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55. Two patterns of monomineral replacement in granites

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Abstract: Metasomatic phenomena of single minerals in granites can be basically classified into two major patterns: 1) hetero-orientation replacement (nibble replacement) and 2) co-orientation replacement. The major formation mechanisms of mineral replacement are the dissolution-precipitation (for hetero-orientation [nibble] replacement pattern) and the cation exchange (for sheet silicates of co-orientation replacement pattern). The simultaneous presence of both the replaced mineral on one side of a grain boundary and the same or similar mineral as the replacive mineral on the other side is a major necessary condition of formation mechanism for hetero-orientation (nibble) replacement pattern.

Clear rim and intergranular albite are formed by replacement of K-feldspar by albite under the effect of pure Na-bearing hydrothermal gas or fluid. If Ca accompanies the Na-bearing gas or fluid, excess SiO_2 from the replaced K-feldspar remains and takes the shape of vermicular quartz in replacive sodic plagioclase.

Perthitic albite lamellae look like they have formed either by metasomatic processes or by exsolution from the primary K-feldspar crystal, but they are probably formed mainly by simultaneous crystallization.

The key evidence for replacement is the presence of relics from the replaced mineral in the newly formed replacive mineral. However, the replacement phenomenon should be distinguished from simultaneous crystallization and normal inclusions in igneous rocks.

Generally, a phenocryst can simply be distinguished from a porphyroblast.

When several metasomatic processes are superimposed, the steps in the replacement process can possibly be determined and understood in the light of the replacement rule.

Keywords: metasomatism (replacement), co-orientation, hetero-orientation, dissolution-precipitation, cation exchange, clear rim, intergranular albite, myrmekite, perthitic albite, porphyroblast, phenocryst, simultaneous crystallization.

Introduction

After formation of granite, gases and solutions (either relevant or irrelevant to magmatic processes) can penetrate into solidified granitic rocks, resulting in instability or change of an individual primary mineral followed immediately by deposition or crystallization of a more stable new mineral, thereby partly changing the primary mineral into a new substance with different local structure.

Lindgren (1925) stated: "Replacement in solid rocks consists in solution of the host mineral, followed immediately by deposition of an equal volume of the guest mineral……The volume of the replacing mineral equals the volume of the mineral replaced. Deposition follows so closely upon solution that at no time can any open space be discerned under the microscope."

Mineral replacement, such as cation exchange, deuteric alteration as well as pseudomorphism, chemical weathering, leaching, diagenesis and metamorphism are all linked by common features in which one mineral is replaced by a more stable one (Putnis, 2002).

Such replacements imply that metasomatism occurs in an open system that is different from classical metamorphism in which in situ mineralogical change occurs in a rock (generally accompanied by loss of water) without appreciable change in the chemistry of the rock.

It is necessary to have gas-liquid fluid from outside to participate in replacement. Many petrographers emphasized that the original rock should have been cataclastically deformed before the gas-liquid fluid can penetrate and

circulate in the rock and cause the metasomatism. Other petrographers observe that replacement really occurs in undeformed rock. The original rock texture has been basically preserved even so far. They hold that under a certain temperature and pressure the gas-liquid fluid surely could have moved into and out of such a solid rock. The period needed for the gas-liquid fluid to reach a certain distance in the rock must be long because the rate of flow is slow, but in terms of geologic time, the duration is short. The metasomatic phenomena surely could have occurred in essentially undeformed rocks for most of the examples illustrated in this article.

Moreover, under new physical-chemical circumstances, the compositional transformation of an old mineral (via cation exchange) locally or wholly into a new one without dissolution-reprecipitation by gas-fluid is also a reaction product of metasomatism.

Generally speaking, the metasomatic process is characterized by the following features:

1) A rock remains in solid state as the whole metasomatic process proceeds.

2) Transformation (reformation) or dissolution of a previous mineral occurs almost simultaneously with formation of regenerated minerals without any evidence of open space.

3) The volume of the replacive guest mineral is equal to the volume of host mineral that is replaced.

If one mineral is partially dissolved by one solution and if after an interval during which open spaces exist and new minerals are deposited in these spaces by solutions of a different composition, this process should not be treated as replacement but as a type of filling.

Metasomatism is conceptionally different and distinguished from isomorphism that occurs during magmatic crystallization. Metasomatic phenomena are similar to cotectic ones when two minerals simultaneously crystallize, so they may often be confused. Besides, metasomatism is easily indistinguishable from unmixing (exsolution) in a solid solution.

The replacing phenomena discussed in this paper apply to single individual mineral replacements in granites that are observed during microscopic thin section studies. The replacement of a primary mineral by an aggregate of new minerals is

more complicated and not discussed here.

Two major patterns of single mineral replacement in granites

According to the author's observation (based on similarities or differences of crystallographic lattice and orientation of replacive and replaced minerals), metasomatic phenomena that occur in single minerals in granites can be basically classified into two major patterns: **1) hetero-orientation replacement (nibble replacement) and 2) co-orientation replacement.**

Hetero-orientation replacement (nibble replacement) pattern

Hetero-orientation replacement (nibble replacement) occurs in undeformed intrusive rocks soon after rock-formation, as well as in broken or gneissic rocks.

Nibble replacement occurs at the boundary between two mineral grains. Taking the crystallographic lattice orientation of the same or similar mineral upon which the replacive mineral contacts, the replacive mineral gradually grows into the adjacent mineral capable of being replaced, as if nibbly eating it. The unreplaced part of the replaced mineral survives in the replacive mineral without changing its crystallographic orientation.

The crystallographic lattice orientations of replacive and replaced minerals must be different or discordant. That is, the nibble replacement occurs at the boundary between two minerals with different orientation. No nibble replacement is possible along the boundary between two minerals (plagioclase and K-feldspar, for example) where they have the same and parallel crystallographic orientation.

Only where no identical or similar mineral is present to allow growth, an impurity in the rock could serve as a crystal nucleus.

Nibble replacement phenomena that are commonly observed in granites are albitization, K-feldspathization, muscovitization, quartzification, as well as berylitization, calcitization and pyritization.

1) Nibble replacement albitization

Nibble replacement albitization in granites, especially rich in alkali, quite often occurs at the grain boundary between plagioclase and K-feldspar as well as two K-feldspars.

a) Nibble replacement albitization at contact of plagioclase with K-feldspar

Taking the crystallographic lattice of the plagioclase as crystal nucleus, the replacive albite grows nibbly towards the adjacent K-feldspar.

A K-feldspar megacryst may always contain inclusions of plagioclase. Albite rim (named 'clear rim' by Phemister, 1929) often surrounds the plagioclase inclusion. The width of albite rim is commonly <0.1 mm, but can be as much as 0.3~0.4 mm in granites rich in alkali, alumina and silica. "There is usually a sharp and smooth contact from the main plagioclase (typically oligoclase) to the albite rim, whereas the albite-K-feldspar boundary is irregular. Some rims contain thin spindles of quartz oriented quasi-normal to the surface" (Smith, 1974).

"Clear rim" occurs only at contacts of plagioclase with differently oriented K-feldspar, but is absent where plagioclase contacts co-oriented K-feldspar (Pl_1 in Fig. 1A) or between two plagioclases or between plagioclase (or K-feldspar) and quartz (Fig. 1A, 1B).

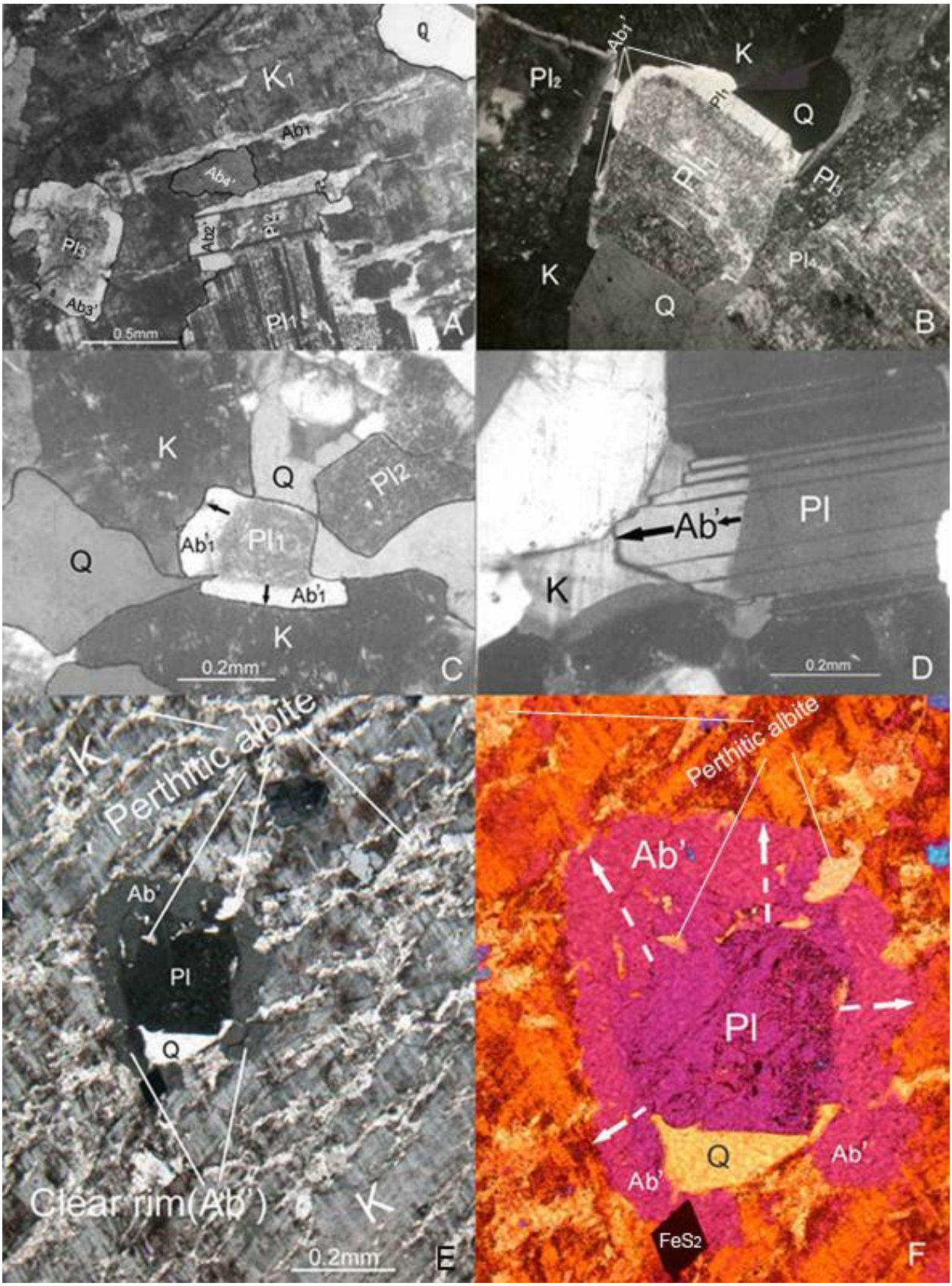
Q
K1
Ab1
Ab4'
Pl2
Ab2'
Pl3
Ab3'
Pl1
0.5mm
A
Ab1'
K
Pl2
Pl'
Q
Pl3
Pl4
K
Q
B
K
Q
Pl2
Ab'1
Pl1
Q
Ab'1
K
0.2mm
C
Ab'
Pl
K
0.2mm
D
Perthitic albite
K
Ab'
Pl
Q
Clear rim(Ab')
K
0.2mm
E
Perthitic albite
Ab'
Pl
Q
Ab'
Ab'
FeS2
F

Fig. 1A. .-Clear rim around plagioclase in contact with K-feldspar.

A---Inclusions of plagioclase (Pl_1, Pl_2, Pl_3) are contained in K-feldspar (K_1). Albite rim (Ab $_2$single prime,
Ab $_3$single prime) occurs at contacts around plagioclase inclusions (Pl_2, Pl_3 oriented differently with K-feldspar) but are absent along the border of plagioclase inclusion (Pl_1 co-oriented with K_1). The growth of albite Ab $_2$single prime is blocked where contacts occur with another plagioclase of perthitic albite. Naqin granite, Taishan County, Guangdong Province.

B---Albite rim (Ab $_1$ single prime) is present only at the contact of plagioclase Pl_1 with K-feldspar. The plagioclase is not sericitized.

C---Albite rim is absent at contact with quartz.

D---Replacive albite occurs at the border of plagioclase with K-feldspar.

E---Relicts of perthitic albite remain in the clear rim Ab’, indicating the replacement origin of the latter.

F---Arrows show the growth direction of the replacive albite.

Small relicts are found in the clear rim in some places where the rim is thicker and the perthitic albite lamellae are more developed (Fig. 1E, 1F, and Fig. 2).

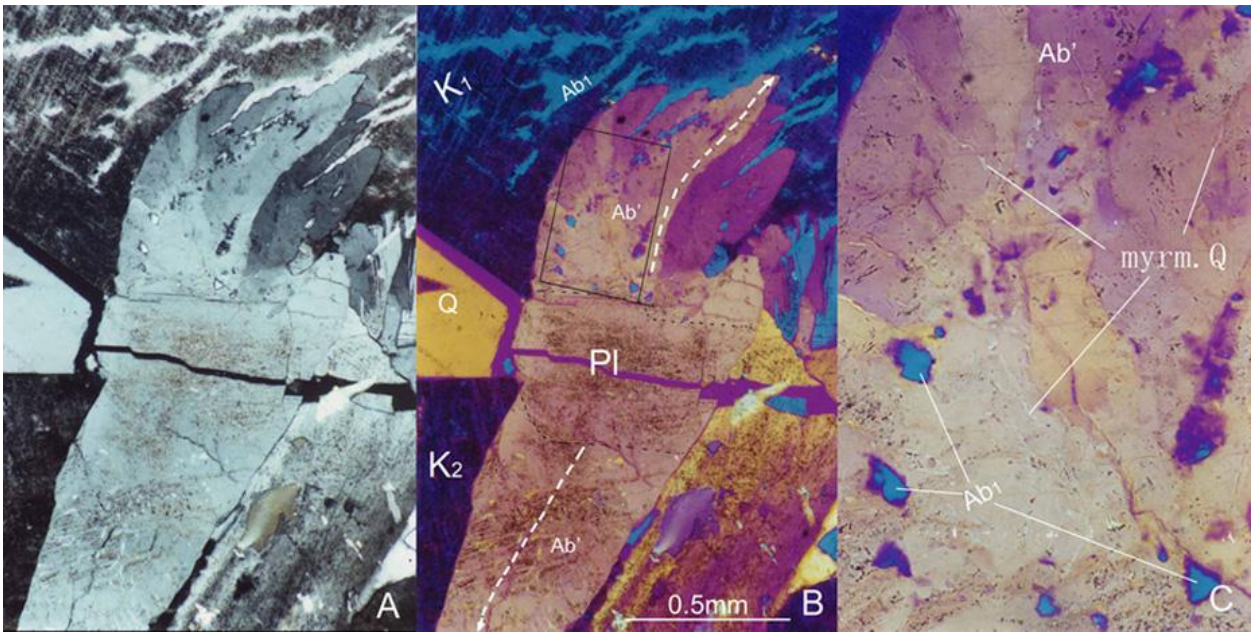

Fig. 2.-Intense nibble replacement of albite (0.8 mm thick) towards K-feldspar. The isolated relicts of perthitic albite Ab_1 remain in the replacive albite Ab single prime containing tiny myrmekitic quartz. A---Crossed polars. B---Plus quartz plate. C---Local magnification of replacive albite. Naqin leucogranite, Taishan County, Guangdong Province.

b) Nibble replacement albitization between two K-feldspar grains

The albite grains often found at a grain boundary between two K-feldspars (K_1 and K_2) with different orientation are named as intergranular albites. The intergranular albite grains can usually be divided into two rows (Ab_1', Ab_2' in Fig. 3 as observed when a quartz plate is inserted under cross-polarized light). Each row (generally < 0.2 mm wide) has an approximate optical orientation as the perthitic albite in the K-feldspar against which it contacts; i.e., it has the same crystallographic orientation as that of the opposite K-feldspar. One row might grow quite well, while the other might develop poorly (Fig. 3C, 3D). It would be difficult accurately to determine the boundary between perthitic albite and intergranular albite if they directly contact each other because they have the same orientation (Fig. 3A, 3B).

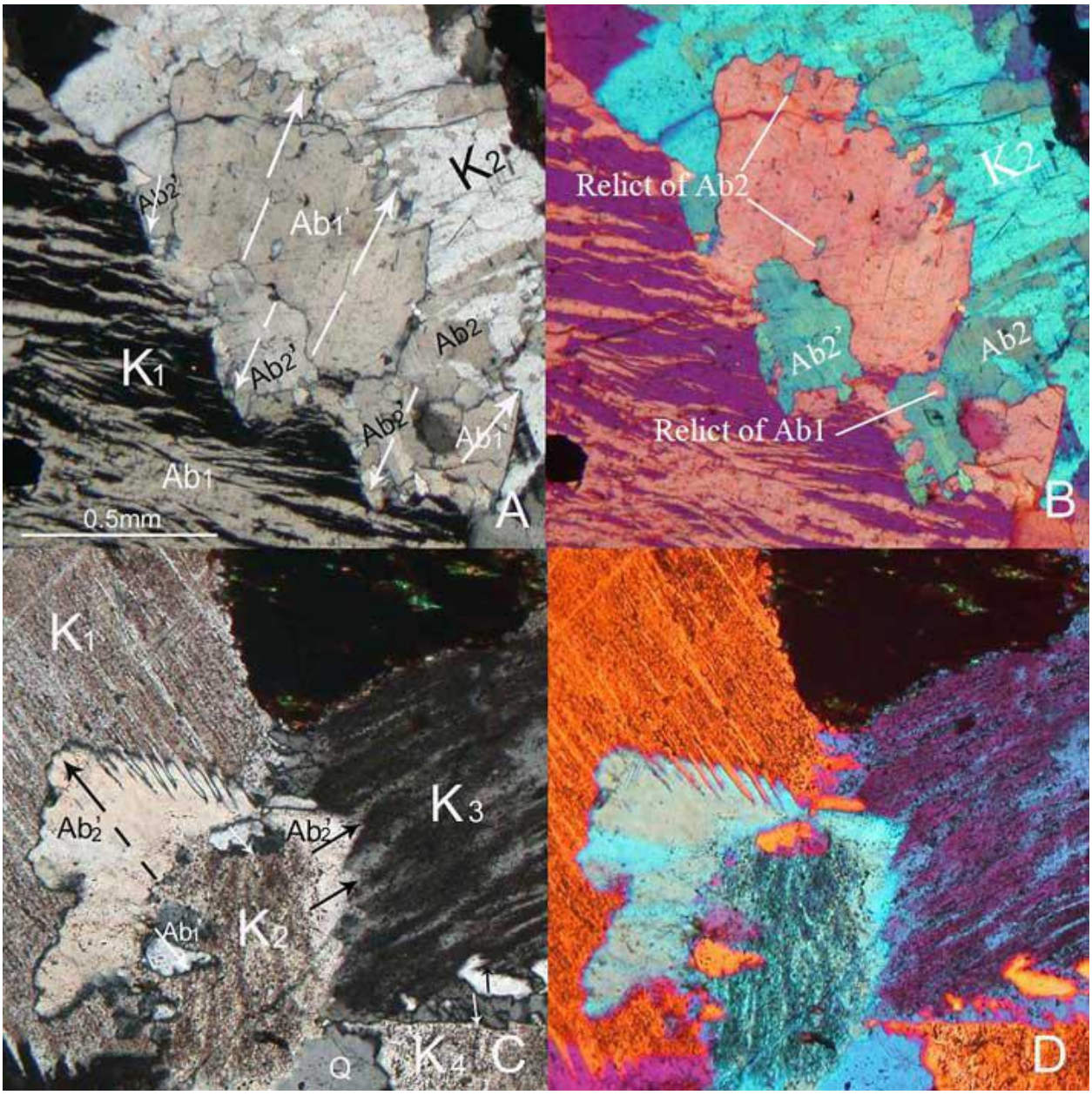

Fig. 3.-Intergranular albite grains at the contact of two K-feldspars.

Both clear albite rim and intergranular albite are situated at contacts with K-feldspars. Their thicknesses in a given rock are similar, although intergranular albite has generally less continuity than that of a clear albite rim.

There are several explanations for the origin of clear albite rims and grain boundary albite grains:

(1) Unmixing (exsolution) of adjacent K-feldspar (Phemister, 1926; Tuttle,

1952; Ramberg, 1962; Phillips, 1964; Hall, 1966; Carstens, 1967; Haapala, 1997);

(2) Late stage crystallization of magma (Rogers, 1961; Peng, 1970; Hibbard, 1995);

(3) The sericite in the rim of sericitized plagioclase is dissolved away by sodic hydrothermal solution (Cheng, 1942, 1962);

(4) Plagioclase is replaced by K-feldspar (Deer, 1935; Schermerhorn, 1956).

Both clear albite rim and intergranular albite are situated at contacts with K-feldspars. Their thicknesses in a given rock are similar, although intergranular albite has generally less continuity than that of a clear albite rim.

The author considers that the following relationships are favorable for determining the genesis of the feldspars.

(1) Tiny relicts of perthitic albite of outside K-feldspar can be found in some places in a thin clear albite rim or intergranular albite (Fig. 1E, 1F, 2, 3A, 3B, 5). The relicts strictly maintain the primary orientation, although they are finer and clearer. Similar but coarser relicts of perthitic albite have also been found associated with clear albite where Na-metasomatism has modified K-feldspar in the Lyon Mountain granite gneiss in New York (Collins, 1997).

(2) A clear albite rim appears at a contact of plagioclase with K-feldspar no matter whether the plagioclase is sericitized or unsericitized (Fig. 1D, 1E).

(3) Very fine vermicular quartz can be found in intergranular or clear rim albite with An >2 (Fig. 2), but is absent in a pure albite rim (An≈0).

(4) A clear rim is blocked where contacts occur with quartz or another plagioclase (Fig. 1A, 1C).

Although the continuity of intergranular albite is less than that of the clear rim, the phenomena are identical, indicating that they are of the same origin (nibble replacement).

It is difficult to determine the relation between perthitic albite and a clear rim, as well as intergranular albite, because ⑴ the chance contacts between them are rare due to their limited development; ⑵ perthitic albite in the form of a wedge or comb penetrates the clear rim (Fig. 3C) or intergranular albite, and in some places even as a veinlet that penetrates the intergranular albite (Fig. 4) as if the perthitic albite replaces the intergranular albite (also see Figs. 428, 429 in "**Atlas of the**

textural patterns of granites, gneisses and associated rock types" (Augustithis, 1973). The bridge-like veinlets (Fig. 4) are relicts that survived albite replacement; Relicts of perthitic albite in clear rim or intergranular albite cannot be seen; and a quartz plate was not inserted under cross polarized light to show minerals of different orientation and color.

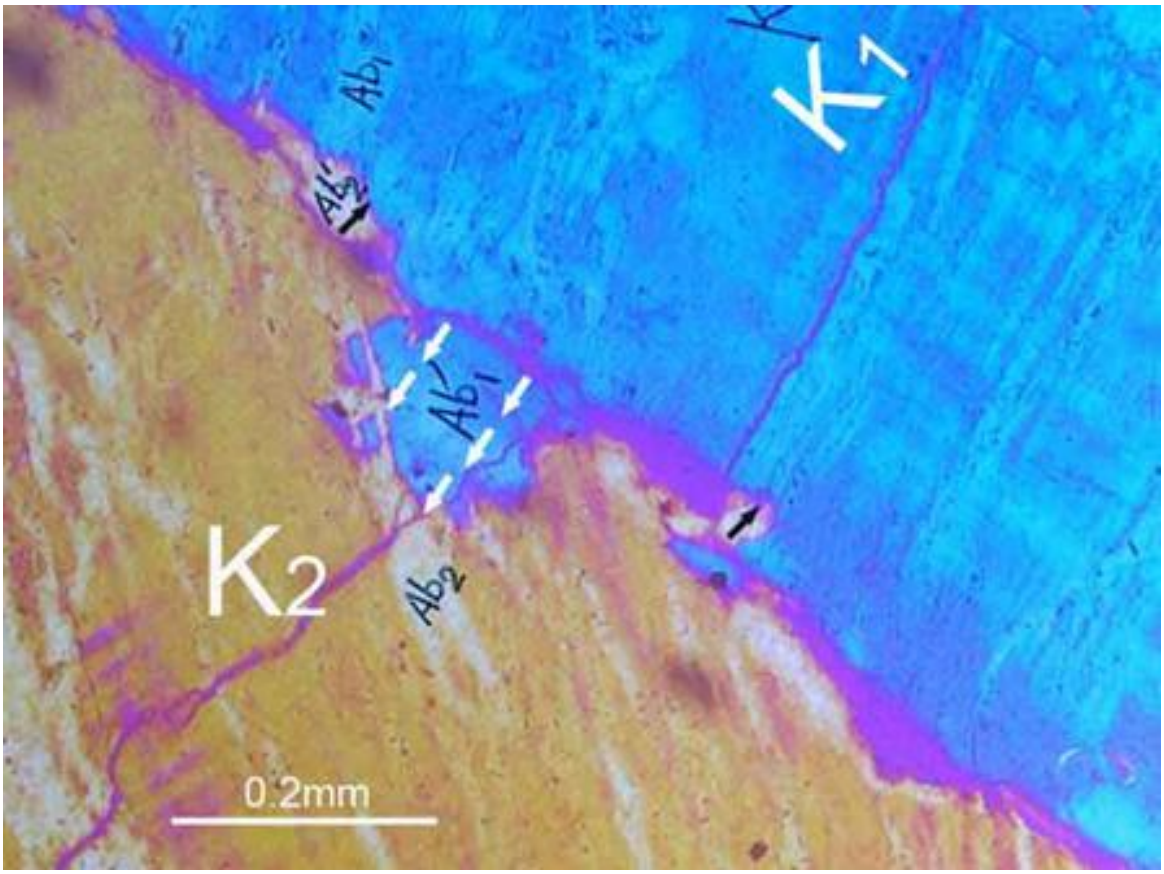

Fig. 4.-Swapped intergranular albite (Ab $_1$single prime, Ab $_2$single prime) at contact of two K-feldspars (K_1, K_2). Relict (bridge like) of perthitic albite is formed in the replacive albite Ab $_1$single prime. Crossed polars plus quartz plate. Sanchakou leucogranite, Hebei Province.

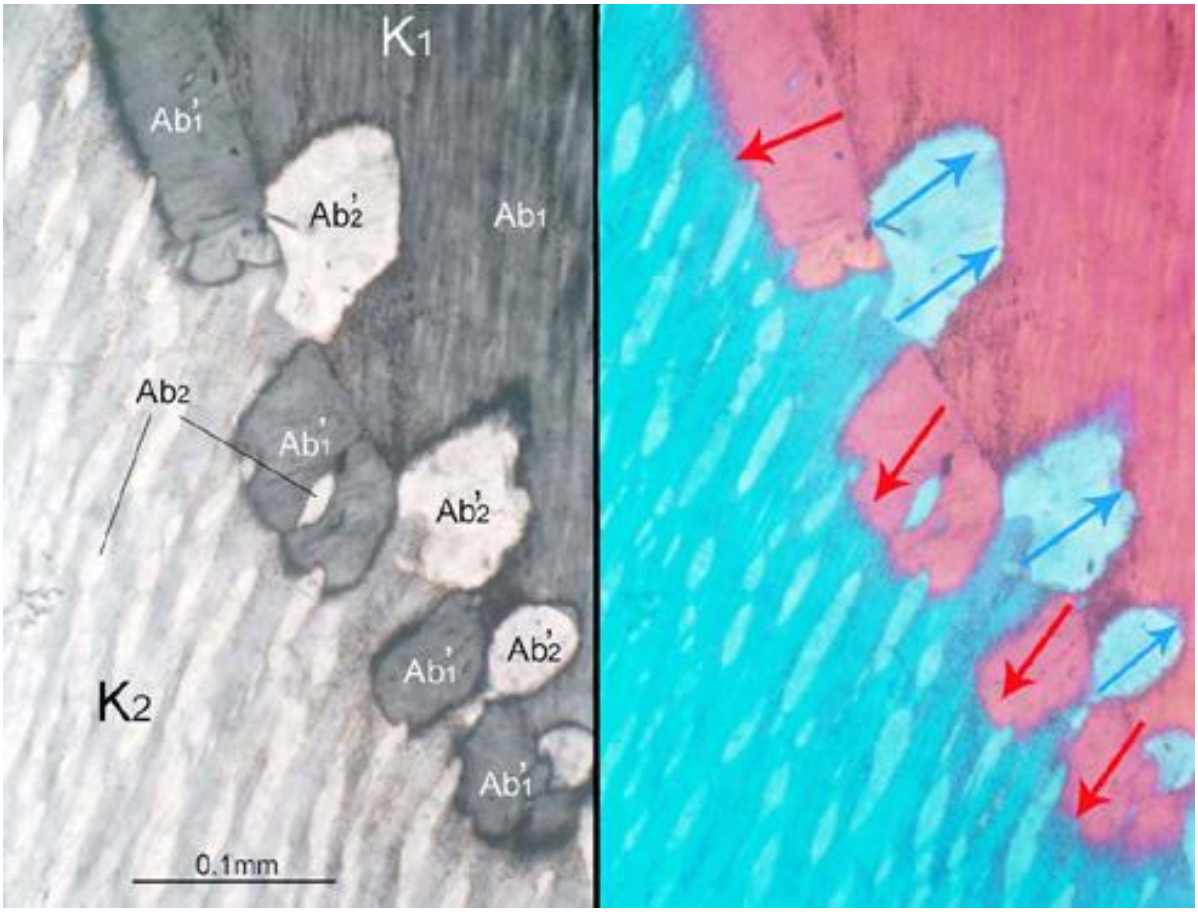

Fig. 5.-Swapped rows of albite at contact between two K-feldspars at contact between two K-feldspars. Relict of perthitic albite (Ab_2) remains in the replacive albite containing very fine myrmekitic quartz (dark grey). Zaojiayao granite, Xuanhua County, Hebei Province.

Although it is difficult for albite to replace an entire plagioclase crystal, the replacive albite may still replace tiny perthitic albite. Moreover, the presence of tiny relicts of perthitic albite in the replacive albite is easily missed if the quartz plate is not inserted.

2) Nibble replacement K-feldspathization

The objects of nibble replacement K-feldspathization are mainly plagioclase and K-feldspar.

a) New K-feldspar nibbly replaces old plagioclase

Plagioclase crystals are often enclosed by K-feldspar.

When nibble K-feldspathization occurs, the grain boundaries of these plagioclases are complicated and circuitous. Some remnants of plagioclase were situated at borders with K-feldspar (Fig. 6).

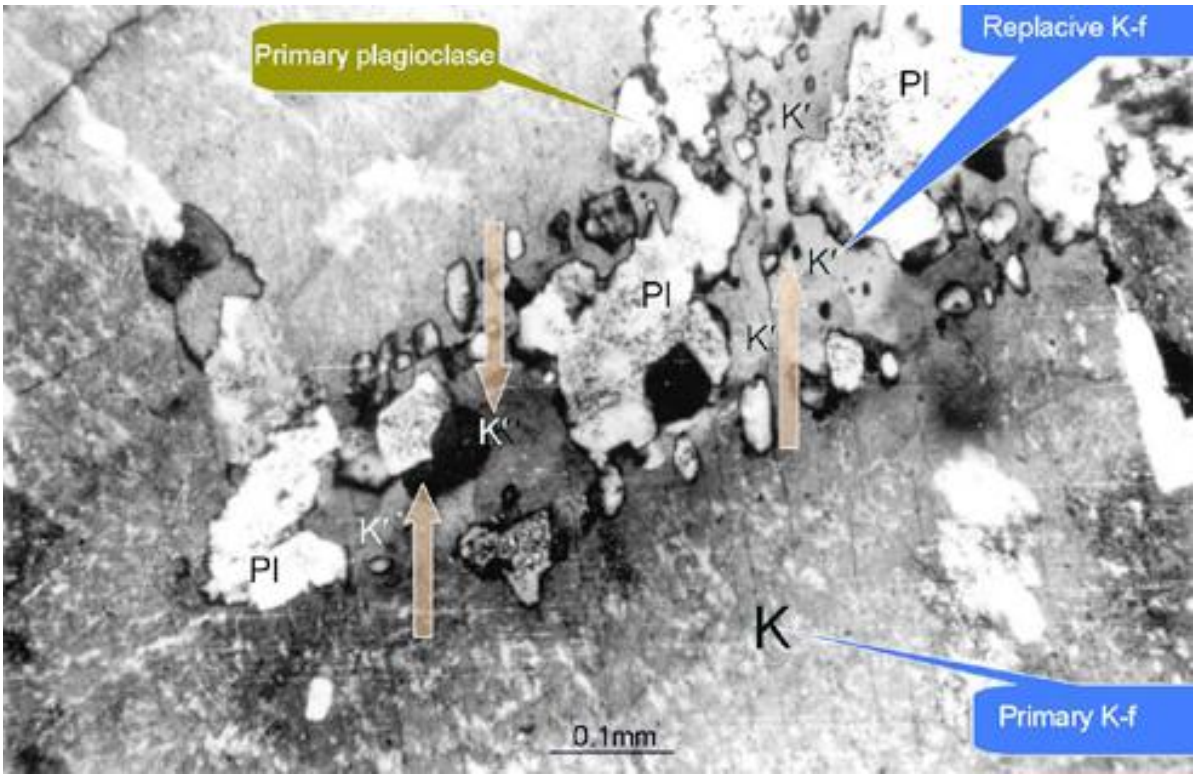

Fig. 6.-Isolated relicts of plagioclase in K-feldspar (K). Plagioclase Pl is replaced by the K-feldspar K single prime. K single prime has the continuous orientation as the primary K-feldspar K, but lacks perthitic albite compared with K. Crossed polars. Huangshatang two-mica granite, Zhuguangshan batholith, Guangdong Province.

