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Orthoclase, Microcline and Albite in Granites

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Abstract

It is argued that MARMO's anti-actualistic division of granites into Precambrian syn- and late-kinematic rarely perthitic microcline granites with primary microcline on the one hand and later postkinematic perthitic orthoclase granites, on the other, the former emplaced more slowly than the latter, does not hold. His hypothesis that rate of growth determines the appearance of orthoclase or microcline so that slowly grown potash feldspar crystalloblasts would consist of microcline only is disproved by the occurrence of metasomatic orthoclase. Perthitic microcline and non- or slightly perthitic orthoclase exist in granites. The processes of triclinization of monoclinic potash feldspar, perthitization and decalcification of primary plagioclase in granites are in many cases inter-related. Decalcification of primary plagioclase leads to an end stage of albite pseudomorphs associated with perthite-free microcline; the sodic material is partly or largely of perthitic origin. The microcline-albite assemblage common in many granites is not inconsistent with magmatic derivation of the rocks: it denotes postmagmatic recrystallization. The microcline in Precambrian granites originated in the same way as microcline in later granites and does not indicate that granites were emplaced in a different way in the Precambrian.

Introduction

Recently MARMO (1958a, b; 1959, and MARMO and PERMINGEAT, 1957), have contrasted orthoclase and microcline granites and presented views on their stratigraphic position, geological setting, tectonic relations and mode of origin that may be summarized as follows:

1. Orthoclase and microcline granites though very similar in all respects other than the character of the potash feldspar have different modes of origin.

2. In granites that only carry microcline of high triclinicity the microcline whether cross-hatched or not is primary; these are the typical microcline granites. In orthoclase granites the potash feldspar is often

partly but never completely transformed to microcline. Microcline is thus either primary or secondary; which it is depends on the geological position of the granite in which it occurs.

3. Microcline granites are typically Precambrian while orthoclase granites are chiefly Paleozoic and later in age.

4. Orthoclase granites are mainly postkinematic, microcline granites synkinematic and late-kinematic.

5. Late- and postkinematic granites always form smaller bodies than synkinematic granites. The latter occur in batholiths and large concordant plutons, the former commonly in dikes (filling fractures) or in bosses and stocks up to several kilometres in diameter.

6. Although the late-kinematic granites have the most pronounced intrusive character among all granites, their microcline-albite assemblage is inconsistent with magmatic emplacement.

7. Microcline is an orogenic mineral while orthoclase is favoured by postkinematic conditions.

8. Orthoclase in granites forms when emplacement and the accumulation of material are relatively rapid, microcline when they are more protracted.

9. As potash metasomatism is a slow process, the potash feldspar introduced into some granites is always microcline.

10. Perthite is typical of orthoclase granites and much less common or absent in the late-kinematic microcline granites.

11. Aplite dikes formed in open fissures contain primary microcline since they crystallized but slowly.

These statements may, even must, be logically carried to the following anti-actualistic conclusions:

I. Precambrian granites are mainly synkinematic and late-kinematic, later granites mainly postkinematic.

II. During the Precambrian granites were formed under conditions generally different from those prevailing later on: emplacement was much slower and took place chiefly under orogenic conditions. After the Precambrian, granites were emplaced much more rapidly and under post-orogenic conditions.

III. Perthitization occurred much more frequently after the Precambrian and is mainly a post-orogenic process.

There cannot be many granite petrologists familiar with both Precambrian and younger granites who would find themselves in agreement with Marmo's assertions or with the conclusions inevitably following from them. As it seems that Marmo generalizes and oversimplifies his particular findings, it is thought justified to examine his statements critically and to record some conflicting evidence. In addition some ideas on the correlation of the processes of perthitization and microclinization of monoclinic feldspar and the decalcification of primary plagioclase in granites are developed.

Orthoclase and Microcline

In accordance with general petrographic practice "orthoclase" is to be understood as optically monoclinic potash feldspar with a moderate to large optic axial angle while "microcline" includes all triclinic potash feldspar, whether twinned or untwinned. Although some authors (LAVES, 1950, 1952; GOLDSMITH and LAVES, 1954) do not regard "orthoclase" as a stable potash feldspar polymorph (in contrast with sanidine and microcline) but as an intermediate stage composed of extremely small triclinic units, a view opposed by others (TUTTLE and BOWEN, 1958), this controversy is immaterial to the following petrological discussion. If LAVES and GOLDSMITH are right, both the orthoclase and the microcline in granitic rocks are inversion products of sanidine, orthoclase representing an earlier unstable stage; if not, then orthoclase is a stable phase from which microcline may develop. According to the same authors potash feldspar shows a strong tendency to crystallize metastably as the monoclinic modification (sanidine) in the stability field of microcline. They and other authors established the existence of structurally intermediate states between monoclinic and triclinic potash feldspar. With increasing triclinicity the Al-Si ion distribution in potash feldspar becomes more ordered (LAVES, 1952).

Important to granite petrology is that GOLDSMITH and LAVES conclude on crystallographic arguments that microcline with cross-hatch twinning originated by transformation of monoclinic potash feldspar and they adduce experimental evidence that suggests that this is also the case for most of the untwinned microcline or microcline twinned only after the Albite or Pericline laws in magmatic, migmatic or metamorphic rocks. Completely untwinned microcline is much rarer in granites than partly or entirely cross-hatched microcline. In partly cross-hatched microcline the twinned portions at least derive from monoclinic feldspar. As most microcline "single crystals" show small areas in structural continuity that are cross-hatched and thus of monoclinic ancestry, LAVES (1955) argued on general thermodynamic grounds that the untwinned areas formed by recrystallization favouring one of the four microcline twinning positions only. Moreover, on petrologic grounds it appears highly unlikely that one and the same potash feldspar crystal would originally have formed with monoclinic areas from which twinned microcline developed and primary untwinned microcline areas.

It may be mentioned in passing that orthoclase phenocrysts have been reported from Precambrian and other rhyolites, rocks therefore in which the potash feldspar certainly separated originally as sanidine, while cross-hatched microcline is also known to occur in volcanites.

