Zeitschrift: Schweizerische mineralogische und petrographische Mitteilungen = Bulletin suisse de minéralogie et pétrographie

Band: 40 (1960)

Heft: 1

Artikel: On the potassium-argon-ages of the granitic rocks

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DOI: https://doi.org/10.5169/seals-31138

On the Potassium-Argon-Ages of the Granitic Rocks

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With 2 figures in the text

Abstract

Usually, the potassium-argon ages of the microcline of the granitic rocks are much lower than the respective ages of micas of the same rocks. In the present paper, an attempt is made to explain this feature on a geological basis. From current theories on the origin of the granitic rocks and from the field data obtained, it is concluded that these discrepancies may be due rather to actual age differences between the microcline and the mica than to the different ability of feldspars and micas to retain argon. This is especially true in the case of the synkinematic rocks. In the late- and postkinematic rocks, the actual age differences between these two minerals are less marked, and the discrepancies in the potassium-argon ages of feldspars and micas extracted from the postkinematic rapakivi granites are of an entirely different character from those obtained for the respective minerals of the synkinematic rocks.

Contents

Introduction

The absolute age of the pre-Cambrian rocks is at present a problem of the utmost interest. Many questions concerning pre-Cambrian geology still remain to be answered, and some of them may be settled by a determination of the absolute ages of the respective rocks.

In this sense, the most topical problem is, of course, the determination of the stratigraphy of the pre-Cambrian rocks, which, especially in the past, has often been based on rather questionable criteria such as the stages of metamorphism. In the light of recent radiogenic age determinations, however, stratigraphy reckoned in such a way has often been shown to be surprisingly wide of the mark.

But there are many other problems to be solved, in addition. TUGARINOV (1956) has suggested that the pre-Cambrian mineralizations are mainly bound to formations of definite age. One such age is $650 \pm 35 \times 10^6$ years (the age of the Katanga formation). This is also a reason why the study of radiogenic ages is often considered of the utmost importance.

Furthermore it may be possible to find a solution to some pre-Cambrian genetical problems, as well, including that of the granites.

Mainly because potassium, one of the commonest elements suitable for age determination, is virtually omnipresent in the rocks critical for the pre-Cambrium, methods of age determination based on this element have especially attracted geologists. The potassium-argon method is probably the one from which the greatest measure of success has been expected. GERLING was probably the first to adopt it for geological purposes (in 1952; see AHRENS, 1956). On the American continent, WASSERBURG and HAYDEN (1955), CARR et al. (1956, 1957), GOLDRICH et al. (1957), etc., have worked on this method, as well as SHILLIBEER et al. (1954) in Canada, and in both places, satisfactory results have been obtained.

But many complications have cropped up in connection with the use of the K^{40}-A^{40}-method, the main difficulty being that different minerals of the same rock may have entirely different ages. And it is this point which will be dealt with in the present paper.

Discrepancies in the potassium-argon ages

Both in the USA and in Russia, it has been observed that the potassium-argon ages obtained for mica and potash feldspar, both extracted from the same rock, may have — and, indeed, usually have — quite different values; and in general the mica appears to be much older than the potash feldspar. ALDRICH et al. (1956) report that their study has shown "the consistency of K^{40}-A^{40} ages on micas and the unpredictable state of there ages on feldspars".

In the hope of clearing up this discrepancy, the leaching out of argon from different minerals has been investigated. At the same time, it has been suggested that the ability to retain argon is radically different for micas than for feldspars.

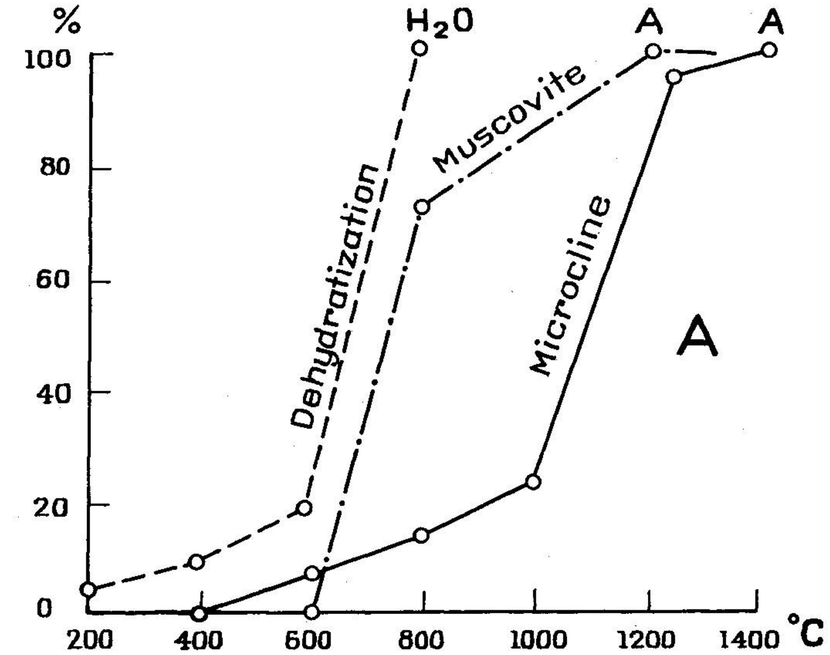
Attempts have been made to rule out some minor discrepancies by postulating the existence of "magmatic argon" (GERLING et al., 1955), taken up by the respective mineral, during its crystallization, directly from the magma itself. Discrepancies due to this cause, however, are in the opinion of GERLING, comparatively seldom met with.