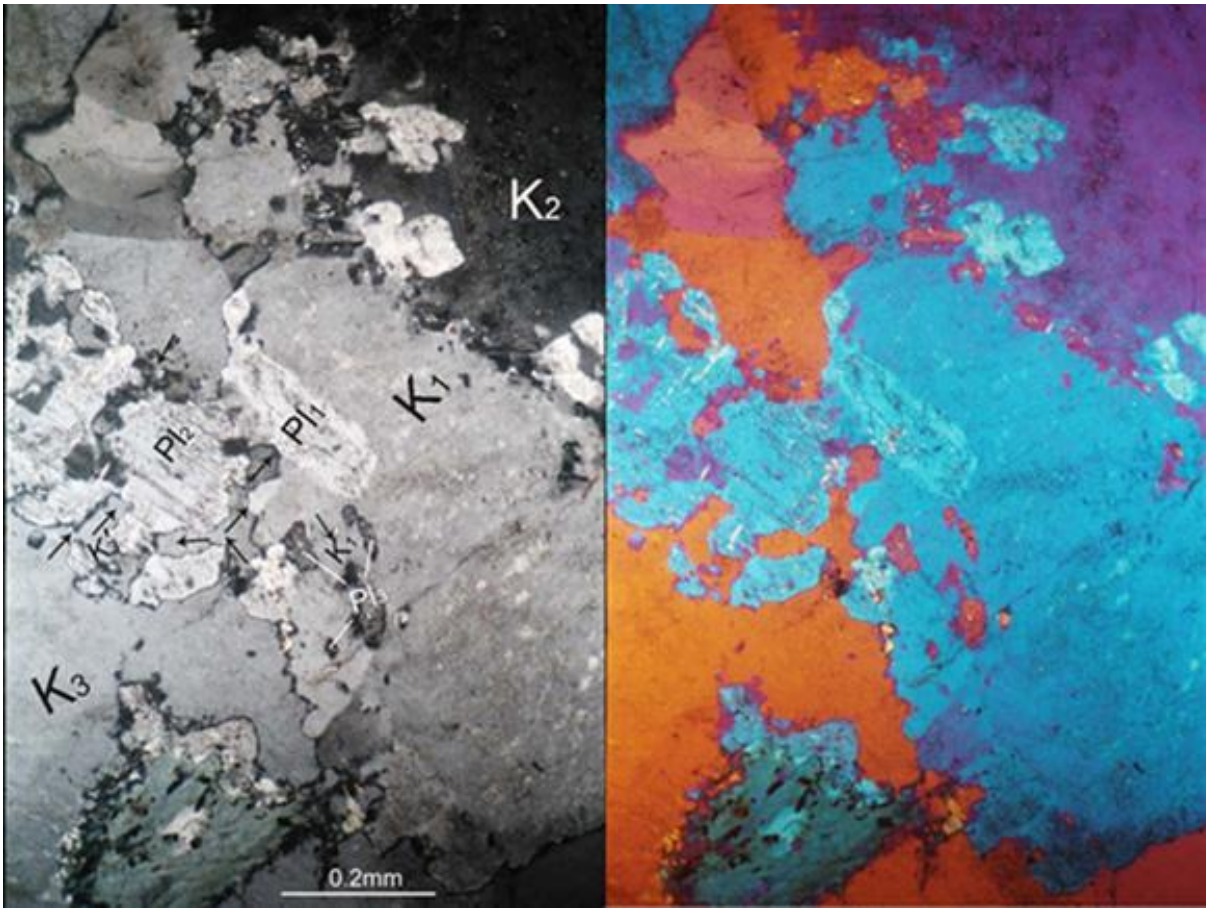

Fig. 7.-Plagioclase grains (Pl_2, Pl_3, Pl_4….) are nibbly replaced by K-feldspathization, except Pl_1 which is co-oriented with K-feldspar K_1. Da-ao granite, Yangjiang County, Guangdong Province.

This phenomenon is always treated as an important evidence of intense K-feldspathization and, therefore, the megacryst of K-feldspar has a porphyroblast origin. Surely, the plagioclase is really replaced by K-feldspar, but the replaced part is mainly focused at the small limited area around the relicts of plagioclase nearby. It is hard to judge whether the whole uniform K-feldspar away from the complicated boundaries has a metasomatic origin.

Fig. 6 shows that the newly formed (metasomatic) K-feldspar penetrating into the relict areas is comparatively pure and containing less perthitic albite than that

in the outside surrounding K-feldspar. The author considers that the latter is the preexisting primary K-feldspar and the former has a metasomatic origin. If the primary K-feldspar (K_3 in Fig. 8) also lacks perthitic albite, there is no apparent border between primary K_3 and metasomatic K_3 – because the two K-feldspars have the same crystallographic lattice, resulting in difficulty to observe the difference between them. As a result, it is easy to reach a conclusion that the whole K-feldspar has a metasomatic origin.

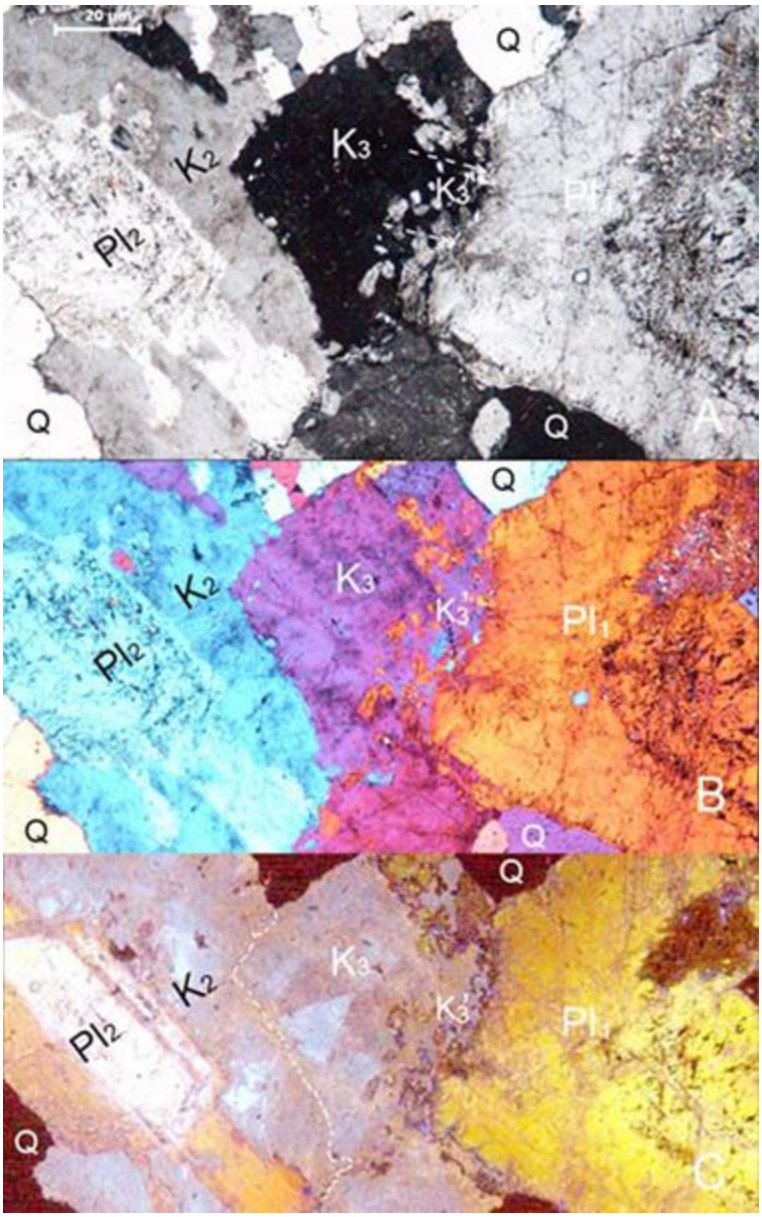

Fig. 8.-Plagioclase is partly nibbly replaced by K-feldspar

A---Cross polarized light. K_3 single prime has nibbly replaced the rim of plagioclase Pl_1 on the basis of primary K-feldspar K_3.
B---Plus quartz plate. The relicts of plagioclase maintain the original orientation.
C---Cathodoluminescent image. K_3 single prime has the similar tone as K_3 except less light blue.

Note that the orientation of the replaced plagioclase inclusions is obviously

different from that of the surrounding K-feldspar (Pl_2, Pl_3, Pl_4 in Fig. 7. The plagioclase Pl_1, having the same orientation as the K-feldspar, may have been preserved because of this relationship and be kept from being replaced by K-feldspathization. Therefore, nibble K-feldspathization aims only at the plagioclase which has a different orientation from that in the K-feldspar. The preservation is not on account of their strong structure (less likely to be fractured) as deduced by Collins and Collins (2002a), but just because their parallel lattice boundaries are strictly sealed, preventing introduction of gas or liquid that would allow replacement to occur.

b) New K-feldspar nibbly replaces old K-feldspar

The appearance of K-feldspar grains in the rock is quite unique at first glance under cross-polarized light. The K-feldspathization that occurs at a contact border between two K-feldspar grains is characterized by the nibble replacement of primary K-feldspar by newly formed K-feldspar. The latter usually contains tiny perthitic plagioclase vermicules with the same orientation as the host replacive K-feldspar, radially pointing toward the border (Fig. 9) instead of the normal perthitic albite stringers enclosed in primary K-feldspar. In some places, the relicts of primary K-feldspar (Fig. 9) or its perthitic albite lamella (Figs. 10, 11) may be enclosed in the newly formed replacive K-feldspar, which can be seen when a quartz plate is inserted.

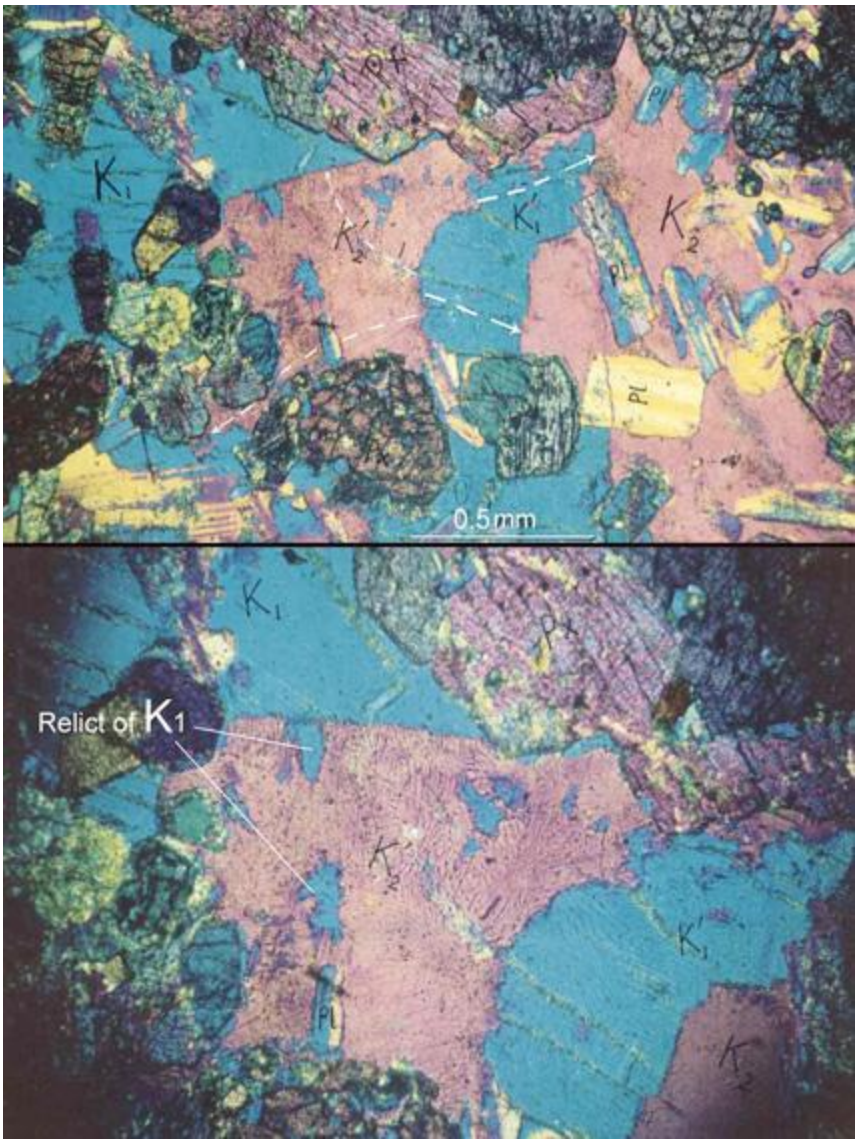

Fig. 9.-Nibble replacement of K-feldspar at contact between two primary K-feldspars (K_1, K_2). Fine vermicular lines of albite and relicts of the primary K-feldspar are found in replacive K_1 single prime and K_2 single prime. Hengling biotite-pyroxene monzonite, Guangdong Province.

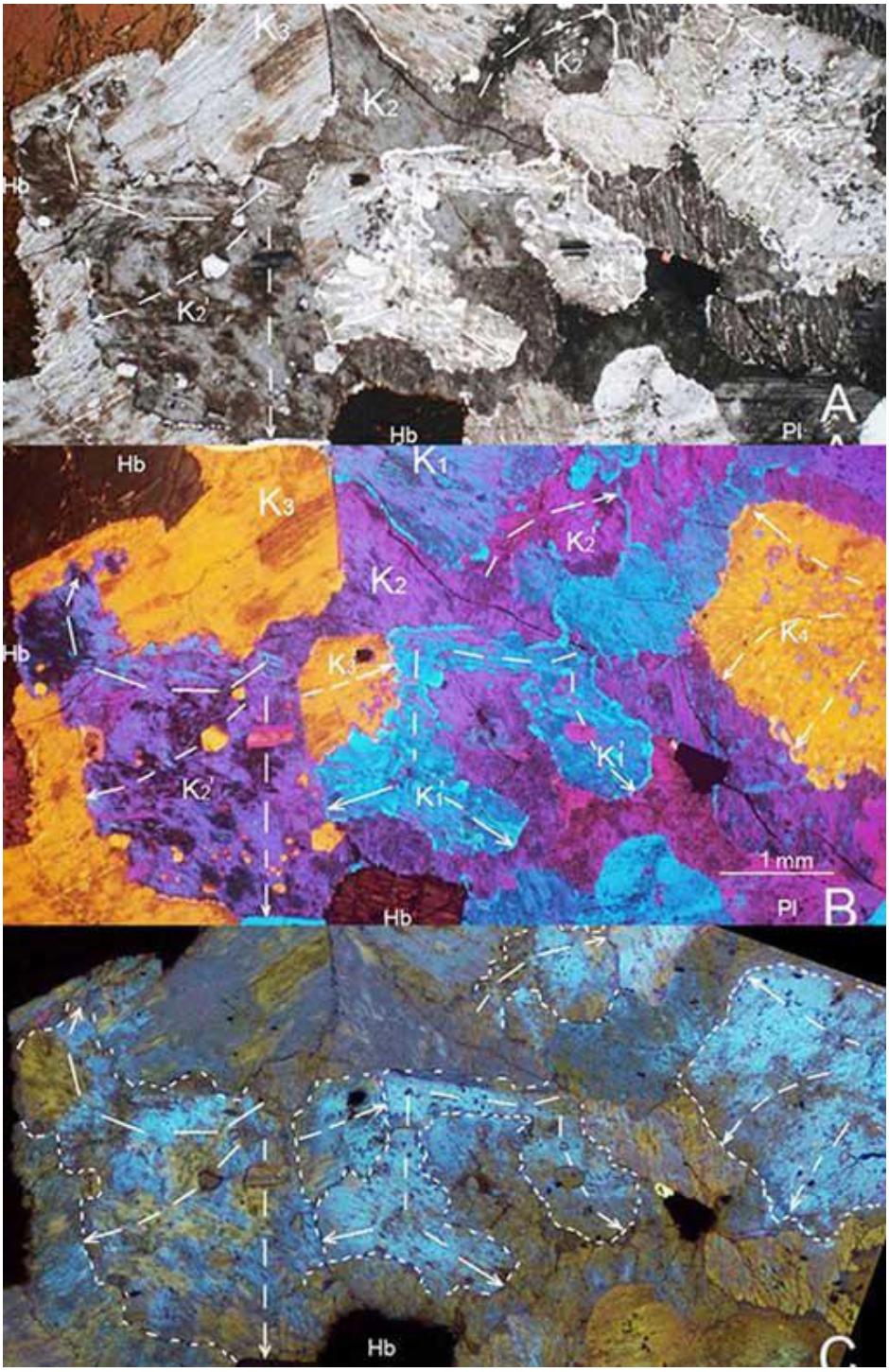

Fig. 10.-Swapped replacive K-feldspar crystals with arrows occurring at the grain boundary between three differently oriented preexisting (probably primary) K-feldspar crystals (K_1, K_2, K_3). A---Cross polarized light. B---Plus quartz plate. C---Cathodoluminescent image. Huangnitian granite. Yangjiang County, Guangdong Province.

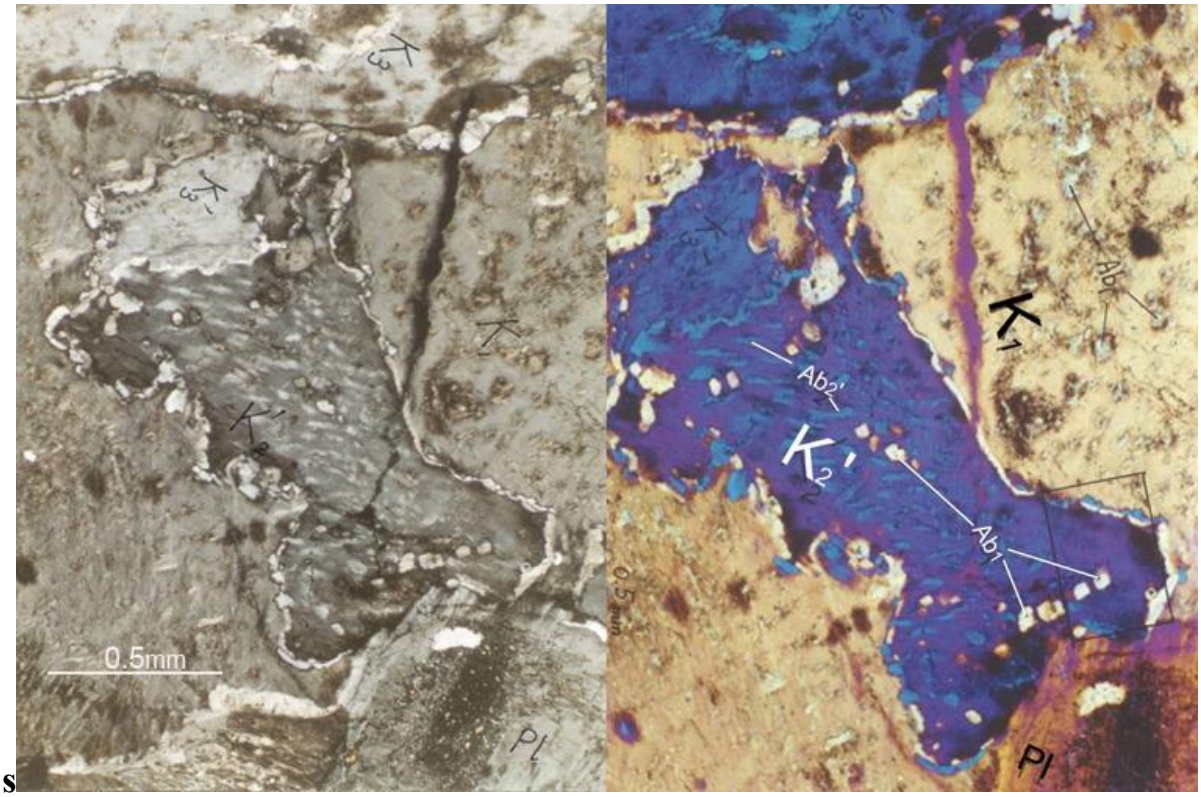

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Fig. 11. Fig. 11.-Complicated K-feldspar (K_1 and K_2) and plagioclase (Pl) in Huangnitian quartz syenite. Relicts perthitic albite (Ab_1) of the primary K-feldspar (K_1) and myrmekitic perthitic albite (Ab_2 single prime) occur in the replacive K-feldspar (K_2 single prime). Plagioclase (Pl) is stable. Huangnitian quartz syenite, Yangjiang County, Guangdong Province.

Fig. 10 shows that the metasomatic K-feldspars (K_1, K_2', K_3') nibbly replace the adjacent K-feldspars (K_1, K_2 , K_3) on their boundaries. K_1' replaces K_2 downwards, K_2' replaces K_3 leftwards and K_1 rightwards, respectively, while K_3' replaces K_2 rightwards.

Cathodoluminescent image (Fig. 10C) shows that the back ground of all K-feldspar luminesces dead-wood tan, that the replacive K-feldspar in many places has bright sky-blue luminescence, and that the primary K-feldspar luminesces pinkish purple. But part of the bright sky-blue color also extends to the primary K-feldspar.

Both the pinkish purple (for primary K-feldspar) and bright sky-blue (for

replacive K-feldspar) disappear at any intensely argirillized part with dark color of K-feldspar.

The orientation of the metasomatic K-feldspar (Kx') is different from that of the replaced K-feldspar, but coincides with the adjacent K-feldspar (Kx) on which it epitaxially grows. Because the size of the replacive K-feldspar may be as much as 3 mm, the primary K-feldspar on which the replacive K-feldspar nucleates may not appear in the same thin section (Fig. 11).

An unusual perthitic K-feldspar, containing vermicular plagioclase lamellae in monzonitic rocks from the Maronia pluton in northern Greece has been reported by Collins (1998c). The unusual perthitic K-feldspar invades other K-feldspar crystals that lack the vermicular plagioclase (Fig. 12). Data come from Georgios Christofides (Department of Mineralogy, Petrology, and Economic Geology, Aristotle University of Thessaloniki, 54006 Thessaloniki, Macedonia, Greece). This kind of structure (vermicular plagioclase lamellae) in K-feldspar is quite similar to the replacive K-feldspar mentioned above.

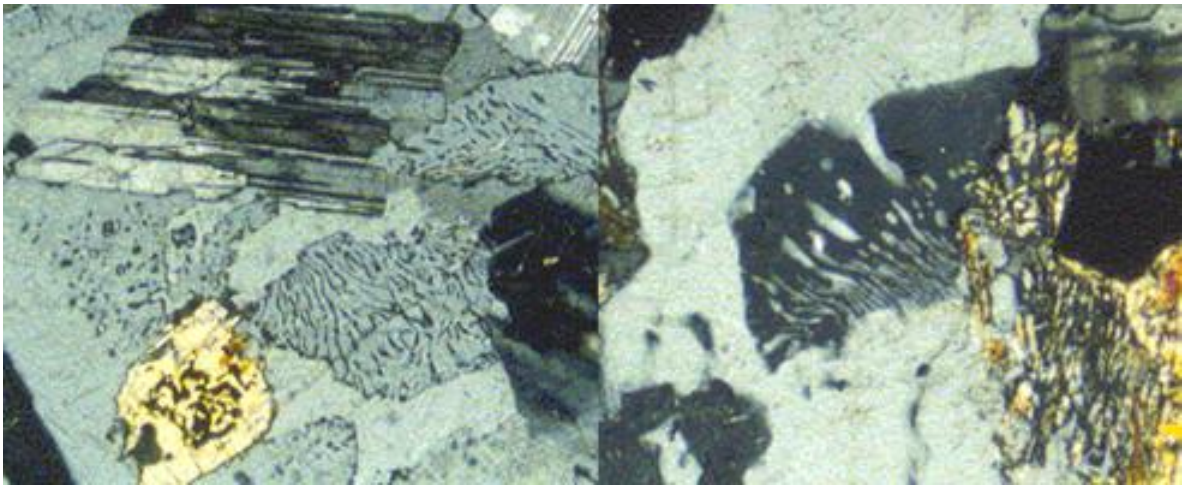

Fig. 12.-An unusual perthitic K-feldspar, containing vermicular plagioclase, occurs in monzonitic rocks from Maronia pluton in Northern Greece. The K-feldspar crystals that contain the vermicular plagioclase invade other K-feldspar crystals that lack the vermicular plagioclase (Reported by Collins, 1998). Work done by Georgios Christofides (Department of Mineralogy, Petrology, and Economic Geology, Aristotle University of Thessaloniki, 54006 Thessaloniki, Macedonia, Greece).

Note that vermicular albite occurs in newly formed K-feldspar replacing the primary K-feldspar, while no vermicular albite occurs in newly formed K-feldspar where it replaces the primary plagioclase.

3) Muscovitization

Many petrographers consider that muscovite is metasomatic in origin. However, some muscovite could have a primary origin (under conditions of >1500 Pa and 750°C), such as anhedral muscovite enclosing the idiomorphic biotite (Fig. 13), or interstitial muscovite (Fig. 14).

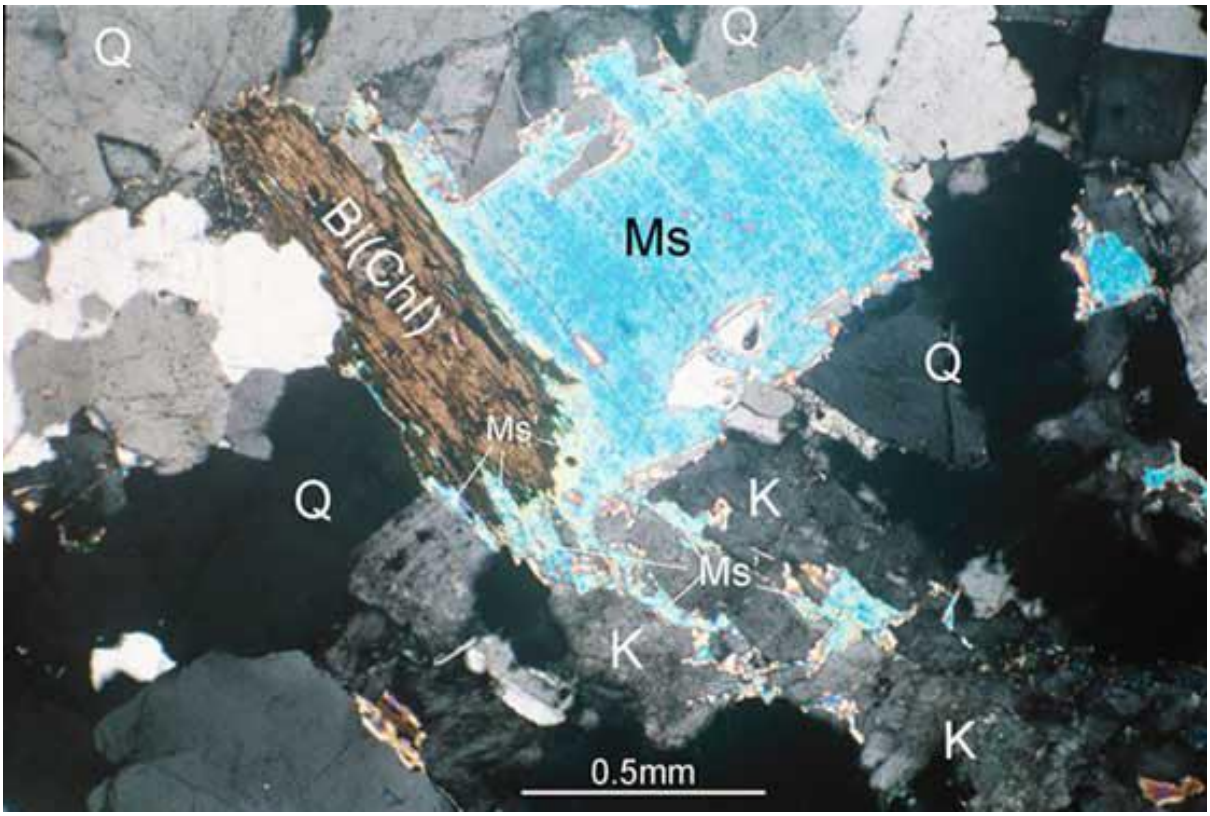

Fig. 13.-Primary muscovite (Ms) and metasomatic muscovite (Ms single prime). The thick schistose muscovite (Ms) in contact with quartz (Q) is of primary origin, while the irregular branch-like muscovite (Ms single prime) replacing the biotite (Bi) and the K-feldspar (K) is of replacement origin. Crossed polars. Huichang granite, Jiangxi Province.

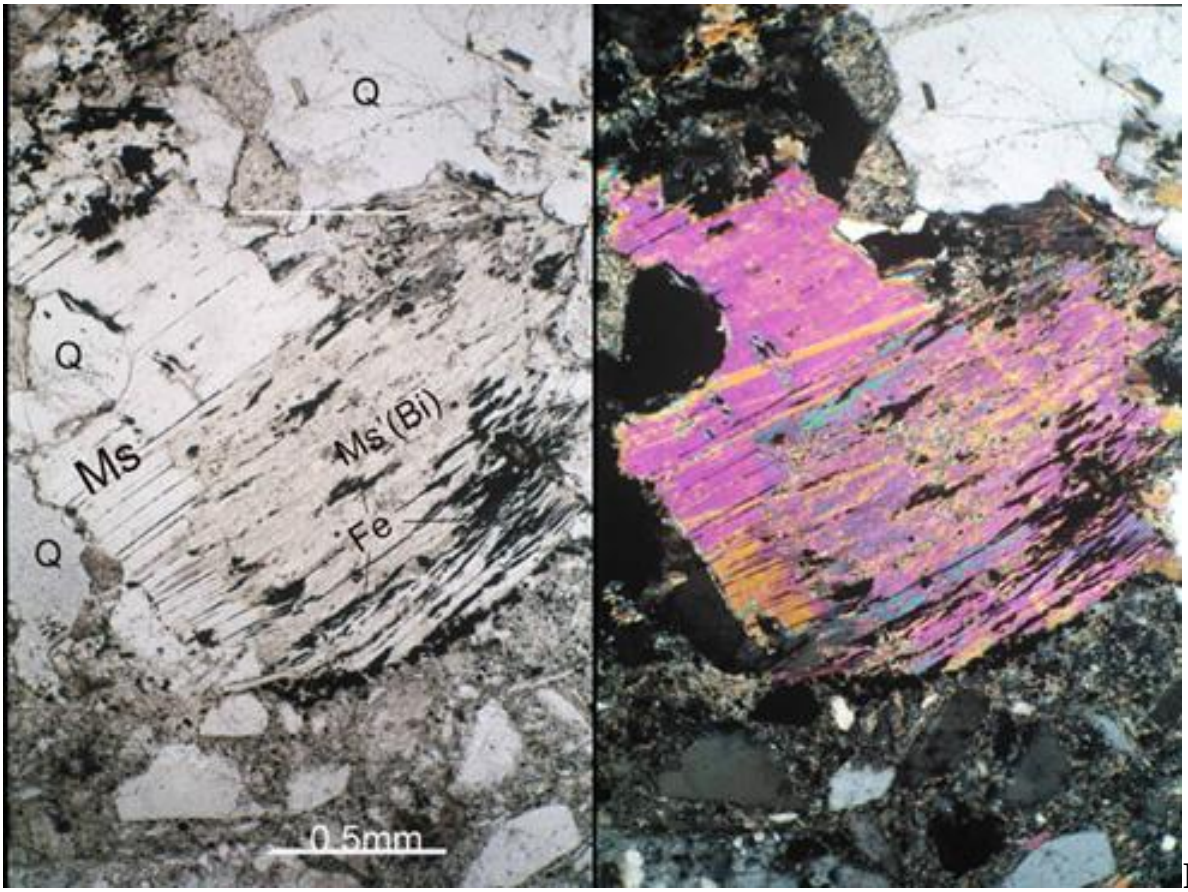

Fig. 14.-Primary muscovite (Ms) and co-orientation metasomatic muscovite (Ms single prime). Left figure, plane-polarized light. Right figure, crossed polars. The clear and transparent muscovite (Ms) epitaxially growing on a primary idiomorphic biotite (Bi) is primary, while the mottled muscovite (Ms single prime) containing the Fe-analyte has a co-orientation replacement origin from biotite. Huichang granite, Jiangxi Province.

a) Muscovite replacing K-feldspar

Nibbly replacive muscovite occurs always in branched form towards and into K-feldspar (Fig. 15).

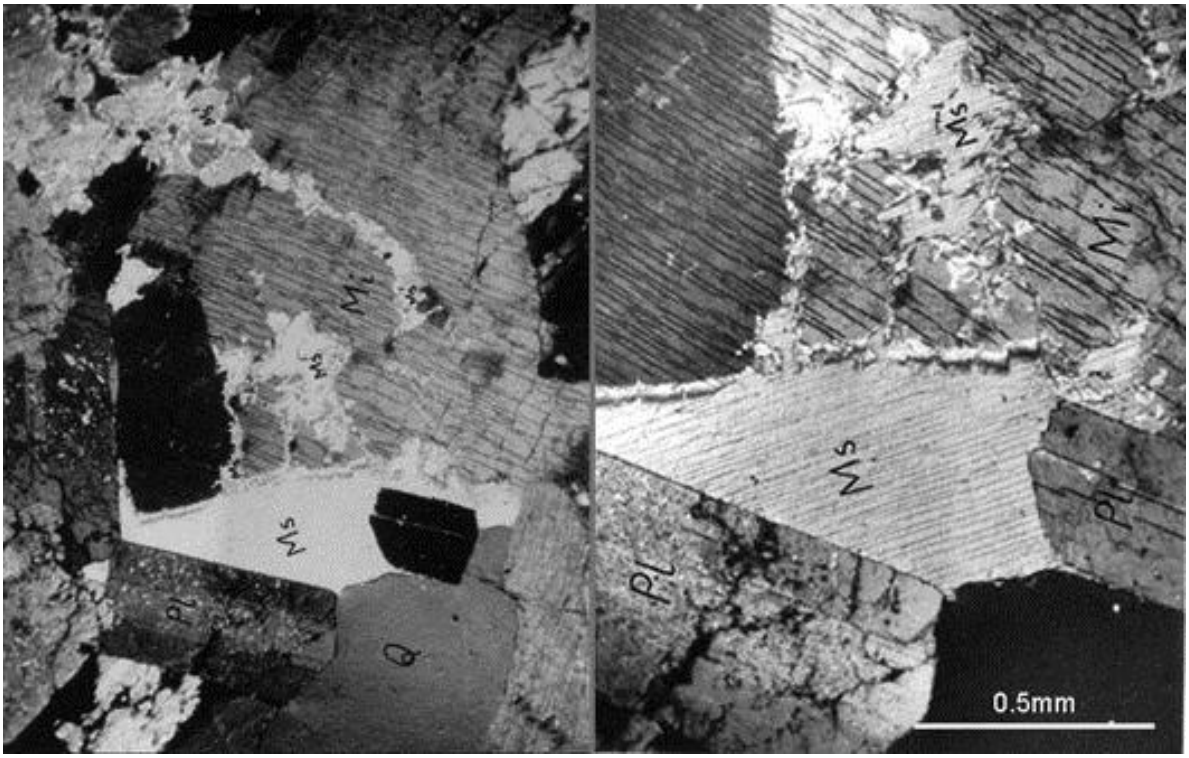

Fig. 15.-Anhedral primary muscovite (Ms) and branch-like replacive muscovite (Ms single prime). The basal cleavage of Ms single prime completely coincides with that of the primary Ms. Ms has sharp boundary with plagioclase Pl, but zigzag contact with K-feldspar after Ms single prime replacement. Crossed polars.

b) Swapped rims of muscovite between two biotite grains

At the grain boundary between two leucocratic biotite grains (protolithionite) in leucogranite, two rows of small grains of muscovite can be seen to nibbly replace the two adjacent biotite grains in some places (Figs. 16, 17). The two rows of muscovite have the same crystallographic orientation as the opposite biotite respectively (according to the consistency of cleavage and the difference in pleochroism and interference color). This phenomenon, however, could easily be absent or hardly exist due to the limited contact of two protolithionites and the tiny growth of replacive muscovite.