Though MARMO does not distinguish between twinned and untwinned microcline in his general conclusions about the primary growth of highly triclinic microcline, it appears from his papers that the microcline in the Precambrian microcline granites to which he refers (from Finland and Sierra Leone) is generally well cross-hatched. In order to meet LAVES' (1955) objections, MARMO modified his original thesis that such microcline whether twinned or untwinned grew completely triclinic by suggesting that though the growing potash feldspar may initially have been monoclinic it became triclinic at a very early stage so that practically the complete feldspar crystal grew in triclinic form: if it is cross-hatched then it grew as such. There are no petrological grounds for this ingenious hypothesis while the assumption that cross-hatched microcline can crystallize directly is disproved by LAVES' conclusions based on crystallographic facts. It may be possible once an orthoclase crystal has been transformed or is transforming to microcline that the potash feldspar continuing to separate around it would do so as the triclinic modification (and potash feldspar replacing plagioclase may in certain cases do so as untwinned microcline when coaxially oriented). It would be expected however from general theoretical considerations on the nature of polysynthetic twinning in feldspars that such microcline would grow as a single crystal. GOLDSMITH and LAVES (1954, p. 104) state on crystallographic grounds that potash feldspar grown as a triclinic material cannot show cross-hatching. Moreover, potash feldspar separating from a granite magma would not invert very early to microcline in view of the temperatures involved. Though MARMO asserts that metasomatic microcline cannot have formed initially as monoclinic feldspar, basing himself on the slowness of crystallization and the assumedly low temperatures, monoclinic potash feldspar slowly grown at low temperatures is known (adularia, authigenic orthoclase) and metasomatic orthoclase does exist in granites, as is shown below. Then, strained potash feldspar recrystallizes much more easily to an unstrained form than plagioclase as is borne out by petrographic evidence. Unstrained or but slightly deformed potash feldspar (beautifully cross-hatched microcline or untwinned microcline or orthoclase) may in granites be accompanied by granulated quartz and severely crushed plagioclase with bent and broken twinning lamellae; recrystallization of the potash feldspar may only be evidenced in the displacement of fragments, each of them homogeneous and unstrained, in broken grains. This should not be mistaken for the later introduction of potash feldspar.

Petrographic evidence of varying kinds shows that in many cases at least triclinization and the development of multiple twinning begin only after the potash feldspar crystals have finished or practically completed crystallization. For instance, they seem to be later than and induced by perthitization, i. e. the unmixing of plagioclase from originally homogeneous potash-soda feldspar, a relationship that is evaluated below. Then, the microcline grill may be dependent in its development on the course of contacts of potash feldspar with adjacent crystals of potash feldspar or other minerals, fading away from or towards the grain boundaries. It is significant that in certain of Marmo's illustrations just such a dependence of the microcline twinning on the course of pre-existing crystal boundaries or on fractures within the microcline grains is shown (for instance, Bild 2 in Marmo, 1959). Since in such cases the complex twinning is later than the potash feldspar crystals in which it developed, not contemporaneous with their separation, the feldspar was initially monoclinic.

The microcline grill moreover is often seen to be especially well developed in or near post-granitic fracture zones. The appearance of complex twinning along the margins of orthoclase grains in sheared granites has also been recorded. A strained state is indicated by the undulose, wavy or patchy extinction common in untwinned intermediate microcline, i. e. potash feldspar with an as yet low triclinicity and not yet cross-hatched.

Internal and external stresses are therefore conducive to the triclinization of monoclinic potash feldspar and the development of cross-hatch twinning. This shows that this type of twinning is secondary and that it forms to cause relief of strain.

Marmo (1958b, p. 36) admits that no "actual proof" against the possibility of monoclinic ancestry of the potash feldspar in true microcline granites could be found, and it may be concluded that his hypothesis that microcline in granites may "practically grow in triclinic form despite the presence of cross-hatching" (1958b, p. 30) is ill-founded.

Evidence from Portuguese Granites

The various types of granites in the Hercynian basement of Northern and Central Portugal comprise in the main older granodiorites (potash-feldspathized to varying degrees and thus locally attaining granitic compositions) and younger potash-rich granites. In one closely studied area of 660 sq. km. in the heart of North Portugal 36 mutually intrusive granite units could be distinguished, divided into ten groups mainly according to textural criteria (SCHERMERHORN, 1956a). They were emplaced in tightly folded, steeply dipping metasediments ranging up to high-grade regional metamorphites. In this area most of the granites contain microcline, many of them seemingly exclusively so, but there are some granites of various types with orthoclase. The microcline is generally partly or entirely cross-hatched. In most of the orthoclase-bearing granites the effects of microclinization of monoclinic feldspar are present in various stages of development. In a few the orthoclase is or seems unaffected while in others it has been largely changed into microcline. Moreover, slides from different parts of the same granite massif may show much varying degrees of triclinization of orthoclase. In several of the other microcline-bearing granites orthoclase relics have been found. In the coarse porphyritic granites, nearly the latest intrusives in the Hercynian cycle, orthoclase is very rare; small easily overlooked orthoclase relics are here found in but one or two thin sections out of every twenty examined, and only occur in a few of the larger microcline crystals. These granites though not synkinematic form large batholiths, it may be mentioned in passing.

$2V_\alpha$ ranges from 53 to 67° for the orthoclase of the orthoclase granites (both younger and older; the values are lowest in those rocks that show little or no microclinization of the potash feldspar), 64—70° for the rare orthoclase relics in the microcline of some of the younger granites, and 76—87° for the "normal" microcline in both older and younger granites. However, the microcline developed from orthoclase does not at first show "normal" or "maximum" microcline optics. It is an "intermediate" microcline with transitional optics: its optic axial angle is notably smaller (64—72°), it has a shadowy undulose extinction grading in patches into vague fine cross-hatching and its extinction angles are smaller (2—12° in sections normal to beta as against 14—17° for "normal" microcline).

The orthoclase is in general but feebly perthitic and the intermediate microcline slightly more so, while the normal microcline is much more perthitic (vein and patch perthite) in granites with little decalcified primary plagioclase, and generally not perthitic or but weakly perthitic in granites in which the plagioclase has been uniformly decalcified to albite or albite-oligoclase (these relationships are further discussed below).