According to GERLING (1956), as well as of many American investigators, the main reason for the discrepancies noted is the weakness of the lattice of perthitic microcline as compared with the lattice of micas (GERLING, in translation):

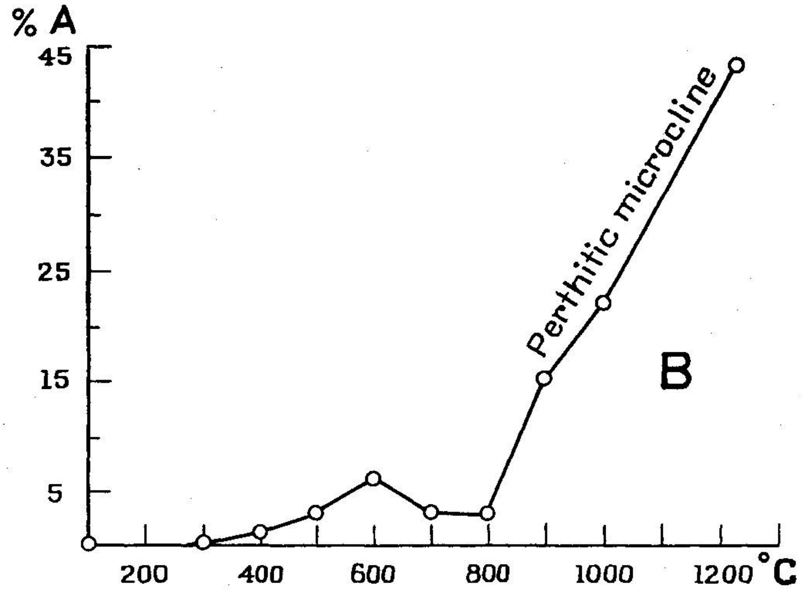
> "According to the data obtained, the ancient microcline perthites lose in comparison with the micas, a considerable amount of argon, a mean of up to 25%. A similar loss of argon is characteristic of plagioclases which contain antiperthitic intergrowths."

Potash feldspar which does not contain any perthite, is, on the other hand, according to GERLING et al. (1955), even better fitted than the micas to keep argon within its lattice, but, as GERLING states, "In Karelia Russian geologists have never succeeded in finding a microcline entirely free from perthitic intergrowths". Therefore he does not set store by the ages of potash feldspar but holds the mica ages to be the only reliable ones.

The data on which he bases his view are both experimental and calculated. Of course, it is legitimate to question whether heating experiments can give reliable information about the conditions of geological processes or not. These experiments, however, are of great interest and importance, and the results have been compiled in fig. 1, which depicts the expulsion of argon from mica and feldspar as a function of temperature. From the curve in fig. 1 it is seen that the expulsion of argon follows a pattern very similar to the dehydration of mica, and that it only begins at a temperature of 600° C, then increasing very rapidly with temperature. The expulsion of argon from microcline, on the contrary, begins at as low a temperature as 400° C, but is rather slow up to 1000° C. Above this temperature, the expulsion of argon from microcline is as rapid as from muscovite. In the same figure, another curve is shown, in which the behaviour of perthitic microcline is shown. According to the interpretation of GERLING, the first shallow peak of the graph (at 600° C) indicates the maximum expulsion caused by the perthitic



A. The expulsion of argon from microcline and muscovite at different temperatures.



B. The amount of argon expelled from microcline at different temperatures. The graphs quoted from GERLING et al. (1955).

Fig. 1.

intergrowths and the related deficiencies of the lattice. At this point, only 5 per cent of the total content of argon has been expelled. The bulk of this element, however, is not expelled until a temperature of 800° C is reached. At this temperature, 12% of the total argon will then have been expelled.

The calculated data indicate that the heat of diffusion of argon in muscovite is about 92 000 cal per gram atom; this amount is of approximately the same magnitude as the chemical bond energy. From this fact it is concluded that muscovite is an excellent material for age determinations. But so also is non-perthitic microcline. According to AHRENS (1956):

"The recoils are insignificant and although argon is a large atom, it presumably occupies a site previously occupied by the large K^+ (1.33 Å) and hence might not cause undue strain in the structure, particularly as the ratio $\frac{\text{A atoms}}{\text{K atoms}}$ is never large."