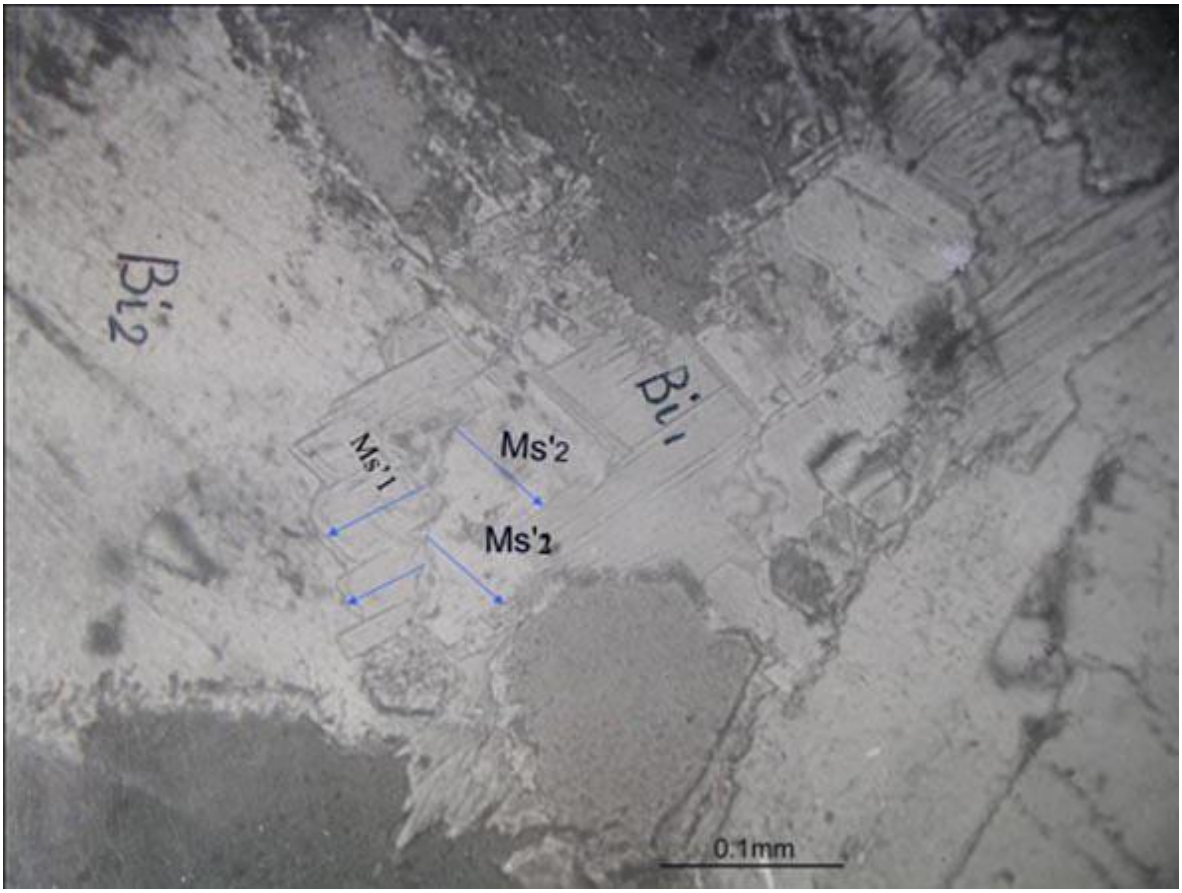

Fig. 16.-Swapped rows of replacive muscovite occurring at the contact between two protolithionites (Bi_1, Bi_2). The replacive muscovite has the same crystallographic orientation as the back-side Bi_1, Bi_2. Plane-polarized light. Beihuan protolithionite granite, Yangjiang County, Guandong Province.

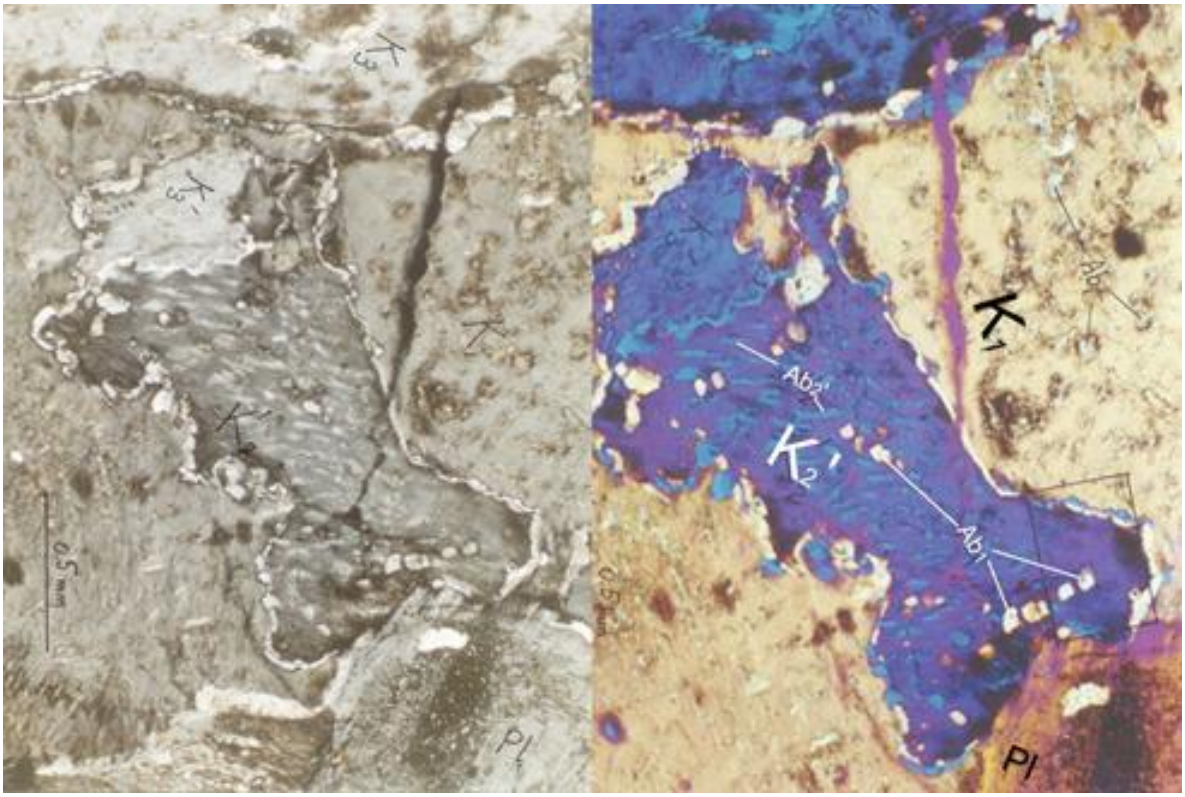

Fig. 17.-Swapped rows of replacive muscovite on the border between two protolithionite crystals (Bi_1, Bi_2). Left figure, plane-polarized light. Right, crossed polars. Beihuan protolithionite granite, Yangjiang County, Guandong Province.

4) Quartzification

K-feldspar can partly be replaced by quartz in leucocratic granites rich in silica and alkali and poor in calcium, magnesium and ferrous iron. The quartz outside the idiomorphic or hypidiomorphic K-feldspar can be inferred as primary in origin. The quartz (Q_1',Q_3') of irregular form inside the K-feldspar has the same crystallographic orientation of the quartz (Q_1,Q_3) outside the K-feldspar. It shows that Q_1',Q_3' grow and extend from primary quartz (Q_1,Q_3), nibbly replacing the K-feldspar (Fig. 18). Quartz, entire plagioclase (albite) and biotite are stable, while perthitic albite is less replaced during nibble quartzification.

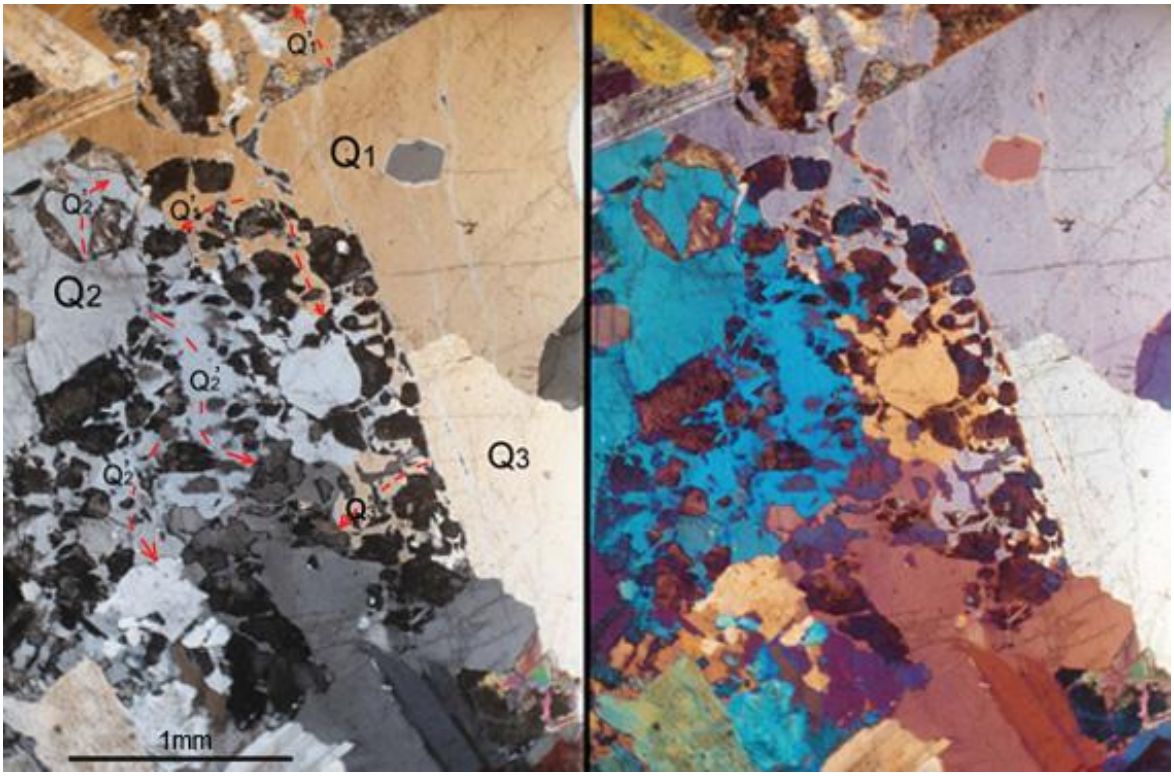

Fig. 18.-Quartz replaces K-feldspar. The replacive quartz (Q_1 single prime, Q_3 single prime) has the same crystallographic orientation as that of the primary quartz (Q_1, Q_3). Beihuan protolithionite granite, Yangjiang County, Guandong Province.

After intense quartzification (and muscovitization), K-feldspar can completely be replaced resulting in residual skeletal perthitic albite and more idiomorphic albite (Fig. 19).

Fig. 19.-Intense replacement of K-feldspar by quartz and muscovite. Idiomorphic plagioclase and residual perthitic albite are retained after intense quartzification and muscovitization. Crossed polars. Beihuan protolithionite granite, Yangjiang County, Guandong Province.

Quartz newly-formed may nibbly replace calcite, after the calcite has replaced primary quartz in sodic metasomatite from Jiling granite, Gansu province (Fig. 20).

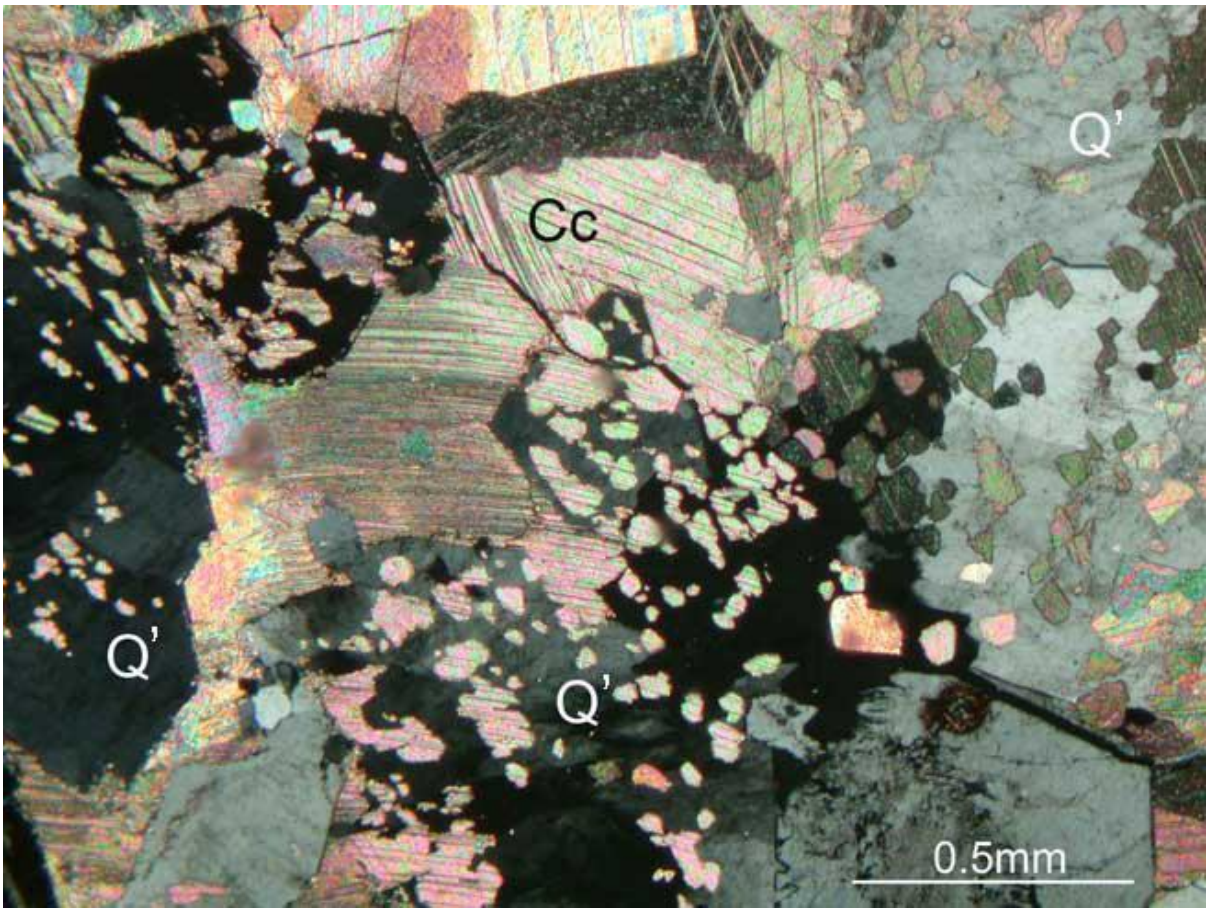

Fig. 20.-Calcite (Cc) is nibbly replaced by newly formed quartz. Primary quartz was at first replaced by calcite (Cc). Later, the calcite is replaced by newly formed quartz (Q single prime). Crossed polars. Sodic metasomatite of Jiling granite, Gansu Province.

5) Berylitization

In some places small miarolitic cavities appear in apical or periphery facies of leucogranite rich in silica and alkali which is formed at late stage of magmatic evolution. In the center of such miarolitic cavities anhedral beryl (Ber) is surrounded by idiomorphic K-feldspar and albite. The anhedral beryl should be primary in origin. The beryl (Ber') distributed irregularly in K-feldspar with the same crystallographic orientation as that of the anhedral beryl outside the K-feldspar has a nibble replacement origin (Figs. 21, 22). Albite and biotite are comparatively stable during berylitization.

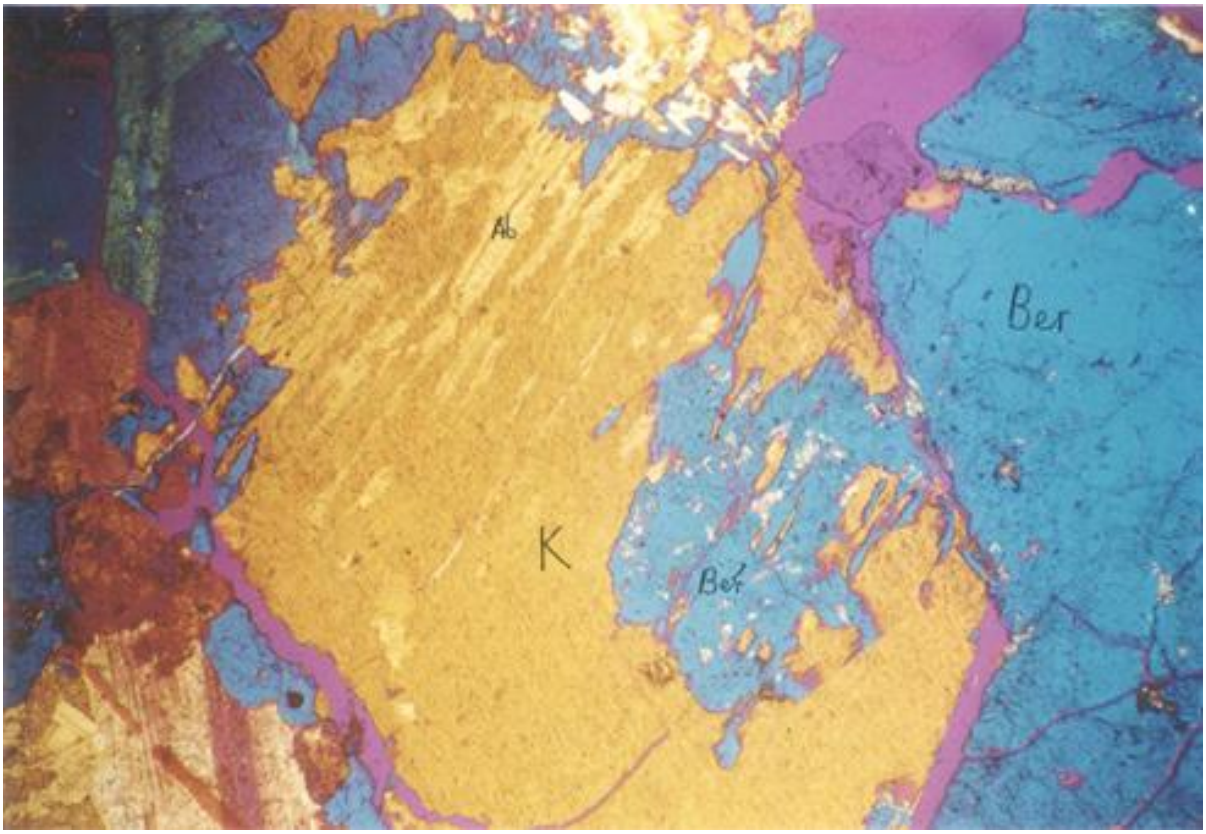

Fig. 21.-Beryl primary (Ber) and replacive (Ber single prime. The anhedral crystal of beryl (Ber) outside the idiomorphic K-feldspar (K) is primary, while the irregular form of beryl (Ber single prime) inside the K-feldspar is of metasomatic. Ber single prime has the same orientation as the Ber. Crossed polars plus quartz plate. Shanbei leucogranite, Taishan County, Guangdong Province.

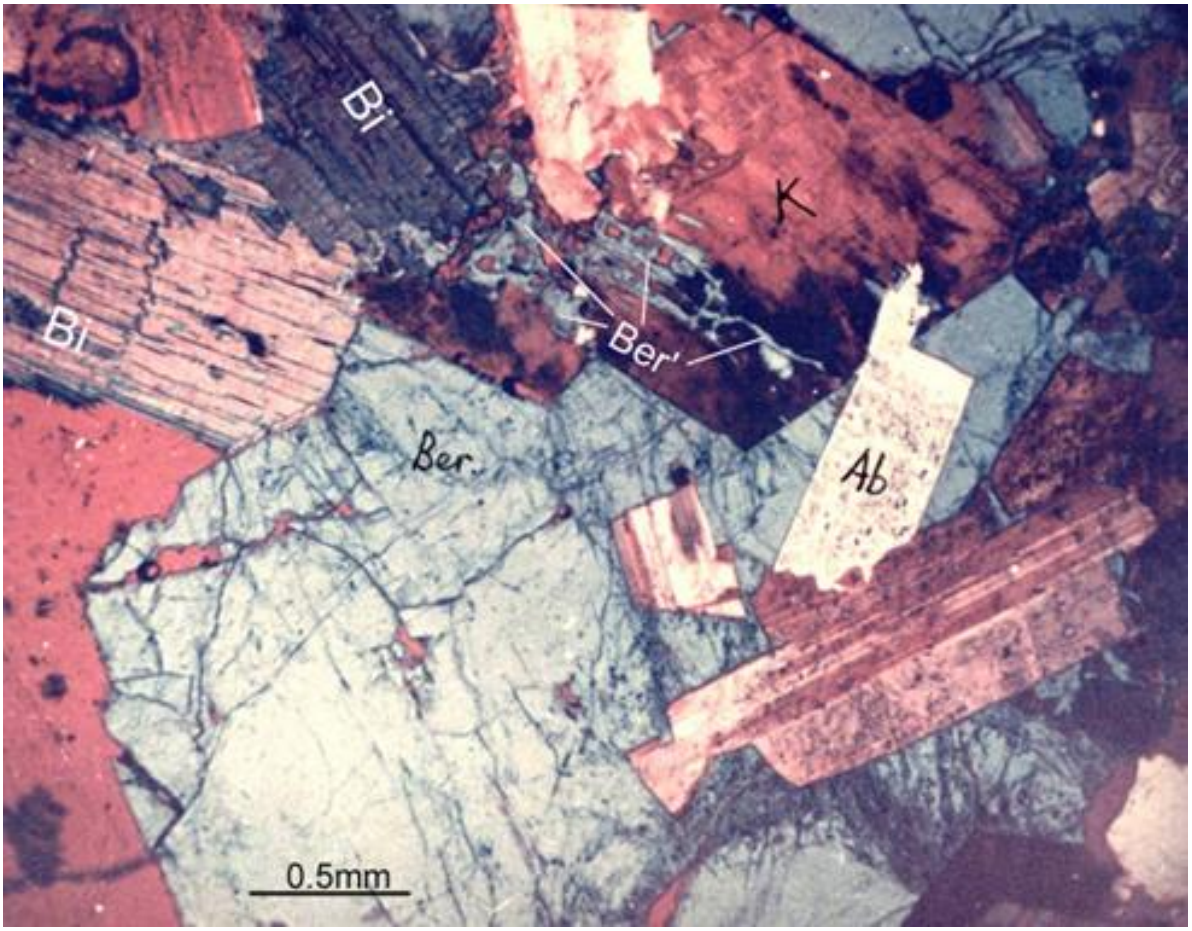

Fig. 22.-Primary beryl (Ber) and replacive beryl (Ber single prime). The anhedral crystal of beryl (Ber) outside the idiomorphic K-feldspar (K) is primary, while the irregular form of beryl (Ber single prime) inside the K-feldspar is metasomatic. Ber single prime has the same orientation as the Ber. Ber single prime replaces mostly K-feldspar rather than plagioclase and biotite. Crossed polars plus quartz plate. Shanbei leucogranite, Taishan County, Guangdong Province.

The above-mentioned nibble metasomatic growth of a rock-forming mineral occurs in granitic rocks where a lot of identical or similar minerals would naturally serve as a crystallographic nucleus for nibble replacement. In those places where no identical or similar mineral occurs, an impurity in a rock could serve as a crystal nucleus for growth; for instance, in sericitization (even muscovitization), calcitization (carbonitization) and pyritization.

6) Sericitization and muscovitization of plagioclase

Numerous randomly distributed schistose sericite, even muscovite (Ms') without any relation and contact with muscovite and biotite outside the plagioclase may be formed inside plagioclase after alteration (Fig. 23).

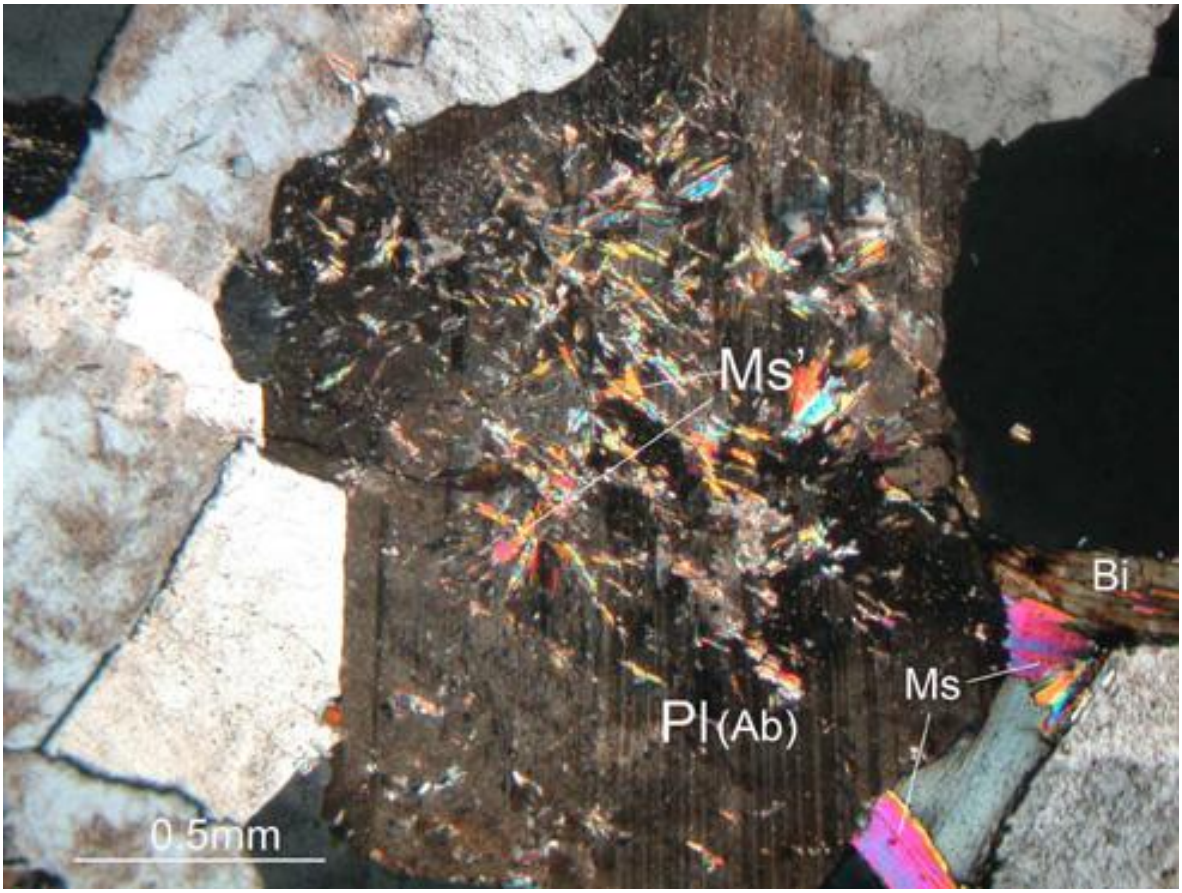

Fig. 23.-Muscovitization inside plagioclase. Fine schistose muscovite distributed randomly inside plagioclase. After muscovitization the plagioclase is transformed to albite.

7) Calcitization (calcite replaces quartz and K-feldspar)

Calcitization is one of the processes of alkali metasomatism in granites. Primary quartz is replaced by calcite (branch-like) (Fig. 24) and then becomes relicts in calcite (Fig. 25), even disappears. If quartz disappears, calcite can further replace K-feldspar resulting in isolated relicts of perthitic albite lamellae in calcite (Fig. 26). At that time, the crystal grains of chlorite (changed from biotite) and albite (transformed from plagioclase) are essentially retained.

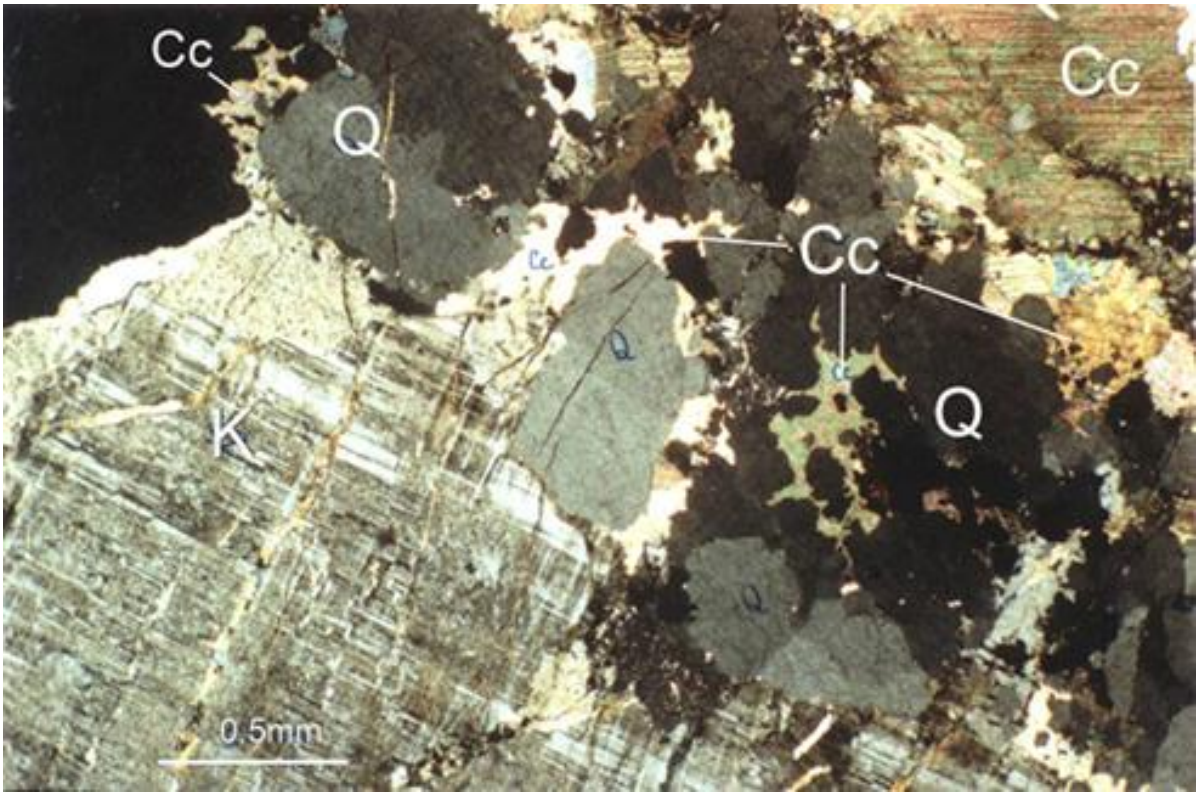

Fig. 24.-Quartz (Q) is replaced by calcite (Cc). K-feldspar (K) is retained. Crossed polars. Jiling monzogranite, Gansu Province.

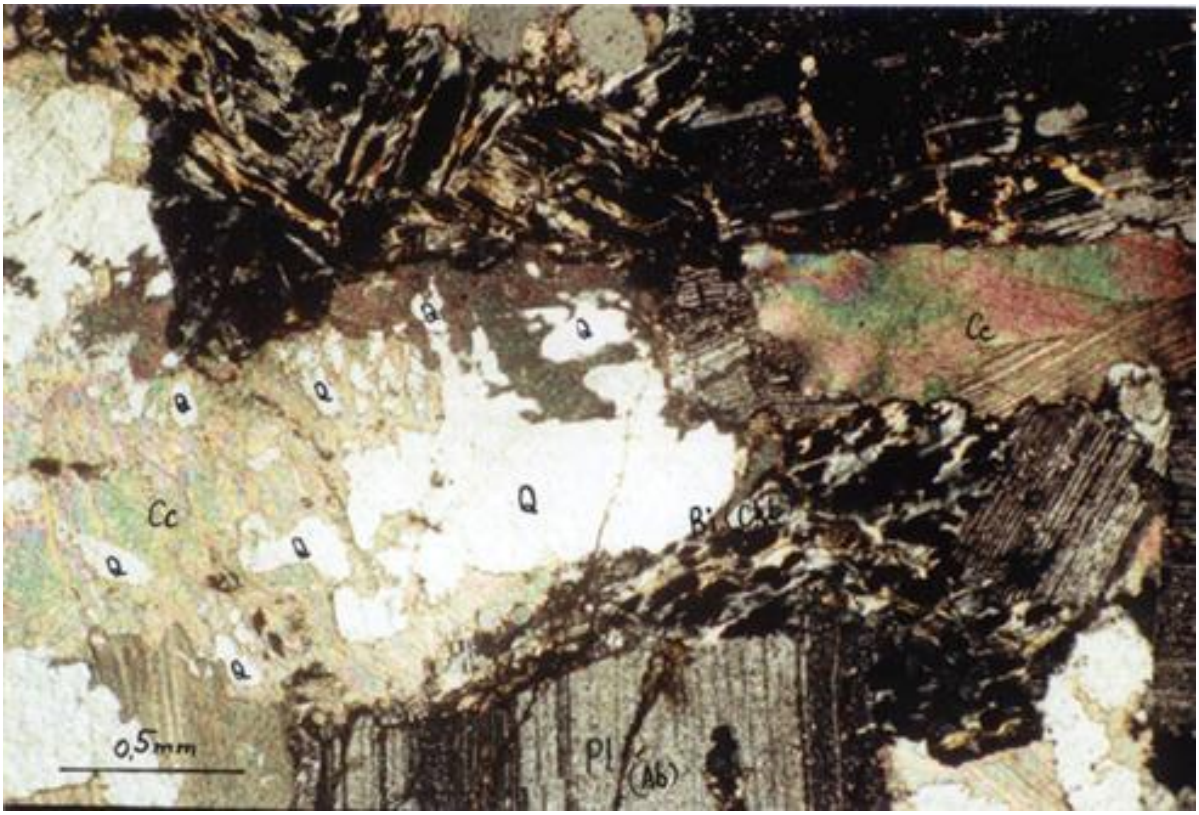

Fig. 25.-Quartz (Q) is intensely replaced by calcite (Cc; left), even completely (right). Plagioclase (albite) and biotite (chlorite) are not replaced by calcite (Cc). Crossed polars. Jiling monzogranite, Gansu Province.

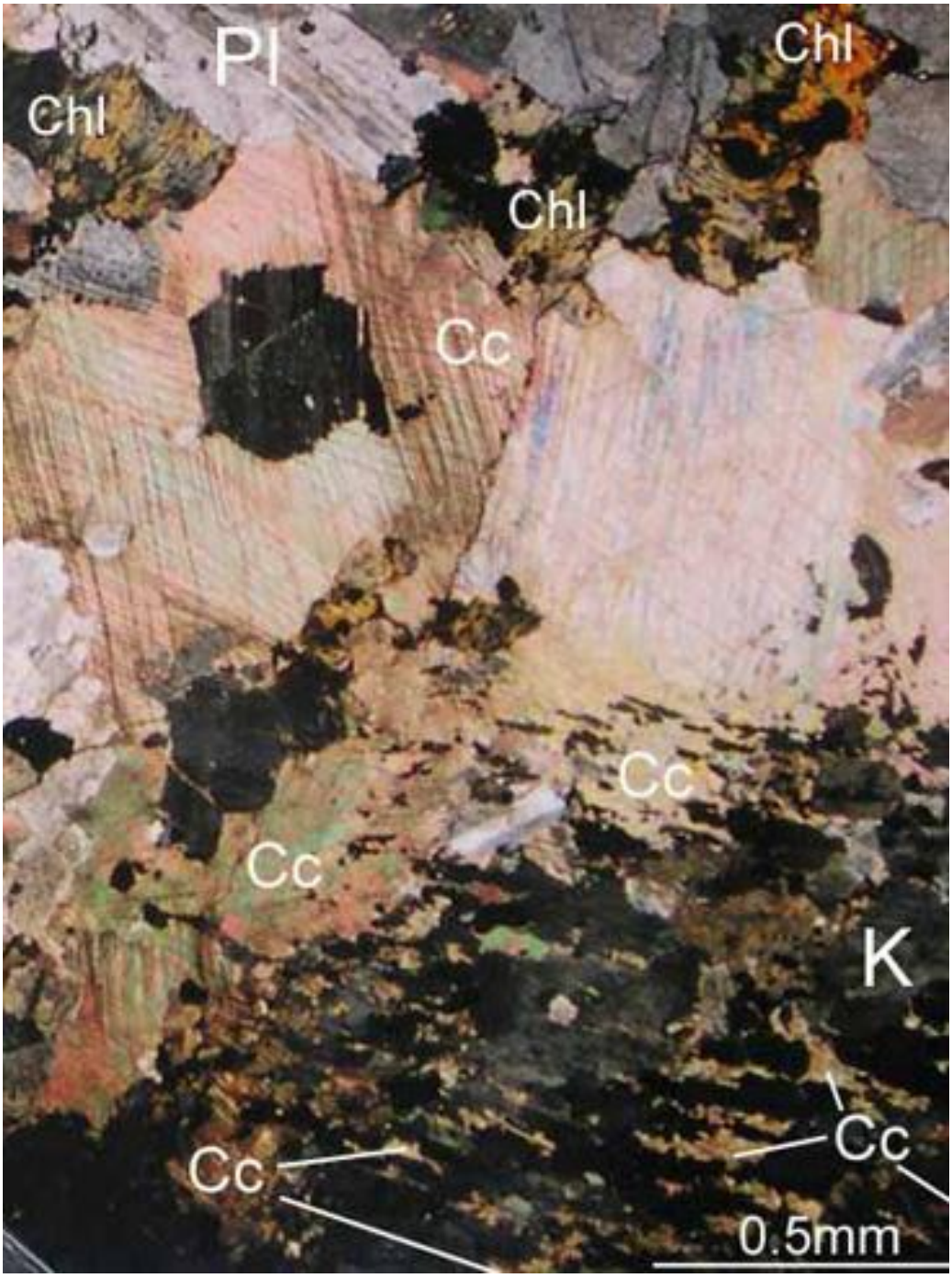

Fig. 26.-Calcite starts to replace K-feldspar after complete replacement of quartz. Relicts of K-feldspar are enclosed in calcite, while chlorite and plagioclase (transformed to albite) are retained. Crossed polars. Jiling monzogranite, Gansu Province.