Thus it cannot be held that perthite is typical for orthoclase granites, not for microcline granites, and that perthite is produced when orthoclase is formed (Marmo, 1958a, b).

The orthoclase relics in microcline crystals occur in untwinned non-perthitic portions of the crystals and the cross-hatch twinning develops around the perthitic veins. The processes of triclinization of orthoclase, leading over untwinned intermediate microcline to cross-hatched highly triclinic microcline, and perthitization are here connected and from a study of the literature it appears that this is the case in many granites. It seems that perthitic unmixing of a homogeneous potash-soda feldspar may trigger the transformation to (twinned) microcline, apparently owing to internal strain caused by the separation of plagioclase (Schermerhorn, 1956a, c).

The Portuguese Hercynian granites were subjected to orogenic stresses to varying degrees during their consolidation for the orientation of their internal structures conforms generally to the Hercynian folding trend and may lie at high angles to discordant contacts. In the area discussed the granites are mainly late-syntectonic.

Therefore, in Portugal we have, *n'en déplaise* Marmo, late-kinematic orthoclase granites while orthoclase has also been introduced into older rocks. This means that orthoclase has grown under orogenic conditions (the waning Hercynian stresses) both magmatically and metasomatically.

Rate of Growth of Potash Feldspar Modifications

Strong geologic and petrographic evidence shows that the potash-feldspathization of older granodiorites in North Portugal was due to metasomatic activity of younger potassic granite magmas (Schermerhorn, 1956a, b). This process leads to the formation of potash feldspar in the older rocks, at first interstitial but in the end stages producing porphyritic granites (*secondary porphyritic granites* in contrast with the *primary porphyritic granites* in which the potash feldspar megacrysts started separation from the original magma). Now the *introduced*, metasomatic potash feldspar is orthoclase in the earlier orthoclase-bearing granites or granodiorites although the magmatic potash feldspar in the neighbouring younger granites is predominantly cross-hatched microcline with hardly any orthoclase relics left. This cannot be explained under MARMO's hypothesis contrasting rate of growth in orthoclase and microcline.

MARMO asserts that metasomatically grown potash feldspar would be bound to be microcline because its material could have accumulated but slowly so that the rate of growth would not be conducive to orthoclase crystallization. Several petrological facts militate against this hypothesis, apart from whether there are any theoretical grounds for it. In some of the Portuguese granites referred to there does occur metasomatic orthoclase. Moreover, the microcline in these granites originated by inversion of primary monoclinic feldspar (as testified by orthoclase relics and the occurrence of intermediate microcline) which feldspar grew both magmatically in consolidating granites and metasomatically in potash-feldspathized rocks. Although the potash feldspar megacrysts in the primary porphyritic granites can be shown on strong and varied evidence (SCHERMERHORN, 1956a, p. 334—342) to have grown from a magmatic fluid, they ended crystallization in a metasomatic phase during which they corroded the adjacent older constituents, forming irregular replacement borders penetrating into the groundmass. If the magmatic phase of crystallization passed rapidly, the replacement phase is bound to have progressed rather more slowly. Yet the metasomatic margins of orthoclase megacrysts also consist of orthoclase. Then, the growth of adularia in veins and vugs and of authigenic orthoclase in sediments are slow processes likewise. All this evidence disproves MARMO's hypothesis and it may be concluded that rate of growth alone is not a factor decisively controlling the appearance of orthoclase *or* microcline.

MARMO contends also that aplite veins formed in open fissures generally contain microcline even when developed in orthoclase granite massifs because they crystallized very slowly, much slower than the parent granite (1958a, p. 363; MARMO and PERMINGEAT, 1957, p. 521). Aplite veins crystallizing from residual material filling fractures opening in consolidated granite or wall rock are of very small volume compared with their country rock. So they cannot very well be conceived to solidify much slower than the enormously bigger parent granites which had already cooled down at the time of aplite emplacement and at the level where the aplites occur. It would seem on the contrary that they have a higher rate of cooling. Aplite dikes in dilatation veins are generally thought to have rapidly crystallized from residual granitic fluids owing to the escape of part of the volatile constituents, in contrast with pegmatites. Hence these aplites should logically, pursuing MARMO's hypothesis, carry orthoclase. Certainly their containing highly triclinic microcline in contrast with the orthoclase of some of the parent granites is no "proof" at all that this or any other microcline is primary. This however is the only one of the "strong arguments" invoked by MARMO (1958a, p. 362) against the monoclinic ancestry of microcline in microcline granites. Moreover, orthoclase aplites do occur, as MARMO admits.

Then, though MARMO finds it difficult to explain complete microclinization of the potash feldspar in aplites encased in orthoclase granites with a much lesser degree of triclinization, this phenomenon may find its explanation like many cases of selective transformation of minerals in adjacent rocks of different petrology in a higher content of volatiles, their varying action, differential stresses, etc.

In a granite described by MARMO and PERMINGEAT (1957) there occurs orthoclase partially transformed to microcline; this granite also contains well-developed microcline crystals which according to these authors seem to have grown independently as primary microcline later than the orthoclase though no evidence for this is adduced. Similarly, in a quartz porphyry dike related to this granite there are found orthoclase and microcline phenocrysts (the latter cross-hatched according to the illustrations); the former would represent true phenocrysts while the latter would have formed later and slower than the orthoclase as porphyroblasts, although the textural relations of the orthoclase and microcline crystals are precisely similar. MARMO and PERMINGEAT believe that the microcline cannot have formed by conversion of orthoclase because it would be difficult to explain in that case why one crystal would have been completely transformed while an adjacent crystal would still be monoclinic. Again, the explanation is to be sought in the selective nature of the process, rather than in assuming without any textural evidence a completely different metasomatic mode of origin for the microcline phenocrysts.

