exactly traced on a network of 204 samples of pelitic and basic schists from the metamorphic Usu Massif in western Timor.

A very interesting distribution pattern of this kind has been published by Wenk (1962) from the western Alps (Tessin). He plotted —after careful and detailed petrographic work in the field— all available data concerning plagioclases from one type of metamorphic pelitic rock (calcareous phyllite) on the geological map. The pattern gave proof to a clear distribution: An-rich plagioclases in the center and An-low plagioclases at the border. Assuming that this sequence corresponds to a decrease in pt-conditions (the rocks having approximately the same bulk composition), the highest temperature is taken to be in the center of the rock mass. In detail, the contours of equal An-content do not coincide with the geological and tectonic units. This proves the isopleths being independent of the tectonic structure and, therefore, the isotherms probably correspond to an uplift of magma at a greater depth.

All these determinations suggest a rather "conservative" behaviour of plagioclase formation during low and medium grades of metamorphism. However, beside this, metasomatic reactions may occur with strong changes of composition. This is most evident at the low temperature ranges in the formation of albite. While this is a very common process in epizonal metamorphism, feldspathization through the formation of K-feldspar only occurs at distinctly higher pt-conditions. Therefore, albitization and K-feldspathization never show transitions. They are always separated from each other, even when occurring in the same rock, by a hiatus in their genetic evolution, i.e. firstly, K-feldspathization, secondly, albitization.

The formation of K-feldspar, mostly in the form of blastic phenocrysts, seems usually to have taken place at the periphery of magmatic massifs. The chemical evolution clearly shows an addition of K (Härme (1959), Mehnert (1960)). From the microscopic texture it is to be concluded that all present minerals can either partially or completely be replaced by K-feldspar. The end-product, therefore, is practically pure K-feldspar, not "granite", as it is sometimes asserted. In the series of increasing feldspathization granitelike rocks are abundant, but the reaction does not stop there, and pure K-feldspar predominates at the end.

Feldspathization always advances as a front, even at microscopic dimensions, leaving behind numerous little particles of unaltered plagioclase. That means: there seems to be no diffusive exchange of alkalies, at least on a larger scale, but, obviously, a complete decomposition of plagioclase followed by a new crystallization of K-feldspar.

Optical, chemical and X-ray investigations show that the blastic

K-feldspar phenocrysts are identical, both in magmatic and metamorphic rocks. Following this, a temperature series can be established in both rock groups, according to the triclinity values of K-feldspar (Heier (1957), Barth (1959), Marmo (1958). Guitard, Raguin and Sabatier (1960), Dietrich (1961), Schermerhorn (1961)). Without now going into discussion about the microcline problem, it can be established, as a general result of recent work on that issue, that two different groups of K-feldspar are to be distinguished. One group corresponds to the phenocrysts of the granitic rocks, especially at the batholith border zone, and in the immediately adjacent host rocks (s. p. 457). This group certainly grew after the main crystallization of the granite. But, it is very important that this group of K-feldspar be systematically distinguished from the K-feldspar, crystallizing together with plagioclase and quartz in the central part of the pluton. It seems that both groups can even be distinguished in one crystal by observing the different growth stages, often separated by a rim of inclusions (Frasl 1954). The problem facing future petrographic work is to determine the quantitative K-feldspar content, according to these different groups. Then, perhaps, some discrepancies as to the explanation of late granites will be better understood.

Anatectic rocks

When the temperature in metamorphic rocks rises above the granitic eutectic temperature, and sufficient water is present, melting begins locally comprising quartz + feldspar. The initial liquid expands by further incorporation of quartz and feldspar ("metatexis"), leaving behind the mafic minerals thus forming marginal rest-rocks. In advanced stages, with the rising of temperature, nearly the whole rock undergoes melting, which then includes also the mafic minerals soluble in the melt ("diatexis").

The An-content of 189 plagioclases of typical metatects were determined by the author (1962). According to thermodynamical principles and experimental results (Winkler (1960)) it has to be assumed that the plagioclases in the metatects ought to be An-poorer than in the rest-rock. But this has not been confirmed in the natural rocks. Plagioclases have the same An-content on both parts, varying only statistically according to the composition of the original rock. This proves an essentially closed system with regard to plagioclase formation, including the metatects and the rest-rocks. The same plagioclases, therefore, crystallize in both parts when the system cools down.