8) Pyritization

Pyrite crystals are usually absent in fresh (unaltered) granite. Perhaps a very small amount of pyrite may exist as an accessory mineral. However, a lot of idiomorphic cubic crystals of pyrite (d≈1.5cm) can be formed in cataclastically-deformed granites (Rong, 1982). Inside the pyrite porphyroblast, a relict of plagioclase is in optical continuity with a large outside plagioclase crystal. Furthermore, the pyrite porphyroblast is idiomorphically formed due to its strong crystallizing strength (Fig. 27).

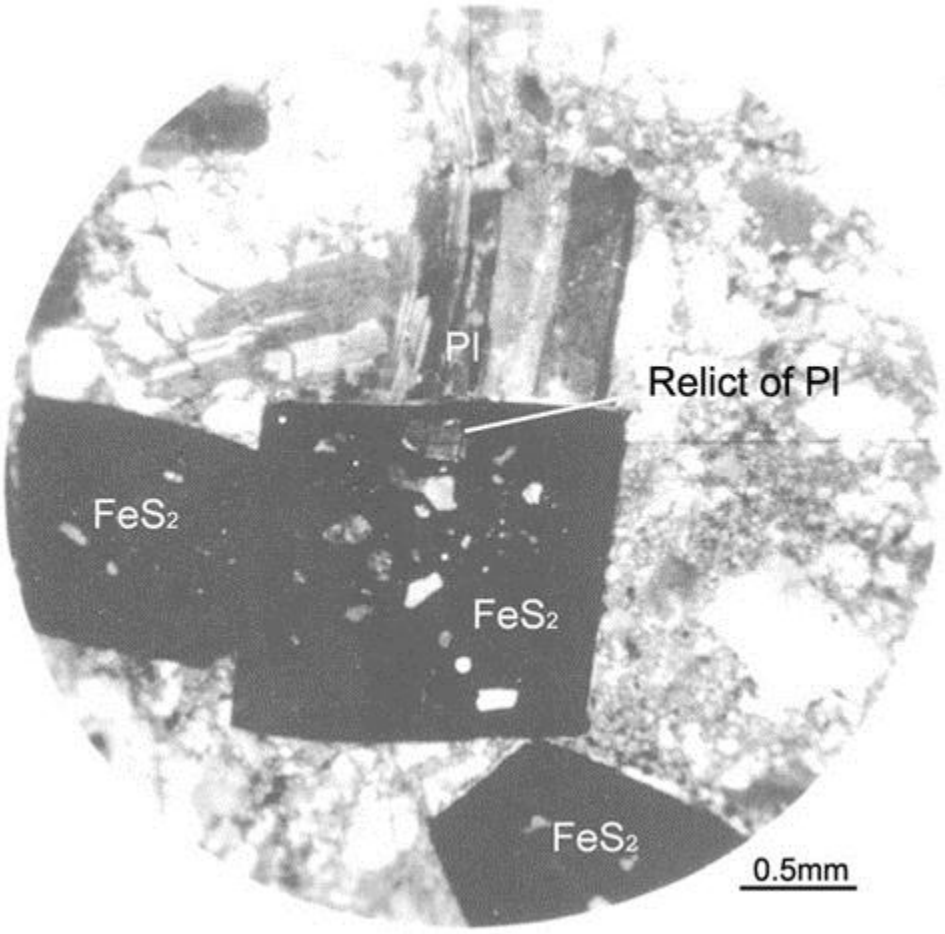

Fig. 27. -Replacement growth of idiomorphic pyrite in cataclastic granite. A relict of plagioclase is seen in the pyrite. Crossed polars. Jiulianshan cataclastic granite, Heping County, Guangdong Province.

Co-orientation replacement pattern

Co-orientation replacement means that the replacive mineral has the same or nearly the same crystallographic lattice as the replaced mineral; i.e., the replacement process proceeds along the lattice orientation of a replaced mineral, resulting in partial or even complete transformation of the original mineral into a new one. Included in the co-orientation replacement pattern are deanorthitization of plagioclase (transformed in situ to albite), co- orientation albitization of K-

feldspar, as well as muscovitization and chloritization of biotite.

1) Co-orientation albitization (deanorthitization) of plagioclase

Deanorthitization of plagioclase is often seen in altered granite. Because of alteration (sericitization for oligoclase and less calcic andesine and saussuritization for more calcic andesine and labradorite), the plagioclase is changed in situ into albite while preserving the original twinning. During deanorthitization, it seems as if the Na ion enters as the Ca ion is subtracted from the crystallographic lattice. In addition to Na, this pattern of replacement needs SiO_2 to be introduced. The surplus Ca and Al from the replacement process as well as other impurities can move out, forming zoisite, clinozoisite, epidote, sericite and even calcite in altered plagioclase. The core with higher An values of normally zoned plagioclase is generally changed to obvious albite while the rim composition remains unchanged (Fig. 28). Tiny grains of topaz and fluorite contained in altered plagioclase (albite) of granite rich in F are also reported (Haapala, 1997). Thus, the whole plagioclase turns into or approaches stable albite. The distribution of sericitization in plagioclase is not homogeneous. The sericitized part of plagioclase is albitized, while the unsericitized plagioclase may retain its original composition (Fig. 29).

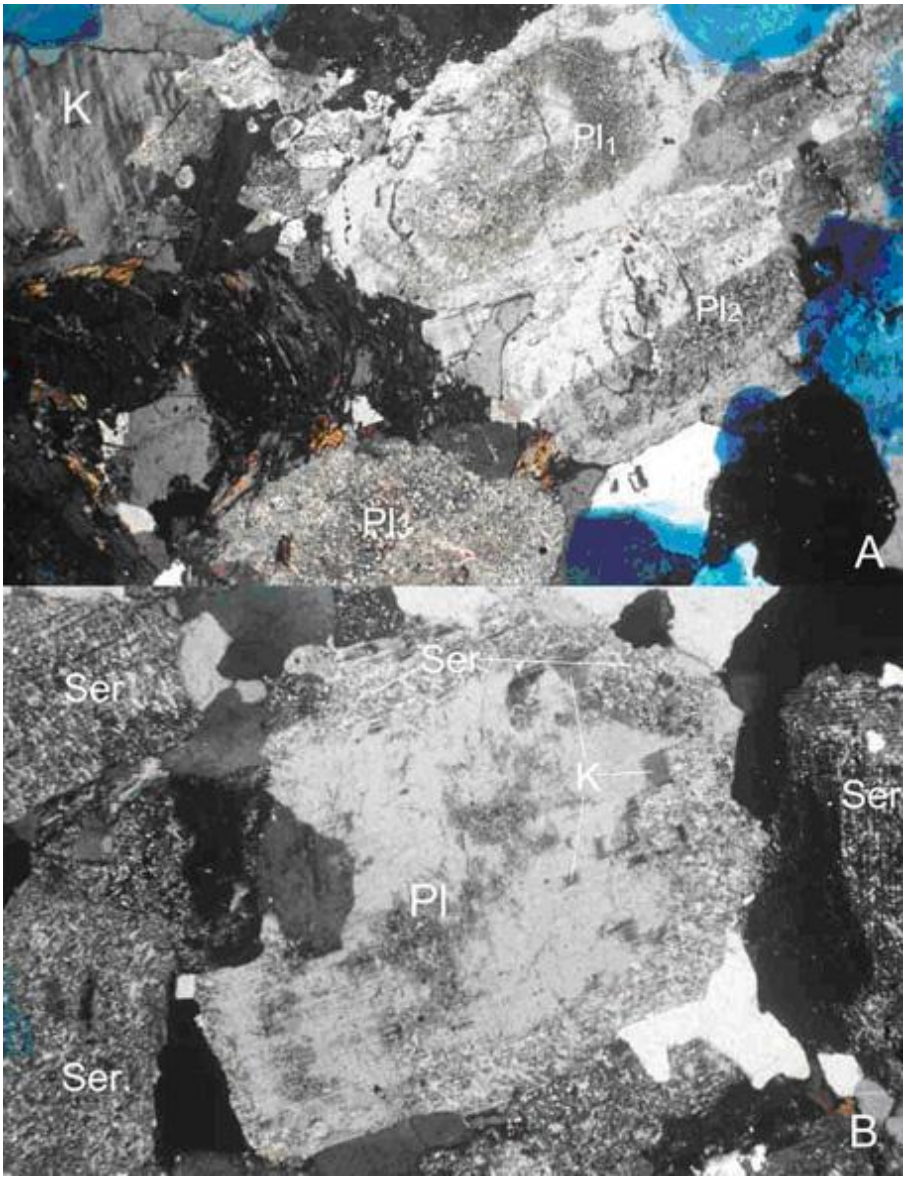

Fig. 28.-Inhomogeneous sericitization and albitization of plagioclase. A---The core part of two plagioclases (Pl_1, Pl_2) is sericitized, while the rim part is fresh and unaltered (An_{17-20}). The plagioclase (Pl_3) is completely sericitized. K-feldspar (K) is unsericitized; B---The rim part of plagioclase (Pl_1) is sericitized, but most parts of Pl_1 remain fresh and unaltered, and contain small patches of K-feldspar (antiperthite). Several crystals of surrounding plagioclase are sericitized and albitized (Ser). Cross polars. Jiling granite, Gansu Province.

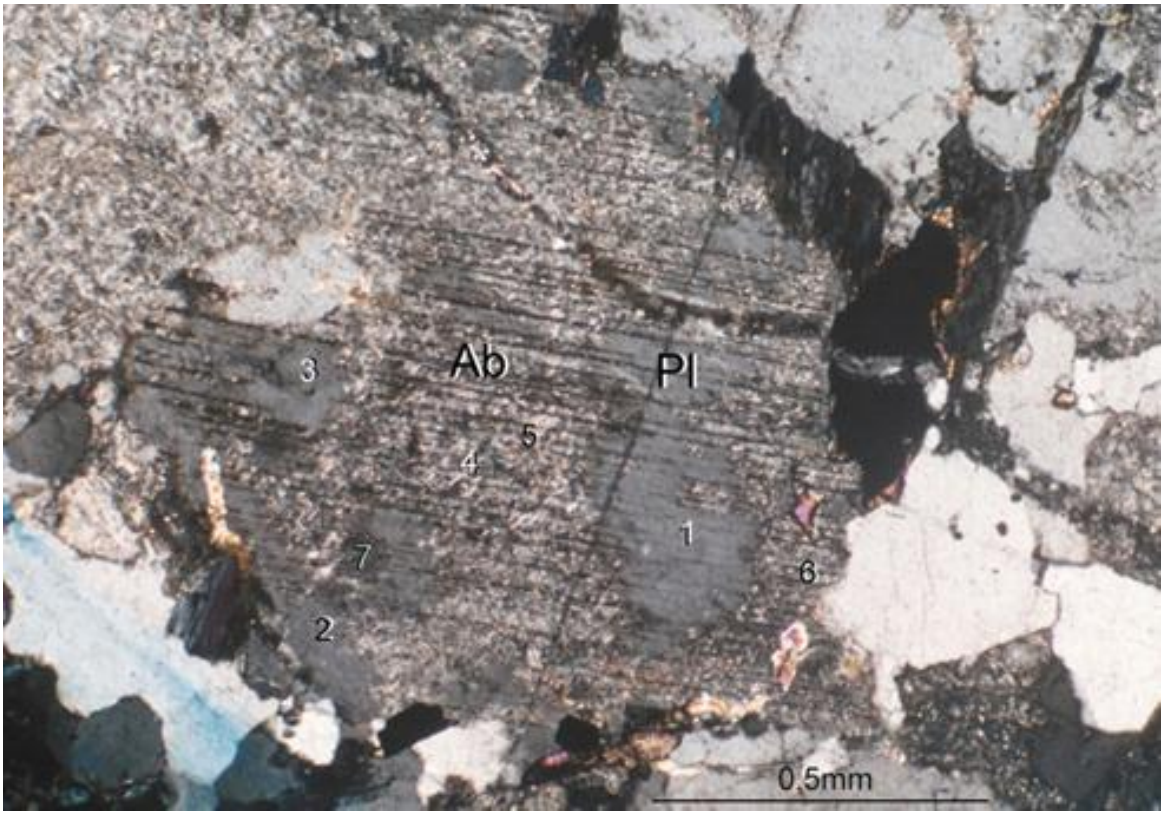

Fig. 29.-Nonuniform sericitization of plagioclase (Pl, An_{20-25}). Microprobe analysis shows that the sericitized plagioclase (points 4, 5, 6) is transformed to albite (An_{2-4}). The unsericitized plagioclase (points 1, 2, 3) maintains primary constituent (An_{20-25}, without clear albite twinning), where the small patches of K-feldspar with very low interference color is still preserved (point 7). Crossed polars. Jiling granite, Gansu Province.

2) Co-orientation albitization of K-feldspar (K-feldspar is transformed into albite)

With intensive action of Na-bearing gas-liquid the sodium ion may seemingly penetrate into the crystal lattice of K-feldspar and substitute Na for K, resulting in the transformation from K-feldspar to albite. The K-feldspar with grid twinning under crossed polars was changed to albite with chessboard twinning. The

compositional plane of chessboard twinning is characterized by zigzag irregularity which is clearly distinguishable from that of common albite twinning.

The intersect line of the three planes (Np_1 Np_2, Nm_1 Nm_2, Ng_1 Ng_2) of corresponding axes of the optic indicatrix of two individual chessboard albite twins is the twin axis. Universal stage study shows the twin axis is b-axis. Therefore, the chessboard albite twin can be called “b-axis twin.”

Fig. 30A, 30B show that chess-board albite can replace K-feldspar in a patch or block pattern. Note that the boundary between the unchanged K-feldspar and the chessboard albite is quite sharp without a blurred transition under the optical microscope, at least. Moreover, the shapes and distribution of the chessboard albite that the boundary between the unchanged K-feldspar and the chessboard albite is quite sharp without a blurred transition under the optical microscope, at least. Moreover, the shapes and distribution of the chessboard areas are different from the perthitic albite, although they have the same crystallographic orientation (Fig. 30C). Some co-orientation replacement albite is very similar to the primary perthitic albite (Fig. 31), except in its distribution.

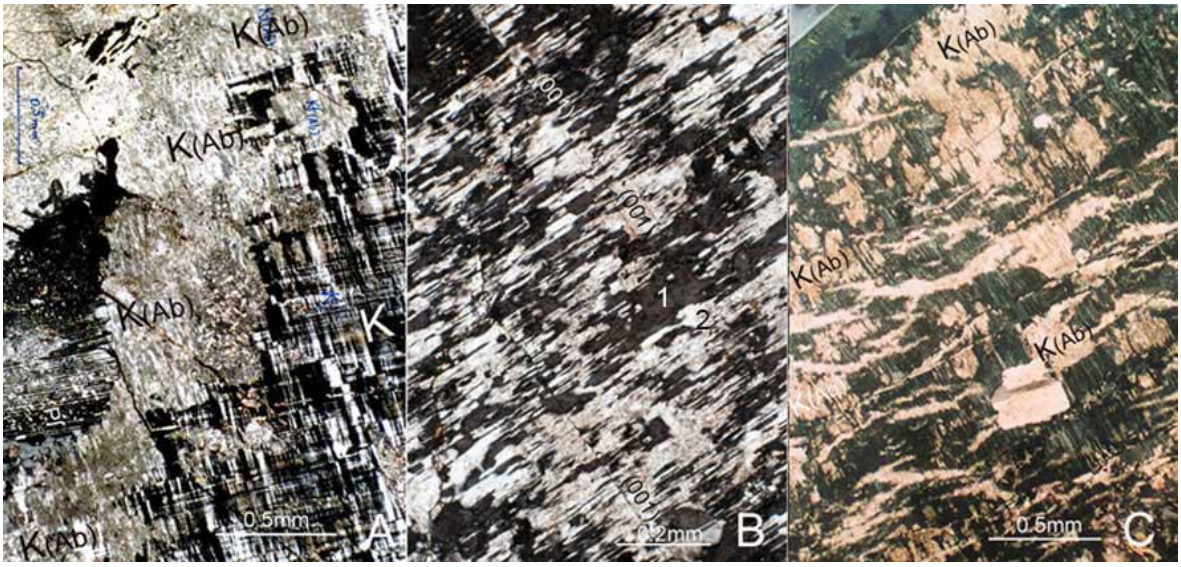

Fig. 30.-Chessboard albitization of K-feldspar. A---Co-orientation albitization (chessboard albite)[K(Ab)] takes place at the border of K-feldspar (with grid twinning) phenocryst. There is sharp contact between the chessboard albite [K(Ab)] and the unalbitized K-feldspar (K). B---Chessboard albite keeps the same orientation as the primary K-feldspar with (001) cleavage. The compositional plane of the chessboard albite is zigzag and variable. C---Chessboard albite patches are distinct from the albite lamellae in K-feldspar. Samples are selected from sodic metasomatite of Jiling granite, Gansu Province.

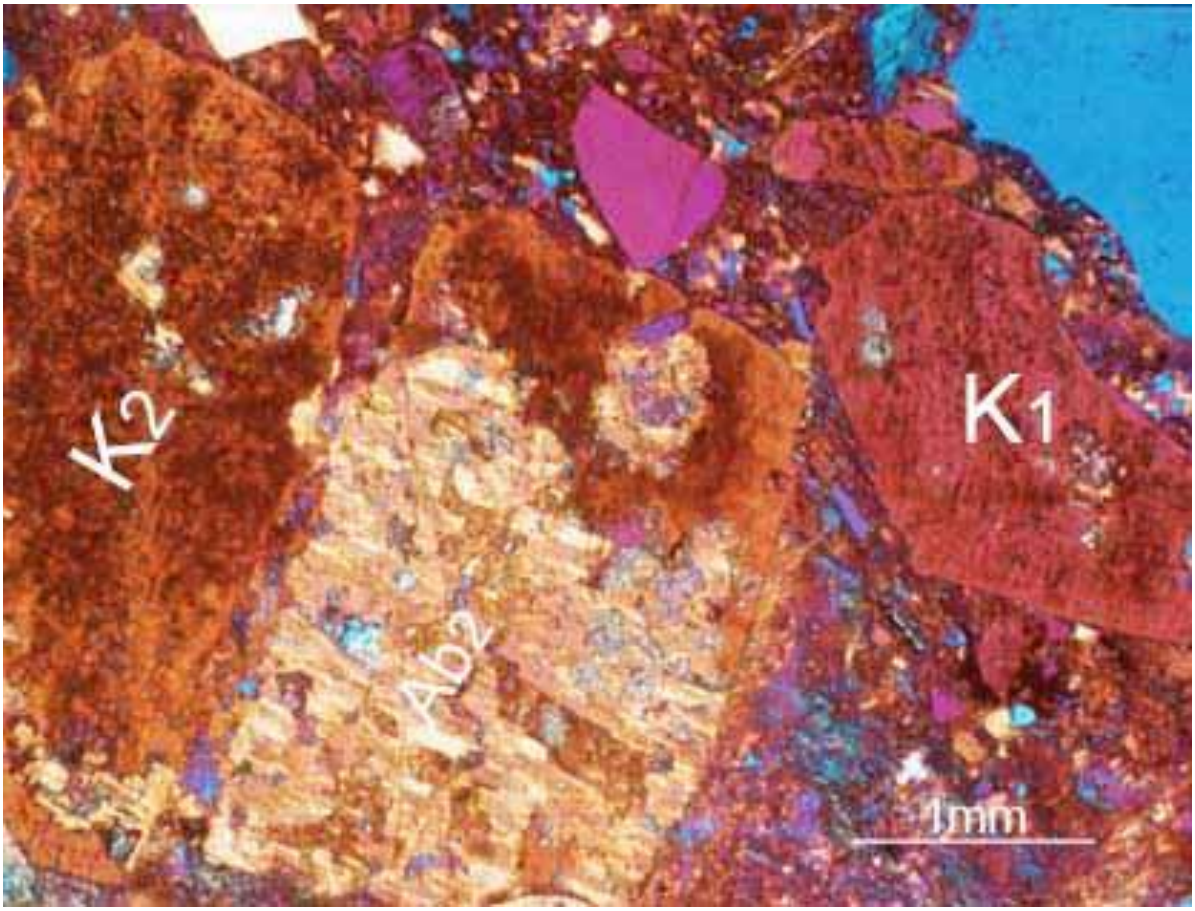

Fig. 31.-Co-orientation replacement of broken phenocryst of sanidine . The primary sanidine phenocryst lacks perthitic albite. Crossed polars plus quartz plate. Xiangshan mortar lava, Le-An County, Jiangxi Province.

3) Biotite is transformed to muscovite

Both muscovite and biotite have a common basal plane (001) and similar crystallographic lattices. Hot gas-liquid fluid containing Si and Al can penetrate along cleavage into biotite, displacing Fe, Mg, and Ti, resulting in transformation from biotite to muscovite (Fig. 32).

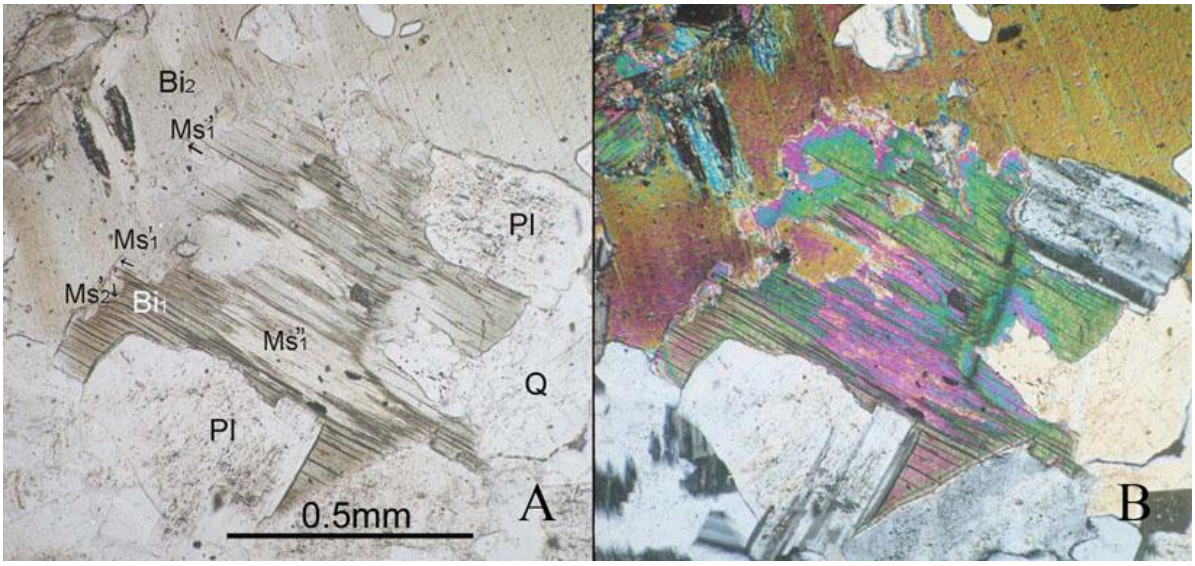

Fig. 32.-Biotite (Bi_1) is transformed to muscovite (Ms_1 double prime). A---Muscovite (Ms_1 double prime) is colorless and transparent in biotite (Bi_1) in plane-polarized light. B---Ms_1 double prime is different from Bi_1 in interference color in crossed polars. Also, nibble replacement muscovite grains (Ms_1 single prime and Ms_2 single prime) occur at the contact between Bi_1 and Bi_2. Baimianshi granite, Huichang County, Jiangxi Province.

4) Biotite is transformed to chlorite

The crystallographic lattice of chlorite is different from that in biotite, but still in many respects resembles the lattice in micas (Deer, 1962). Both contain basal cleavage (001). After alteration, biotite is prone to be replaced by chlorite in pseudomorphic form (Fig. 33).

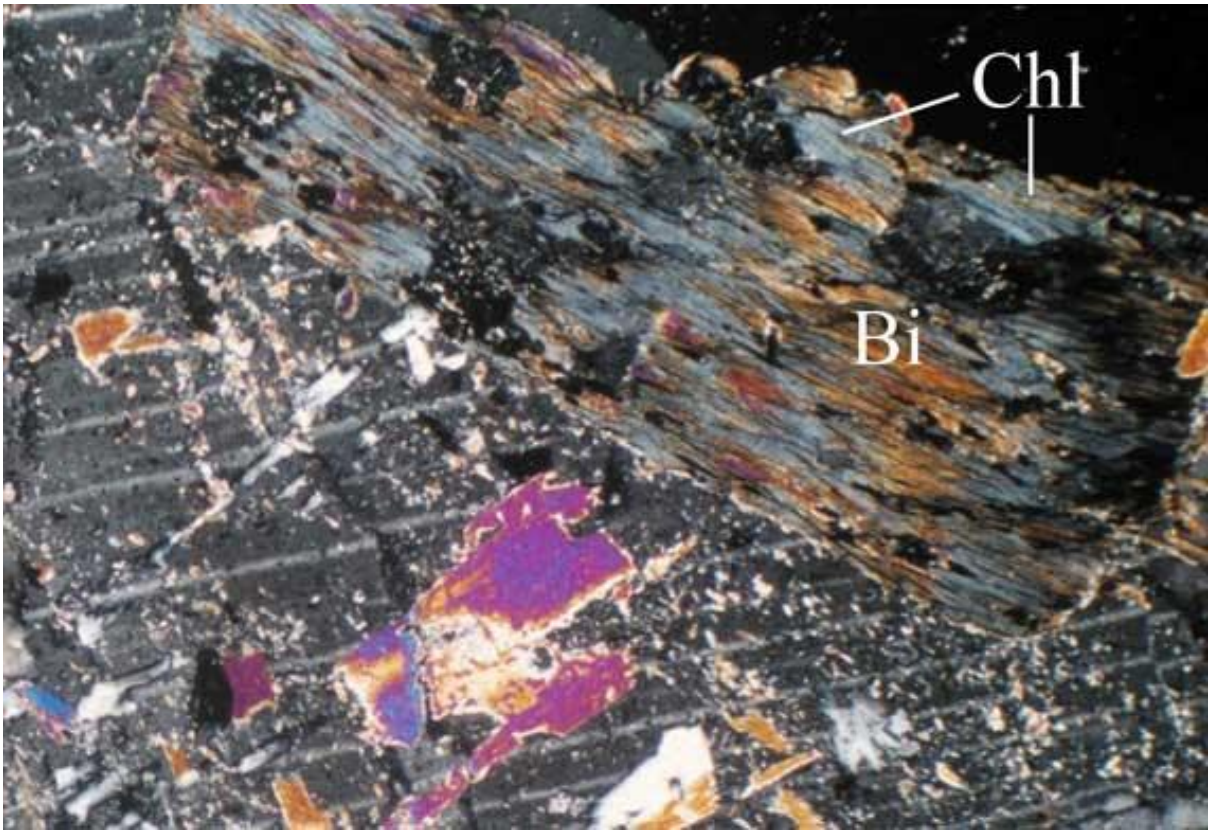

Fig. 33.-Biotite is in part transformed to chlorite. K---K-feldspar, Pl---Plagioclase (hydromicazationed). Crossed polars. Baimianshi granite, Huichang County, Jiangxi Province.

Formation mechanism for mineral replacement

Replacement mechanism

The major mechanisms of mineral replacement are the dissolution-precipitation (or – re-precipitation, in fact, dissolution-crystallization) and the cation exchange.

Cation exchange mechanism means that the old mineral is partly or even wholly transformed to newly replacive mineral by the cation exchange without partial or whole dissolution of the old mineral.

Dissolution-precipitation mechanism implies that the new mineral precipitates

(crystallizes) in the space where the old mineral is locally dissolved. Obviously, the mechanism aims at the hetero-orientation replacement (nibble replacement) pattern.

The author considers that the two different mechanisms of replacement should occur separately rather than simultaneously; i.e., no cation exchange occurs when dissolution-precipitation happens, and no dissolution-precipitation occurs when cation exchange proceeds.

For the dissolution-precipitation mechanism some researchers suggest that as a replacive (guest) mineral grows, it must exert an excess pressure (Ostapenko, 1976), an induced stress (Carmichael, 1986), a force of crystallization (Maliva and Siever, 1988), or a growth-driven stress (Merino et al., 1993) on its neighbor (host) mineral and promote its dissolution.

Merino et al. (1993) stated that in a rigid rock, the growth-driven stress between guest and host minerals has two immediate effects: 1) increase the solubility and rate of pressure solution of the host mineral and 2) decrease the rate of growth of the guest itself (due to decrease of the supersaturation because of increase in the solubility of the guest mineral) so that the value of the two volumetric growth-rates of guest B and dissolution of host A become equal.

The authors seemed to stress that appropriate dissolution of replaced mineral is promoted by a force driven by growth of the replacive mineral. Merino et al. even emphasized (1998): “any mineral may in principle replace any neighbor, provided there is sufficient affinity for its growth, regardless of whether the two have an element in common, of whether the two are isostructural or not, and of which mineral has the greater formula volume.”

According to the author’s observation, during a certain mineral replacement in a dissolution-precipitation mechanism, some minerals are easily replaced, while others are not (Table 1). It is by no means certain that any mineral may be replaced by a particular replacive mineral. Therefore, whether a mineral may be replaced or not depends not only on the growth-driven stress of replacive mineral but also on the appropriate dissolubility of the replaced mineral under a new kind of gas-liquid composition and P-T condition.

Table 1. Replacive minerals versus minerals easily and hardly replaced in nibble replacement

Replacive minerals	Minerals easily replaced	Minerals hardly replaced
albite, quartz , beryl	K-feldspar, fine perthitic albite, calcite	entire plagioclase, quartz, biotite
K-feldspar	K-feldspar , plagioclase	quartz, biotite, hornblende
muscovite	K-feldspar, biotite	quartz
calcite	quartz , K-feldspar	entire plagioclase, biotite

Also, there are great discrepancies in different patterns of replacement. For example, albite can easily replace an entire plagioclase in a co-orientation replacement pattern, but can only partially replace tiny fine perthitic albite in a hetero-orientation replacement pattern (nibble replacement pattern).

Necessary conditions for replacement mechanism

The necessary conditions for both the cation exchange and precipitation mechanisms are the following:

1) Participation of the replacive material, such as K for K-feldspathization, Na for albitization, Si for quartzification, Al for muscovitization, and so on. These materials occur as ions in solution in a gas-liquid state, probably mainly in gas.

Introduction of gaseous-liquid fluid from outside into the rock needs to pass through microfractures, grain boundaries and cleavage planes of minerals.

There would be no microfractures in rock unless stress occurred.

2) Presence of an opening for gas-liquid to enter and migrate

A grain boundary is always present in a rock. Microscopically, subtle openings are bound to be present either between two different minerals or between

two similar (in component and crystallography) minerals with different orientations. Fig. 34 displays a compact boundary (a parallel arrangement of crystallographic lattices) without a micro crevice between A and C (contact boundary between two co-oriented minerals or twin plane) because they have the same crystallographic orientation. There must be an opening along the boundary* between B and C (of the same, similar or different minerals) because they have different orientations.

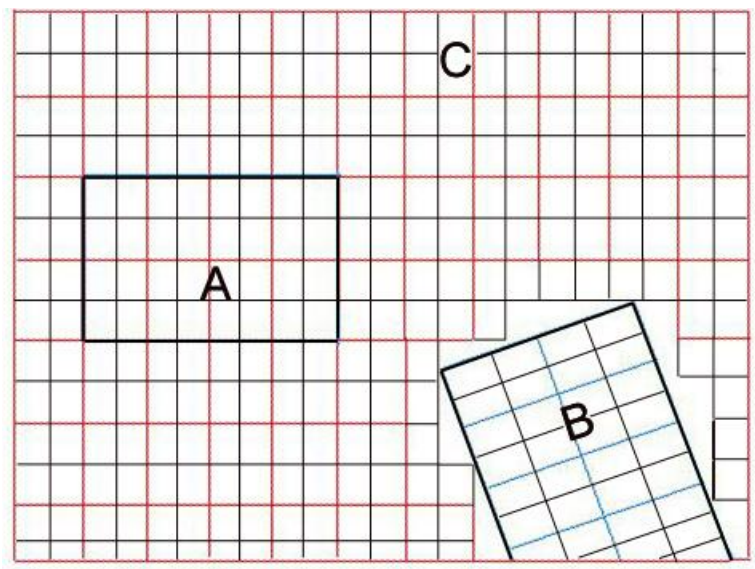

Fig. 34.-The grain boundary between A and C is tight and compact, where they have the same crystallographic lattice and orientation. A boundary crevice exists between B and C with different orientations even if their crystallographic lattices are the same.

It is hard to imagine that such a narrow width of a grain boundary (only at nanometer scale) can still be circulated by a hot gas-liquid fluid. So many researchers are deeply convinced that the rock must have been broken before a gas-liquid can enter and circulate causing a replacement.

Microscopic observation indicates that the real replacement phenomena have surely occurred in a rock without obvious traces of deformation. So the author believes that under the increasing pressure of gas-liquid and surrounding pressure the hot gas-liquid from outside could have entered and circulated along the grain boundary, although very narrow.

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*Width of grain boundaries in granitic mylonites has been studied by various researchers using transmission electron microscope (TEM) and high-resolution electron microscope (HREM). The width ranges from <100nm (Behrmann, 1985), 3~5nm (Farver and Yund, 1995) to 0.5nm (Hiraga et al., 1999).

3) Presence of mineral prone to be replaced on one side of the opening

With the three above mentioned conditions, the mineral replacement by cation exchange mechanism can proceed; for example, muscovitization and/or chloritization of biotite.

The crystallographic structure of muscovite is close to that of biotite. When the cations (Fe^{2+}, Mg^{2+}) are exchanged by cation Al^{3+}, the biotite is transformed to muscovite.

Although chlorite has a different crystallographic structure from that in biotite they are similar. According to a scanning electron microscope study, chloritization of biotite occurs mainly through the exchange of two potassium interlayer sheets and two tetrahedral sheets ($(Si,Al)O_4$) in biotite by the brucite-like interlayer ($Mg_3(OH)_6$). The crystallographic lattice of biotite has not been destroyed (Veblen and Ferry, 1983; Toshihiro Kogure and Banfield, 2000).

The replacive guest mineral formed by cation exchange mechanism naturally maintains the orientation of the host mineral.

However, only with the above mentioned three conditions the hetero-oriented (nibble) replacement by dissolution-precipitation mechanism still would not occur.

With different orientation from that of the replaced mineral, the replacive mineral should have its own crystallographic orientation. Without nucleation substrate, the replacive mineral would hardly grow.

Therefore for the dissolution-precipitation mechanism the following fourth

condition is indispensable.

4) Presence of the crystal nucleus on the other side on which the replacive mineral can epitaxially grow

The common crystal nuclei are the same or similar kind of replacive minerals.

When they are absent in the rock, an impurity (lattice defect, interstitial foreign element, etc.) may act as a nucleation substrate if the metasomatic process should have occurred.

Compared with the cation exchange the dissolution-precipitation is the most common and extensive replacement mechanism, which fits the replacement of different and the same or similar kind of minerals, especially the hetero-orientation (nibble) mineral replacement. The co-orientation replacement should also probably occur by the dissolution-precipitation if it does not happen on account of cation exchange.

