Formation mechanisms for mineral replacement are dissolution–precipitation (crystallization) and ion exchange.

Co-oriented replacement of a certain mineral may arise from appropriate hydrothermal fluids entering along grain boundary with tiny cracks. For hetero-oriented replacement, however, two additional prerequisites are required: (1) a mineral prone to be replaced on one side; (2) a same or similar mineral as replacive one on the other side, acting as nucleation center for its growth. Without the second prerequisite, the hetero-oriented replacement would hardly occur.

The passage for hydrothermal fluids from outside is discussed first.

### 2.1 Passage for Gas and Liquid from Outside

For entering and moving of hydrothermal fluids from outside, the largest openings must be fracture fault zones. The smaller openings are joints and fissures in rocks, while the tiniest openings are grain boundaries, cleavages and micropores in minerals.

Many researchers consider that the rock should be broken to provide a space for hydrothermal fluid to enter and then to cause metasomatism. Some researchers (e.g., Collins L.) believe that the rocks had once been broken, but then recovered, i.e., the traces of deformation were fully eliminated after recrystallization.

This idea is quite doubtful. The texture of the rock subjected to metasomatism, however, is quite complete rather than cataclastic. Mineral replacement develops widely in entirely solid rocks, not only in fracture zone or along joint and its sides. The granites that have been subjected to multiple metasomatism might not have been broken before.

General speaking, under compression stress, quartz is easily affected, resulting in undulatory extinction from weak to strong, and biotite is deformed, while feldspars are more stable. Under stronger stress, smaller crystals may be crushed to aggregates, and cleavage of biotite and twinned lamella of plagioclase may be curved or disrupted, while K-feldspar, especially larger grains, remain nearly unchanged because of its higher compressive strength and tenacity, and only peripheral corners may be abraded and ground. Nevertheless, whole granitic rocks are still characterized by their original magmatic hypidiomorphic granular textures although having been subjected to tectonic and metasomatic processes.
Furthermore, no triple junction textures typical for recrystallization occur throughout the whole rock. Therefore, the absence of hints of cracks cannot be simply explained by their elimination due to recrystallization. At most there is coalescence phenomenon in weakly broken quartz.

Microscopic observation indicates that the real replacement phenomena have surely occurred at one side or both sides of grain boundaries without obvious traces of deformation. So we can not but admit that grain boundaries and cleavages, as well as micropores are the passages available for a gas–liquid to permeate and circulate.

However, the width of tiny microcrack along grain boundary is too narrow to be measured by using an ordinary optical microscope. It has been studied by various researchers using transmission electron microscope (TEM) and high-resolution electron microscope (HREM). The width of a measured grain boundary ranges from <100 nm (Behrmann 1985), 3–5 nm (Farver and Yund 1995) to 0.5 nm (Hiraga et al. 1999).

It is hard to imagine that hot gas–liquid fluid from outside can still enter such a narrow grain boundary (only at nanometer scales), giving rise to metasomatism. However, if you pay attention to the polished granite slate stone paved on floor in a building, you may occasionally or even frequently find the dark trace of water- or oil-soaked stain dispersed irregularly at the marginal part of the slate (Fig. 2.1). Although the depth of stain is unknown, it surely means at least that oil or water may infiltrate into such compact granite slate stone even nowadays, much more the hydrothermal fluid under high pressure and temperature. The time needed for the gas–liquid fluid to extend through solid rock and to cause metasomatism must be quite long. However, this time interval makes up just a short episode in the long history of geological evolution. Perhaps, simulation experiment for metasomatism in compact granitic rocks may be carried out in the future.

Why does the hetero-oriented metasomatic process occur only at the grain boundaries between minerals of different kinds with different orientations rather than that between minerals of the same or similar crystallographic lattice and with the same orientation?

Grain boundaries serving as openings for entering and circulation of hot gas and fluid can be understood by the following explanation.

Figure 2.2 shows that the grain boundary (contact) between two minerals A and C is coherent (tight) when they have the same crystallographic orientation, while a boundary crevice exists between B and C either they have different orientations or they are different minerals.