The graphs in fig. 1 indicate, however, that the actual difference in the rate of expulsion of argon from muscovite and from potash feldspar occurs between 400 and 600° C, and that the amount expelled during this temperature interval does not exceed 5% of the total content of argon. Between 600 and 800° C, muscovite is less suitable than microcline. To indicate the significance of this 5 per cent in a determination of absolute age, it is necessary to quote here the formula used by GERLING (1956) for his age calculations:

$$t = \frac{\lg\left(\frac{A^{40}}{K^{40}} + 0{,}1094\right) - \lg 0{,}1094}{2{,}39 \times 10^{-10}}$$

Certainly such a loss would not be sufficient to explain such age discrepancies as the following:

Mica:	1700 ± 50 Mill.	1800 ± 50 Mill.	1770 ± 50 Mill.
Feldspar:	1590 ± 150 ,,	1490 ,,	1490—1580 ,,

In the opinion of the present writer, these discrepancies may be explained geologically, as well. POLEVAJA (1956), one of GERLING's pupils, has a strong belief in microcline ages (op. cit., p. 52, in translation):

"The age of feldspars is very variable, and in two cases only was it in agreement with the mica ages. It is of interest to note that in all samples in which a discrepancy between the ages of feldspar and mica is observable, the presence of a secondary microclinization could be proved in thin sections.... These data, as well as the considerable number of ages determined for the granites of the Ukraine, support the hypothesis that both the accessory minerals and the micas remain in the metasomatic granites as 'relicts' of the older rocks, unaltered by the metasomatic processes; the feldspatic part of the granite, on the other hand, is undoubtedly the younger constituent..."

In her paper, POLEVAJA took as an example the metasomatic granite of Saksagal, for which the following ages were obtained (POLEVAJA, 1956, p. 53): age of microcline – 1610 my.; age of microcline porphyroblasts – 1660 my.; age of biotite – 1980 my.; age of orthite (determined by Rik and Tugarinov) – 2200 my.

Recently, Smulikowsky (1958) of Warsaw has expressed very similar views concerning the ages of feldspars and micas.

It may also be of interest to note that Shillibeer and Watson (1955) have reported some pairs of K^{40}-A^{40} ages for perthites and micas occurring in the same rock, which do not deviate much from each other:

Dill Twp:	perthite – 900 ± 70 my.	mica – 900 ± 70 my.
Conger Twp:	,, – 930 ± 70 my.	,, – 1030 ± 80 my.

For the age determinations of some Lewisian and Fennoscandian pegmatites, Holmes, Shillibeer, and Wilson (1955) used almost exclusively the K^{40}-A^{40} ratio of perthites.

Geological aspects of the concept of absolute ages

The *radiogenic age* is the time that has elapsed since an element liable to radioactive decay began to produce the products of its radioactive disintegration. In the words of Rankama (1954), p. 110), "it gives the time during which radioactive decay has gone on in a closed system". Furthermore, Rankama defines the *absolute age*, of a mineral or rock as "the time elapsed since its final deposition, solidification, or crystallization".

Consequently, strictly speaking, the *radiogenic age* does not necessarily give us any *absolute age*, as far as the age of a rock is concerned; in many cases, however, it *may* give us the absolute age of a mineral.

The present understanding and use of the concepts of absolute and radiogenic age are based on the assumption that the formation of the particular mineral whose radiogenic age is to be determined was more or less contemporaneous with the formation of the rock in which this mineral occurred. Such an assumption may be regarded as valid if, for instance, the time of crystallization from a magma is the starting point from which the absolute age is to be reckoned, which may then be arrived at from the radiogenic ages determined. Hence, for strictly magmatic minerals we may reckon with an absolute age, which would then mean the time that had elapsed since the mineral crystallized from a molten magma. However, in as far as the pre-Cambrian plutonic granites and gneisses are concerned, a considerable degree of uncertainty immediately arises.

Before going into these problems, some questions may be formulated:

1. A solid rock disintegrates as a result of weathering. The potassium of this rock goes into aqueous solution. Does the radiogenic ratio change during this process? Probably not, if solid products are concerned. In the case of argon on the contrary, this gaseous product will probably be entirely removed.

2. If the mica of the disintegrated rock is altered into clay minerals, will the radiogenic ratio be changed? Probably not, with the exception of argon, which will probably be expelled to some extent.

3. Shale is altered, during the process of regional metamorphism without fusion, into biotite schist or biotite gneiss. Will the radiogenic ratio be changed by these processes? Probably not, and the argon will also probably be completely retained, or lost to a minor extent only.

These questions and answers already entitle us to draw some conclusions:

The non-gaseous products of radioactive decay will probably survive in the minerals through the stage of regional metamorphism. According to KRYLOV (1955), they will also survive the alpine folding (in the Caledonian rocks of the batholith of Terski Ala-Tan, folded at the Alpine stage, all the radiogenic ages of micas obtained have proved to be Caledonian ones). Even radiogenic argon may survive the whole evolution (including the folding — KRYLOV, 1955) provided that the potassium has not passed through a stage of aqueous solution. If the clays converted into metamorphic mica gneisses primarily contained solid particles derived from pre-existing rocks, e. g. potassium feldspar particles, the argon of these may likewise survive the whole complicated evolution and, consequently, have very much "to high" an age.