But this will only happen if the metatects are not moved too far from the rest-rock, i.e. usually some mm (or cm in coarse grained rocks, presumably rich in volatiles). Those initial states of anatexis are obviously closed systems with respect to most chemical components, except H_2O. With rising *pt*-conditions the systems become more and more open and differentiations begin to influence the formation of feldspars.

The plagioclases assume a rather complicated structure: The inner parts of the crystals contain irregular spots of varying size with slightly differing An-contents. Broken shells, partially replaced, prove spots to be remnants of older plagioclases formed by a replacement process, probably identical with the liquefying (melting) process. The main part of the plagioclase is relatively homogeneous with a slight increase in the An-content toward the margin of the crystal. This marginal zone always has idiomorphic forms; the highest degree of idiomorphism coinciding with the highest An-content. Beyond this zone there extends a xenomorphic rim of decreasing An-content, down to pure albite.

This structure may possibly be explained in a similar manner as the inverse zonal structures in metamorphic rocks (Barth (1956)): Increasing An-contents correspond to a higher temperature of formation. But such an inverse zonal structure can only be preserved from resolution, if the inner parts of the crystals are completely separated from the solvent or melt by the outer parts. In this way a further reaction is stopped. That such a shielding process is quite valid can be evidenced by the polygenetic zonal structures in magmatic rocks.

Homogenization of the plagioclase rims apparently does not take place in many rocks because of the simultaneous exchange of Al/Si known as a very slow process (Goldsmith (1952)). Wyart and Sabatier (1959) have shown that this exchange is accelerated by the presence of water. Perhaps due to the increase of H_2O content in the rocks,plagioclases of low-temperature formation are often homogenous, in contrast to high-temperature plagioclases showing strong heterogeneities.

The K-content of natural plagioclases has been investigated by means of 76 samples of magmatic and metamorphic rocks by Sen

(1959). The plagioclases in rocks of the amphibolite facies contain (on an average) 0.9% Or, those of granitic rocks 2.3% Or, those of different rocks formed in the granulite facies contain 4.0% Or and those of volcanites 6.5% Or. The sequence is interpreted as the result of increasing temperature of formation. But a strict parallelism between the K- and the An-content of the plagioclases has not been established in rocks of different composition.

Finally, the investigation of Taylor and Heier (1960) of the trace element variations in alkali feldspars is to be mentioned. The distribution of Li, Na, K, Rb, Cs, Pb, Tl. Ca, Sr and Ba in alkali feldspars from granites, pegmatites, and anatexites have been established by means of 88 samples. Apart from various details in the geochemical correlation of those elements, there are two main principles of the foregoing considerations confirmed by the distribution of major and minor elements in the feldspar group:

1. In large bodies of granites, pegmatites, etc. a considerable range of feldspar fractionation is usually developed. The isopleths generally correspond to the form and mode of emplacement of the rock massif, but they are independent of the various surrounding rocks. Regarding the feldspars, a clear successsion can be established, ranging from high to low temperature compositions. This, in general, agrees with the assumption of an emplacement as a magma (with special regards to the very complex postmagmatic evolution).
2. In small rock bodies of metamorphites, anatexites and feldspathized rocks, the feldspars usually show significant relations to the composition of the surrounding rocks. Accordingly, the distribution patterns are far more complex than those above. Genetical considerations drawn from these data are only valid with respect to equal parent rocks (equal bulk composition including volatiles [H_2O]).

However, it has to be stated that, regarding the distribution laws of feldspars, there are still numerous questions open. In many respects the extent of available quantitative data is as yet unsufficient for significant statistical statements. Thus, the following problems obviously need more quantitative work:

a. The distribution of *primary* plagioclases in magmatites, especially granites, in contrast to the secondary plagioclase or albite, and with respect to the high/low temperature structures of plagioclases.

b. The distribution of the various laws of plagioclase twinning.

c. The distribution of *primary* K-feldspar formed during the main crystallization in contrast to the postmagmatic metasomatic K-feldspar, with special regard to the orthoclase/microcline ratio.

d. The distribution of perthites and antiperthites.

There are, of course, many single observations in literature concerning the composition and distribution of feldspars. However, statistical investigations based on a reasonably great number of rock samples have so far been made for only a few selected rock bodies. Therefore, it will be necessary to investigate the problems more *extensively* with respect to the natural spectrum of genetic rock variance.

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