"Metamorphic" Granites

According to MARMO (1958a, p. 361), if it should transpire that in granites potash feldspar crystallizes in a monoclinic modification afterwards in many cases inverting to microcline, all microcline granites must be considered as metamorphic granites. This goes too far: rhyolites are not considered to be metamorphic because their high-quartz phenocrysts were transformed to low quartz or their high-temperature plagioclase to low-temperature plagioclase or their sanidine to orthoclase or microcline in the course of cooling.

Although "synkinematic" granites have often been potash-metasomatized to varying extents so that the potash feldspar introduced may render them truly granitic in composition (with more potash feldspar than plagioclase), this does not mean per se that such granites originated by "granitization" (implying that the rocks were originally non-granitic (s. l.) in composition). Regional potash-metasomatism of older less potassic by younger more potassic granites is widespread in orogenic granite complexes. It is known, to cite only two instances, from Finland (Eskola, 1927) and Portugal (Schermerhorn, 1956a, b). The term "granitization" should be applied only to cases where non-granitic rocks are made over to granites, not to those cases where already granitic (s. l.) rocks such as granodiorites are potash-feldspathized. Though made more "granitic" than they were before, it would confuse the issue to call such rocks "granitized" (and to cases where for instance quartz diorites are changed into granodiorites through slight potash-feldspathization the term would not be applicable at all). Too often the term granitization is used where potash-feldspathization is meant.

Marmo (1958b, p. 35) is of the opinion that, "the perthite-bearing late-kinematic microcline-granite could be magmatic if: 1. it can be proved that in all cases the microcline was formed owing to the rearrangement of the Al-Si framework of an orthoclase; 2. the formation of albite and microcline can be proved as being due to the complete exsolution of a single K-Na feldspar through the perthite stage or it is due to co-crystallization of both feldspars under magmatic conditions." It is well possible for a truly metasomatic granite to contain orthoclase or microcline derived from monoclinic feldspar. As to the second condition for magmatic origin, it will be shown next that neither of the two possibilities admitted is the case (the formation of albite and microcline are in fact related to perthitic unmixing but not in the way Marmo envisages as the albite is secondary, pseudomorphosing primary plagioclase). A granite is magmatic if the field and petrographic evidence prove its crystallization from a magma.

Decalcification of Primary Plagioclase

As regards the mineral assemblage of microcline-albite granites believed by Marmo to be non-magmatic because of this association, it is vain to try deducing from chemical analyses the composition of a single initial potash-soda feldspar from which *all* plagioclase and potash feldspar would derive (MARMO, 1958b) if the texture as in most granites shows that plagioclase (barring perthite and late anhedral albite) crystallized as a primary mineral in separate grains (as illustrated in many of the figures accompanying MARMO's papers). The co-existence of albite in large sub- to euhedral crystals and microcline as the only feldspars in many granites is due neither to magmatic co-crystallization nor to complete unmixing of the soda feldspar from a single homogeneous potash-soda feldspar, no primary plagioclase existing, but to secondary transformation of primary plagioclase more calcic than albite and potash feldspar, and this follows from the fabric. In some (not all) syenites and quartz syenites no primary plagioclase exists, all available soda and lime apparently having been taken up in a single high-temperature K-Na-(Ca) feldspar which on cooling unmixed to perthite; this again is evidenced by their fabric. In granites however this is very rare and confined to certain unusual types of perthite-quartz rocks.

BOWEN and TUTTLE (1950) who are cited by MARMO in this respect established experimentally that a single homogeneous potash-soda feldspar separates from sodipotassic melts, unmixing at lower temperatures into two feldspars (see also TUTTLE, 1952; TUTTLE and BOWEN, 1958). However, they also state that if appreciable lime is present both plagioclase and alkali feldspar will crystallize, the plagioclase being richer in lime than the liquid (as in the magmas of extrusive rocks) so that the latter becomes depleted in lime and moves towards the one-feldspar field; alkali feldspar therefore ceases deposition later than primary plagioclase. This explains the appearance of primary plagioclase in granites, as was long known from textural evidence. Felsic igneous rocks with primary plagioclase (more calcic than albite originally whatever its composition may have become afterwards) and potash-soda feldspar (whether perthitic or not) such as granites are in fact overwhelmingly more common than igneous rocks with only perthite.

However, TUTTLE (1952) suggests that complete unmixing of originally homogeneous alkali feldspar during cooling may completely separate potash feldspar and plagioclase and apparently assumes that all plagioclase in granites originates in this way. TUTTLE and BOWEN (1958, p. 140) believe that the initial texture of all magmatic granites is much like the fabric they illustrate in their Plates 2 and 6, showing granites with a granular ("granitic" or "saccharoidal") texture in which all the plagioclase is in solid solution in the alkali feldspar. This texture would change with proceeding unmixing and irregular plagioclase would appear, especially at the intersection of a number of grains. These authors envisage a crystallization sequence from quartz-perthite granite over quartz-perthite granite with irregular albite borders around perthite grains to a granite made up of discrete grains of microcline, plagioclase and quartz. It is difficult to agree to this sequence representing the normal cooling course of magmatic granite. Quartz-perthite granites (with late albite) are exceptional and the normal type of granite contains plagioclase, whether albite or more calcic feldspar, in large discrete crystals, often sub- or euhedral, and independent in their distribution from potash feldspar by which they may have been corroded. Then, the Westerly, Rhode Island granite illustrated in TUTTLE (1952) with subhedral (altered) plagioclase grains with clear albite rims (apparently due to decalcification; see below) in contact with potash feldspar is believed by TUTTLE and BOWEN (1958, p. 140) to have "originally carried much of, and perhaps all, the plagioclase in solid solution in the potassium feldspars." This does not seem borne out by the textural relations of plagioclase and potash feldspar; in many granites with this hypidiomorphic texture the large first-generation plagioclases can be proved on several different lines of evidence to have separated before potash feldspar or at least before that portion of potash feldspar crystals with which they are in contact (SCHERMERHORN, 1956a, pp. 314, 320, 335, 337; 1956c). The Skye granite on the other hand, as illustrated in Plates 4 and 5 in TUTTLE and BOWEN (1958), with very irregular plagioclase grains enclosed by potash feldspar crystals represents a granite type in which this plagioclase may derive from exsolution but such rocks are rare.