Thus the age of a mica extracted from a mica schist or paragneiss will give the age either of the deposition of the sediment from which this paragneiss was formed, or worse still, the age of the rock of which the clay was a disintegration product. As far as the argon ages are concerned, however, the radiogenic age of a mica would most probably indicate some time between the deposition of the clay and the last stage of the regional metamorphism of an orogenic cycle.

The absolute age of the granitic and granodioritic plutonic rocks

All the possibilities outlined above have been well known to the students of the radiogenic ages. Therefore, endeavours have been made to carry out the sampling in such a way that only rocks of undoubtedly magmatic origin are collected. Consequently, where plutonic granites and granodiorites are concerned, only those believed to be of magmatic origin are accepted. It has been assumed that the palingenetic rocks may be included in this category.

Unfortunately, however, such a method of sampling is largely dependent upon subjective attitudes with regard to the origin of the respective rocks. A magmatically minded investigator may and will accept many samples as magmatic, which, in the opinion of very many other geologists, are metasomatic. This in itself affects the result. Furthermore, if a magmatically minded geologist is collecting a sample for age determination and states that his specimen represents, say, a magmatic granite, this view is accepted by the age-physicist without reservation. If then, discrepancies appear in the determinations, for instance differences between the K^{40}-A^{40} ages of the mica and feldspar, the physicist ignores the possibility that the geologist's interpretation may be wrong, and tries to attribute the discrepancies to, say, deficiencies in the lattice of perthitic potash feldspar. In the opinion of the present writer, such a way of thinking may easily distort the whole picture of the absolute ages. There appear, in such cases, biases based on an incorrect geological generalization, and if in addition wrong interpretations have been used, the errors made will be multiplied at the stage of interpretating the meaning of "absolute ages" and of the discrepancies thereby revealed. As long as controversies exist regarding the origin of the granitic rocks, one should refrain from conclusions concerning the radiogenic ages of the minerals of respective rocks, all the more so because there exists a considerable amount of evidence in support of the metasomatic interpretation. Furthermore, in many magmatic-looking granites, a definite age difference appears between the microcline and the other constituents of the rock, especially the micas. This is particularly marked in the case of the synkinematic granites and granodiorites. In the following pages, these features will be shortly discussed; the proposals made are still tentative, but, in the opinion of the present writer more promising and plausible than those hitherto made.

The synkinematic granitic rocks

Most present-day petrologists agree that, in the overwhelming majority of cases, the synkinematic granitic rocks are composed of quartz diorite to granodiorite. Often they contain only small amounts of potash feldspar, and it is exclusively microcline. If the amount of microcline in such rocks is increased, they may attain the composition of a granite. Furthermore, the distribution of the microcline in these rocks is very irregular, and in different parts of an apparently homogeneous batholith, the amount of potash feldspar may vary from nil to considerable quantities. Microcline is especially abundant in the tectonically disturbed portions of such a batholith.

In the synkinematic rocks the microcline is usually interstitial and definitely younger than the other constituents of the rock. One of the oldest constituents is biotite. The age difference between these constituents is considerable. The deposition of the microcline must therefore have taken place long after the consolidation of the rest of the rock. Concerning the young age of the microcline of the synkinematic rocks, many present-day petrologists are unanimous. In 1956, Eskola wrote that most, and possibly all, of the potash feldspar of the synkinematic rocks has been metasomatically introduced. In other words: Insofar as the synkinematic rocks contain potash feldspar, they are granitized quartz diorites or granodiorites. The primary, granitized material, how-

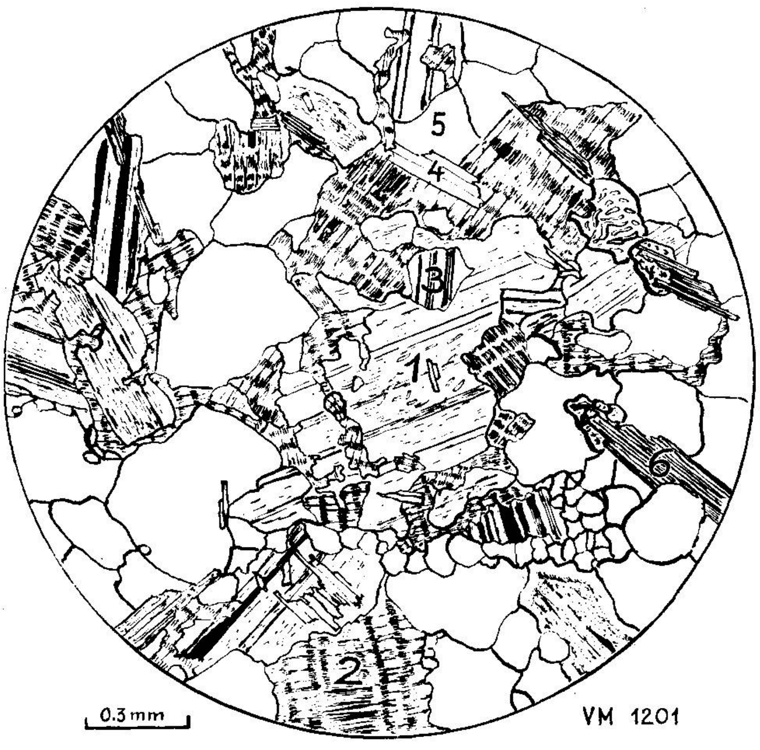


Fig. 2. Synkinematic granodiorite. The microcline is distinctly younger than the other constituents of the rock. It mainly occurs as a filling in the interstices of other minerals.
1 = plagioclase; 2 = microcline; 3 = young plagioclase; 4 = muscovite; 5 = quartz; 6 = biotite.