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1Triple junction texture means that adjacent rock-forming minerals (feldspars and quartz) contact each other by straight planes with the apical angle of 120° in thin section. The texture is typical for recrystallization of high degree metamorphic rocks.
orientation, while the grain boundary between minerals C and B must have tiny openings because they are of different kinds or they are situated with different orientations even if they are of the same or similar kind. Therefore, we postulate that there must be subtle crack at the boundary between minerals c and b as a passage for hot gas–fluid to enter rather than at the boundary between minerals A and C.

2.2 Mechanism of Dissolution–Reprecipitation

Dissolution–precipitation is the most general mechanism which is appropriate for explaining hetero-oriented (nibble) replacement pattern of either different kinds or the same (or similar) kind of minerals.

The dissolution–precipitation mechanism implies that a new mineral precipitates (crystalizes) in the space where an old mineral was locally dissolved during metasomatism.

It means that in the process of metasomatism an old mineral dissolves partially and gradually, while a new mineral precipitates immediately and simultaneously at the right place. The volume of the precipitated mineral is equal to that of the dissolved mineral.

For 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 adjacent (host) mineral to promote its dissolution.

Merino et al. (1993) stated that in a rigid rock, the growth-driven stress between the guest and host minerals has two immediate effects: (1) an increase in the solubility and rate of pressure solution of the host mineral and (2) a decrease in the rate of growth of the guest mineral (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.

Merino et al. seemed to stress that appropriate dissolution of a replaced mineral is promoted by a force driven by growth of the replacive mineral. They even emphasized: “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” (Merino and Dewers 1998).

2.2.1 Different Degree of Hetero-Orientation Replacement for Various Minerals

According to the senior author’s observation, during hetero-oriented replacement, some minerals are easily replaced and some are not, while others are even barely replaced (Table 2.1), depending on their different stability and solubility under a certain metasomatic condition.

Most common metasomatic processes in granite are albitization, K-feldspathization, quartzification, and muscovitization (including sericitization in plagioclase).

Table 2.1 Several replacive minerals and easily to hardly replaced minerals in hetero-oriented metasomatism

| Replacive minerals | Easily replaced | Not easily replaced | Hardly replaced |
|--------------------|-----------------|---------------------|-----------------|
| Ab Q               | K Cc            | Perth.Ab            | Pl Q Bi         |
| Ber                | K               | Perth.Ab            | Pl Q Bi         |
| K                  | K               | Perth.Ab Pl         | Pl Q Bi Hb Cpx  |
| Ms                 | K Bi            | Pl                  | Q               |
| Ser                | Pl              | K                   | Q               |
| Cc                 | Q K             | Perth.Ab            | Pl Bi           |

Ab Albite; Q Quartz; Ber Beryl; K K-feldspar; Ms Muscovite; Ser Sericite; Cc Calcite; Pl Plagioclase; Perth.Ab Perthitic albite; Hb Hornblende; Cpx Clinopyroxene
K-feldspar is always by far the most easily replaced mineral in nearly all metasomatism, such as albitization, K-feldspathization, quartzification, muscovitization, and beryllization. In some places, a few tiny perthitic albites in K-feldspar may also be replaced. Nevertheless, quartz, whole (most or all) plagioclase (albite) and biotite (chlorite), as well as the majority of perthitic albite remain unchanged.

Many researchers concluded that the solubility of calcite is inversely proportional to that of quartz according to different pH values. Figure 2.3 shows that quartz and calcite have opposite solubility in different pH solutions (no matter whether fresh water or sea water). In alkaline solution, the solubility of quartz is higher while that of calcite is lower and vise versa. Therefore, quartz is replaced by calcite in alkaline condition, and calcite may be replaced by quartz when the hydrothermal condition becomes acidic.

In earlier evolution of alkali metasomatite, primary quartz is replaced by calcite from partly (Figs. 1.56 and 1.57) to completely (Fig. 1.59) during alkaline circumstances. Later on, when hydrothermal solution becomes acidic, calcite may be replaced by newly formed quartz (Fig. 1.50) as indicated by contrary change of solubility in quartz and calcite along with the variation of pH (Fig. 2.3). It shows that the more alkali the solution, the higher solubility of quartz and the lower solubility of calcite. On the contrary, the more acidic the solution, the higher solubility of calcite and the lower solubility of quartz.