Although it is certainly true that many changes take place in composition and polymorphic forms of the minerals in granites during cooling, as stated by TUTTLE and BOWEN (1958, p. 142), it seems highly unlikely that the textural relations among the primary minerals change likewise in such a way as to entirely obscure previous relationships. More specifically, sub- and euhedral plagioclase crystals enclosed by and/or corroded by potash feldspar, even if now consisting of homogeneous albite, cannot be taken to indicate formation by exsolution of the primary plagioclase.

In most granites primary plagioclase occurs in discrete sub- to euhedral tablets as distinct from late albite. It may have been partly or completely decalcified and this secondary albite derives partly or entirely from material driven out from exsolving potash-soda feldspar. The unmixing of perthite tends towards an ultimate stage in which all sodic substance is expelled from the potash feldspar, not to form separate grains elsewhere (replacing which older minerals?) but to *decalcify primary plagioclase*. In support of this are the following observations. In the Portuguese granites referred to above the earlier potash-metasomatized granites are in part albite granites with all primary plagioclase decalcified to albite or albite-oligoclase, while the massifs of the younger potash-dominant granites with plagioclase up to andesine in composition may contain areas of albite granite. In these albite granites the potash feldspar (mostly microcline) is generally not or but feebly perthitic. In those rocks in which more calcic plagioclase occurs the microcline is much more perthitic (vein and patch perthite); here decalcification has often started to act on the primary plagioclase, forming discontinuous narrow albite rims which significantly occur only *at plagioclase-potash feldspar boundaries*. This observation is not infrequently found in granite descriptions though not explained, except by TUTTLE (1952, p. 115) who has described "secondary" albite formed at potash feldspar-plagioclase boundaries. From this distribution he concluded that at least a portion of the plagioclase unmixed from the potash feldspar, even in rather high-lime granites. He stated that there is no obvious method of determining how much of the plagioclase not represented by this albite rim owes its origin to exsolution. However, it is not the plagioclase crystals that formed by exsolution from potash feldspar since the grains often show by their shape and textural relations that they separated prior to potash feldspar but on the contrary it is the composition of the earlier plagioclase that was altered *where the crystals were exposed to potash feldspar*, by a process of *decalcification*. These albite rims are secondary since they follow irregular corrosion outlines which cut across the primary growth zones of plagioclase crystals. In the course of decalcification the rims broaden. In slides from one and the same granite massif the process can be observed from its early stages of albitic rims (at first very narrow with an abrupt decrease in anorthite content (Becke line) from primary plagioclase to decalcified rim, later wider with a gradual transition) to its end stage of *homogeneous albite pseudomorphs after primary plagioclase*.

The Relationship between Perthitization and Decalcification

The succession given above shows moreover that decalcification proceeds from without inwards in plagioclase crystals, i. e. external metasomatism, and that it starts from potash feldspar crystals. This indicates that the sodic material derives at least in part from potash feldspar, as was assumed by TUTTLE (1952), and it may be safely concluded that it is perthitic in origin, migrating from unmixing potash-soda feldspar, in views of the associations *much perthite-little decalcification* and *little perthite-much decalcification* where the potash phase in perthite is microcline. But in rocks with still weakly perthitic orthoclase the plagioclase is not or but little decalcified (albite rims) and this accords with the *triclinization-perthitization* relationship set forth above.

Thus, although MARMO (1958b, p. 33) sees no reasons why exsolution should continue beyond the stage of a coarse perthite, it undoubtedly does, and the potash feldspar in orthoclase granites is certainly not invariably strongly perthitic (significantly the "intensely perthitic" orthoclase granites Marmo lists contain mainly hair perthite and cryptoperthite, i. e. beginning exsolution).

The unmixing sodic material in perthite is at first oriented upon its potash host forming regular intergrowths but in the coarse end stage it coalesces into large irregular patches. These contract with the expulsion of sodic material until only a few haphazardly distributed small albite blebs are left or the stage of perthite-free microcline is attained. The sequence *fine perthite-coarse perthite-expulsion of soda feldspar* is in accordance with theoretical considerations as the reduction of plagioclase-potash feldspar boundaries leads to a lower state of energy.

Perthite, as proved experimentally (BOWEN and TUTTLE, 1950), is derived from homogeneous potash-soda feldspar. As is clear from experimental evidence, theoretical considerations relating to the formation of mix-crystals and petrographic (textural) relationships, potash and soda feldspar crystallizing below the solvus temperature do not form perthitic intergrowths, contrary to what is sometimes claimed. Perthite in metasomatic rocks indicates replacement at fairly high temperatures by potash-soda feldspar with subsequent unmixing. Perthite as stated by TUTTLE (1952, p. 116) is "evidence per se of high temperature".

Decalcification of primary plagioclase may be accompanied by the development of myrmekite. This type of myrmekite is to be distinguished from the later myrmekite forming in late albite replacing potash feldspar (designated as myrmekite I and II respectively in SCHERMERHORN, 1956a, c).

The process of pseudomorphic decalcification of plagioclase evidently involves ion exchanges: Na and Si enter, Ca and Al go out. The Ca and Al expelled may either go to form epidote-zoisite or else migrate altogether in which case their fate may be obscure. Alkalies and silica are present in the residual fluids of consolidating granite magmas. In granite in which part of the body has primary plagioclase as calcic as andesine while in other parts it has been decalcified to albite-oligoclase or albite with little or no epidote-zoisite present it is demonstrated that the calcic components do indeed migrate.

TUTTLE states that the "late-stage" albite rims at potash feldspar-plagioclase boundaries set a limit beyond which diffusion in the solid state apparently did not operate. However, the existence of all gradations between narrow sharply bordered decalcification rims and albite pseudomorphs after primary plagioclase show that the range over which this type of metasomatism could act is at least of the order of the size of plagioclase crystals in medium- and coarse-grained granites.