ever, may be of either magmatic or sedimentary origin. This fact has been stressed by the present writer in several papers (for instance, 1956). In figure 2, the typical mode of occurrence of microcline in a synkinematic rock is illustrated.

During the process of granitization, the introduction of potash feldspar takes place either as ions, or mole by mole, and quite possibly under hydrothermal conditions. Consequently, no argon is present during the deposition of potash feldspar. Therefore, the K^{40}-A^{40} age of a potash feldspar, if this age is otherwise reliable, would represent the time elapsed since granitization of the rock. The respective mica age of the same rock measured under similar conditions would then indicate the date of the consolidation of the rock, if the granitized rock was primarily of magmatic origin; or some time between the date of granitization and of deposition of the sediment, if the granitized rock itself originated from a sediment.

There are, however, certain serious complications: There may have been several stages of granitization, some of them remote; or several stages of potassium metasomatism during the same period of granitization. In the porphyroblastic granites, for instance, the porphyroblasts are often of a different generation of potash feldspar than the microcline occurring interstitially in the matrix. The present writer (Marmo, 1956 b) has described and illustrated cases in which the microcline porphyroblasts have grown across fractures originating in a solid rock, whilst in the matrix there is microcline which is distinctly older than the fractures. Furthermore, instances are known in which a still younger microcline penetrates the porphyroblasts, as well. In such cases, the ages of the mica and the microcline, beyond the limits of error, must really be different, as they are in the synkinematic rocks in general. But, in addition, the different microcline generations may also be sufficiently remote in time for differences in the radiogenic ages to exist, as well.

What is the magnitude of these age differences?

There are metamorphosed pre-Cambrian schists which have never been granitized (they do not contain any potash feldspar) alongside the granitized gneisses; but there occur strongly granitized tertiary sediments, as well. Hence, there may be very different intervals between sedimentation and granitization, if this term is taken to mean the stage of introduction of potassium (metasomatically) into a rock causing there a bulk compositional change resulting in a granitic composition. In any case, the minimum age difference must also be rather large, because granitization is a phenomenon charateristic of great depths, burial to which must take tens or hundreds of millions of years. Whether, in the case of magmatic rocks emplaced at great depths, this difference is small or not, is at present an unsolved question.

Age differences of 200 to 300×10^6 years, such as are often noted in radiogenic ages, seem to be quite within the bounds of possibility, but there are, of course, instances of granitized material 10^9 years or more older than the stage of granitization.

In table 1, some examples of mica and feldspar ages of the same rock, determined by the potassium-argon method, are listed. Among the "feldspar ages", some determinations from a bulk sample of a rock are included. All these ages were determined by GERLING or by POLEVAJA, and they have used the same constants as in all age determinations carried out in the laboratories of Leningrad, quoted in the present paper. These constants are the following:

$$\lambda_e = 0.602 \times 10^{-10} \times \mathrm{yr}^{-1}$$
$$\lambda_\beta = 4.9 \times 10^{-10} \times \mathrm{yr}^{-1}$$

Table 1. *Some K^{40}-A^{40} ages of micas and feldspars extracted from the same rock, according to Gerling (1955) and Polevaja (1956)*

Rock sample	Feldspar or bulk rock	Mica	Difference
Saksagal, granite	$1610—1660 \times 10^6$	1980×10^6	$\sim 350 \times 10^6$
Bothnian granites	1500×10^6	1800×10^6	300×10^6
Karelian granites	1330×10^6	1560×10^6	230×10^6
Tshupa, Eastern Karelia, granites	$1430—1490 \times 10^6$	$1800 \pm 50 \times 10^6$	$\sim 350 \times 10^6$

The data published so far concerning the potassium-argon ages of the pre-Cambrian rocks are mostly insufficient, because they seldom contain a careful petrological description of the respective rock. Therefore, considerable difficulties are involved in attempts to evaluate the discrepancies occurring between the mica and feldspar ages. Furthermore, in the calculation of the ages different constants have often been used, and no mention of these may exist in the publications. Thus, according to the oral communication of Dr. O. KOUVO, the K^{40}-A^{40} ages reported by GERLING are systematically 50 to 80×10^6 years lower than those determined in the West. This depends upon the use of different constants in the USSR, and in the USA and Europe.