In general case of hetero-oriented metasomatism, K-feldspar is an easily replaced mineral, indicating that it has higher solubility than other minerals. Later on, however, an inverse fact appears that plagioclase is replaced by K-feldspar, showing that the solubility of plagioclase becomes higher than that of K-feldspar in a new circumstance.

What circumstances or conditions effectively force the inverse change of solubility of the above two minerals, i.e., from a replaced mineral to a replacive mineral? That is the puzzling question to be investigated and solved.

A further mysterious fact is that old K-feldspar may hetero-orientedly be replaced by new K-feldspar, which has only slightly higher Na$_2$O and less K$_2$O content than that of the old one (see Table 1.3). Surely it does not mean that the solubility of the old K-feldspar is higher than
that of the new one? Is there any other condition affecting the solubility? What is the actual reason? These questions are not clear yet.

What is the real physical–chemical circumstance or condition controlling the change of solubility of the two kinds of feldspars and even of the same K-feldspars, whether it is old and new? This is an enigma for petrologists and mineralogists.

2.2.2 Presence of Crystal Nucleus on Which the Replacive Mineral Can Epitaxially Grow

The second prerequisite is the presence of crystal nucleus on which the replacive mineral can epitaxially grow. Since replacive minerals basically are the major rock-forming minerals, such as plagioclase, K-feldspar, quartz, muscovite, protolithionite, which are extensively or locally distributed in granites, the second prerequisite can easily be reached.

However, carbonate mineral like calcite is absent in granite. Why can the calcitization really happen? How can it be explained reasonably?

As a conjecture, an impurity probably plays a role as nucleus center. Upon the impurity a crystallite of replacive mineral can be produced. Once the initial crystallite is formed, upon which the replacive mineral would keep on growing successfully. In other words, only when a metasomatic process should have occurred, while its same or similar mineral is absent, an impurity (interstitial foreign element, etc.) may act as a nucleus center instead, such as calcitization in alkali metasomatic granite, pyritization in cataclastic granite and sericitization in plagioclase.

Generally speaking, however, as a rock-forming mineral, the replacive mineral would only take the same or similar one as its nucleus center rather than impurity. Perhaps, it is because the same or similar mineral that acts as nucleus basis much easier than impurity.

2.2.3 Explanation 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 the boundary between K-feldspar and differently oriented plagioclase, the nibble replacement of albitization is initiated by albite growth. Since plagioclase is stable and K-feldspar is unstable and soluble, the replacive albite cannot replace the plagioclase, but unilaterally replaces the K-feldspar, forming a so-called “clear rim” of albite, which is taking the same crystallographic orientation as the adjacent plagioclase.

As Na-rich gas–liquid penetrates the boundary between two K-feldspars K₁ and K₂ (differently oriented), the replacive albite can grow at either K₁ or K₂. The direction of replacement depends on either the stronger of the crystallization ability of replacive albite or the less energy needed to dissolve the K-feldspar lattice. Both alternatives are possible and it is hard to be judged. However, the width of the nibbly replacive albite can be measured. According to the senior author’s extensive observations, the width of replacive albite along axes a and c is always greater than that along axis b, resulting in an irregular flat-plate form which is much similar to the form produced by the crystallizing growth habit of plagioclase in magma, i.e., the relative growth velocities along the axes are \( a \geq c \gg b \). Of course, the outline of a replacive mineral growing in the solid state is certainly irregular.

These observations precisely confirm the points of view of Merino (1988), Maliva and Siever (1988), and Carmichael (1986) that a growth-driven stress of replacive mineral on its neighbor (host) mineral may promote its dissolution. Accordingly, can it be deduced that the growth dimension of replacive mineral is proportionally related to its growth-driven stress and is seemingly independent of the energy needed to dissolve the replaced mineral?
The surface of the grain boundary into which a gas–liquid infiltrates can be named as a “metasomatic active front” or “reaction interface” (Rong 1982, 2009). As the newly formed replacive albite crystallographically coincides with the K-feldspar on which the albite epitaxially grows, once a metasomatic albite is formed along crack, the original crack seals and disappears, and the nibble replacement can no longer take place there. The crack is transferred forwardly. Because the crystallographic orientations of the replaced K-feldspar and the nibbly replacive albite are invariably discordant, there is always an opening between them. Therefore, the metasomatic active front would continuously advance toward the replaced K-feldspar during the process. The neighboring metasomatic active fronts can be merged together into one row and march forwardly. Thus, so-called “swapped rims (or rows)” of albite can be formed (Fig. 2.4).