Decalcification of plagioclase denotes a change to a lower mineral facies than that in which the plagioclase crystallized. Plagioclase more calcic than albite becomes unstable under the PT-conditions of the albite-epidote amphibolite and the greenschist facies and will be altered to albite in the presence of Na and Si. Although decalcification is a fairly low-temperature process it may be frozen in its various stages before attaining the stable end stage of homogeneous albite. Also, it may be re-activated, for instance by metamorphism or by the contact actions of younger magmas furnishing heat and metasomatizing fluids.

In the younger granites in North Portugal decalcification is due to autometasomatism during cooling. Although the process starts by sodic metasomatism acting from unmixing potash-soda feldspar, it may well be that towards its later stages the sodium present in the postmagmatic residue plays a role too. In earlier granites decalcification was caused in part by autometasomatism and in part by the contact effects of later magmas (SCHERMERHORN, 1956a, p. 368; 1956b, p. 346).

The associations *perthitic microcline-primary non-albitic plagioclase with primary growth zoning and often with narrow decalcified albite rims* and *less or non-perthitic microcline-decalcified plagioclase* seem to occur in many granites. Decalcification of plagioclase due to soda (auto-)metasomatism is widespread, not only in granitic rocks, though in granites especially it derives its material from perthite. Complete decalcification of primary plagioclase seems to be more common in muscovite-bearing granites than in rocks in which this mica is lacking.

The Relationship between Microclinization, Perthitization and Decalcification

The two associations mentioned may furthermore be correlated with the nature of the potash feldspar in the same rocks. Both microclinization and decalcification are to a large degree dependent on perthitization. Thus, in granites not having undergone later alterations orthoclase just beginning to show perthitic unmixing and microclinization would generally be associated with primary plagioclase more calcic than albite (little or not decalcified as yet); microcline would be perthitic when associated with similar or more decalcified plagioclase and less or non-perthitic (with the highest triclinicity and the largest 2V values) when accompanied by albite. These relations do in fact occur and show that in granites the two feldspars are closely connected in their evolution.

The relationship non-perthitic microcline-decalcified plagioclase is exemplified in many microcline-albite granites such as those MARMO has especially studied.

It is concluded that in granites the following processes run parallel in many cases and that they are interrelated:

1. perthitic unmixing → expulsion of perthite plagioclase.
2. orthoclase → microcline.
3. primary plagioclase → decalcified plagioclase.

Or, tabulated:

perthitization →			
homogeneous K-Na-(Ca) feldspar	beginning exsolution (fine perthite)	complete exsolution (coarse perthite)	expulsion of plagioclase

triclinization →	
monoclinic potash feldspar	microcline

decalcification →		
primary plagioclase (more calcic than albite)	thin albitic rims, gradually broadening, at plagioclase-potash feldspar boundaries	homogeneous albite pseudomorphs after primary plagioclase

When these processes have run to completion a non-perthitic microcline-albite granite results. Thus granite with orthoclase (-perthite) and calcic plagioclase is to be regarded as a non-equilibrial assemblage and the stable end stage towards which granite evolution tends as regards the state of the feldspars is an equilibrial low-facies non-perthitic microcline-homogeneous albite assemblage. This end stage may be and often is reached under favourable postmagmatic crystallization conditions.

From these relations it may be deduced that orthoclase with coarse patch perthite associated with calcic plagioclase or homogeneous monoclinic potash-soda feldspar with albite (decalcified plagioclase) or highly triclinic well cross-hatched non-perthitic microcline with calcic plagioclase would not occur in normal granites. As far as could be made out from the literature this seems to be the case.

Another consequence is that all perthitic potash feldspar must have crystallized monoclinically.

It is considered that favourable postmagmatic crystallization conditions for the processes mentioned comprise two main factors: sufficiently slowly decreasing temperatures and the presence of water.

It would seem that time alone is not a main factor in bringing about either perthitization or triclinization of potash feldspar since very old rocks may still contain little or non-perthitic monoclinic potash-soda feldspar while temperature alone may decrease too rapidly (frozen homogeneous or little perthitic monoclinic potash-soda feldspars as in volcanites). The studies of BOWEN and TUTTLE (1950) showed that high vapour pressures of water strongly promote perthitization, facilitating mobility, and petrographic evidence supports this. In Portugal coarse patch perthite and completely unmixed perthite-free microcline associated with decalcified plagioclase are especially common in muscovite-rich granites, rocks therefore in which late-stage fluids were active since most of the muscovite is postmagmatic and blastic. As volatiles are known to be conducive to polymorphic transitions in minerals, the presence of residual fluids thus promotes the conversion of monoclinic feldspar both directly and indirectly (by facilitating exsolution).

It may therefore be concluded that microclinization as induced by perthitization depends on *favourable time-temperature relations*, whether attained during cooling or owing to later granite intrusions or to metamorphism, and *activating solutions*. However, as has been referred to above, external stress plays also a role in the development of the microcline grill (it is not clear in how far it likewise facilitates the development of non-twinned intermediate microcline). And as stress may probably act as a catalytic factor promoting ion exchanges it seems likely to facilitate perthitization too and thus indirectly triclinization of the potash feldspar host. *Stress*, though accidental as it depends on the tectonic history of the rocks, must therefore be likewise counted a factor. Then, though the rate of triclinization of potash feldspar (a process involving the ordering of the strongly bonded Al and Si ions in the feldspar framework) proceeding at low temperatures may not be appreciable as compared with the rate of this process at the rather higher temperatures of the end stages of granite formation, it may perhaps not be negligible over very long periods. *Time* might thus be regarded as a minor factor.

Ages of Orthoclase and Microcline Granites

From the literature it would appear that orthoclase granites are most common in Mesozoic and later settings (not only mountain chains) while not infrequent in the Paleozoic but distinctly rare in the Precambrian (to which MARMO has drawn attention), exceptions being formed according to MARMO by the Precambrian rapakivi and granulite granites of Finland. The latter are banded garnet-quartz-feldspar plutonites which are not strictly granites. These are certainly not the only exceptions: from Finland ESKOLA (1951) described orthoclase (straight extinction, $2V = 50—66°$) from the Precambrian mantled granite-gneiss domes in the Pitkäranta area which are remobilized and potash-metasomatized (!) synkinematic (!) granodiorites and (quartz-)diorites, and from some younger Precambrian late-kinematic (!) granites in the same area. He established a "pronounced" Orthoclase Province" within the Pitkäranta area" (l. c., p. 40) and refers also to orthoclase in Precambrian charnockites in Sweden and Finland. Orthoclase and intermediate microcline have also been reported from Precambrian charnockite and granulite granites in India, Africa and elsewhere.