The values of table 1, however, were all obtained by the same authors, using the same constants. An attempt has been made to collect in this table synkinematic rocks only. There the mica age for the Svecofennide granites is approx. 1800×10^6 years. For the Geological Survey of Finland, Prof. J. K. GERLING has carried out some additional mica age determinations, using the same methods and constants. There, for the micas of undoubtedly synkinematic rocks, he obtained the ages of 1720, 1740, and 1720×10^6 years. From these results it may be deduced that in the Fennoscandian pre-Cambrian synkinematic rocks, an important stage of evolution, perhaps deposition or recrystallization of sediments and emplacement of magmatic material, took place some $1800 \pm 80 \times 10^6$ years ago; and that these rocks became granitized some $1500 \pm 70 \times 10^6$ years ago.

The late- and postkinematic granites

For the late- and postkinematic granites, the age difference between micas and potash feldspar is mostly small or absent. They seem to be of more or less the same age (MARMO, 1956). In contrast to the synkinematic rocks, the granites proper (including the ideal granites of ESKOLA) are typical of these two groups.

In the field, the late- and postkinematic granites behave as true intrusives, as has been pointed out by ESKOLA, READ, etc. Consequently, they behave like real magmatic rocks. In the latekinematic granites, however, there is microcline instead of orthoclase, which is typical of the postkinematic granites. Therefore it has been suggested (MARMO, 1958) that the late-kinematic granites are intrusive but not necessarily magmatic, and that they have been formed at a temperature below, or not much exceeding, 500° C. This temperature is the most probable one for granitization, as well, as may also be deduced from the experiments of WYART and SABATIER (1958) regarding the mobility of Si and Al in crystals of feldspar. They found that for feldspathic replacements, only water is needed to make them active at 500° C.

Whether these granites are magmatic or otherwise intrusive, there, too, the potassium has been intruded in such a dispersed form that it probably could not have contained any argon. Therefore, the age obtained for the potash feldspar extracted from these granites must indicate the age of such rocks — provided that the values for the potassium-argon ages of these feldspars are otherwise reliable.

As is revealed by the curves in figure 1, at 500° C the loss of argon, including perthitic potash feldspar, is still comparatively small, and there is no reason to believe that the temperature rose after the emplacement of these granites. Therefore, in this sense also, the feldspar ages here in question should be reliable.

In the late- and postkinematic granites, the micas are usually scanty, and in many cases are represented mainly by muscovite. Often these granites tend to be aplitic, containing micas in negligible amounts only. If, however, this is present, it will give an age close to that of the potash feldspar of the same rock.

The late- and postkinematic granites may contain biotite as well. In many cases, however, and especially in the former, the biotite is of relictic character. The late-kinematic granites usually contain large ghost-like or skialithic remnants of thoroughly granitized older rocks. Therefore it may reasonably be expected that in the late-kinematic granites, there may be discrepancies not only in the potassium feldspar ages, but also in the mica ages. Furthermore, because the sampling carried out for the age determinations often favours the larger segregations, and these particularly tend to contain relict biotite, this often comes to be used for age determinations. The muscovite occurs in these rocks as fine scales recoverable only by a tedious separation process.

Still more does this apply to the postkinematic granites which usually contain much orthoclase besides lesser amounts of microcline. In the Finnish and Ukrainian rapakivi granites — typical postkinematic granites — all the coarse potash feldspar is orthoclase, partially microclinized. But, in addition, a younger microcline of perfect triclinicity is always present, as well. It forms an interstitial filling or minute veinlets penetrating the rest of the rock. The same relationship between orthoclase and minute microcline veinlets has frequently been observed in the younger, Alpine, postkinematic granites also (see for instance: Marmo and Permingeat, 1957). Consequently, for the postkinematic granites, three different age groups are to be anticipated:

1. The greatest age for the relict mica (usually biotite);
2. An intermediate age for the younger muscovite and orthoclase (the age of the emplacement of granite?);
3. The lowest age for the interstitial microcline.

Such a distribution of ages has in fact actually been observed. Polevaja (1956) remarks that for the rapakivi granites of the Ukraine, not only are the feldspar ages very variable, but the ages of the micas also display a considerable scatter.

For different minerals extracted from the rapakivi and related granites of the massif of Korosten, Ukraine, she reports some ages, quoted in table 2.

Table 2. *Radiogenic K^{40}-A^{40} ages of some minerals of the rapakivi and related granites of the Ukraine, according to Polevaja (1956). The constants used are given on p. 27.*

Rock type	Age determined from bulk sample	Age of potash feldspar	Age of mica
Rapakivi, Korsun-Novomirgorod	1640×10^6	1500×10^6	1590×10^6
Rapakivi, Korsun-Novomirgorod	1600×10^6		1580×10^6
A granite cutting the rapakivi, Korsun-Novomirgorod	1430×10^6		1700×10^6
Rapakivi pegmatite, Korsun-Novomirgorod		1560×10^6	

In this table, the mica ages of the rapakivi granites are lower than the age of the orthoclase-rich bulk rock, and, if the theory of GERLING is correct, that perthitization, by bringing about a loss of argon, causes age discrepancies (see p. 19), these discrepancies should be especially large in the rapakivi granites because in these granites the orthoclase is conspicuously perthitic. This, however, does not appear to be the case from the ages given in table 2. The mica of the granite penetrating the rapakivi is obviously a relict. Otherwise it is difficult to explain why the mica of a younger (penetrating) granite should be older than the mica of the granite penetrated. This relationship is much better portrayed by the feldspar (= bulk sample) ages.