The fact that a clear albite rim is present along the periphery of some small plagioclase inclusions in a K-feldspar megacryst shows that Na-bearing fluid can surely penetrate into K-feldspar along its cleavage. However, the fact that no replacive albite occurs along the cleavage results probably from lack of much more energy needed to dissolve the K-feldspar along both sides of the cleavage with neat and order arrangement of crystal lattice. Besides, it does not conform to hetero-oriented replacement regulation.

No nibble replacement growth of albite occurs at boundaries between K-feldspar and quartz. This is because the replacive albite cannot grow on quartz, although K-feldspar can be replaced by albite, meanwhile quartz cannot be replaced by albite, although the replacive albite can grow on K-feldspar. With the same reason, nibble replacement of albite cannot occur at boundaries between two plagioclases, plagioclase and quartz, plagioclase and biotite, or between other minerals.

There are sufficient minerals that may act as substrate for nibble replacement in rocks. So, it is unnecessary and unlikely for a replacive mineral to select an impurity as a nuclear center. If there are no identical or similar minerals in rocks, or the identical or similar minerals are absent at an adjacent side, then an impurity or a crystal lattice defect would act as a substrate, e.g., the sericitization or muscovitization in plagioclase and the calcitization in granite.

![Fig. 2.4 Growth of swapped rows of replacive albite. a (+). Preliminary growth of swapped rows of albite. b Diagram of successive growth of swapped rows of albite](attachment:image.png)
2.3 Mechanism of Ion Exchange or Substitution

Ion exchange mechanism means that the old mineral is partly or even wholly transformed into newly replacive mineral by the ion exchange without partial or whole dissolution of the old mineral.

The ion exchange mechanism is appropriate for the co-oriented replacement patterns of sheet minerals, such as the muscovitzation and chloritization of biotite.

The structures of biotite and muscovite are similar. They have a common basal plane cleavage (001) and similar crystallographic lattices. Hot gas–liquid fluid containing $\text{Al}^{3+}$, $\text{Si}^{4+}$ can penetrate along cleavage into biotite, substituting $\text{Fe}^{2+}$, $\text{Mg}^{2+}$, and $\text{Ti}^{4+}$, causing a pseudomorphic transformation from biotite to muscovite (Figs. 1.61 and 1.62).

The crystallographic lattice of chlorite is different from that in biotite, but still resembles the lattice of mica in many respects (Deer et al. 1963). After alteration, biotite is prone to be replaced by chlorite in pseudomorphic form (Fig. 1.63).

In recent three decades, the transition processes from biotite to chlorite have been studied by many researchers (Veblen and Ferry 1983; Banes and Amourc 1984; Kogure and Banfield 2000) (Fig. 2.5). According to observation and analysis during mapping by use of high-resolution (atomic) transmission electron microscopy, two kinds of transition mechanisms from biotite to chlorite are found: a. Mechanism 1. Growth of a brucite-like $(\text{Mg(OH)}_2)$ layer into the interlayer (K) between two TOT mica layers. Mechanism 1 requires introduction of substantial material and results in an increase in volume. b. Mechanism 2. Formation of a brucite-like layer by removal of the two tetrahedral sheets $(\text{Si, Al})_4$ from one TOT mica layer. Mechanism 2 requires a net removal of material from the crystal and results in a decrease in volume. Veblen and Ferry (1983) estimated that approximately 85 % of chloritization is produced via mechanism 2 and 15 % via mechanism 1. Therefore, the final volume of chlorite basically remains unchanged.