MARMO and PERMINGEAT (1957) comment on the great, to them puzzling, chemical, textural and geological similarity between a Paleozoic orthoclase granite and some Precambrian microcline granites. They themselves admit that this fact would naturally lead to concluding to microclinization of orthoclase in the latter rocks. Yet they reject this possibility solely because the triclinicity of the microcline in the Precambrian granites is so perfect in contrast with the inhomogeneous partly triclinized character of the potash feldspar in the younger granite. Even if the Precambrian microcline granites contain no orthoclase relics at all, there is no reason to assume that potash feldspar in granite would have crystallized under different conditions in the Precambrian. The Paleozoic granite forms a single high-level pluton intruded into non- or little metamorphic rocks while the Precambrian granites from Sierra Leone with which it is compared by these authors were emplaced in older granodiorites and gneisses (MARMO, 1958b). Then, the Paleozoic granite has partly microclinized orthoclase with vein perthite associated with oligoclase and no muscovite while the Precambrian Sierra Leone granites have non-perthitic microcline associated with albite and, it is stated for one of them, muscovite (MARMO, 1958b). All this concords perfectly with the relationships set forth above.

There are reasons why in Precambrian rocks of granitic affinities orthoclase is especially found in the charnockite-granulite group and in the rapakivi granites while much rarer in normal granites. In the former the monoclinic feldspar is often in a state of transformation to microcline and generally shows incipient perthitization expressed in the finer perthite forms (cryptoperthite, hair, string, spindle, bleb perthite). The rapakivis with their peculiar texture are granites emplaced at a high level in the crust which resulted in a rapid completion of crystallization. The preservation of orthoclase is here due to freezing. These rocks have not undergone later activation since there are no later granites or periods of metamorphism. Thus there was not enough time to complete perthitization and microclinization of orthoclase when the conditions were favourable. In the granites of the charnockite and granulite group with their typically very low water content perthitization did not in general proceed beyond the first stage of unmixing and the triclinization of potash feldspar was arrested in its commencement. Though there was enough time for these processes to run to completion under favourable thermal conditions since these deep-seated rocks cooled but slowly, the lack of volatiles inhibited complete perthitization and microclinization. In normal granites on the other hand the completion of crystallization is slow and volatiles are present. Even so, the occurrence of orthoclase and intermediate microcline, of intermediate perthite stages and of incompletely decalcified plagioclase indicate that conditions were not always sufficiently favourable to permit of the end stages being attained. Granites occur in series, earlier less potassic rocks being followed by later more potassic rocks, so that in frozen granites the three processes mentioned may be reactivated by later granites. It would thus be expected that monoclinic potash feldspar is to be found especially in single high-level granite intrusions rather than in the mutually intrusive granite complexes of deeper crustal levels; owing to erosion it is generally the latter deeper type of granite that is exposed in Precambrian areas. It is no coincidence that orthoclase and monoclinic feldspar approaching sanidine have been found especially in high-level granites intrusive into sediments.

Similarity of Orthoclase and Microcline Granites

MARMO's opinion (1958a, p. 362) that both orthoclase and microcline granites are very similar rock types, tending to be aplitic, commonly pink, fine- to medium-grained rocks, mainly occurring in veins and dikes, is an unwarranted extrapolation from the doubtless many granites with which he is familiar that display this character. Coarse porphyritic granites emplaced in the later stages of mountain building and forming large massifs are common both in Europe and Africa. Now, in their paper on the Hercynian Azegour granite (Morocco) MARMO and PERMINGEAT (1957) describe this orthoclase granite as being postkinematic while very similar Precambrian microcline granites to which they refer would be late-kinematic. MARMO (1958a, p. 362) states in addition that the Precambrian late-kinematic microcline granites are commonly very similar to younger postkinematic orthoclase granites and cannot be distinguished from them in hand specimens or in the field, the only difference apparently being the nature of the potash feldspar.

"Late-kinematic" and "postkinematic" thus have apparently come to indicate merely whether a granite carries microcline or orthoclase. It is considered that this use of tectonic terms for a mineralogical classification is confusing. Whether a granite is late- or postkinematic is to be decided on structural evidence. The classification of granites as syn-, late- and postkinematic bodies was set up by ESKOLA (1927, p. 138) on the basis of structure and crosscutting relationships.

It is certainly unwarranted to conclude from the nature of the potash feldspar alone that the Precambrian microcline granites have been emplaced much more slowly than younger orthoclase-bearing counterparts which are entirely similar apart from the potash feldspar as regards geological setting, contact relations, shape, structure, mineralogy, texture and composition.

The Origin of Low-Temperature Mineral Assemblages in Granites

MARMO (1958b) is puzzled by the apparent contradiction between the obviously magmatic intrusive character of late-kinematic microcline granites in the field and their low-temperature mineral assemblage (microcline-albite, implying non-magmatic crystallization) under the microscope. This paradox is easily resolved: the assemblage is *postmagmatic*. The low-temperature assemblages shown by many granites are secondary, autometamorphic, and by themselves not inconsistent with magmatic parentage of the rock as they can in most cases be proved to derive, generally by pseudomorphism, from an original higher-temperature magmatic assemblage. This is evidenced by textural and mineral relics (*textural:* hypidiomorphic consolidation fabric, idiomorphic primary accessories and their preferential concentration in the older main constituents, oriented inclusions in feldspar, etc.; *mineral:* quartz bipyramids, orthoclase relics in microcline, oligoclase relics in albite, etc.). The mere occurrence of microcline and albite in a granite is not sufficient to declare the rock to be non-magmatic in origin.