POLEVAJA (1956) reported some examples for the late-kinematic granites, as well (table 3).

Table 3. *Radiogenic K^{40}-A^{40} ages of some late-kinematic granites, according to Polevaja (1956). The constants used are given on p. 27.*

Rock type	Age determined from bulk sample of rock	Age of potash feldspar	Age of mica
Plagioclase granite, Saksogan	2000×10^6	2060×10^6	1970×10^6
Granite, Kirovograd	2020×10^6		1815×10^6
Granite, Kirovograd	1760×10^6	1790×10^6	1800×10^6
Granite, Korosten	1360×10^6	1380×10^6	1610×10^6
Granite, Korosten	1290×10^6		1650×10^6

Tables 2 and 3 confirm the assumptions made above by the present writer concerning the mineral ages of the late- and postkinematic granites.

Some ages, however, may still be added here. These ages are those of the rapakivi granites of the Viipuri area, published by POLKANOV (1955) and measured at GERLING's laboratory. The constants used in calculating the ages are given on p. 27.

Rapakivi granite, bulk sample	1440×10^6
Orthoclase ovoids of rapakivi 1400, 1420	1360×10^6
Microcline of rapakivi	1180×10^6
Graphic feldspar of rapakivi pegmatite .	1400×10^6
Mica of rapakivi pegmatite	1500×10^6
Aplite cutting the rapakivi	1180×10^6

For the Geological Survey of Finland, GERLING has carried out determinations of the following K^{40}-A^{40} mica ages for the postkinematic granites:

Rapakivi, Utö	1440×10^6
Postkinematic granite, Onas .	1440 and 1450×10^6

For the Finnish late-kinematic granites, GERLING obtained the mica ages of 1500 to 1580×10^6 years, and in one case 1700×10^6 years. These mica ages are in good agreement with the ages determined at the Toronto laboratory by SHILLIBEER, using the bulk samples of the Finnish postkinematic granites (KAHMA, 1956). In his determinations, KAHMA recognized two age groups among these granites: 1400 to $1450 \pm 100 \times 10^6$ years and 1770 to $1860 \pm 120 \times 10^6$ years. The ages published by KAHMA are here quoted in full awareness that, even if they are comparable with each other, they may not necessarily be directly comparable with the ages published by GERLING, but the average magnitude of the ages published by KAHMA is surprisingly close to the ages of GERLING. In KAHMA's calculations, the constant $\lambda_\beta = 5.03 \times 10^{-10} yr^{-1}$ was used.

The ages quoted above are all close to the ages of the feldspars of the synkinematic granites (table 1). This may confirm the hypothesis that the granitization of the synkinematic rocks and the emplacement of the late-kinematic granites were more or less contemporaneous phenomena. This hypothesis has been advanced by the present writer on a petrological basis (MARMO, 1958).

On examining the ages of rapakivi granites reported by GERLING, an interesting feature appears: the microcline of the rapakivi granite of Viipuri and the aplite of the same area are of similar age. It is noteworthy that, when studying the postkinematic granite of Azegour, Morocco, MARMO, and PERMINGEAT (1957) found a very close genetical relationship between the interstitial microcline occurring in this postkinematic orthoclase granite, and the microcline aplite penetrating this granite.

The pegmatites may likewise contain relict biotite. In actual fact, this has been proved by the age determinations published by POLKANOV (1955) and SCHURKIN (1955): In Ylälega, Eastern Karelia, there occurs a mica schist containing mica of an age (K^{40}-A^{40}) of 1500×10^6 years; but it is cut by a pegmatite containing a biotite 2400×10^6 years old. According to POLKANOV, these ages have been carefully verified, and the latter checked by determination of the isotope ratio.

From South Karelia, SCHURKIN (1955) reports pegmatites, the bulk samples of which have an age of 1430 to 1650×10^6 years, but the age of the biotite of this pegmatite was 2380 to 2430×10^6 years. No doubt, there too, the biotite must be a relict.

Some comparisons of different radioactive ages

Regarding the ages of feldspars and micas, there is yet another problem of the utmost importance: the relationship between the K^{40}-A^{40} and the Rb^{87}-Sr^{87} ages.

These two ages have often been determined for the same minerals. WETHERILL et al. (1956) have found that the K^{40}-A^{40} ages of the feldspars of pegmatites are uniformly too low, but that the Rb^{87}-Sr^{87} ages of the same feldspars are about the same as the respective ages of the micas.