On the basis of microprobe analysis on pseudomorphic chlorite from biotite sampled

![Fig. 2.5 Schematic representations of two different mechanisms for forming a single layer of chlorite in biotite (Veblen and Ferry 1983). The degree of distortion of the TOT layers is exaggerated. Circles indicate interlayer cations K. a Mechanism 1. Growth of a brucite-like layer into the interlayer region between two TOT mica layers results in an increase in volume. Direction of growth of the layer is indicated by the arrow. b Mechanism 2. Formation of a brucite-like layer by removal of the tetrahedral sheets of one TOT mica layer results in a decrease in volume. Direction of dissolution of the tetrahedral sheets is indicated by the arrows](image-url)
from Jiling granite, Gansu Province (Table 1.5), MgO and ∑FeO contents in chlorite have increased to 27.58 and 12.69 %, compared with 22.1 and 8.23 %, respectively, in the original biotite, which indicates that not only brucite-like layer Mg(OH)₂ but also Fe(OH)₂ had participated in substitution for the interlayer K and the two tetrahedral sheets ((Si, Al)O₄) during chloritization.

The replacive mineral formed by ion substitution naturally maintains the original orientation of the host replaced mineral.

2.4 Co-oriented Replacement of Feldspar Minerals

With reference to the albitization of plagioclase, it generally means that plagioclase is replaced by albite co-orientedly rather than hetero-orientedly. On the contrary, the albitization of K-feldspar normally implies that K-feldspar is replaced by albite hetero-orientedly (nibbly) rather than co-orientedly.

However, plagioclase, especially small grains or lamellae, may be hetero-orientedly replaced partly by albite. K-feldspar may also be co-orientedly replaced by albite in sodium metasomatites.

All the co-oriented replacement phenomena of feldspar minerals, in the authors’ opinion, belong only to albitization from either plagioclase or K-feldspar. The authors have never observed a real example of co-oriented replacement of plagioclase by K-feldspar.²

²Co-oriented K-feldspathization of plagioclase was mentioned by several researchers (Collins 1998, 2003; Collins and Collins 2002; Putnis et al. 2007). Labotka et al. (2004) carried out an experiment study of replacement of albite by K-feldspar. Amelia albite powder grains (about 50–200 µm in diameter) were used to react with ¹⁸O-enriched KCl (aq) (1 and 2 mol) at 600 °C and 200 MPa. After 6 days, the 150 µm diameter albite grains had 5–20 µm rims of K-feldspar in which the O was strongly enriched in ¹⁸O. The contact between the core albite and the rim K-feldspar is sharp and decorated with numerous pores of various sizes. Although it is considered as pseudomorphic replacement, the reaction rim of K-feldspar (reaction product) in respect to the optical continuity with the host (Amelia albite) is still unknown.

2.4.1 Co-oriented Albitization of Plagioclase

Plagioclase is easily altered by hydrothermal fluid. After alteration, oligoclase and/or sodic andesine become blurred and sericitized, while more calcic andesine and/or labradorite become saussuritized, and the whole plagioclase is co-orientedly transformed into albite.

2.4.2 Co-oriented Albitization of K-Feldspar

Generally, K-feldspar is barely altered by hydrothermal fluid. The co-oriented albitization of K-feldspar may occur only during intense sodium metasomatism and may not appear in ordinary alkali metasomatite.

2.5 Presence of Micropores in Feldspar Is Probably One of the Key Factors to Allow the Co-oriented Replacement

In the last 30 years more detailed studies of feldspars (mainly plagioclase) in common igneous rocks have been carried out by using electron microscope, scanning electron microscopy, and high-resolution transmission electron microscope. These studies have been made either on fractured surfaces (Dengler 1976; Que and Allen 1996; Wang and Liu 2009) 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 micropores³ (within altered plagioclase) (Fig. 2.6a).

Small crystals of sericite have grown in the micropores, and the plagioclase surrounding the pores is transformed into albite. The clear part of plagioclase, mainly in the rim, but also in the

³There are different opinions on the origin of micropores: original (Roedder and Coombs 1967; Montgomery and Brace 1975); secondary (Smith and Brown 1968; Parsons 1978); both original and secondary (Que and Allen 1996).
inner part, free or less amount of either micropores or sericite crystals, retains its original composition. Perhaps, the presence of micropores is a key factor that allows the alteration of plagioclase. Micropores ranging from several nm to μm in size (Worden et al. 1990) are irregular in shape and commonly elongate, slot-like (Fig. 2.7) which are generally considered to be interconnected. The width of transition from unaltered plagioclase to altered albite is only 40 nm (Fig. 2.6b) (Engvik et al. 2008; Hövelmann et al. 2010).