Description of nibble replacement of albitization

According to the rule of dissolution-precipitation (nibble replacement), albitization can be explained as follows:

When Na-rich gas-liquid enters into the boundary between K-feldspar and differently oriented plagioclase, the replacive albite should grow on the plagioclase, unilaterally nibbly replacing the K-feldspar and forming a so-called “clear rim” of albite, because plagioclase is more stable than K-feldspar in that case.

As Na-rich gas-liquid penetrates the boundary between two K-feldspars K_1 and K_2 (differently oriented), the replacive albite can grow either at K_1 or at K_2. The direction of replacement depends on either the stronger crystallization ability of nibbling albite or the less energy needed to dissolve the K-feldspar lattice. Although the latter is hard to judge, the width of the nibbly replacive albite can be measured. According to the author’s observations, the biggest width of replacive albite is along its a-axis, while the smallest is along the b-axis, which is similar to that in crystallizing magmatic melt.

The surface of the grain boundary into which a gas-liquid infiltrates can be

named as the metasomatic active front. Because the crystallography of the newly-formed replacive albite coincides with the crystallography of the K-feldspar on which the albite grows, the original crack disappears, and nibble replacement can no longer take place there. Because the crystallographic orientations of the replaced K-feldspar and the nibbling albite are invariably discordant, there is always an opening along the grain boundary between them. Therefore, the metasomatic active front would continuously advance towards the replaced K-feldspar during the process. The neighboring metasomatic active fronts can be merged into one row and extend farther. Thus, the so-called "swapped rims (or rows)" of albite are formed (Fig. 35).

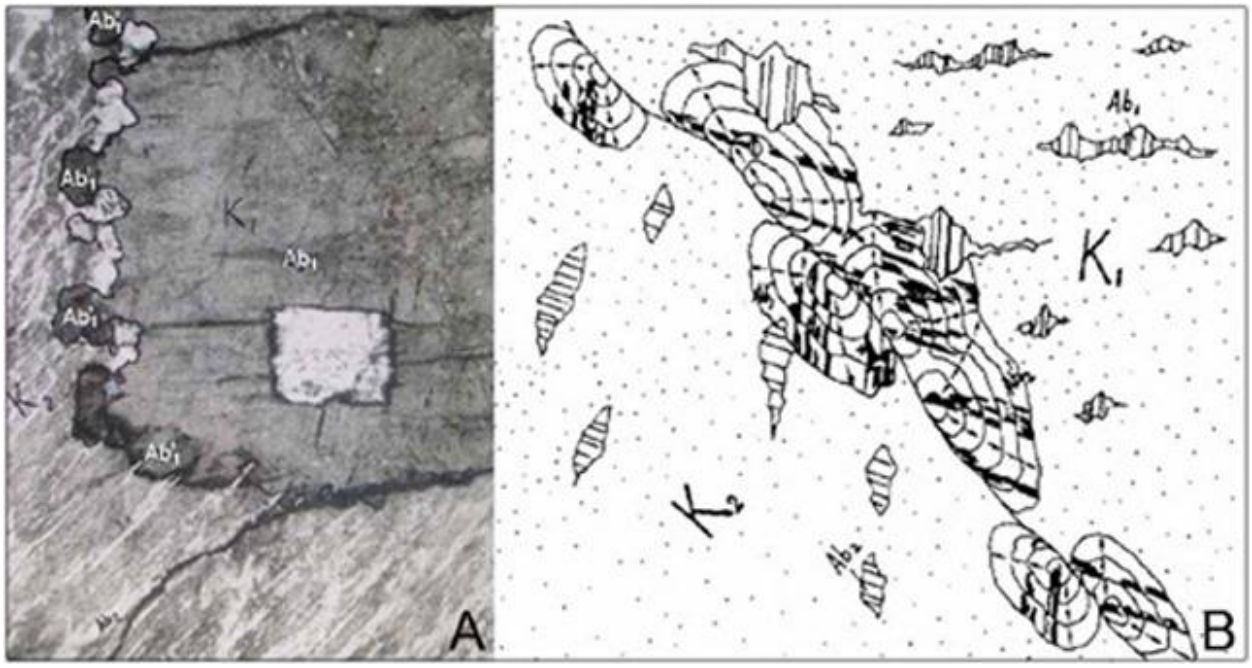

Fig. 35.-Growth of swapped rows of replacive albite. A---Preliminary growth of swapped rows of albite. B---Diagram of successive growth of swapped rows albite.

The fact that a clear albite rim may be present along the periphery of some small plagioclase inclusions in a K-feldspar megacryst shows inevitably that Na-

bearing gas or liquid fluid can surely penetrate K-feldspar along its cleavage. However, the lack of replacive albite along the cleavage is probably due to the orderly arrangement of the crystal lattice of the K-feldspar and because much more energy is needed to dissolve the K-feldspar along both sides of the cleavage.

No nibble replacement growth of albite can occur at boundaries between K-feldspar and quartz, two plagioclases, plagioclase and quartz, biotite and quartz, etc., because replacive albite can neither grow on the lattice of quartz or biotite although K-feldspar can be replaced; nor on K-feldspar because quartz cannot be replaced.

In most places the substrates for nibble replacement are identical with or similar to minerals which are widely distributed in granitic rocks. Thus, there are sufficient minerals that may act as substrates for nibble replacement. It is unnecessary and unlikely that a replacive mineral will select an impurity as a substrate rather than the abundant preexisting identical or similar minerals. If there are no identical or similar minerals in rocks, or the identical or similar minerals are not present at an adjacent side, an impurity, such as a crystal-lattice defect, would act as a substrate; for example, the sericitization or muscovitization in plagioclase.

Whether the co-orientation replacement albitization of plagioclase and/or K-feldspar* is by cation exchange or dissolution-precipitation mechanism has not been determined.

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*Whether there is co-orientation K-feldspathization of plagioclase (or albite) should be proved later on.

Presence of micropores is probably one of the key factors to allow alteration of plagioclase.

In the last 30 years more detailed studies of feldspars (mainly plagioclase) in common igneous rocks have been made by using the electron microscope, scanning electron microscopy and high-resolution transmission electron microscope. These studies have been made either on fractured surfaces (Dengler,

1976; Meideno Que and Alistair R. Allen, 1996) or on polished and ion-milled surfaces (Montgomery and Brace, 1975) and have shown the presence, in addition to micro cracks, of numerous now-empty micropores (within altered plagioclase) (Fig. 36). These micropores range from several tens to < 1 μm (Worden et al., 1990). Small crystals of sericite have grown in the micropores, and the plagioclase surrounding the pores is transformed to albite. The clear part of the plagioclase (mainly in the rim, but also in the inner part Fig. 28), being free of either micropores or sericite crystals, retains its original composition. Perhaps, the presence of micropores is one of the key factors to allow the alteration of plagioclase.

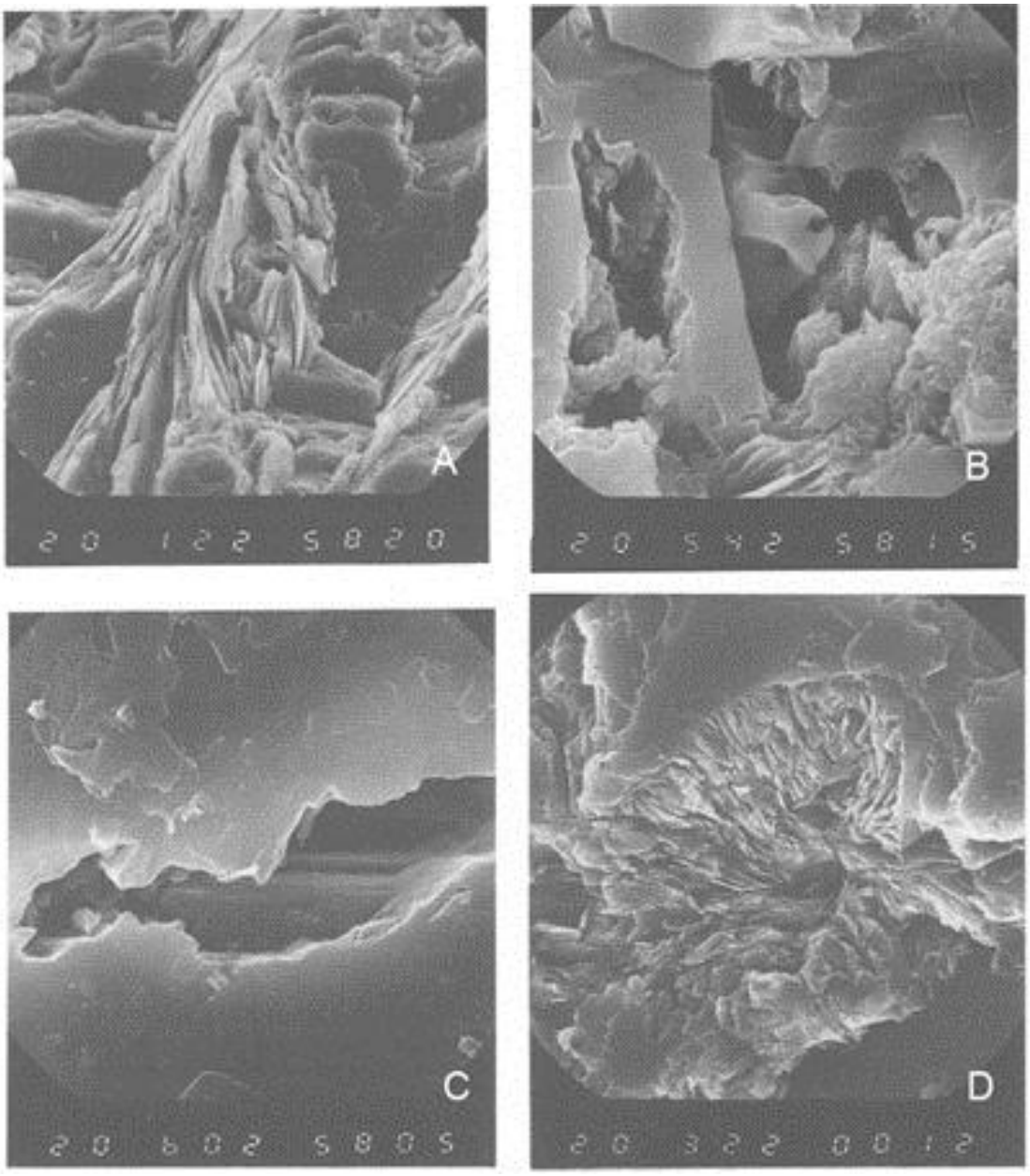


Fig. 36.-Scanning electron micrograph (secondary electron image) of unpolished plagioclase fragment (taken from Meideno Que and Alistair R. Allen, 1996). A.-Sericite, altered plagioclase and micro pores in plagioclase, x 1000. B.-Micro pores in plagioclase, x 4500. C.-Elongated clot-like micro pores in plagioclase. Smaller pores at depth within the main pore also occur, x 5000. D.-Sericite flakes in a micro pore of plagioclase.

There are also numerous micropores in alkali feldspar, basically along the boundary of microperthitic lamellae, and much less or no micropores in the K-feldspar phase (Fig. 37). Perhaps, this may be one of the reasons why K-feldspar is nonsericitized. Only when the rock is deformed (micro fractured) and subjected to intense action of sodium-bearing fluid may the K-feldspar be thoroughly transformed to co-oriented albite.

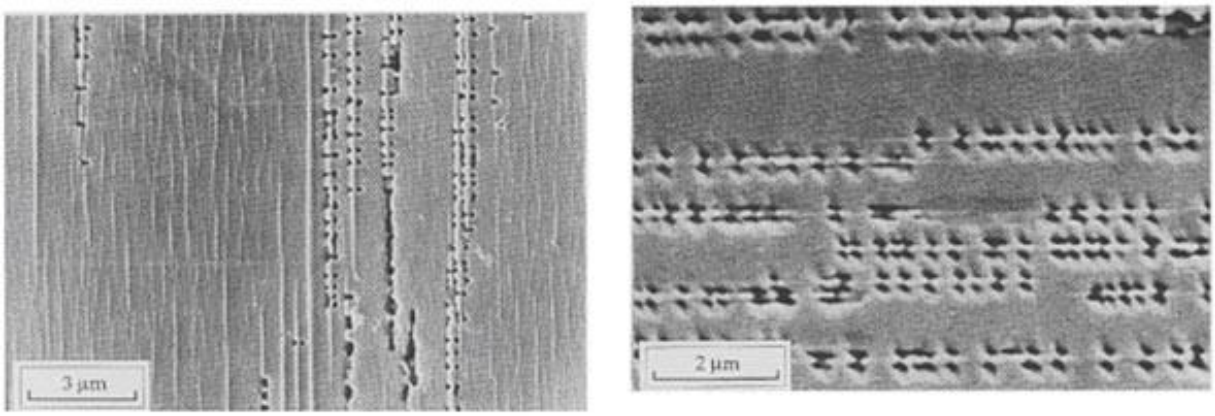


Fig. 37.-SE image of a HF-etched K-feldspar fragment. Left image is of (001) cleavage fragment. Lamellae greater than ~100 nm in width are decorated by pairs of etch pits. Narrower lamellae have few or no etch pits. The platelet-rich area (left) and some of lamellae are completely free of etch pits. Right image is of (010) cleavage fragment. Pairs of nm-sized etch pits with a distinctive two-fold symmetry straddle the albite lamellae. (SE image and description is taken from Lee et al., 1995).

There are two major hypotheses for the origin of micropores in feldspar:

a) primary origin (Roedder and Coombs, 1967; Lofgren, 1974; Montgomery and Brace, 1975, and b) secondary origin (Smith and Brown, 1968; Parsons, 1978). Que (1996) suggests that most micropores occur during crystallization of the plagioclase, but may subsequently have been enlarged by later fluid action. The researchers supporting the primary origin of micropores suggest that the sericitization and albitization of plagioclase is formed soon after the melt crystallized and earlier than the clear rim, intergranular albite and myrmekite,

while the researchers preferring the secondary origin of micropores suggest that the sericitization and albitization of plagioclase must occur later. The writer supports the latter opinion. However, although the sericitization and albitization of plagioclase are distributed widely, such alterations do not necessarily occur everywhere as do the clear rim and intergranular albite. This observation logically indicates that the partial sericitization and albitization of plagioclase is formed later than the pervasive clear rim and intergranular albite. Therefore, the author deduces that the sodic gaseous-liquid at first penetrates along grain boundary and cleavage, resulting in the nibble replacement of clear rim and /or intergranular albite, and then passes through the microfractures and micropores into the inner part of the plagioclase, giving rise to sericitization and albitization of plagioclase.

The chessboard albitization of K-feldspar, not easily seen even in alkali metasomatites (in South China), appears seemingly only in the alkali metasomatites that were affected by extreme intense metasomatism. Once the chessboard albitization appears, nearly all the K-feldspars are transformed into chessboard albites within the whole alkali metasomatic body (several to more than ten meters wide and several tens to hundreds of meters long). The sudden and abrupt change from complete K-feldspar to thorough albitization can be discovered only with careful examination of several thin sections in a local place, and cannot be found by field observation because both rocks look the same in the field. Dissolution-precipitation and cation exchange are the two different replacement mechanisms. Generally speaking, a sharp boundary is produced by the dissolution-replacement mechanism, while a blurred boundary is probably generated by the cation exchange replacement mechanism.

The hetero-orientation replacement pattern occurs conforming to the dissolution-precipitation mechanism. As for the co-orientation replacement pattern, some sheet silicate minerals utilize the cation exchange mechanism, but framework silicates may probably be modified by the dissolution-precipitation mechanism. The boundary between sericitized and unsericitized plagioclase in the same plagioclase is not very clear under the microscope, but, in fact, has a sharp demarcation (no more than tens of nanometers between them) observed with

microprobe, SEM and TEM (Engvik, et al., 2008). The interface between the K-feldspar and the co-orientation chessboard albite in the same K-feldspar is also suddenly changed. Therefore, the co-orientation albitization of plagioclase and/or chessboard albitization of K-feldspathization are probably caused by dissolution-precipitation rather than by cation exchange.

Entering the rock, the hot gaseous-liquid fluid at first circulates along the grain boundary (and cleavage) causing hetero-orientation (nibble) replacement. Later the gas-liquid may enter the inner part of some mineral, giving rise to co-orientation replacement. So, the two replacement mechanisms, as well as the two replacement patterns happen sequentially. Possibly, the dissolution-precipitation mechanism (hetero-orientation pattern) occurs first, and the cation exchange mechanism and co-orientation pattern replacement happens later.

Discussion of origin of mineral textures in granite

Origin of cleavelandite albite

A Li-F granite in which Li, Be, Nb, and Ta mineralizations occur is the latest intrusion of a multicyclic batholith. The typical L-F granite is characterized by having a small rock body and vertical zonation. From the bottom up the composition of plagioclase is gradually changed from sodic plagioclase to albite, and the abundance of the plagioclase increases. The small platy albite is enriched in the epical and top facies as the volumes of K-feldspar and quartz decrease. Also, upwards the mica compositions changes from lithium-bearing biotite, protolithionite or two micas, to muscovite or lepidolite. The small platy albite (cleavelandite) crystals are distributed at random (Fig. 38) and in some places have interzonal arrangement (Fig. 39).

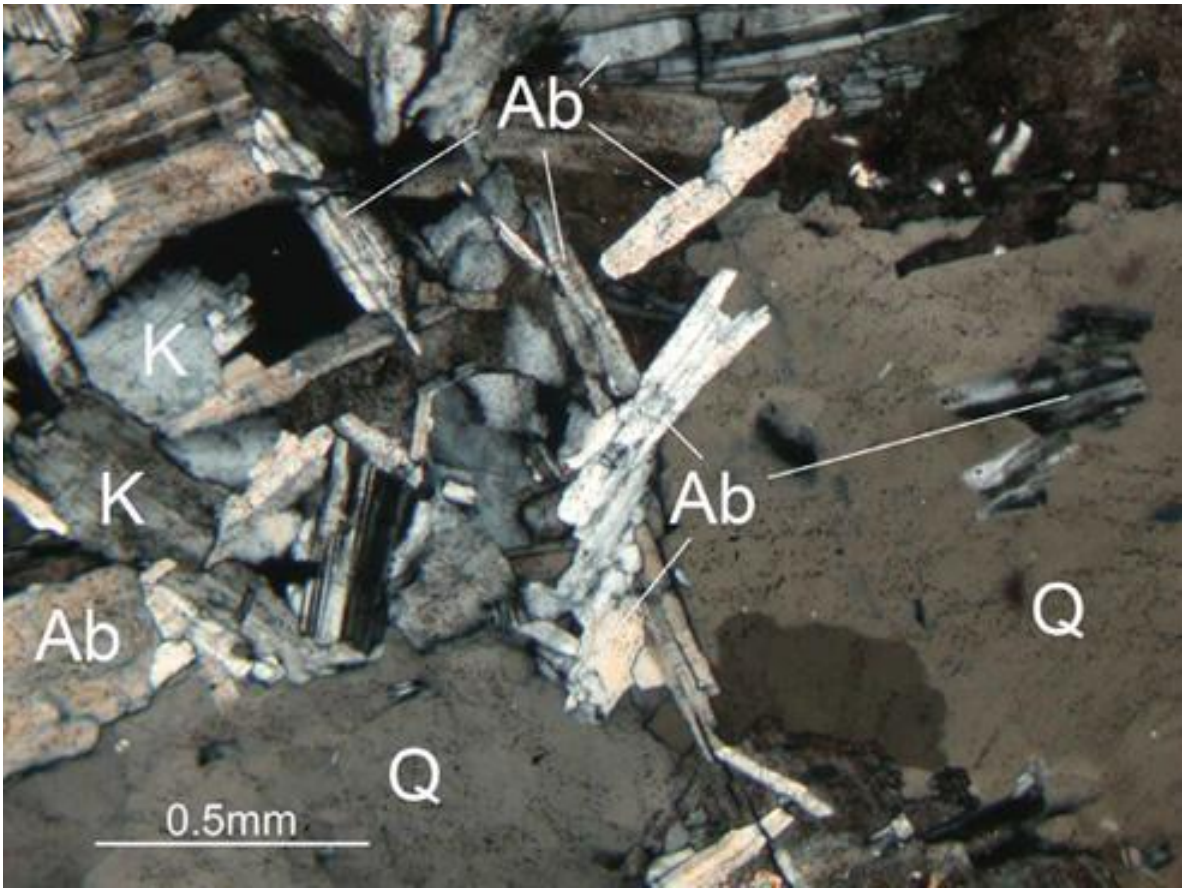


Fig. 38.-Random distribution of fine platy albite in quartz and K-feldspar. Crossed polars. Yashan Li-F granite, Jiangxi Province.

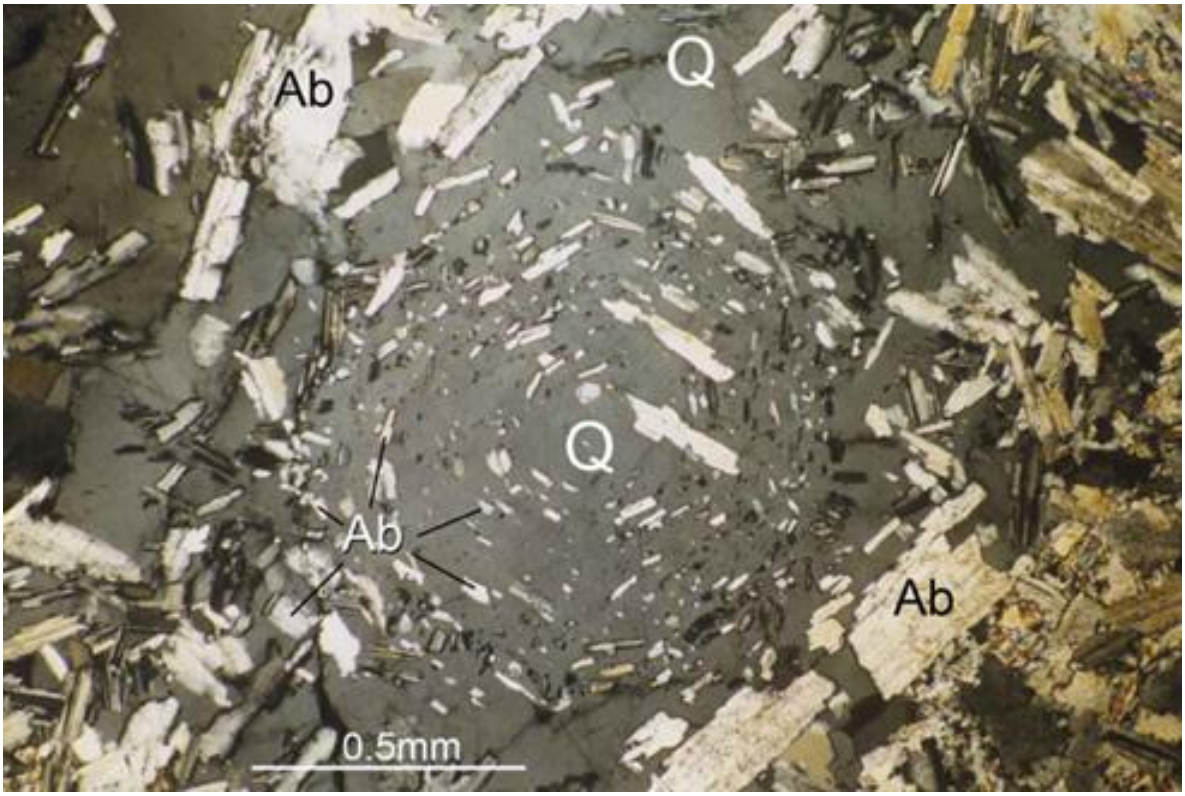


Fig. 39.-Concentric scatter of platy fine albite in inner part of quartz. Crossed polars. Yashan Li-F granite, Jiangxi Province.

Masgutov (1960) considered this kind of albite to be random albitization (or chaotically replacement), one of the three types of albitization he summarized (the other two are perthitization of K-feldspar and deanorthitization or saussuritization of plagioclase).

Beus (1962), however, suggested that the interzonal small platy albite laminae and the enclosing megacrysts of K-feldspar and quartz all were metasomatic in origin.

Many researchers consider that Li-F granite rich in cleavelandite (named apogranite) is formed by post-magmatic hydrothermal alteration from normal granite (Beus, 1962), resulting in the separation of rare metals from mica and feldspars and the formation of ore deposits (Masgutov, 1960; Beus, 1962; Aubert, 1964; Burnol, 1974; Hu Shouxi, 1975; Wang Defu, 1975; Hong Wenxing, 1975;

Stemprok, 1979; Imeopkaria, 1980; Yuan Zhongxin et.al., 1987; Wang Zhonggang et. al., 1989; Xia Hongyuan, 1991). Other researchers, however, insist on the magmatic origin of the Li-F granites as well as the primary genesis of rare metal mineralization (Wang Liankui et.al., 1970; Kovalenko, 1971; Liu Yimao, 1975; Eadington, 1978; Rong Jiashu, 1982; Du Shaohua, 1984; Raimbault, 1984; Zhang Jintong, 1985; Cuney, 1985; Xia Weihua, 1989; Zhu Jinchu, 1992; Taylor, 1992).

According to the rule of nibble replacement, if the nibble replacement pattern is accepted as a believable and ubiquitous metasomatic rule, the origin of the small platy albite lamellae can be judged as primary rather than metasomatic. The nibbly replacive albite should occur regularly at the grain boundaries of plagioclase with K-feldspar or between two K-feldspars rather than randomly or zonally in quartz or K-feldspar.

The discovery of ongonite, the study of fusion inclusions and an experimental petrological study have also shown that Li-F granite can directly be formed from a granitic melt rich in Li-F at the top of an intrusion during decreasing temperature.

Origin of myrmekite

Myrmekite, an intergrowth of plagioclase and quartz vermicules, often occurs in felsic-to-intermediate, calc-alkali plutonic and gneissic rocks. Myrmekite is found along the grain boundary between plagioclase and K-feldspar (Fig. 40). No myrmekite appears at the contact of plagioclase with quartz (Fig. 41).

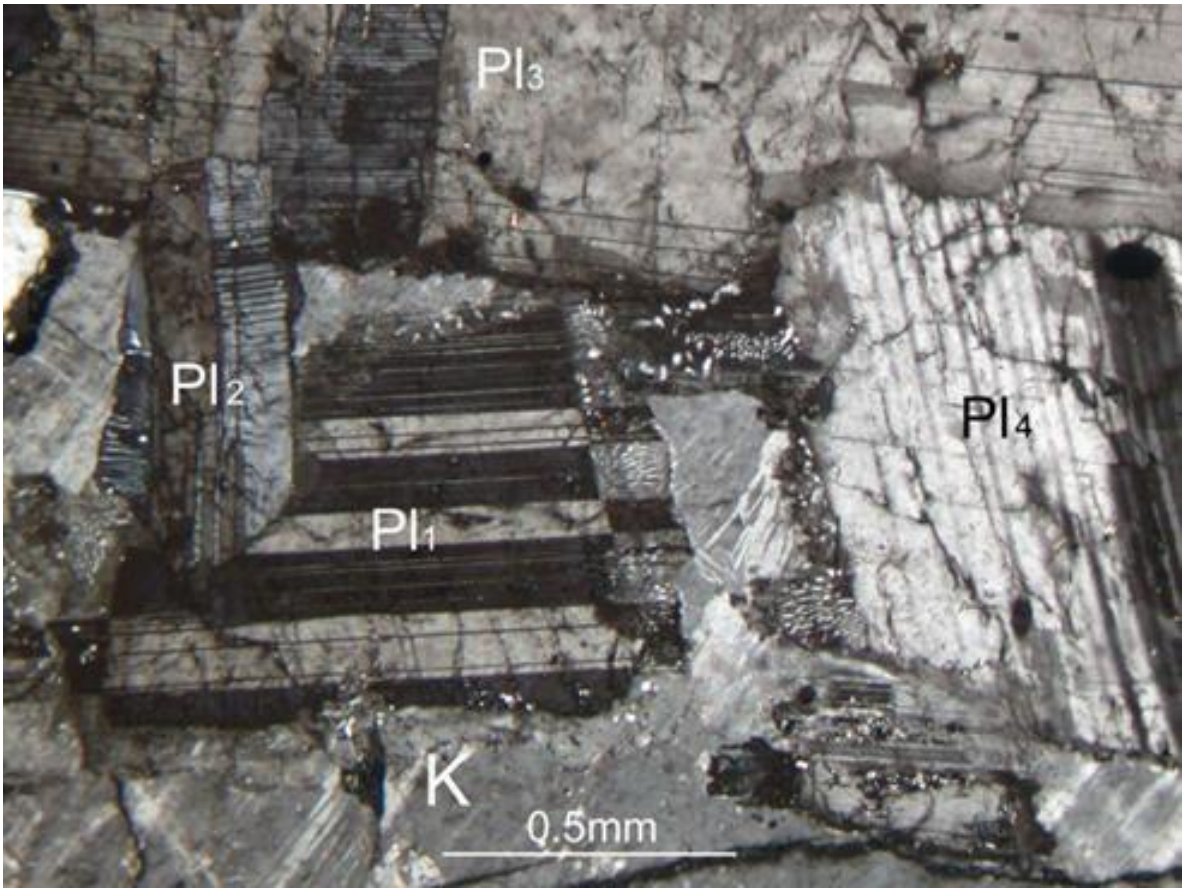


Fig. 40.-Myrmekite occurs at contact of plagioclases (Pl_1, Pl_2, Pl_3, Pl_4)(An_{28}) with differently oriented K-feldspar. No myrmekite is present on border between two plagioclases. The myrmekitic plagioclase is An_{14}. Crossed polars. Lantian granite, Shaanxi Province.

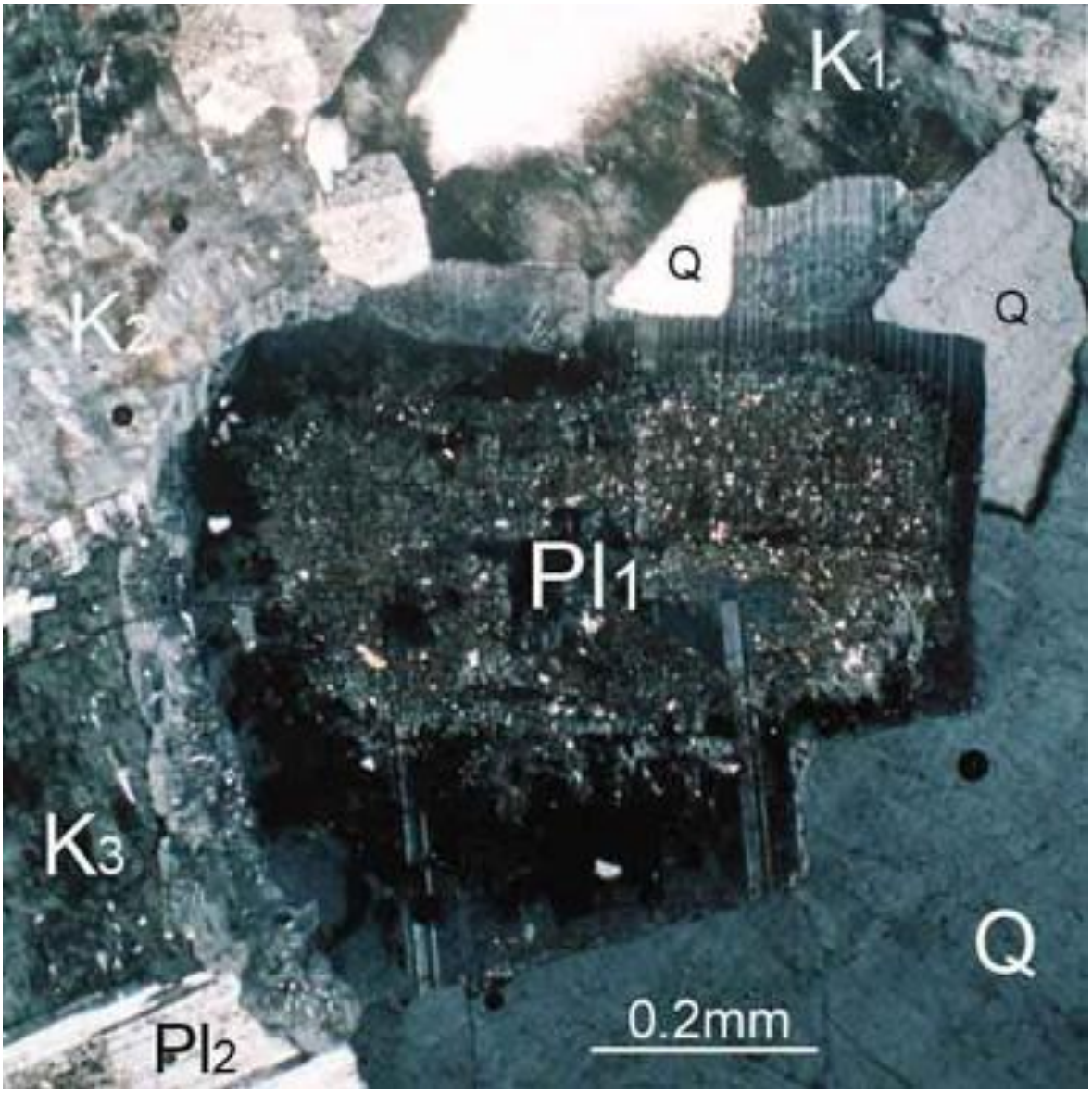


Fig. 41.-Myrmekite appears at boundary of plagioclase (Pl_1) with K-feldspar (K_1, K_2, K_3) lacking any quartz. Crossed polars. Lantian granite, Shaanxi Province.

The quartz in myrmekite is vermicular (tapered, curved, and/or sinuous) and rod like with round to oval sections and elongated toward the myrmekite border. The volume percent of quartz vermicules is directly proportional to the An content of myrmekitic plagioclase (Fig. 42).

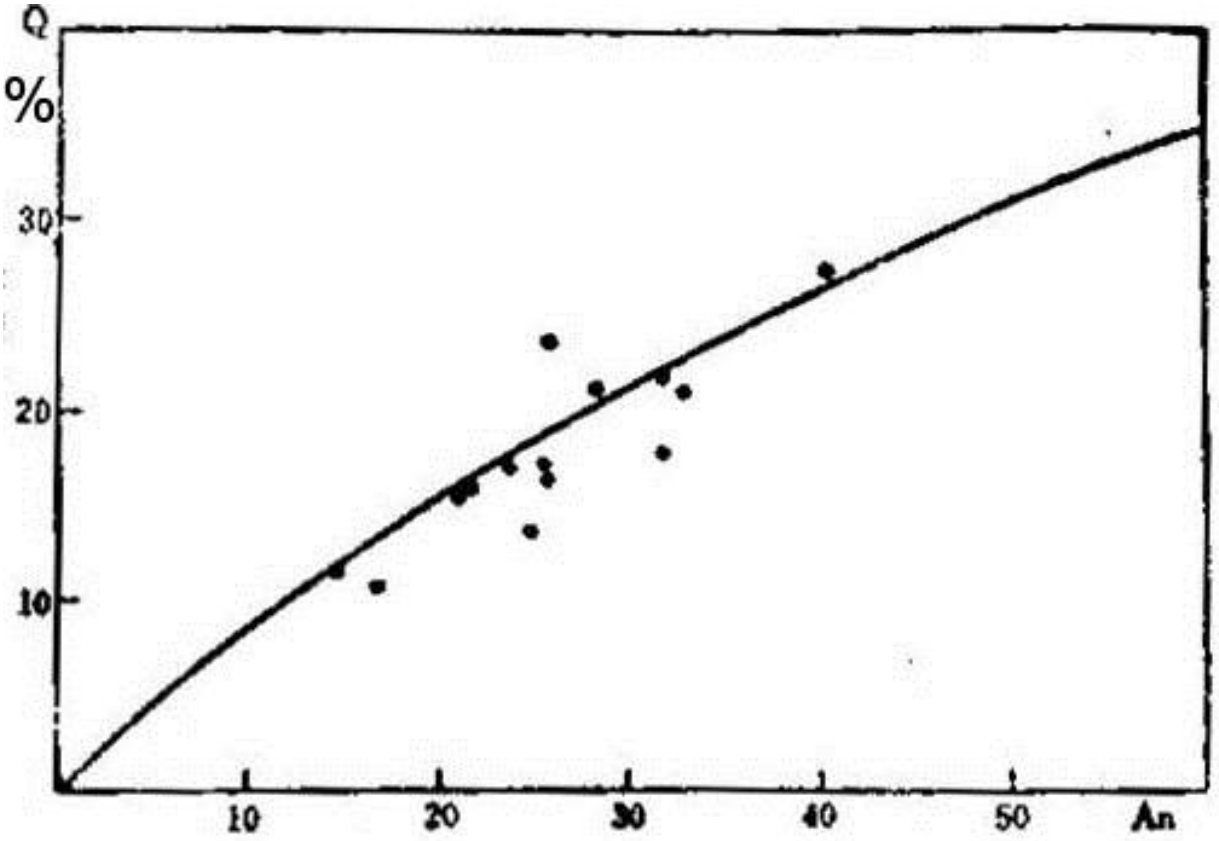


Fig. 42.-Theoretical curve of volume percent of vermicular quartz versus An content of myrmekitic plagioclase (Asworth, 1972). Points measured by Phillips (1968).