GAST, KULP and LONG (1958) have examined this relationship in particular, and they report, for instance, the following age pairs (for the rocks of the Winniped River-Johnston Lake area):

Mineral	Rb-Sr age my	K-A age my
Lepidolite	2680 ± 90	2440 ± 60
Muscovite	2650 ± 45	2340 ± 50

For the muscovite of the granite of Kaavi, Finland, KOUVO has determined the following ages (private communication):

Rb^{87}-Sr^{87} age	1780 and 1810×10^6 years
K^{40}-A^{40} age	1761×10^6 years

The zircon and biotite ages for the same granite (Kouvo, 1958) are 1845 ± 45 and 1780 ± 47 my. respectively.

According to Gast et al. (1958), the Rb^{87}-Sr^{87} ages are more consistent and somewhat higher than the respective K^{40}-A^{40} ages; and they state that an argon loss from micas was commonly as great as 15% — this concluded from the lower K^{40}-A^{40} ages. From these facts the question arises of whether the K^{40}-A^{40} ages are dependable or not.

As yet, one is not entitled to draw any conclusions in this matter, but some proposals may be made. In the opinion of the present writer, one cause of the lower K^{40}-A^{40} ages, as compared with the respective Rb^{87}-Sr^{87} ages, may be the different behaviour of the respective atom ratios in the minerals.

As has been suggested on p. 23, during the dissolution of a mineral, the Rb^{87}-Sr^{87} ratio is not expected to change very much. During the same phenomenon, all the argon, however, may be completely expelled. During the recrystallization, the ratio of Rb^{87} to Sr^{87} will still remain unchanged, but important changes may occur in the content of A^{40}. During the hydrothermal introduction of potassium, Rb^{87}-Sr^{87} may remain more or less intact; the argon, however, will probably be entirely removed. Consequently, it is quite possible that the Rb^{87}-Sr^{87} ages of a microcline or a mica have an entirely different meaning from the K^{40}-A^{40} ages of the respective minerals. Which of these two ages is correct? Probably both are correct, but they have different zero points. As yet, however, we are probably not able to interpret the meaning of these two ages.

On the other hand, it seems that the K^{40}-A^{40} ages are not always lower than the Rb^{87}-Sr^{87} ages. Bullwinkel et al. (1958) reported a set of radioactive ages for the syenite complex of Coldwell, north of Lake Superior. There, for instance, for the biotite extracted from the nepheline syenite, the potassium-argon age equals 1100 ($\pm 5\%$), and the rubidium-strontium age 1000 ($\pm 4\%$) M. years (the constants used, however, are unknown to the present writer). According to Davis et al. (1958), the biotite ages of the Baltimore gneiss according to the authors, both anomalously low, are 390 my. for rubidium-strontium and 560 my. for potassium-argon.

Conclusions

The discussion carried out in the present paper may be epitomized into the following conclusions, bearing in mind the K^{40}-A^{40} ages, in particular:

1. In the synkinematic rocks, an age difference for mica and microcline is to be expected, because, according to the petrological findings, in almost every case studied the potash feldspar is definitely younger than the rest of the rock, including the mica.

2. Geologically, in the late- and postkinematic granites, such an age difference does not exist. On the other hand, in the granites containing skialiths in particular, a relict mica may also be present in abundance. Therefore, the average ages of mica and feldspar extracted from such granites should approach each other; in detail however, because of the presence of relict mica and of several generations of potash feldspar, considerable deviations from the mean value are to be expected both for mica and feldspar ages.

3. For the pre-Cambrian rocks of Finland, there seems to occur, in the synkinematic rocks, an age group of about 1700 to 1800 my. This may represent the age of deposition of recrystallized sediments or the time elapsed since they were regionally metamorphically recrystallized into mica schists; or some indefinite stage of the regional metamorphism, all depending upon the ability of micas to retain argon at different stages of the earlier geosynclinal evolution.

4. The K^{40}-A^{40} ages of a microcline of the synkinematic rocks are, on the average, close to the ages of the late-kinematic granites. This may indicate that the granitization of the synkinematic rocks and the formation of the late-kinematic granites are more or less contemporaneous phenomena.

5. Starting from the theory regarding the origin of granites adopted by the present writer in his earlier papers (Marmo, 1958), the different radiogenic ages obtained may have the following interpretations:

a) biotite of the synkinematic granodiorites b) biotite of a non-granitized schist of the same formation	age of the synkinematic stage of the orogeny, or of still earlier time.
c) muscovite of late- and postkinematic granites d) microcline of synkinematic granitized rocks e) microcline of late-kinematic granites f) orthoclase and microcline of postkinematic granites g) microcline porphyroblasts of a porphyroblastic granite	widely diverging ages but still always younger than those of the synkinematic micas. They probably cover the whole stage — perhaps of considerable duration — during which the potassium metasomatism, and the related or subsequent formation and intrusion (hydrothermal) of late- and postkinematic granites has taken place.

The above scheme is suggested on an entirely petrological and geological basis.

Acknowledgements

The present writer wishes to express his sincere thanks to Dr. Olavi Kouvo of the Outokumpu Co., for fruitful discussions and for the useful suggestions made by him.

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Received: 22th of September 1959.