Micropores preferentially developed in the core of plagioclase with the clear margin free of micropores.

Worden et al. (1990) considered that micropores are abundant in coarsened areas of perthitic lamellae, in which porosities may be as much as 4.5%.

Lee et al. (1995) reported that in alkali feldspar, micropores are distributed by pairs along the borders of albite lamellae (Fig. 2.8).

According to the authors’ observation, micropores in K-feldspar basically occur in places of intense argillation alteration where dense fine perthitic albite lamellae have formed (Figs. 2.9 and 2.10). Micropores are independent of cleavage (001).

What is the mechanism for feldspar to be co-orientedly replaced by albite?

The sharp and abrupt contacts between unaltered plagioclase and co-orientedly replaced albite seem hardly to be explained by the ion exchange mechanism. If co-oriented albitization is explained by dissolution–precipitation mechanism, it would be in contradiction with the rule of hetero-orientation replacement, because the latter should not take place if the crystallographic orientations of both replacive and replaced minerals are in accordance with each other. The authors are very much puzzled by this contradiction. The actual mechanism awaits further investigation.

Putnis et al. (2007) reported that there are many micropores several hundred nm in diameters in the newly formed K-feldspars which have replaced plagioclase (Fig. 2.11). Micro-hematite crystals occur in the micropores resulting in reddening of the K-feldspar.

In K-feldspar, however, there is nearly no sericitization, although micropores are also present in it.

As for the genesis of micropores in feldspar, there is primary origin (Roedder and Coombs 1986).
There are two hypotheses for the secondary origin of micropores: (1) the secondary micropores are caused by release of coherent elastic strain energy between K-rich and Na-rich phases in semicoherent micoperthite. So, micropores are present at both sides of perthitic

Fig. 2.7 Scanning electron micrograph (secondary electron image) of unpolished plagioclase fragment (Que and Allen 1996). a Sericite, altered plagioclase and micropores in a plagioclase grain, ×1000 (Fig’s width 65 μm). b Micropores in plagioclase, ×4500 (Fig’s width 14 μm). c Elongated clot-like micropores in plagioclase. Smaller pores at depth within the main pore also occur, ×5000 (Fig’s width 13 μm). d Sericite flakes in a pore of a plagioclase grain.

Fig. 2.8 SE image of a HF-etched K-feldspar fragment. Left image is of (001) cleavage fragment. Lamellae greater than ~100 nm in width is 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 twofold symmetry straddle the albite lamellae (Lee et al. 1995)
lamellae and are absent at the periphery of coherent cryptoperthite (Brown and Parsons 1993); (2) hydrothermal fluid (bearing NaSiO$_3^-$) entered into feldspar crystal along microfissures, causing replacement. The micropores are formed because the molar volume of the newly crystallized feldspar is not equal to, but slightly less than that of the dissolved old feldspar (Worden et al. 1990; Putnis 2009; Putnis et al. 2007; Hövelmann and Putnis et al. 2010). The microfissures disappeared by coalescence later on and left fluid inclusions are distributed linearly.

The mechanism for co-oriented replacement of feldspar has not been identified so far. There are still two hypotheses: (1) ion exchange mechanism; (2) dissolution–precipitation mechanism.

According to the hypothesis of ion exchange, the co-oriented albitization of both plagioclase and K-feldspar is formed by substitution of metallic ions within the unchanged aluminosilicate crystalline lattice.

The co-oriented albitization of plagioclase is produced by substitution of Ca$^{2+}$ by Na$^+$ with slight addition of Si$^{4+}$. The co-oriented albitization of K-feldspar is formed by substitution of K$^+$ by Na$^+$. However, the boundary between altered and unaltered is too narrow, say only 40 nm for plagioclase, which arouses skepticism.

Another hypothesis is dissolution–precipitation (or interface-coupled dissolution–precipitation nominated by Putnis et al. 2007) by which the co-oriented albitization of feldspar is formed when hydrothermal fluid entering. Along with dissolution of an old mineral, a new replacive mineral immediately crystallizes, and this new mineral may take the same orientation as that of the old one because replacement is proceeded within the mineral.