Thus a magmatically emplaced granite may through autometamorphism (or autometasomatism) during cooling alter to a low-temperature mineral assemblage, for instance muscovite-epidote-microcline-albite-quartz as in granites MARMO mentions. Such an assemblage denotes a low mineral facies, in itself inconsistent with magmatic crystallization. But in granites, and this is the point, it is found in conjunction with high-temperature igneous fabrics and frequently in an intrusive setting. It must be realized that these low-temperature facies are reached in the course of postmagmatic cooling. In alkali-rich granites the late and postmagmatic highly alkaline residual fluids act as the agents of internal metasomatism during the later stages of consolidation. In granites such as MARMO refers to and which he reluctantly puts down as being non-magmatic in spite of appearances ("All field evidence illustrates their magmatic origin", "...despite their undoubtedly intrusive character", "...the emplacement... could not take place in a molten state", "...the transformistic views can better explain the field observations *(sic)*", MARMO, 1958b, pp. 19, 36, 40) there exists likewise a contradiction between low-temperature mineral assemblage and high-temperature texture, and this alone would suffice to show high-temperature, i. e. magmatic descent. Textures in contrast with the easily recrystallizing granite minerals become remoulded only by thorough metamorphism. Now, although MARMO (l. c., p. 24) states, "It is the composition and texture of the late-kinematic granites which offer the most serious objections against the magmatic origin of these granites", he does not at all describe nor discuss their texture. In a magmatic granite the plagioclase may have been entirely decalcified to albite, the biotite replaced by chlorite, the monoclinic potash feldspar microclinized and the perthitic plagioclase completely expelled, but still the original hypidiomorphic fabric and other magmatic textural features would persist in a recognizable form since the processes mentioned are essentially pseudomorphic. The growth of late secondary quartz, albite (not the albite produced by decalcification of primary plagioclase), muscovite, epidote, etc. attacks and may obscure the primary textural relations but often the crystallization of these late minerals along intergranular spaces and intragranular structural directions is evident. Thus late postmagmatic blastic textures may become superimposed on a primary magmatic fabric. In the more alkaline, especially the potash-dominant, granites the textural crystallization sequence is as follows: the initial magmatic hypidiomorphic consolidation texture is superseded towards the end of the magmatic phase by increasingly more replacive magmatic corrosion textures (potash feldspar and quartz), followed in a postmagmatic metasomatic phase by the more or less agressive blastic growth of pure replacement minerals and the recrystallization of older minerals. It is emphasized that in most granites the *initial hypidiomorphic framework* of the rock (evidenced especially by the earlier major components: biotite, hornblende and primary plagioclase) remains recognizable. The replacive processes are not inferred from the final results in which low-temperature minerals have completely superseded earlier higher-temperature minerals (by recrystallization and neo-crystallization) but from the arrested intermediate stages to be seen in the same or other granites.

In a similar way a magmatically intruded dolerite may have been completely autometasomatized (spilitized) to an albite diabase in which a low-temperature albite-chlorite-serpentine-epidote assemblagereplaces the original high-temperature labradorite-pyroxene-(olivine) assemblage. The high-temperature fabric of the rock is preserved or remains recognizable.

Only rocks of granitic mode and norm which show low-temperature minerals in a relatively low-temperature texture (certain granoblastic quartz-microcline-albite-mica assemblages) may present difficulties in evaluating a possible magmatic origin. In that case the presence or absence of other magmatic texture relics such as the preferential distribution of primary accessories (Schermerhorn, 1956a, c) may in addition to field and other evidence yield valuable clues as to the origin of the rock.

If as Marmo believes the late-kinematic granites had been emplaced in a "solid" state mobilized by a small amount of water, protoclastic textures should be common which is not the case. Also, the intricate fissure-infilling apophyses at many granite contacts indicate that the material was emplaced in a mobile essentially fluid state. Metamorphic and metasomatic phenomena at granite contacts likewise show that such granites were emplaced at relatively high temperatures — for instance, the magmatic andesine in a granite and the metasomatic andesine formed in the wall rock of that granite crystallized at the same stage of mineral development; this cannot be explained by assuming that the andesine crystals in the granite already existed when the granite was emplaced as a solid mass. The concept of granite emplacement by "plastic crystalline flow" in solid bodies, even when taking into account "stress recrystallization", does not stand up to petrographic examination. When partly or completely crystallized granite is forced to move, as for instance in the outer parts of granite bodies owing to the upward pressure of the unconsolidated inner parts, resulting in gneissic borders, (blasto)protoclastic to (blasto)mylonitic granulated textures are superposed on the primary igneous fabric altering or even obliterating it. Normally granites do not display such textures.

It would seem that speculations on the origin, the emplacement and the mode of crystallization of granites are vain when not taking into consideration the crystallization sequence as revealed by texture.

Conclusions

It must be concluded that the existence of primary microcline in granites remains unproved, that the crystallographic arguments for derivation of cross-hatched microcline from monoclinic potash feldspar stand unshaken, that the evidence at hand (experimental, petrographic and geologic) indicates that most if not all microcline in granites is of monoclinic ancestry, that the albite in albite granites is postmagmatic and that potash feldspar and plagioclase are closely related in their evolution during the later stages of granite formation in the processes of perthitization, triclinization and decalcification.

Moreover, the distribution of orthoclase in Precambrian granites is still insufficiently known for want of more precise data on their potash feldspar. The great Precambrian areas of the world lie mostly still outside the range of specialized study except for the Fennoscandian Shield (it is perhaps no coincidence that here orthoclase-bearing granites have been found) and have been mapped, as in Africa, mainly by field geologists with neither the time nor the equipment to distinguish carefully between the various potash feldspar modifications. Only the rarer rock types such as charnockites have received more attention and orthoclase has been found in them. Even in Europe and North America it is only in the last decade or so that granite has come to be restudied more closely, perhaps under the influence of the transformationist challenge. It is felt therefore that it is too early to state categorically that Precambrian granites are microcline granites except for the Finnish rapakivis and granulites. All that can be said at present is that microcline is more abundant and orthoclase less common in Precambrian than in later granites.

Thus far there is no reason to jettison the actualistic principle and Precambrian granites do not seem to be significantly different from younger granites or to have been emplaced in different ways.

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