1) Hypotheses for explaining the origin of myrmekite

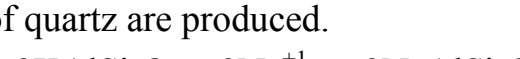
There are at least five major hypotheses for the origin of myrmekite.

a) Replacement of preexisting plagioclase by K-feldspar (Drescher-Kaden, 1948)

Drescher-Kaden considered that myrmekite is formed from replacement of plagioclase by a fluid bearing K and Si, and that some vermicular quartz was once contained in K-feldspar. Myrmekite is obviously older than K-feldspar. If replacement proceeds thoroughly, the plagioclase can be replaced by K-feldspar. It is just this theory granitizers hold that the K-feldspar is produced by K-feldspathization of plagioclase. The theory is also supported later by Collins (2002b).

b) Replacement of preexisting K-feldspar by sodic plagioclase (Becke, 1908)

Because the SiO_2 content needed for the formation of the anorthite end member is less than that contained in K-feldspar and albite, the surplus SiO_2 (after the replacement of K-feldspar by sodic plagioclase) then was precipitated as vermicular quartz. For each molecule of anorthite that is introduced, four molecules of quartz are produced.



$$2KAlSi_3O_8 + 2Na^{+1} \rightarrow 2NaAlSi_3O_8 + 2K^{+1}$$

$$2KAlSi_3O_8 + Ca^{+2} \rightarrow CaAl_2Si_2O_8 + 4SiO_2 + 2K^{+1}$$

c) Exsolution or unmixing of K-feldspar (Schwantke, 1909)

Both ($NaAlSi_3O_8$) and the so-called Schwantke molecule [$CaAl_2Si_6O_{16}$ or $Ca(AlSi_3O_8)_2$] are supposedly contained in a former high-temperature K-feldspar (Schwantke, 1909; Spencer, 1945). With decrease of temperature the exsolution of $NaAlSi_3O_8$ and $CaAl_2Si_6O_{16}$ occurs, resulting in the formation of myrmekite. Each Schwantke molecule recrystallized to form $CaAl_2Si_2O_8$ and $4SiO_2$ are released to form vermicular quartz in the myrmekite. The inner diffusion drives the exsolved material onto the plagioclase nearby.

d) Recrystallization of plagioclase (Collins, L., 1988)

Plagioclase is altered by hydrothermal solutions after cataclastic deformation and prior to introduction of K-bearing fluids. In local places in the altered plagioclase lattice, the loss of Ca and Al and the retention of Na are accompanied by an increase in excess silica, resulting in formation of quartz vermicules in myrmekite when these places recrystallized. The An content of plagioclase of myrmekite is about half the An content of the primary plagioclase (in some kinds of granitic rocks that are modified by K-metasomatism but not all).

e) Complex hypothesis (Ashworth, 1973; Phillips, 1974, 1980)

Myrmekite can be formed by both exsolution and replacement. The exsolution origin is suitable for an undeformed high level intrusion, forming rim myrmekite, grain boundary myrmekite and enclosed myrmekite. The replacement origin is appropriate for deformed metamorphic rocks, forming wartlike myrmekite (especially where the K-feldspar is quite small compared with adjacent large myrmekite).

2) Discussion of the origin of myrmekite

Myrmekite is characterized by the stable correlation of volume percent of myrmekitic quartz with An content of myrmekitic plagioclase (Fig. 42). The correlation is obviously not accidental. Hypotheses b), c), d) and e) are consistent with this correlation. Drescher-Kaden (1948) concluded that some vermicular quartz in K-feldspar may be relicts of replaced myrmekite, occurring as "***ghost*** myrmekite" (Fig. 43). This relationship might serve as tenable evidence indicating that K-feldspar replaces the plagioclase of former myrmekite, and, therefore, the whole K-feldspar must be metasomatic in origin. This phenomenon, however, can be explained by the so-called ***superimposed reversed K-metasomatism***, which takes place after the formation of myrmekite ceased. The newly formed K-feldspar (being of nibble replacement pattern, too) grows on the preexisting K-feldspar behind, taking its crystallographic orientation and nibbling at the myrmekite in front. In this way, the myrmekite is locally destroyed by the second reversed K-feldspathization. The quartz vermicules of myrmekite remain as relicts because they are only partly or even hardly ever replaced by K-feldspathization.

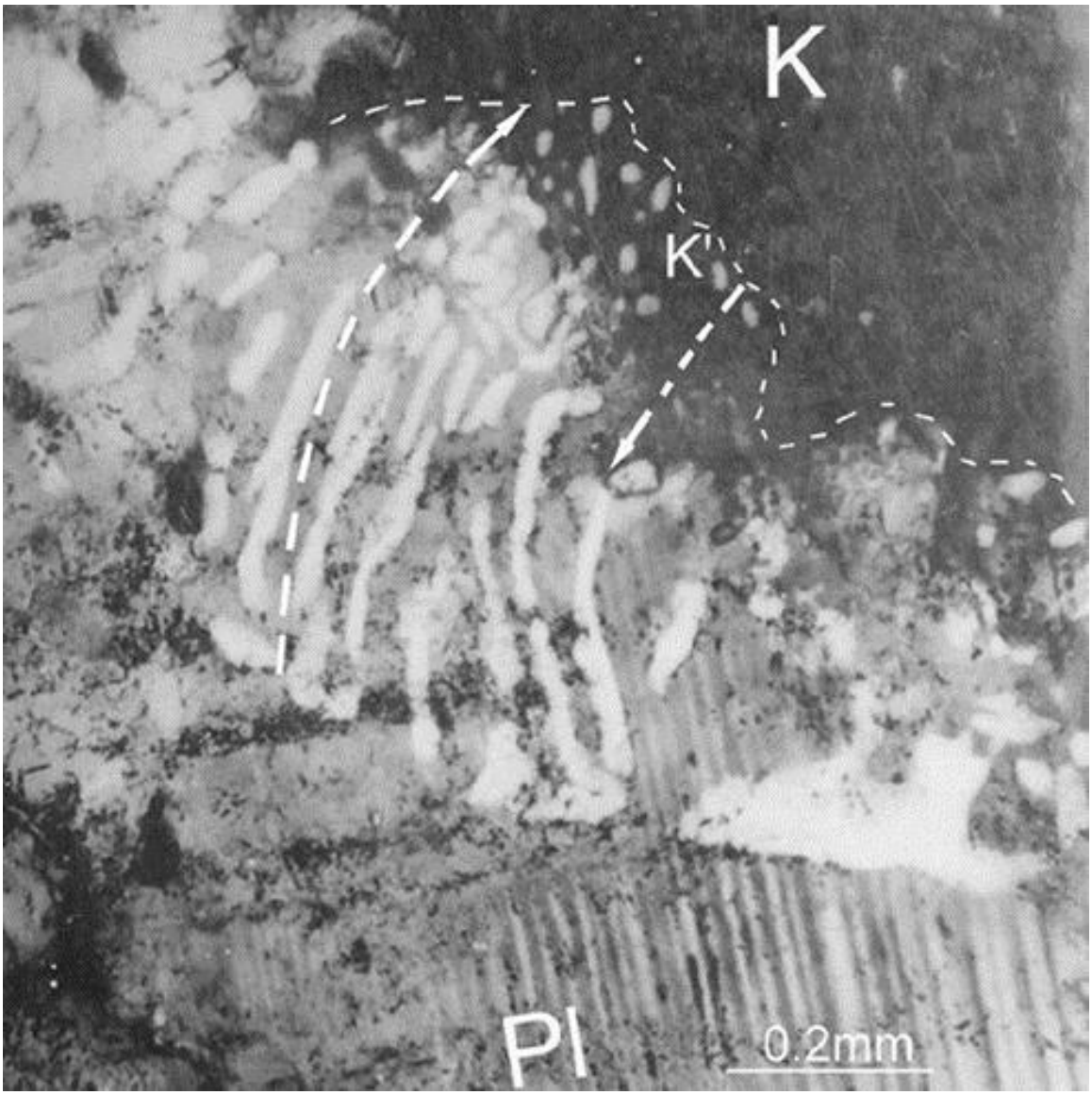


Fig. 43.-Ghost myrmekite is formed by superimposition of myrmekite by the follow-up (sequential) K-feldspar replacement. Myrmekite replaces K-feldspar at first, followed by K-feldspathization replacing the myrmekitic plagioclase as vermicules of quartz remain.

Many small-sized myrmekite grains are often developed around the border of a K-feldspar megacryst in granite-gneiss, but no obvious plagioclase occurs against which the myrmekite abuts. An outstanding example of a myrmekite corona occurs as a rim on a residual rounded K-feldspar porphyroclast (Fig. 44) in ultramylonite, Cima di Vila, Eastern Alps, Italy (Cesare, B. et. al., 2002). The fact

that the myrmekite corona has not been affected by mylonitization shows that myrmekite is formed after mylonitization. Apparently, as mylonitization proceeds, around the K-feldspar porphyroclast there must be cataclastic debris of various minerals including feldspars, which obviously may serve as nucleus for the growth of myrmekite. Therefore, myrmekite is not formed by the replacement of plagioclase by K-feldspar, but, on the contrary, of K-feldspar by plagioclase.

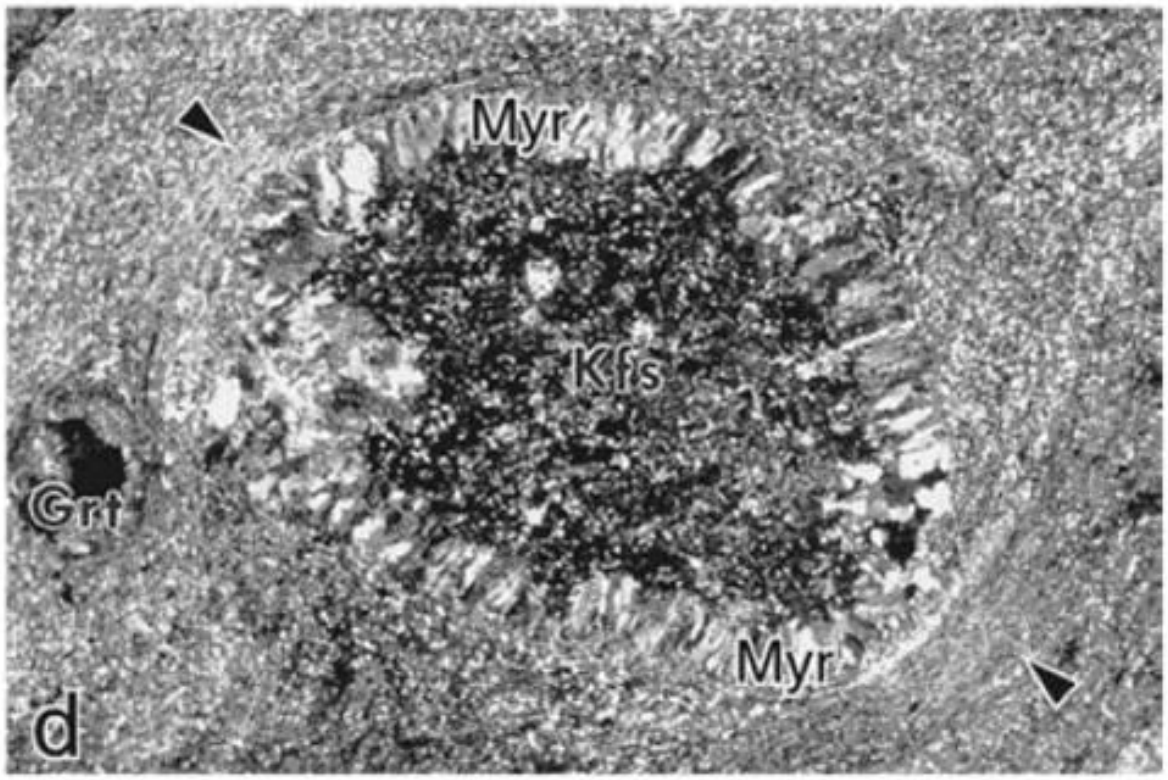


Fig. 44.-Residual rounded K-feldspar porphyroblast in ultramylonite, Cima di Vila, Eastern Alps, Italy. K-feldspar porphyroblast is rimmed by a continuous, about 1 mm thick corona of myrmekite (Myr). From Cesare et al., 2002.

The hypothesis d) (recrystallization of altered plagioclase) does not seem to apply to granitic rocks containing myrmekite in China that the author has studied for the following reasons:

(1) The shape of myrmekite does not look like primary plagioclase.

(2) The granitic rocks containing myrmekite are not necessarily affected by

deformation, alteration, and recrystallization.

(3) Myrmekite is not formed during saussuritization and sericitization.

(4) Myrmekite may occur regularly in swapped grains at the contacts between two K-feldspar crystals.

(5) An number of myrmekitic plagioclase is not necessarily equal to the half An-number of primary plagioclase, but is generally lower than that of primary plagioclase.

Exsolution is an attractive hypothesis because no penetration of fluid material is needed from outside. That is consistent with the idea of those researchers who do not believe (hence do not consider) that solid granitic rocks might have been circulated by Ca- and Na-bearing fluid from outside.

Moreover, the presence of the Schwantke molecule has not yet been proved. In addition, in some places the large size of myrmekite coexisting with a small K-feldspar crystal makes it impossible for the myrmekite to have formed by exsolution from the adjacent smaller volume of K-feldspar.

The origin of perthite is also commonly explained by exsolution. The crystallographic orientation of both guest perthitic albite and host K-feldspar coincides consistently with each other, while the orientation of myrmekitic plagioclase is regularly different from that of the host K-feldspar, but identical with that of the plagioclase against which the myrmekite abuts. Moreover, no myrmekite occurs along the borders of perthitic albite, as well as on the border between K-feldspar and plagioclase with the same orientation.

Swapped myrmekite (Figs. 45, 46), consisting of double rows, although rare, still occurs on the boundary between two K-feldspar crystals with different orientations. The fact that each row of myrmekite has the same orientation as that of the opposite K-feldspar strongly indicates that myrmekite is formed by nibble replacement; i.e., K-feldspar is replaced by Na-bearing gas-liquid, involving calcium.

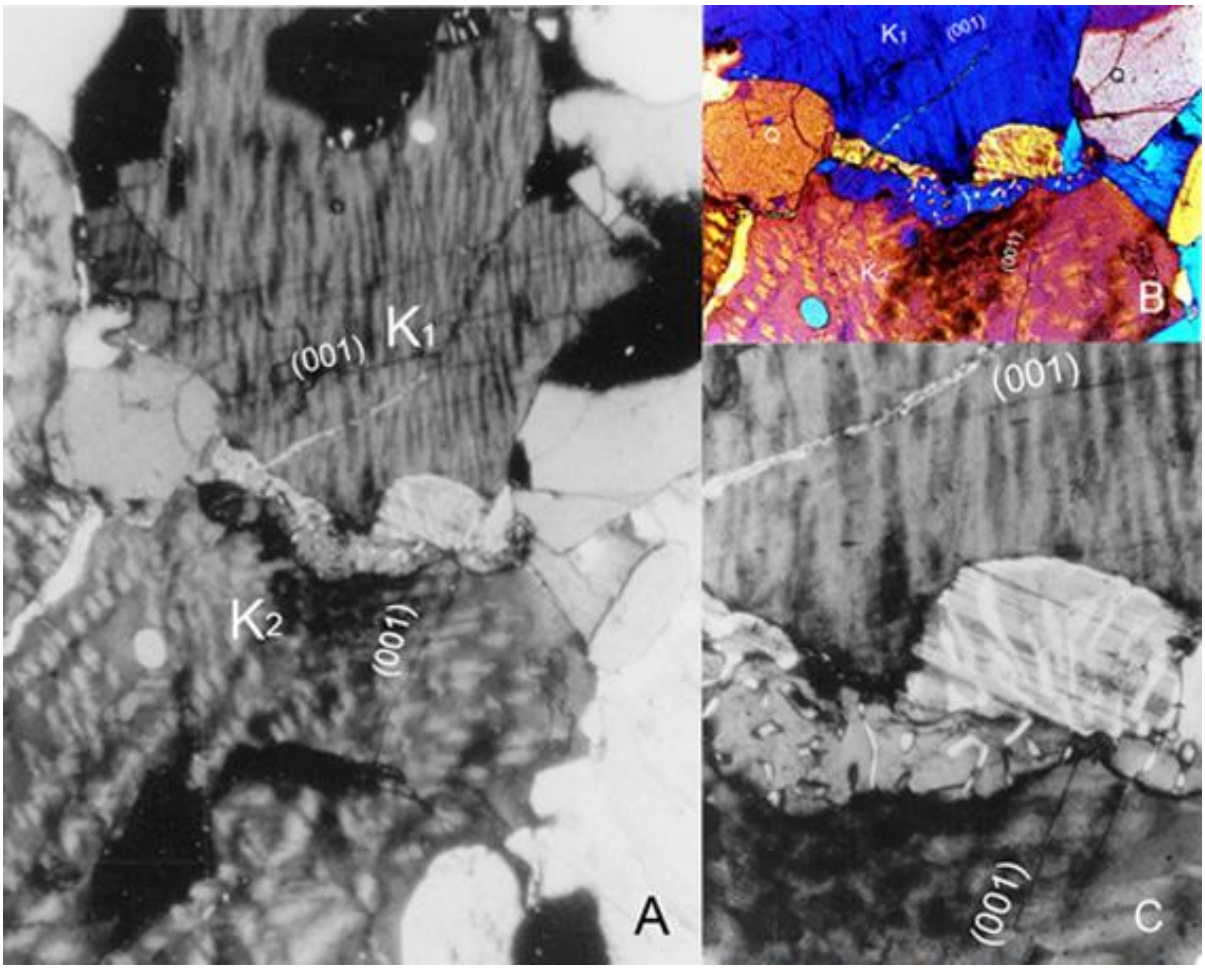


Fig. 45.-Swapped myrmekitic grains occur at contact between two K-feldspars. Each row of myrmekitic plagioclase has the same orientation as that of the opposite K-feldspar. The albite twin plane (010) of the upper myrmekitic plagioclase is nearly perpendicular to the cleavage (001) of the lower K-feldspar (K_2).

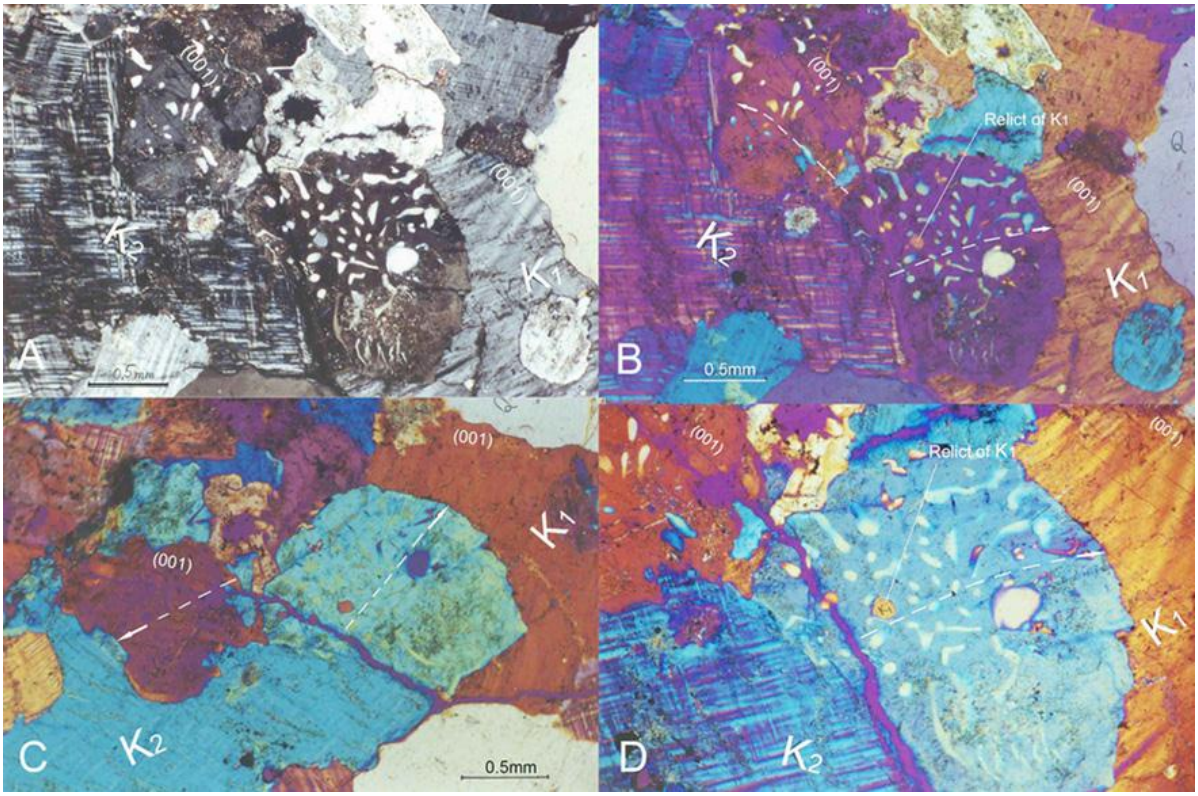


Fig. 46.-Swapped grains of myrmekite appear at contact between two K-feldspars. Notice the cleavage (001) and interference color of the myrmekitic plagioclase coincide with that of K-feldspar on the back side of the myrmekite. A relict island of K_1 is enclosed in the right myrmekite.

The more calcium that is involved in the sodic metasomatic process, the more volumetric percent of quartz would be included in myrmekite and the greater the An number of myrmekitic plagioclase.

The plagioclase against which a myrmekite grain abuts may not be necessarily cut by the thin section, if the width or size of that myrmekite is large enough (Fig. 47). Serial thin sections through the rock, however, would show this plagioclase in the third dimension.

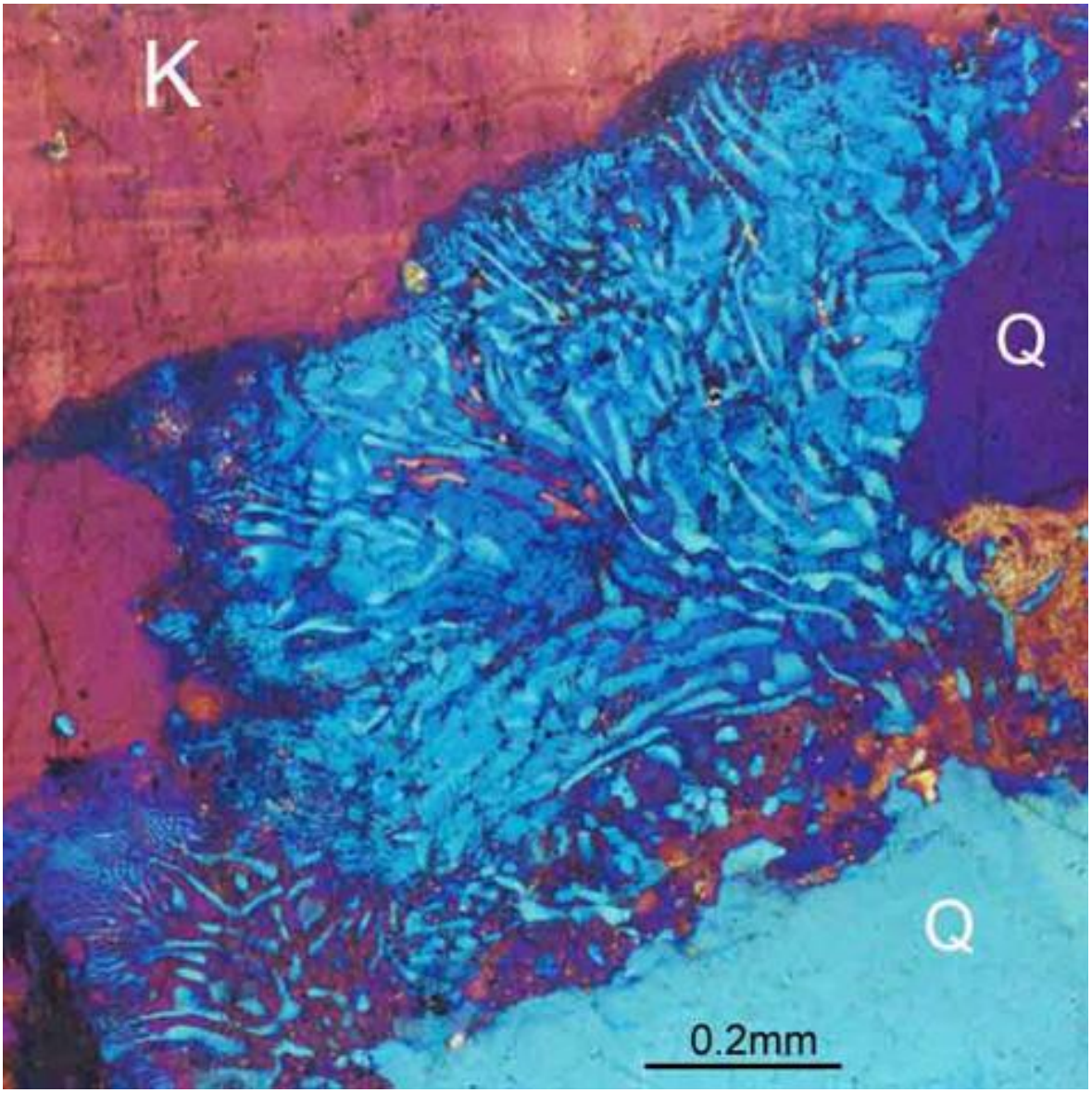


Fig. 47.-Myrmekite with thickness more than 0.8 mm. The plagioclase on which the myrmekite abuts is not cut by the thin section. Crossed polars plus quartz plate.

Compared with replacive albite, the myrmekite is more capable of replacing the perthitic albite. Therefore, relicts of perthitic albite are rarely seen in myrmekite.

Origin of perthite

K-feldspars in granites or pluton rocks often contain perthitic lamellae of albite.

1) Content and shape of perthitic albite

The content of albite lamellae in perthite varies with the composition of the rock type. Generally, the perthitic albite lamellae are fewer and scattered in plutonic rocks rich in Ca, Fe, Mg and poor in Si and alkali, while more and abundant in rocks rich in Si and alkali and poor in Ca, Fe, and Mg. The volumetric percent of perthitic lamellae ranges from trace amounts to 30-50 % and can even surpass the content of K-feldspar (Fig. 48).

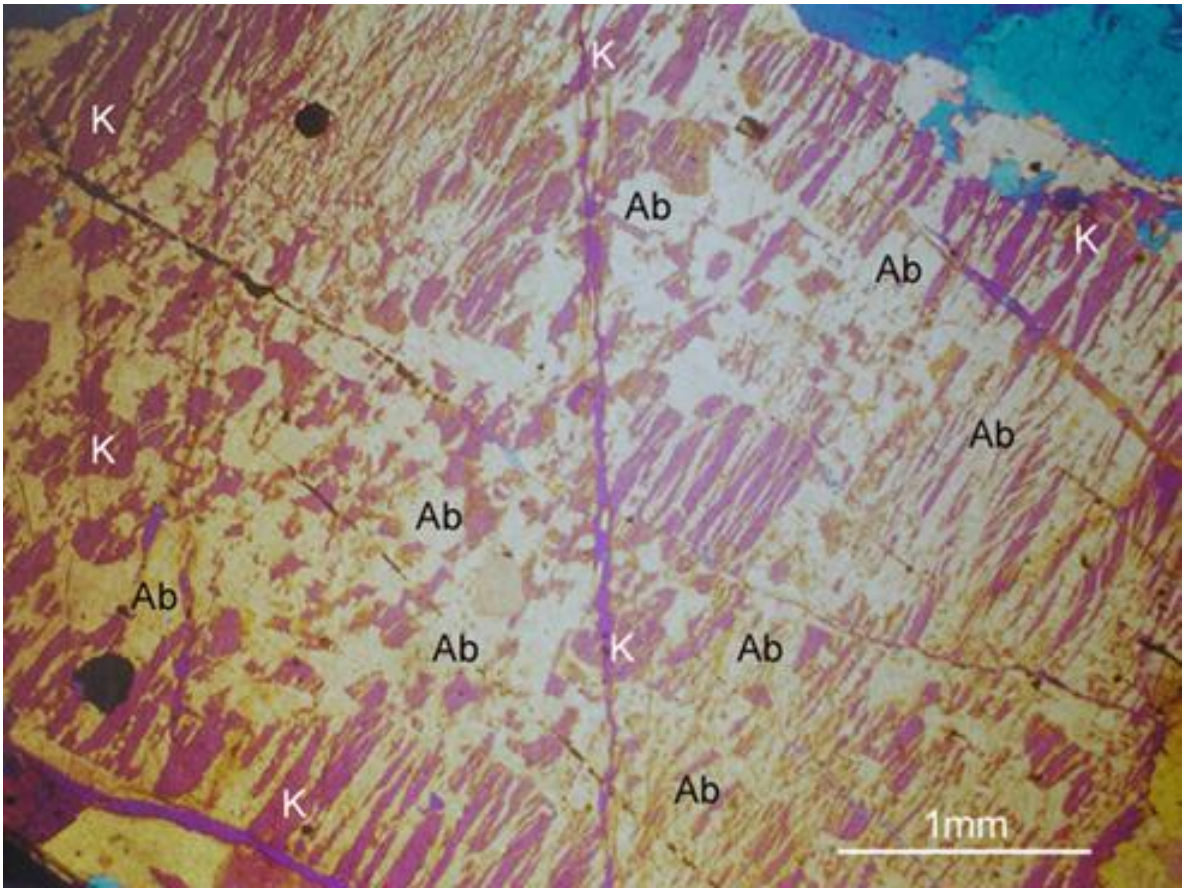


Fig. 48.-The volumetric amount of perthitic albite is almost equal to or even surpasses that of the host K-feldspar. Crossed polars plus quartz plate.

Alling (1938) depicted various types of perthite as stringlets, strings, rods, beads, films, bands, patch, plume, flame, vein, braid, etc.

2) Distribution of perthitic albite

The distribution and orientation of perthitic albite lamellae in K-feldspar are more or less homogeneous. The elongate plane of perthitic albite lamella is basically parallel to the b-axis and close to (100), near 64° to (001) or along the Murchison plane (-601), (-701), or (-1-502), near 65~73° to (001), which is clearly

seen in the (010) section. The (100) and the Murchison plane are close to the projective line of Nm of perthitic albite in the (010) section. In addition, the perthite lamellae are also oriented parallel to (110), (1-10) (forming a braided texture) and rarely parallel to (010)

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3) Hypotheses for origin of perthitic albite

There are several hypotheses for the origin of perthitic albite:

a) Exsolution from solid solution of K-Na feldspar

b) Replacement

c) Simultaneous crystallization.

Some authors consider that there might be perthite of various origins.

a) Exsolution from solid solution of K-Na feldspar

The exsolution hypothesis is the most popular so far, because it has theoretical and experimental support. Moreover, the distribution of perthitic albite in K-feldspar can be consistent within the same facies. The perthitic albite in a phenocryst of K-feldspar is more abundant than in smaller K-feldspar crystals in the ground mass. It is unnecessary to consider the effect of a gas-liquid from outside to explain how the perthitic albite may form inside the K-feldspar.

b) Replacement

A replacement hypothesis is also supported by many researchers, particularly when the perthitic albite lamellae are vein-like or branch-like. Such lamellae look like they penetrate the twin composition plane (010) (Fig. 49), or have irregular distribution, especially when the thin section intersects the perthitic lamella at a small angle (Fig. 50). The fact that polysynthetic twinning of perthitic albite coincides with the grid twinning of K-feldspar looks morphologically as if the perthitic albite is formed by replacement in the same way that the co-orientation replacement of albitization can surely occur.

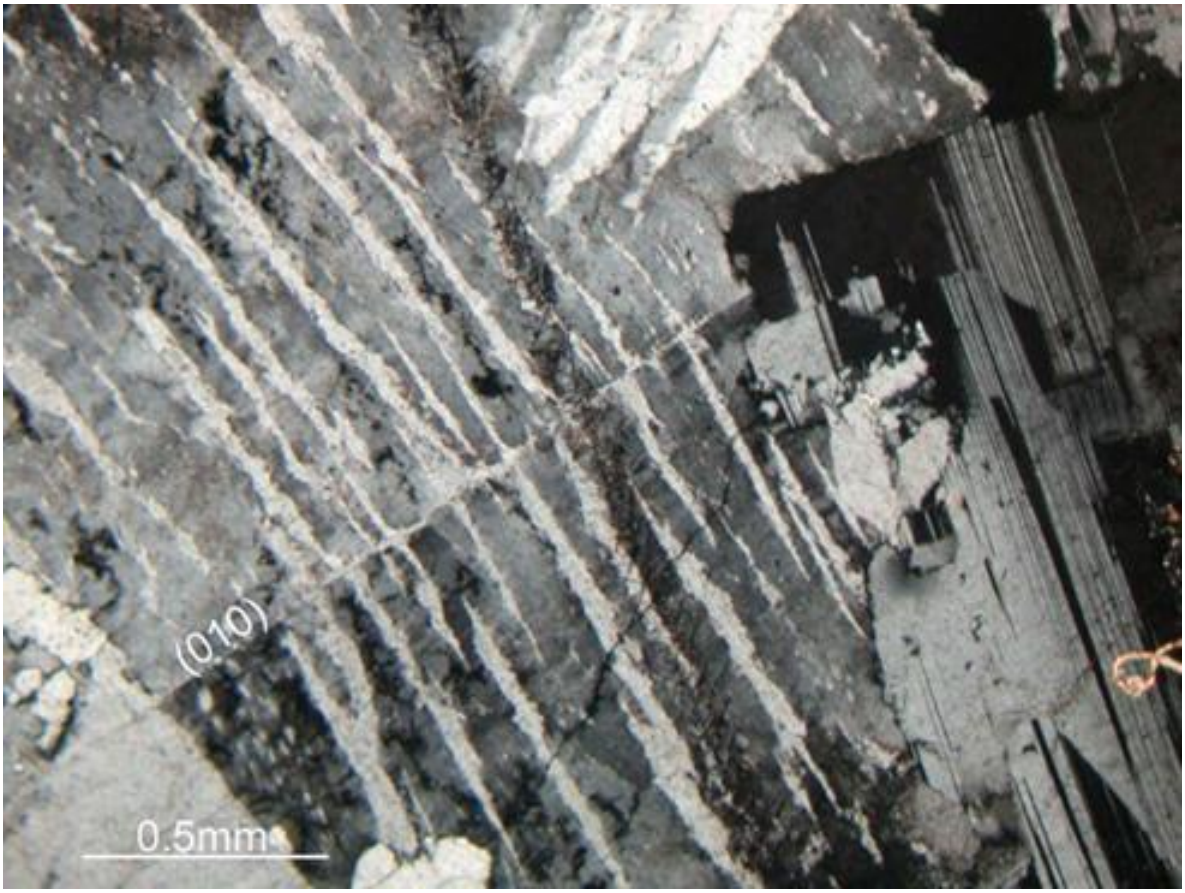

Fig. 49.-Vein-like perthitic albite lamellae seem to cut the twin composition plane (010). Crossed polars. Naqin granite, Taishan County, Guangdong Province.

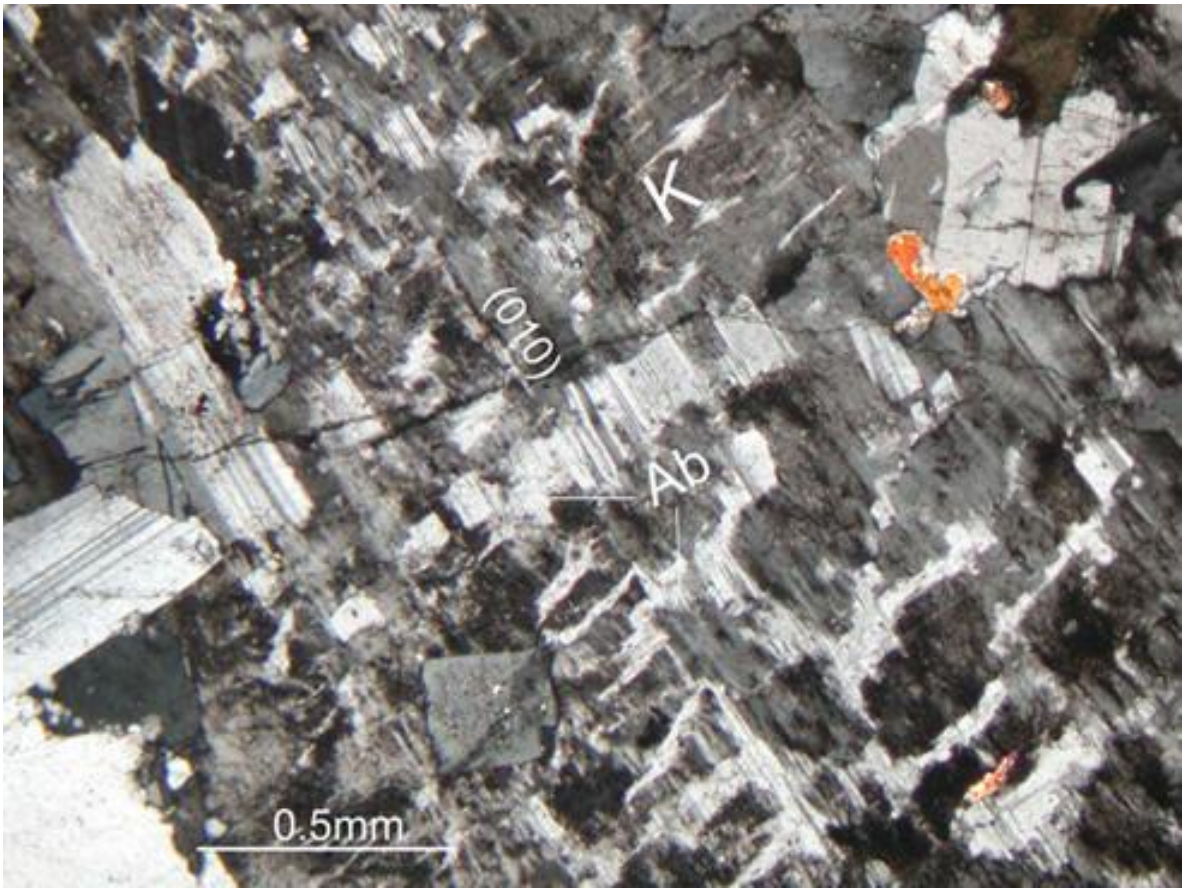

Fig. 50.-Irregular distribution of vein-like perthitic albite lamellae. The thin section intersects the perthitic lamellae at a small angle. Crossed polars. Naqin granite, Taishan County, Guangdong Province.

Nevertheless, the shapes and distribution of perthitic albite in K-feldspar in some granitic rocks are similar, identical or consistent, which is quite different from that produced by co-orientation albitization of K-feldspar. The albite formed by co-orientation albitization appears abruptly and abnormally, i.e., locally in many places in blocky or stacked arrangements or thoroughly transformed to chess-board albite that is absent in normal perthitic K-feldspar.

In some places vein or string perthitic albite penetrates the K-feldspar and even transects the Carlsbad twin plane (010) and optical orientations of albite lamella on both sides of the Carlsbad twin are alike in the same way. Actually, both

the albite twin and the Carlsbad twin have a common composition plane (010), while their twin axes are different, i.e., c for the Carlsbad twin and b for the albite twin. Because the Nm of the indicatrix of albite is close to the axis plane of bc, it is hard to distinguish between the different optical orientations of the perthitic albite in the two sides of the Carlsbad twin.

In (010) section of the Manebach twin (Fig. 51), the intersection angle of the perthitic albite lamellae in both twin sides can be as much as 60~70° (or 110~120°) and their optical orientations are obviously different. On that basis, naturally the impression that vein-type perthitic lamellae are cutting through the twin composition plane (001) would not appear.

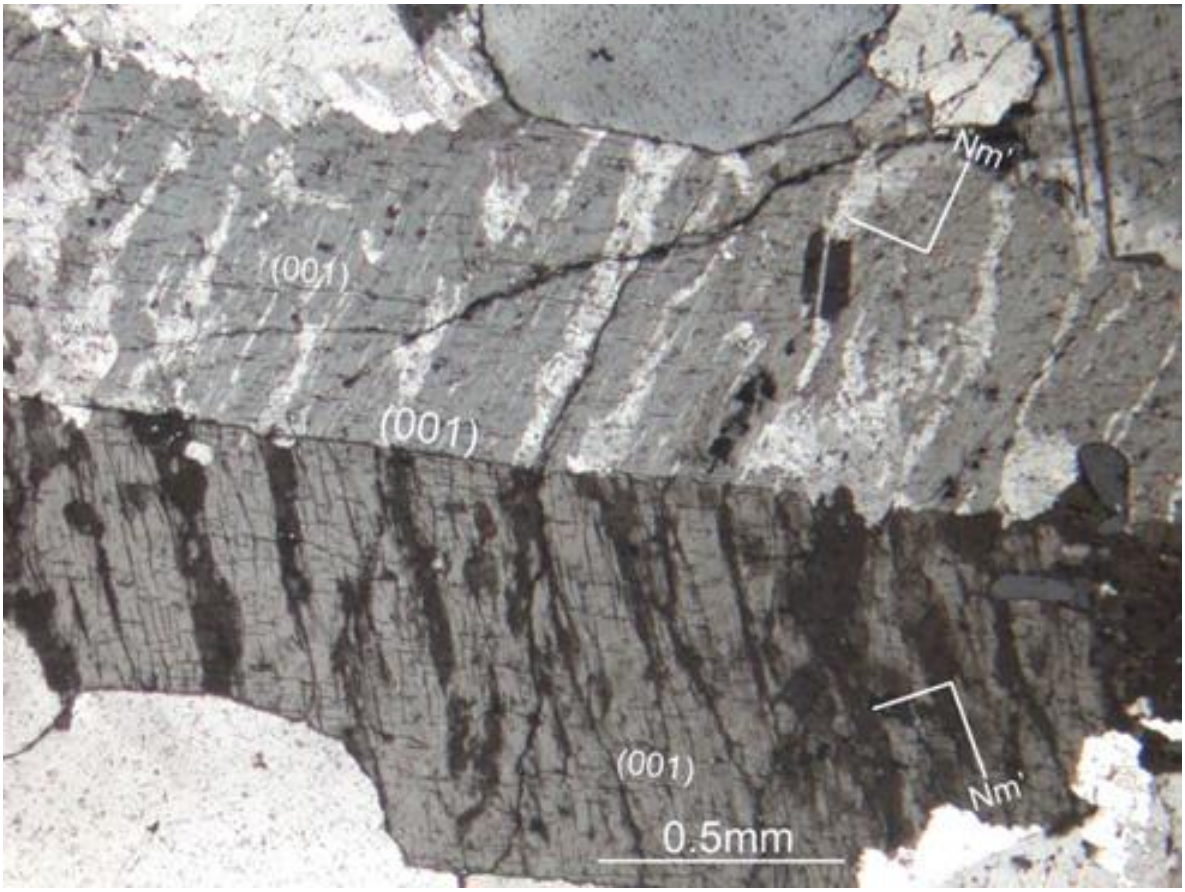

Fig. 51.-Distribution pattern of perthitic albite lamellae of Manebach twin of K-feldspar. The thin section is nearly perpendicular to b axis. The optical orientations of perthitic albite lamellae of the two sides are obviously different. Crossed polars. Naqin granite, Taishan County, Guangdong Province.

As mentioned above, when a clear rim or grain boundary albite is in contact with perthitic albite, some tiny relicts of perthitic albite can be enclosed in the clear rim or grain boundary albite, indicating that the relicts are formed by replacement and are earlier than the clear rim or grain-boundary albite.

The metasomatic model for the origin of perthitic lamellae is doubtful because the perthitic albite lamellae generally do not contain vermicular quartz although their An values may be as much as 5~14, obviously higher than that of the nibbly replacive albite (An_{3-5}) which contains fine vermicular quartz. Only if the

vermicular or water-drop-like quartz is contained in perthitic albite lamellae (such an example may be rare but exist somewhere), the perthitic albite might be formed by replacement processes.

c) Simultaneous crystallization

The simultaneous crystallization hypothesis suggests that perthitic albite lamellae are synchronously formed with host K-feldspar. Plagioclase-sanidine intergrowths that resemble perthite have been grown directly from ternary feldspar melts by Lofgren (1977). The intergrowths are of two general types: regularly-spaced, parallel lamellae up to 10 μm wide that resemble microperthite and irregular or patchy intergrowths that resemble patch perthite. The plagioclase lamellae in the intergrowths are $An_{25-15}Or_{5-20}$ and mainly elongated along (100).

4) Directional inclusions in feldspar

Below are some examples showing that the simultaneous crystallization hypothesis is possible.

a) Pencil-like albite crystals contained in K-feldspar

Several fine pencil-like albite crystals are enclosed in a K-feldspar phenocryst. The albite inclusions are generally scattered randomly (Fig. 52), but some (more than 12 grains) as well as small drop-like inclusions (vertical pencil-like albite) are distributed with the same orientation and nearly parallel to the orientation of perthitic albite lamellae (Murchison plane).

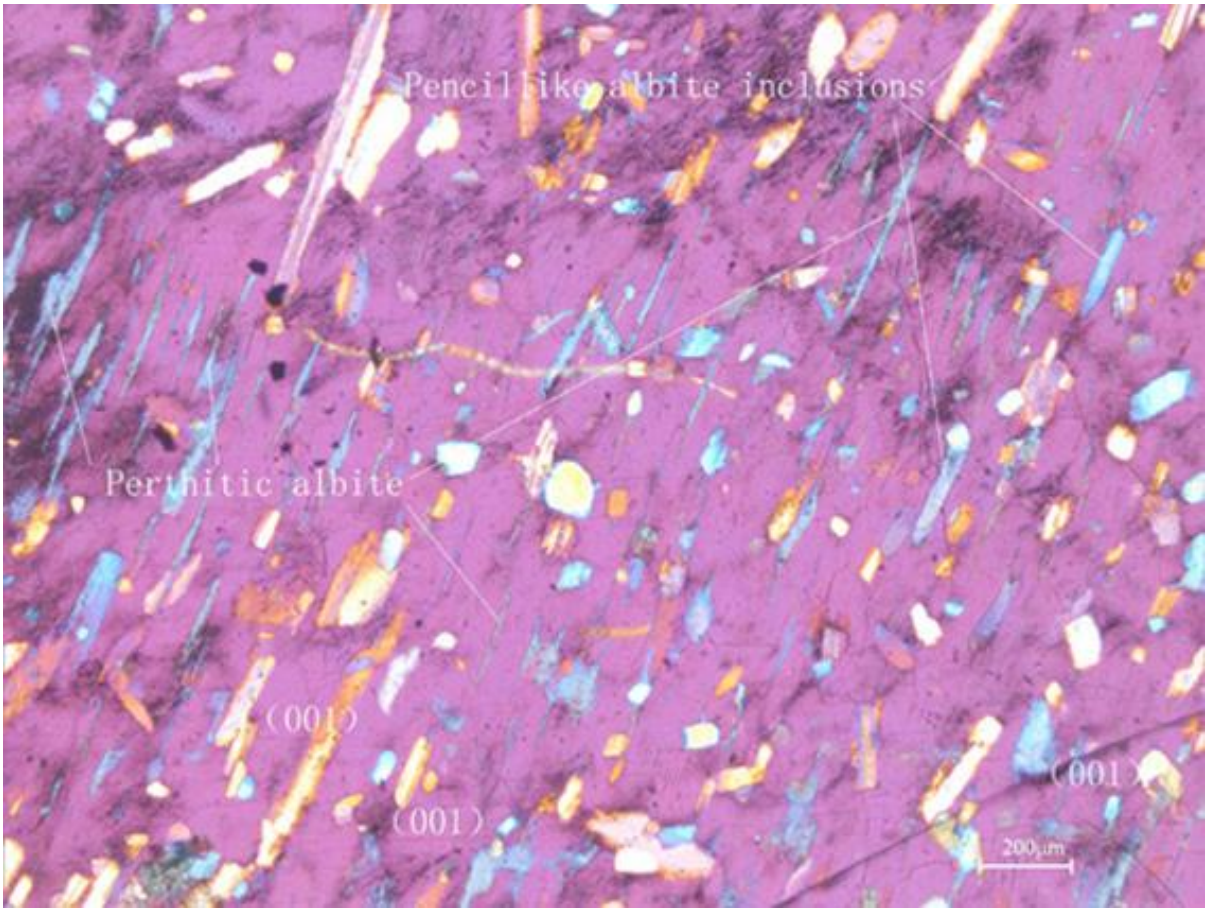

Fig. 52.-Many fine pencil-like albite inclusions are enclosed in a K-feldspar phenocryst. The fine pencil-like albite inclusions are distributed differently, but some of them as well as drop-like albite (vertically oriented) are arranged roughly parallel to the direction of perthitic albite lamellae (Murchison plane). Crossed polars plus quartz plate. Rotated horizontally in order to compare more easily with Fig.53. Chenkou granite, Zhuguangshan batholith, Guangdong Province.

Needle-shaped inclusions of apatite enclosed in albite are arranged along the Murchison plane.

Needle-shaped inclusions of apatite in vein albite were reported by Smith and Stenstrom (1965). The needles tended to align in the Murchison direction.

Note that many parallel acicular crystals of apatite are also found in primary albite in the Shanbei leucogranite, Taishan county, Guangdong province (Fig. 53B) (Rong Jiashu, 1982). Most are parallel to the (010) plane of albite, and are arranged

in the Murchison direction approximately parallel to the projection Nm' of Nm on the (010) plane, inclined by about 65° to the (001).

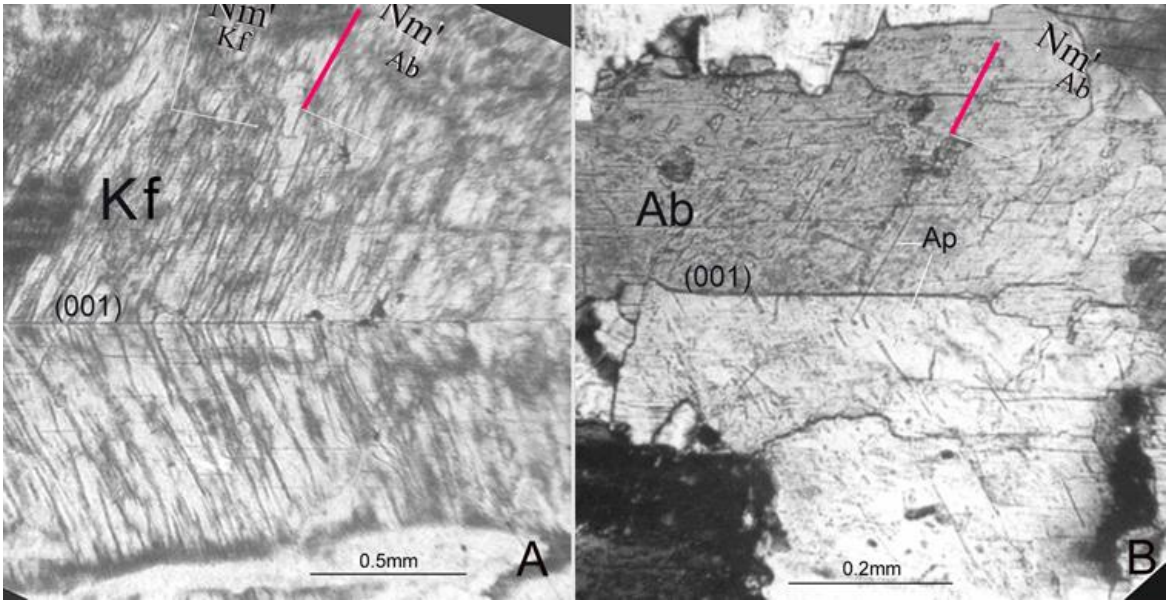

Fig. 53.-Comparison of distribution of perthitic albite lamellae in K-feldspar (A) with acicular apatite inclusions in albite (B). Both thin sections perpendicularly cut the b axis of the Manebach twin. The orientation of the acicular apatite is parallel to the projection Nm single prime of Nm on the (010) plane. Plane polarized light. Shanbei leucogranite, Taishan County, Guangdong Province.

5) Possible origin of perthitic albite

The orientations of pencil-like albite in K-feldspar as well as oriented needle-like apatite in plagioclase are comparable to oriented perthitic lamellae in K-feldspar. The pencil-like albite and oriented needle-like apatite, however, are obviously explained by neither exsolution nor metasomatism. The similarities of these orientations imply that the pencil-like albite and acicular apatite were normally enclosed in feldspar under the control of the strongest crystallizing force of the feldspar in a stable environment.

Therefore, the author deduces that the perthitic lamellae distributed semi-regularly along the Murchison plane might be formed in the following way:

A few albite crystals could have grown epitaxially and dispersively on a

crystallizing K-feldspar. During further crystallization it was generally easier for albite to grow on its own mineral than on K-feldspar, and K-feldspar, similarly, grew easier on its own mineral than on albite. Because the direction of the strongest crystallization force of feldspar is approximately identical to that of the arrangement of the needle-like apatite, perthitic lamellae developing roughly along (-1-502) might thus be formed.

Therefore, the perthitic lamellae distributed semi-regularly along the Murchison plane result probably from simultaneous crystallization, while extremely thin, straight and strictly parallel lamellae of perthitic albite perhaps are caused by exsolution (Fig. 54).

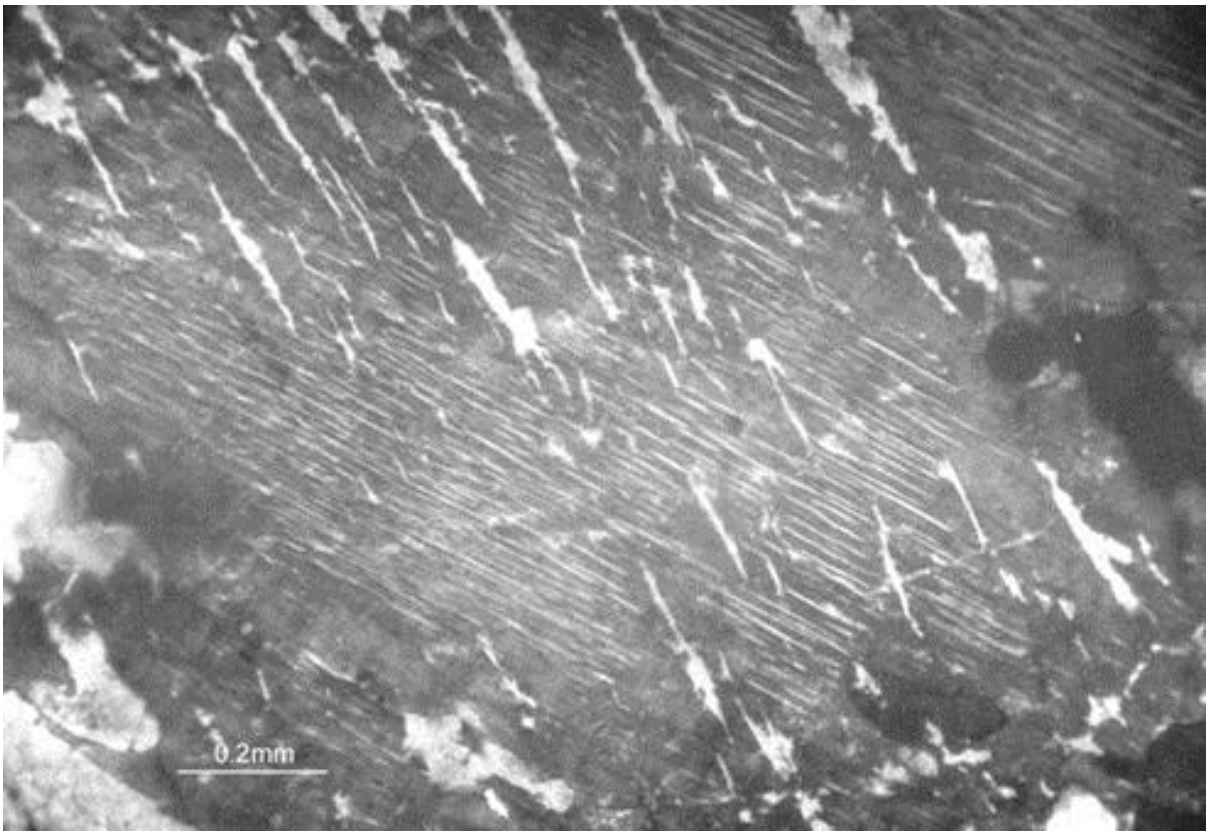

Fig. 54.-Thin and dense parallel albite lamellae are probably of exsolution origin. Crossed polars.

Phenocryst or porphyroblast

One of the key points regarding the genesis of granitic rocks is the origin of feldspars, in particular, K-feldspar. The controversy over granite actually is a controversy regarding the origin and formation of K-feldspar.

Correctly distinguishing the difference between a porphyroblast and a phenocryst is one of the key points with regard to the genesis of granitic rocks, whether they have a metamorphic or magmatic origin.

Autocathasis of porphyroblast

Autocathasis described by Harker (1950) in his classical book "**Metamorphism**" as follows: "Growing crystals endeavour to clear themselves by expelling foreign inclusions of any kind, but their power to do so depends upon their inherent force of crystallization…..a growing crystal has been able to brush aside foreign material, resulting in the grains of inclusions along certain directions in which the force was least effective".

These points of view are doubtful. The unreplaced relicts should be preserved ***in situ*** without changing their own primary crystallographic orientations, because the metasomatism process is carried out while a rock is in the solid state. However, the unreplaced residue might be deviated and/or slightly rotated, because plastic deformation could take place during metasomatism. Nevertheless, it is still impossible to push the unreplaced relicts aside and to arrange them zonally or in oscillatory patterns.

A serial drawing (Hippertt, 1987), showing the metasomatic replacement of plagioclase by microcline and the development of microcline porphyroblasts in augen gneiss, Niteroi, Brazil, was cited in "**Rock-forming minerals**" (Deer, Howie, Zussman, 2002 edition, page 585, Fig. 417). In the drawing (see Fig. 55) (a) the original metamorphic rock is composed mainly of plagioclase crystals, (b) during the beginning of microclinization the small plagioclase crystals recrystallized around microcline, (c) some adjacent crystals of microcline have merged into one porphyroblast enclosing some plagioclase inclusions arranged with long dimensions roughly parallel to lattice planes of the microcline, and (d)

the porphyroblast is transformed into an idiomorphic shape and able to replace thoroughly the enclosed plagioclase inclusions.

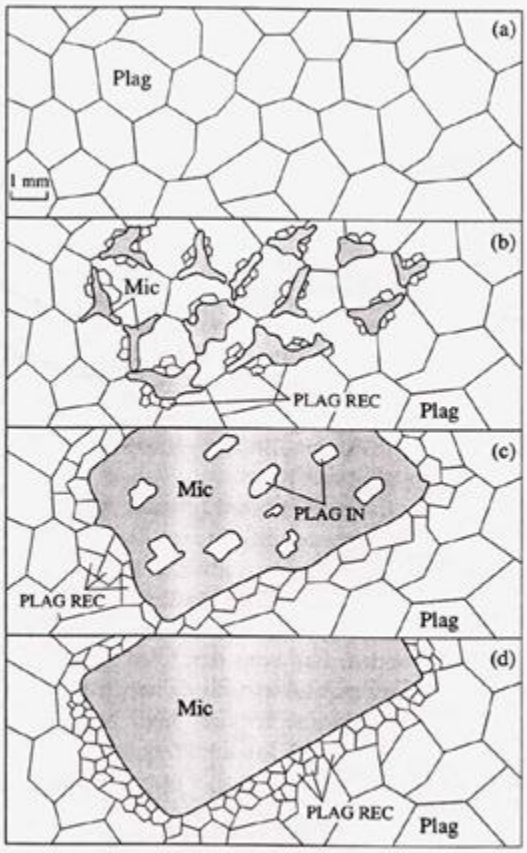

Fig. 417. Serial drawings showing the metasomatic replacement of plagioclase by microcline and the development of microcline porphyroblasts in augen gneiss, Niterói, Brazil (after Hippertt 1987); in, inclusion; rec, recrystallized.

Fig. 55.-Serial drawings showing the metasomatic replacement of plagioclase by microcline and the development of microcline porphyroblasts in augen gneiss, Niteroi, Brazil (after Hippertt, 1987), transferred from "Rock-forming minerals" (Deer et al., 2002, p. 585). IN---inclusion; REC---recrystallized.

The major problem with this model is how several small microcline crystalloblasts with different orientations can merge to form a large one with a uniform orientation.

Megacryst of K-feldspar may occur in melt

Crystallization of granitic melts occurs only when they are undercooled below the liquidus temperature. The various values of undercooling degree ΔT affect the different nucleation density and growth rates of major rock-forming minerals and, therefore, the rock texture.

At ΔT=100-120ºC, nucleation densities of plagioclase and K-feldspar are nearly the same (10^3~10^4), while the growth rate ($1x10^{-6}$(cm/sec)) of K-feldspar may be over 100 times more than that of plagioclase, resulting in the formation of a K-feldspar megacryst, either euhedral or anhedral, with much smaller inclusions of plagioclase, zonally arranged in some megacrysts (Swanson, 1977).

Many points of evidence, especially igneous microstructures and structures resulting from solid-state deformation, indicate that K-feldspar megacrysts in deformed granites are residual phenocrysts, not porphyroblasts (Vernon, 2002). Evidence of an igneous origin includes the following features: crystal shapes, simple twinning, zonally arranged euhedral biotite and plagioclase inclusions, and oscillatory compositional zonation (especially Ba content).

Some residues of a replaced mineral might be preserved without changing its original orientation in a porphyroblast even if the porphyroblast has a very strong force of crystallization (such as an idiomorphic porphyroblast of pyrite in cataclastic granite). The author holds that during porphyroblastization the residues can remain only ***in situ***, and it is impossible to push them aside and to make them be rearranged as Augustithis said.

Major distinction between phenocryst and porphyroblast

According to the T-P conditions for mineral crystallization in magma and to the rule of nibble replacement, the author considers that the major distinctions (only by microscopic observation) between a phenocryst and a porphyroblast may be summarized as follows:

Those megacrysts, which enclose a residual texture of the primary rock, such as schistosity and gneissosity, and keep the orientation of this texture unchanged or hold a recognizable change of its orientation while growing simultaneously to enclose the texture of the schistosity or gneissosity should be regarded as a

porphyroblast (Fig. 56a).

Those megacrysts, which include zonally arranged minerals, should be considered as phenocrysts Fig. 56b).

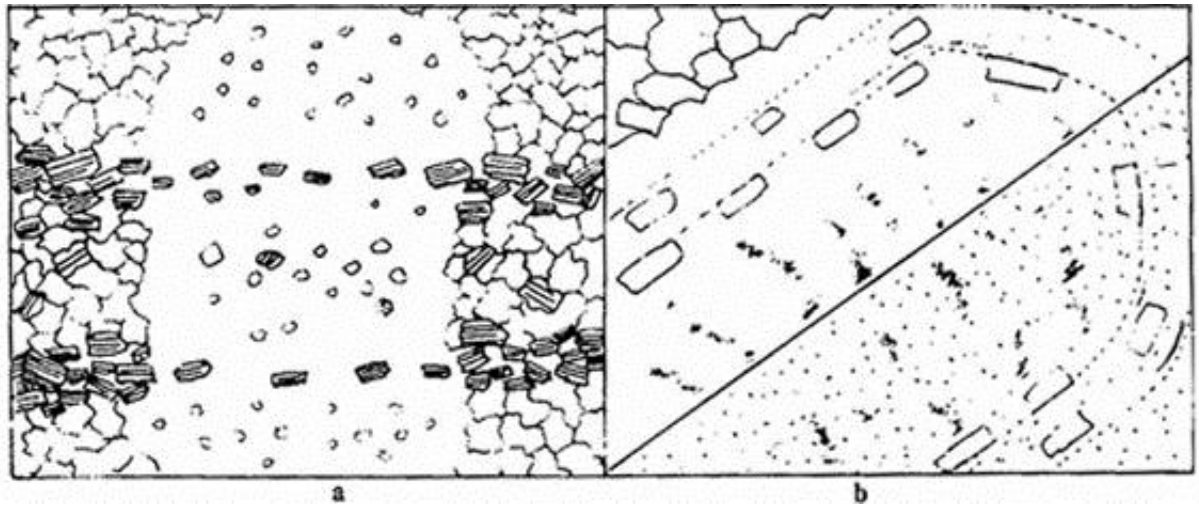

Fig. 56.-Features of porphyroblast and phenocryst. a---Porphyroblast contains schistosity and gneissosity; b---Phenocryst zonally encloses a lot of small crystals.

Those megacrysts, which are obviously zonal in structure due to difference in composition or optical properties, are probably magmatic in origin.

Either phenocryst or porphyroblast is possible if each encloses other small mineral inclusions randomly.

Inside a megacryst of K-feldspar, the phenomenon of nibble replacement of enclosed plagioclase crystals can certainly be observed. Many petrographers insist on treating this phenomenon as an important criterion to determine that the whole K-feldspar has a porphyroblastic origin. However, according to the rule of nibble replacement, an original K-feldspar should be selected as substrate on which the nibbly metasomatic K-feldspar can grow towards plagioclase with different orientation. Moreover, the perthitic albite develops poorly in many places in the newly formed K-feldspar (commonly <0.n mm wide) where isolated relicts of plagioclase are distributed. Fig. 12 shows that the nibbly metasomatic K-feldspar (K’) and the primary K-feldspar (K) have the same crystallographic orientation without obvious boundary between them. The sole distinction might be the

different content of perthitic lamellae, indicating that the major part of K-feldspar is present prior to the K-feldspathization. A false impression, however, that the whole K-feldspar is of metasomatic origin could easily be made, especially when primary K-feldspar has few perthitic albite lamellae (Figs. 7, 8).

Whether the most part of predominant pure K-feldspar has thoroughly replaced the inclusions of plagioclase as well as biotite and even quartz?

Quartz and biotite can hardly be replaced during K-feldspathization according to extensive observation under the microscope. Where the replacement of plagioclase by K-feldspar is observed, the residual amount of plagioclase in K-feldspar is comparable with the amount within the thin section. There is no gradual or gradational transition from plagioclase being slightly replaced to that being thoroughly replaced in thin section; i.e., either plagioclase is slightly or locally replaced by K-feldspar with small relics of plagioclase in it, or K-feldspar is pure and clear, without any tiny inclusions of plagioclase. Therefore, the author holds that the pure and clear part of K-feldspar without any relics of plagioclase represents the primary K-feldspar rather than the metasomatic product of complete replacement of plagioclase.

Study of sequential steps during metasomatism

The texture of a certain rock becomes complicated due to the formation of newly formed minerals after several metasomatic processes.

The successive sequence of mineral replacement can be deduced according to the rule of monomineral replacement and the contact relationship between the replacive minerals.

Nibbly metasomatic albite should occur earlier than the co- orientation albitization of K-feldspar

Fig. 57 shows that swapped rows of nibbly metasomatically-growing albite occur at the contact between two chess-board albites (transformed from two

primary K-feldspars). The swapped albite would not have been produced if the two K-feldspar crystals had been transformed into chessboard albite. On that basis the nibbly metasomatic albite must have been produced earlier than the co-orientation albitization of K-feldspar. This relationship is in accordance with geological observation because swapped albite is found everywhere in the whole body and must have been produced during a postmagmatic process soon after one episode of intrusion. In comparison the transformation of K-feldspar into chessboard albite occurs only in local regions after all stages of the granitic magmatic intrusion have ceased.

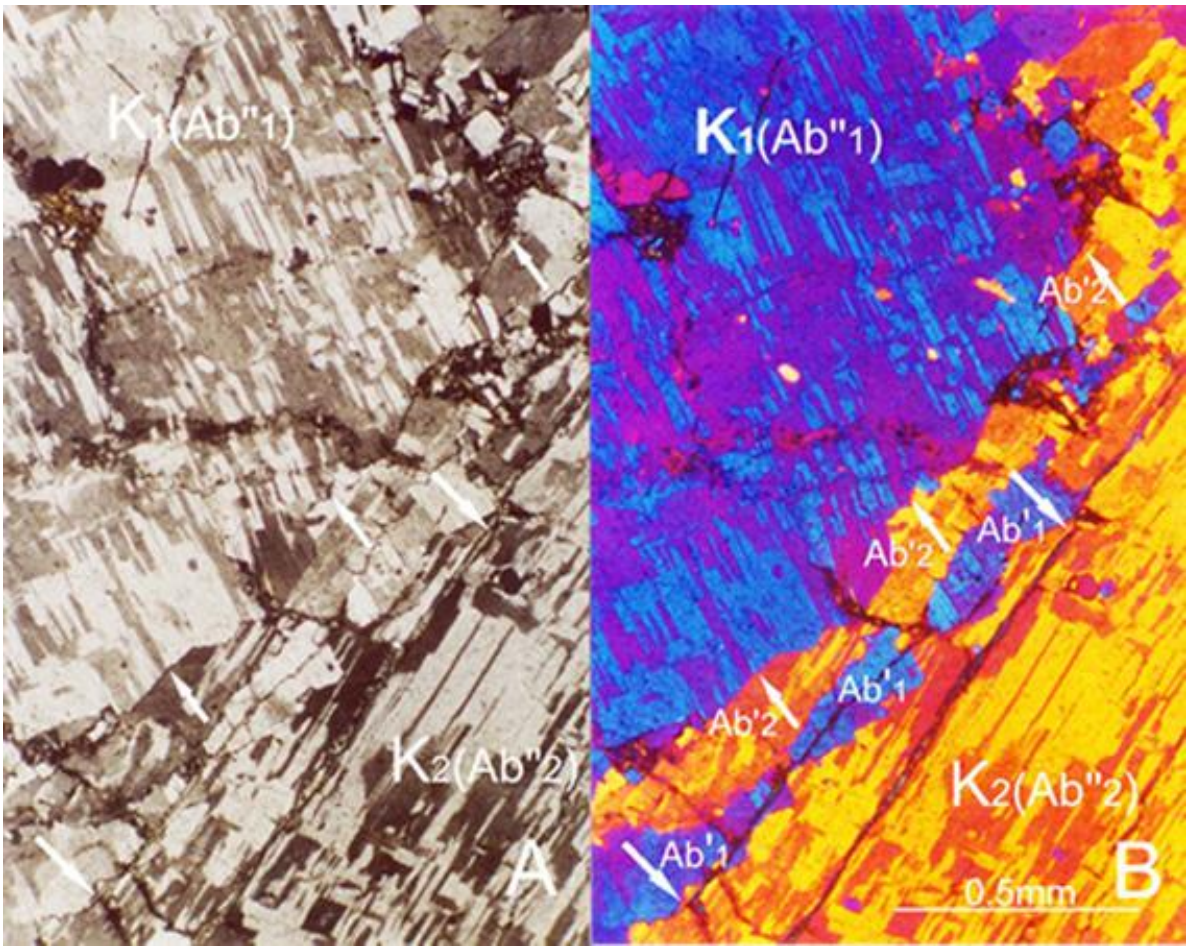

Fig. 57.-Swapped rows of albite present on the border between two chessboard albite. It is reasonably suggested that the swapped albite rows are formed when the two predecessors of the chessboard albite were former K-feldspars. Later, the two K-feldspars were converted to chessboard albite during co-orientation replacement of albitization. So the swapped albite (of hetero-orientation replacive origin) should be formed earlier than the chessboard albite (of co-orientation replacive origin). Sodic metasomatite from Gaoxi medium-coarse grained biotite granite, Zhuguangshan batholith, Jiangxi Province.

Triple nibble replacement (albitization, K-feldspathization and slight realbitization proceed sequentially)

A complicated texture (Fig. 58) can be seen at the contact between two K-feldspars in the earlier granitic intrusion (Huangshatang medium-fine grained

porphyritic two-mica granite, formed during the third period of the Indosinian cycle, in the Zhuguangshan batholith, Guangdong province). Here, nibble replacement occurred three times. First, two rows of swapped albite (Ab_1'Ab_2') are formed by nibble albitization that replaced the K-feldspars (K_1,K_2). Each row of the replacive albite is 0.3~0.4 mm thick. The swapped albite is sericitized later. The second replacement is the nibble K-feldspathization (K_1'',K_2'') that replaced the swapped albite. The K_1''and K_2'' are 0.2~0.3 mm thick and have less perthitic albite than the primary K-feldspars. The third time of replacement occurs during slight nibble re-albitization that produces albite clear rims (0.1 mm thick), which locally replaces the just formed replacive K-feldspar (K_1'',K_2''). The clear rims appear only at contacts with K-feldspar that is differently oriented. No clear rim occurs at contacts between two sericitized plagioclase (albite) crystals.

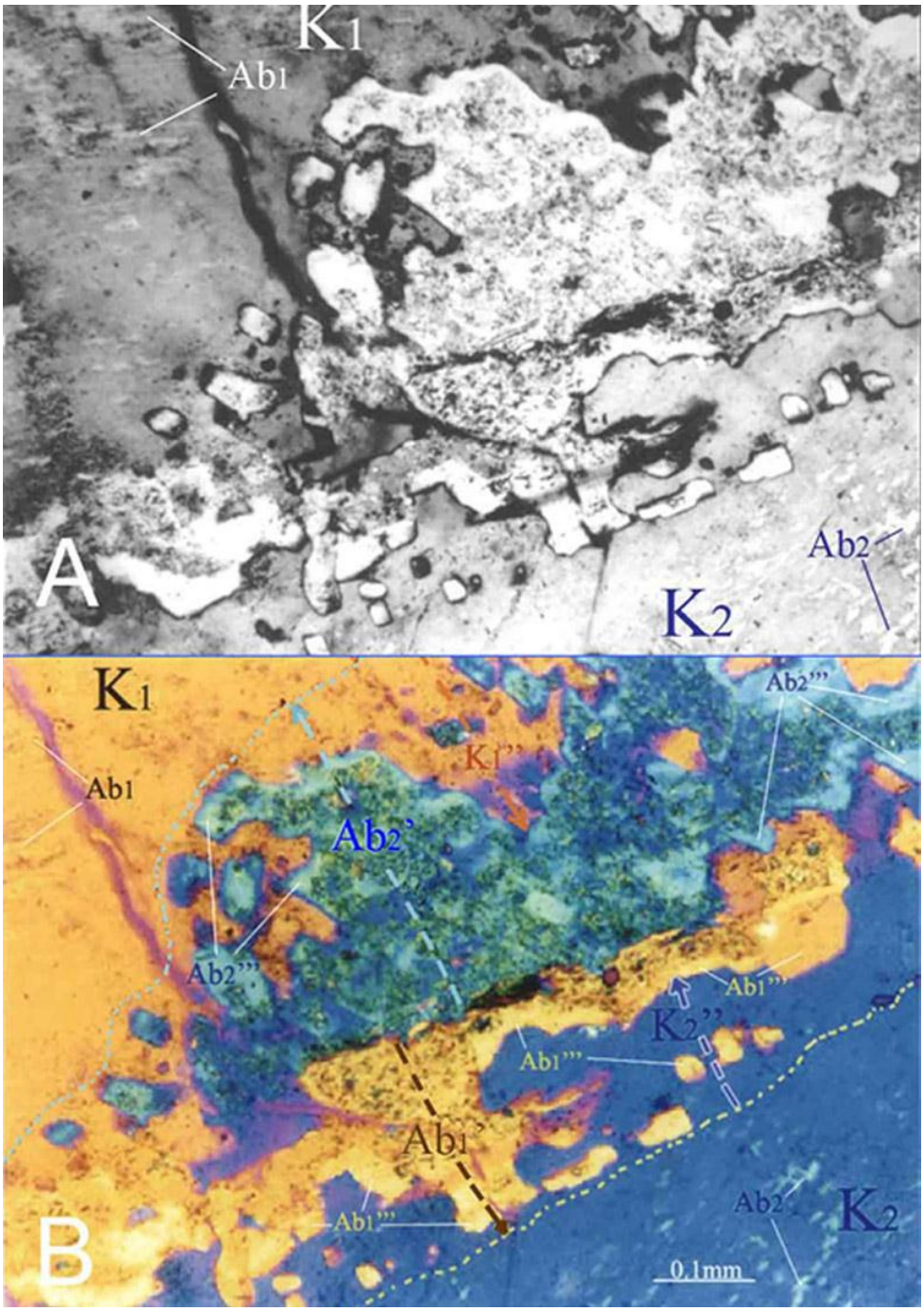

Fig. 58.-Nibble replacement occurred three times at the boundary between two K-feldspars (K_1, K_2). Nibble albitization took place first, followed by the second nibble K-feldspathization that replaced the swapped albite. Finally, the third slight nibble albitization replaced the K-feldspar. Huangshatang medium-fine grained porphyritic two-mica granite, forming at third period of Indosinian cycle, in Zhuguangshan batholith, Guangdong Province.

Another example exists where several small albite crystals appear at the contact of two K-feldspars (Fig. 59). These albite crystals are divided into two groups. Each group is separately located in one individual K-feldspar and each has similar or nearly the same crystallographic orientation as the perthitic albite of the opposite K-feldspar. Two major replacement processes occur here. First, nibble metasomatic albitization occurs, resulting in the formation of swapped rows of Ab_1" and Ab_2" (0.2 mm thick). Then, nibble metasomatic K-feldspathization takes place, forming K_1"and K_2". As the nibble metasomatic K-feldspathization becomes extensive, the thickness of the newly formed K-feldspar can be as much as 0.2 mm, resulting in the disappearance of most parts of the swapped rows of albite and even changing the initial border between the two original K-feldspars.

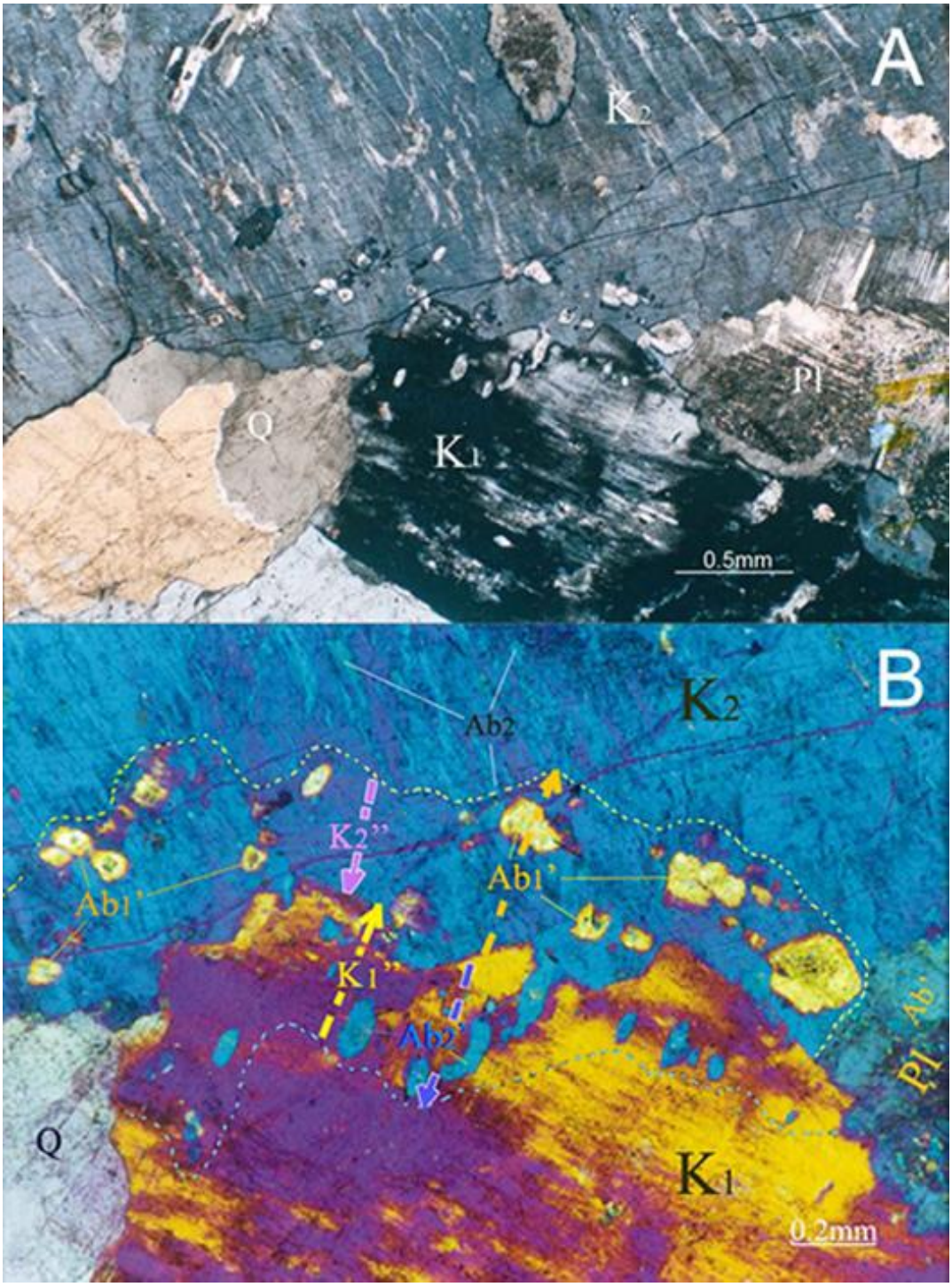

Fig. 59.-Nibble albitization occurs first, followed by nibble K-feldspathization at the contact between two K-feldspars (K_1, K_2). The swapped albite is retained as two groups of albite relicts because the width of K-feldspathization is nearly equal to that of the swapped albite. Medium-grained porphyritic granite in Zhuguangshan batholith, Guangdong Province.

Nibble swapped albite occurs first, followed by quartzification

Both albitization and quartzification have nibbly replaced K-feldspars Fig. 60). On the basis of the contact characteristics of the swapped albite rows with the newly formed quartz, the nibbly metasomatic albite should be formed in the condition that the original grain boundary between the two primary K-feldspar crystals K_1 and K_2 (i.e., the grain boundary between Ab_1' and Ab_2') should have been maintained completely so that quartzification could not have occurred there. If the formation of quartzification had taken place earlier and had destroyed the border of the two K-feldspars, then the complete swapped albite rows should be impossible to form. Therefore, the quartzification must occur later; i.e., after the end of the metasomatic albitization.

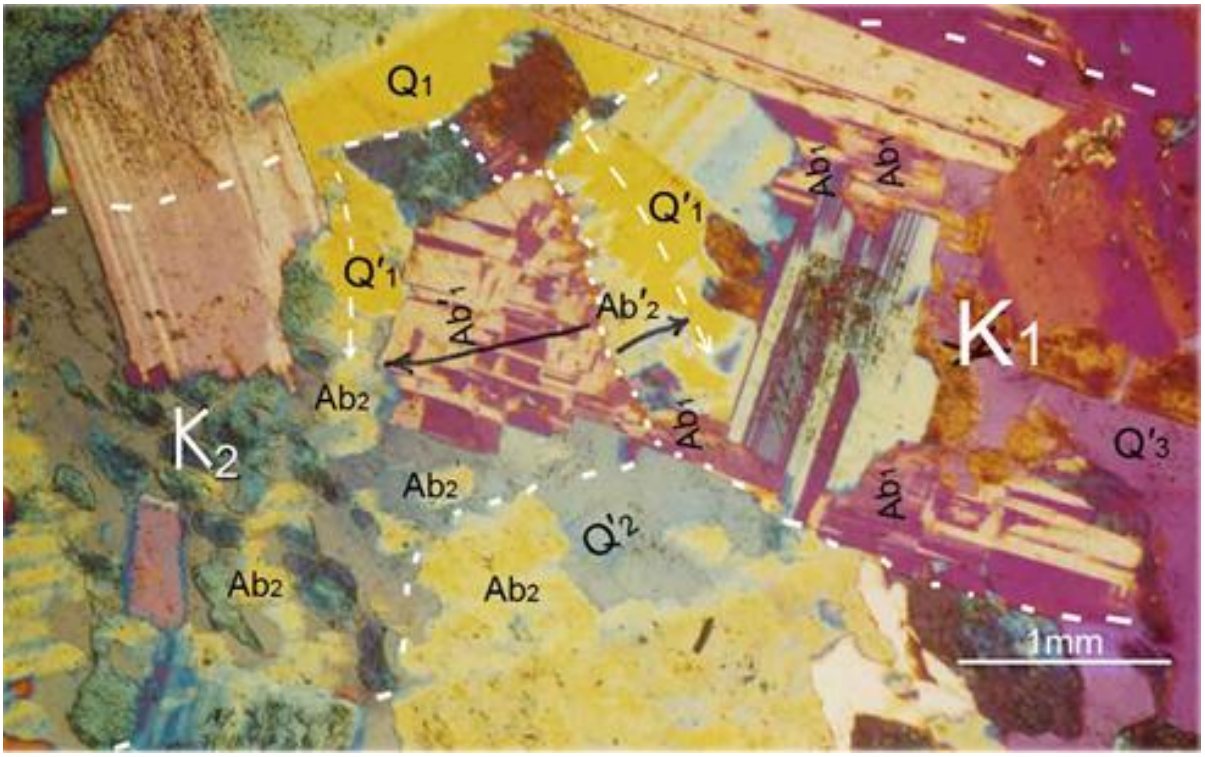

Fig. 60.-Nibble albitization occurred first, followed by nibble quartzification. Crossed polars plus quartz plate. Beihuan leucogranite, Yangjiang County, Guangdong Province.

Swapped albite rows are formed first, followed by berylitization

Small pegmatite miarolitic cavities are distributed in the apical facies of a leucogranite intrusion (Shanbei granite), Taishan County, Guangdong province. These cavities are filled with anhedral beryl, surrounded by euhedral K-feldspar and plagioclase. Irregular beryl crystals that enclose perthite albite lamellae are scattered in the K-feldspar. The anhedral beryl (Be) in the cavities outside the euhedral K-feldspar is primary, whereas inside the K-feldspar the irregularly distributed beryl (Be') with the same orientation as that of the anhedral beryl (Be) outside the euhedral K-feldspar is metasomatic (Fig. 61). The swapped rows of albite (Ab_1'and Ab_3', Ab_1'and Ab_2' in Fig. 61 A, C, D) occur and still remain at the grain boundary between the residual K-feldspars K_1 and K_3 or K_1 and K_2, which are partly replaced by Be'. The tiny swapped rows of albite Ab_1'and Ab_3' must have

formed earlier than berylitization, because they are even surrounded by metasomatic beryl (Fig. 61 C, D).

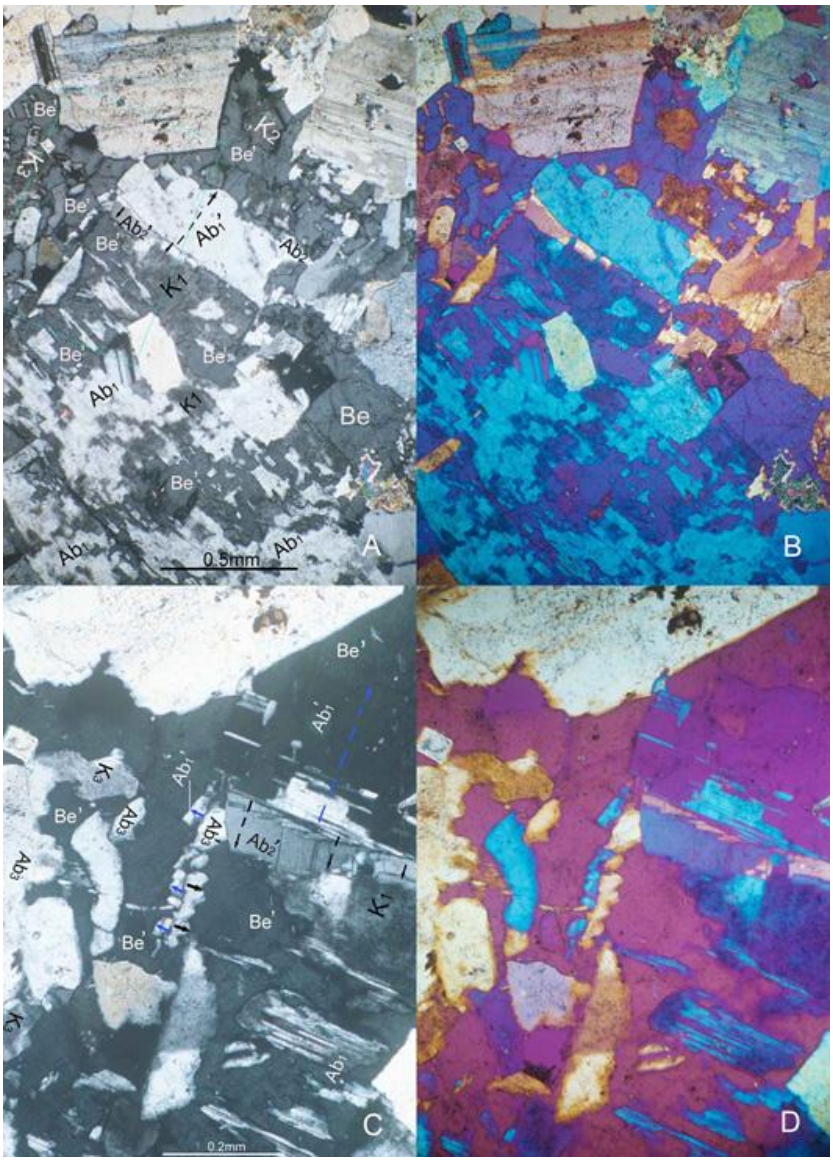

Fig. 61.-Nibble albitization happened first, followed by nibble berylitization (Both mainly replace K-feldspar). The anhedral beryl (Be) outside the euhedral K-feldspar is primary, while the irregularly growing beryl (Be single prime) inside the K-feldspar is formed by nibble replacement. The swapped rows of albite (Ab_1 single prime and Ab_3 single prime, Ab_1 single prime and Ab_2 single prime in Fig. 61 A , C, D) occur and still remain at the grain boundary between the residual K-feldspars K_1 and K_3 or K_1 and K_2 , which are partly replaced by Be single prime . The tiny swapped rows of albite Ab_1 single prime and Ab_3 single prime must have formed earlier than berylitization, because they are even surrounded by metasomatic beryl (Fig . 61 C , D). Shanbei leucogranite, Taishan County, Guangdong Province.

Chloritization and muscovitization of biotite

A complicated phenomenon appears at the contact of the primary euhedral biotite (transformed into chlorite) with muscovite (Fig. 62). The muscovite is divided into two parts (Ms and Ms’). The clear Ms contacted by quartz in many places is primary, while the Ms’ penetrating irregularly into biotite-chlorite is metasomatic. As the biotite is replaced by Ms' and Chl (individually or separately), there is no direct relationship between them. It is difficult to judge which occurs first, chloritization or muscovitization. But, as a general rule, the author postulates that the nibble muscovitization should have occurred prior to the co-orientation chloritization.

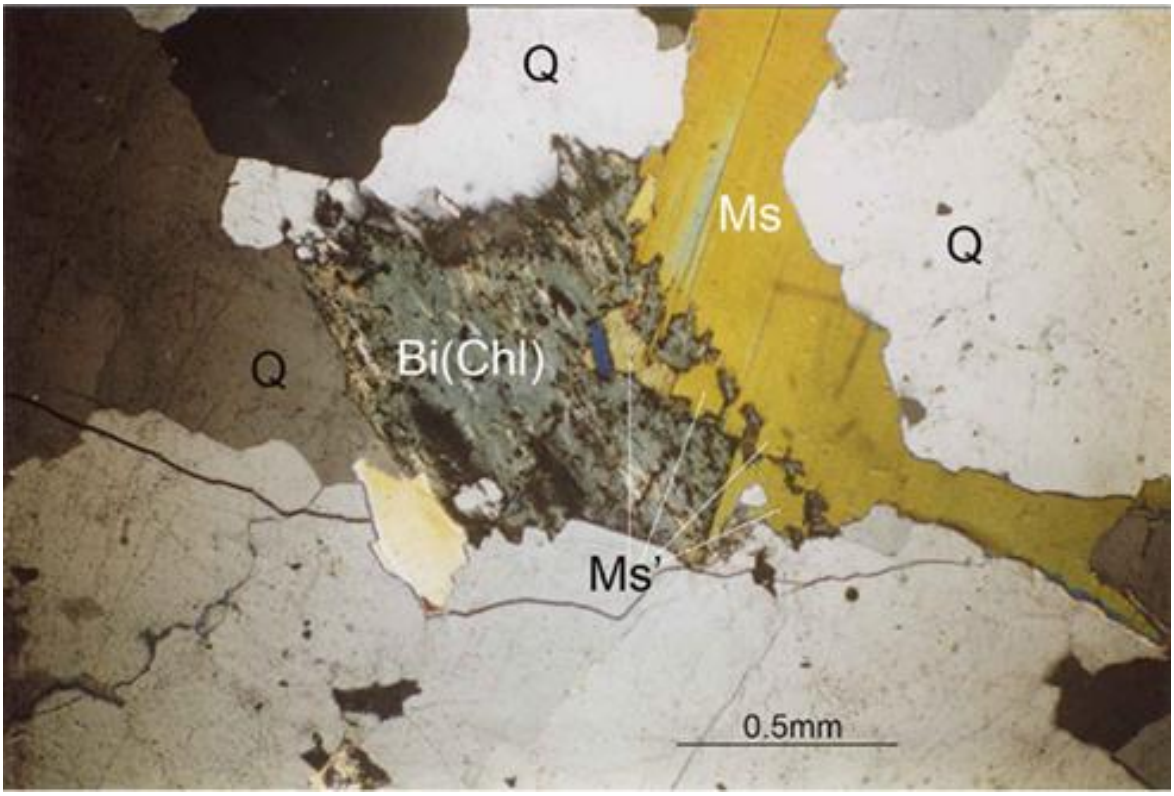

Fig. 62.-Euhedral biotite (chloritized) with complicated muscovite. The upper right border of euhedral biotite (Bi) changed to chlorite (Chl) is somewhat destroyed by muscovite. The latter can be divided into two parts (Ms and Ms single prime). Ms outside Bi is primary, while Ms single prime inside Bi is formed by nibble replacement. It is still difficult to judge which one occur earlier, co-orientation chloritization or hetero-orientation muscovitization. As a general rule, the author postulates that the nibble muscovitization should have occurred prior to the co-orientation chloritization.

Criteria for distinguishing a metasomatic texture from other textures

The replacement texture sometimes is easily confused with other textures. The presence of small isolated grains of mineral B with identical orientation in mineral A is one of the major characteristics of replacement. However, it does not necessarily mean that B grains are relics of replacement and A is the replacive mineral. The phenomenon might be caused by the following conditions.

Intergrowth and cotectic crystallization of feldspar with quartz

During the late stage of melt crystallization at the cotectic point, two minerals (K-feldspar and quartz) crystallized nearly simultaneously. Quartz may be more idiomorphic than K-feldspar, showing that the end of quartz crystallization is earlier than K-feldspar (Fig. 63A).

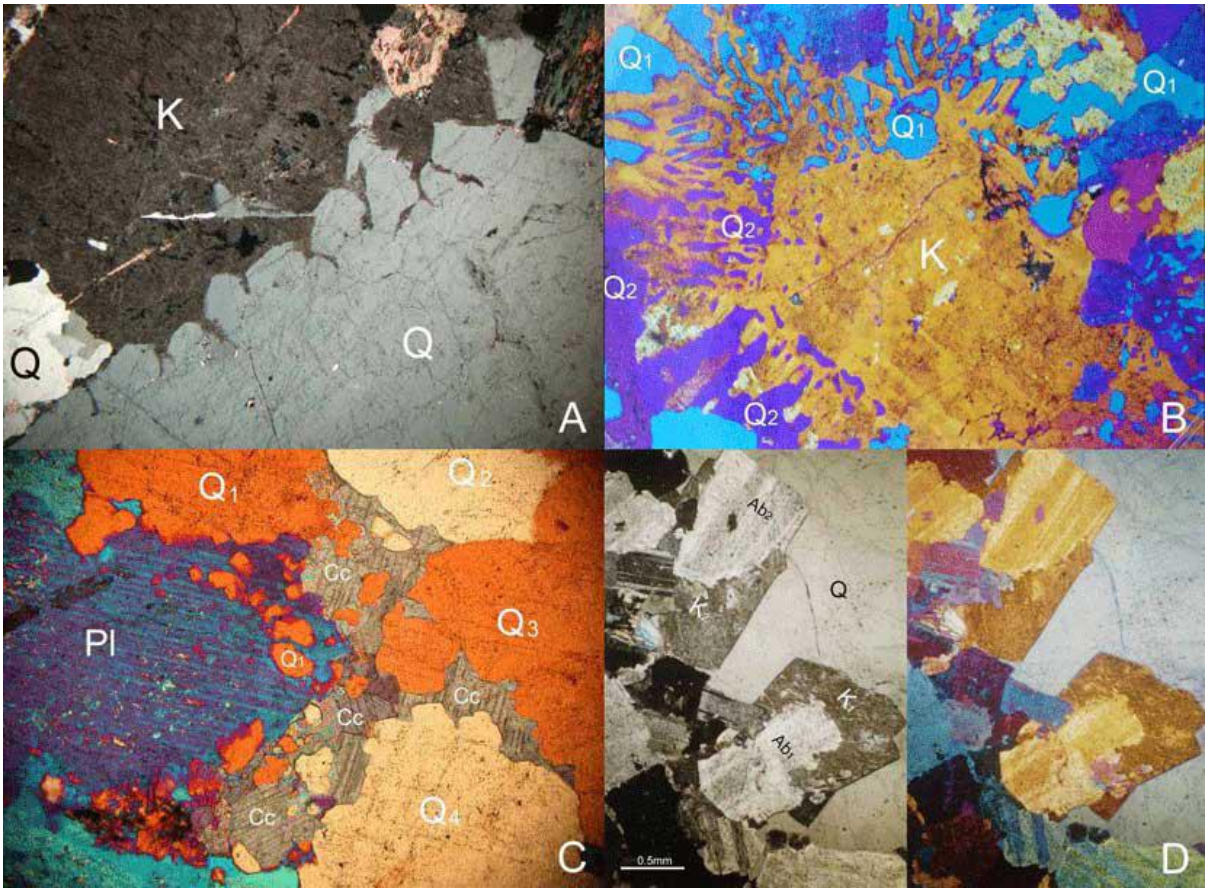

Fig. 63.-Cotectic or simultaneous crystallization of two minerals. A---Cotectic texture of K-feldspar with quartz at final stage of crystallization. Branch-like K-feldspar penetrates quartz as if the former replaces the latter. B---Cotectic or simultaneous crystallization of K-feldspar with quartz. The grain size of both cotectic minerals became bigger from their interiors outwards. C---Relicts of quartz in calcite indicate that quartz is replaced by calcite. Plagioclase is rimmed by quartz grains just as quartz is also replaced by plagioclase. However, the quartz-

plagioclase relationships are probably due to cotectic crystallization. D---Two euhedral allied crystals of K-feldspar with albite. K_1, K_2 has the same orientation as that of Ab_1, Ab_2. They are primary rather than metasomatic.

The grain boundary is zigzag or tortuous, resulting in a false impression* that quartz is replaced by K-feldspar (as quartz is penetrated by K-feldspar) or vise versa, if the thin section is cut along the grain boundary.

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*The inclusion relationship among minerals observed in individual thin sections may produce a false impression because of the limitation of a single thin section. Therefore, attention must be paid to the vast majority of the phenomena in many thin sections rather than focus on the isolated cases observed by chance.

Micrographic or micropegmatic texture due to the specific cuneiform shapes of quartz grains is hardly mistaken for replacement intergrowth, whereas the granophyric texture (i.e., several small rounded, spherical or irregular micrograins of quartz with the same orientation as that of the outside quartz grain which are enclosed in feldspar, mainly K-feldspar) is more easily confused with replacement (Fig. 63B, 63C).

Overgrowth or epitaxial growth of potash-sodium feldspar

The overgrowth or epitaxial growth of potash and sodium feldspars (Fig. 63D) formed in melt is easily confused with metasomatic texture because they all have the same orientation. The morphologic and distribution patterns of epitaxial growth of K-feldspar with plagioclase are more or less stable or similar in a certain rock facies and even in a whole rock body, whereas the co-orientation albitization of K-feldspar takes place abruptly and irregularly, and the whole K-feldspar is rapidly transformed into thoroughly co-orientation metasomatic chessboard albite.

Coarse myrmekite

Coarse myrmekite means that the vermicular quartz grains contained in

myrmekite are coarse. Several vermicular quartz grains with the same crystallographic orientation are seemingly replaced by plagioclase. In fact, the vermicular quartz grains are formed from excess silica after nibble replacement of K-feldspar by relatively calcic plagioclase. Coarse myrmekite can also be formed by Ca-metasomatism (nibble replacement) of sodic plagioclase (Dymek and Schiffries, 1987) or by K-metasomatism of relatively calcic plagioclase (Collins, 1988) where local residual altered plagioclase lattices contain much Ca that combines with much residual Al to leave excess Si in coarse quartz vermicules. In such places the coarseness of the quartz vermicules is proportional to the An content of the primary plagioclase. The higher the An content of the primary plagioclase, the coarser are the quartz vermicules.

Perthite and antiperthite

The perthitic, vein-like or small blocky guest crystals contained irregularly in a host crystal are easily mistaken as being formed by replacement because both guest and host minerals have the same orientation.

The distribution of irregular patches of K-feldspar in co-orientation plagioclase is treated as evidence of replacement of plagioclase by K-feldspar (Collins, 1998a, 2002a, 2003). From my point of view, however, it is neither co-orientation replacement of plagioclase by K-feldspar nor vice versa, but antiperthite resulting from simultaneous epitaxial crystallization. Nevertheless, Collins holds that the K-feldspar is likely formed by replacement if such K-feldspar occurs sequentially and with increasing abundance in microfractured plagioclase as indicated by many thin sections across rocks from undeformed to deformed rocks. Therefore, the examination of many thin sections may be necessary to determine whether irregular patches are formed by simultaneous epitaxial crystallization or by replacement.

Unmixing (exsolution) of solid solution

A mineral with solid solution, which crystallized at high temperature, would exsolve at lower temperature, resulting in the formation of regular intergrowth of

two phases (host and guest minerals) (orthoclase or microcline and albite), i.e., perthite. The texture of regular intergrowth thus formed is called exsolution texture, and the corresponding mineral paragenesis phenomenon, exsolution paragenesis.

The phenomenon seems to be the co-orientation replacement product of either the replacement relict (guest mineral) replaced by the host or the host mineral replaced by the vein like guest mineral because they have the same crystallographic orientation. The exsolved guest mineral, however, usually occurs in form of dense, flat, uniform and homogeneous thin films, which differs from either the irregular or the vein like perthitic albite.

The above mentioned phenomena can be easily confused with replacement texture.

Therefore, the mineral intergrowth should be observed and analyzed comprehensively in order to exclude a non-replacement texture from a replacement texture.

The author considers that all intergrowths of feldspar (K-feldspar or plagioclase) with several quartz crystals enclosed in feldspar are probably primarily formed by simultaneous crystallization rather than by replacement of quartz by feldspar, except myrmekite. All intergrowths of several feldspar fragments enclosed in quartz are possibly caused by replacement of feldspar (perthitic) by quartz.

Besides, monzonitic texture (several euhedral or subhedral plagioclase crystals are enclosed in allomorphic K-feldspar) usually observed in monzonite, quartz monzonite, monzogranite and granodiorite should be distinguished from the phenomena of plagioclase crystals replaced along cracks by K-feldspar, as noticed by Collins (1998b).

Conclusion

After formation of granite, the gases and solutions either relevant or irrelevant to magmatic process can penetrate into solidified granitic rocks, resulting in partial

dissolution of unstable primary minerals and local crystallization of more stable secondary minerals; i.e., during mineral replacements that change the primary minerals and local structure. Metasomatic phenomena, especially feldspathization, are observed in granitic gneisses and granites in many places, even in solidified and undeformed granites.

According to the author's observation (based on similarities or differences of crystallographic lattices and orientations of replacive and replaced minerals), metasomatism can be classified into two patterns: 1) hetero-orientation replacement (nibble replacement) and 2) co-orientation replacement. The metasomatic growth by nibble replacement would occur at a grain boundary where there is a mineral prone to be dissolved (replaced) on one side while the same or similar mineral can act as a nucleation site of a replacive mineral on the other side. An impurity may serve as a nucleation site for metasomatism if the same or similar mineral that could act as a nucleation site is absent.

On the basis of the rule of nibble replacement, the fine-grained platy crystals of albite (cleavelandite) in Li-F granite are primary rather than being formed by "chaotic" replacement processes.

Clear rim albite and grain boundary albite are formed by replacement of K-feldspar where hydrothermal gas or fluid is introduced with pure Na. If Ca accompanies Na in the gas or fluid, excess SiO_2 from replaced K-feldspar would remain and take the shape of vermicular quartz in replacive sodic plagioclase.

Perthitic albite looks like plagioclase that has formed either by metasomatic processes or by exsolution from a solid solution; however, such perthitic albite in rocks studied by the author in China probably is formed by simultaneous crystallization.

The key evidence of replacement is the presence of relics of the replaced mineral in the newly formed replacive mineral. However, such relics should be distinguished from crystals formed by simultaneous crystallization and from normal inclusions in igneous rocks.

Generally, a phenocryst can simply be distinguished from a porphyroblast. When several metasomatic processes are superimposed, the steps preceding each replacement can possibly be analyzed and understood in the light of the

replacement rule.

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