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Fig. 2.9 BSE image of K-feldspar. Micropores in K-feldspar appear mainly at the adjacent area around the microperthitic albite lamellae and absent or much less present at the area of nonperthite and cryptoperthite (lower right and upper left). There is no relation with the cleavage (001). Huangnitian quartz syenite

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Fig. 2.10 BSE image. (b) Magnified frame in (a). Micropores in K-feldspar K accompanied with intense argillation and dense albite lamellae. Huangnitian quartz syenite
For albitization of plagioclase, the more developed the micropores, the more intense is the co-oriented albitization.

As for K-feldspar, the situation is somewhat confusing. The co-oriented albitization of K-feldspar begins in the K-feldspar phase accompanied or pioneered with cloudy hydro-goethitization (Fig. 1.68) and neither along cleavage nor close to perthitic albite lamellae. The rule of developing micropores in K-feldspar is not very clear, so the understanding of the co-oriented albitization mechanism for K-feldspar is still deficient.

2.6 Relation Between the Two Patterns of Replacement

What is the relation between the two patterns of replacement?

Hetero-oriented replacement occurs at grain boundaries between two minerals, while co-oriented replacement takes place inside the replaced mineral. Obviously, it is easy to imagine that a hydrothermal gas–fluid moves first along grain boundary before entering the interior of mineral, therefore hetero-oriented replacement.
happens generally earlier than co-oriented replacement. Certainly, it may also infer that the two patterns of replacement might take place almost simultaneously.

The rock-forming minerals which may undergo both hetero-oriented and co-oriented replacement processes are mica and feldspar. Biotite may be either hetero- or co-orientedly replaced by muscovite. Both K-feldspar and plagioclase may be either hetero- or co-orientedly replaced by albite. Plagioclase can be hetero-orientedly replaced by K-feldspar. However, the authors doubt whether plagioclase, including albite, as well as K-feldspar may be co-orientedly replaced by K-feldspar.

2.6.1 Muscovitization of Biotite

Biotite commonly may be transformed into muscovite because of co-oriented replacement by muscovite (Figs. 1.61 and 1.62). Muscovite may also hetero-orientedly replace biotite (Figs. 1.41 and 1.42) in mild degree. They appear singly and separately. The authors have not seen where the two kinds of replacing muscovite meet together so far. The process sequence between them is not clear yet.

2.6.2 Albitization of K-Feldspar

Albitization of K-feldspar is divided into two patterns: hetero-oriented and co-oriented replacement. They may be observed in a sodium metasomatite. Then, what is the relationship between them?

As far as we know, the earliest hetero-oriented albitization of K-feldspar was formed at post-magmatic or deuteric stage and was widespread in the whole granitic body. Much later than the former, the co-oriented albitization of K-feldspar occurred due to action of intense alkali hydrothermal solutions in a local region, where at least microbroken deformation took place after solidification of multiple pluton in a batholith. However, no example of co-oriented albitization of K-feldspar in deuteric stage has been found so far. Nevertheless, the late hetero-oriented albitization may also emerge after the calcitification which postdates the co-oriented albitization of K-feldspar.

The intensity of hetero-oriented albitization might be represented by the size of newly formed albite grains, ranging from small (<0.1 mm) to large (>0.5 mm). However, no co-oriented albitization of K-feldspar has been observed even in granite with large size (up to 0.5–1 mm) of newly formed albite consisting of 15 % of the whole rock (Figs. 1.8, 2.12 and 2.13). It means that the co-oriented albitization of K-feldspar could not be initiated even if the hetero-oriented albitization of K-feldspar developed intensely.

On the other hand, in the alkali metasomatite that has been subjected to intense sodium metasomatism nearly all the primary K-feldspar crystals up to 30–45 % were transformed or co-oriented albititized to chessboard albite. Here the size of clear albite rim belonging to hetero-oriented albitization remained as the same (<0.1 mm) without broadening (Figs. 2.14 and 2.15), and the width of swapped albite rows was similar as before (Figs. 2.16 and 2.17). In other words, there is no trace of enhancing the hetero-oriented albitization after the K-feldspar was co-orientedly albitized completely to chessboard albite. So, the intense co-oriented albitization of K-feldspar also does not promote the

Fig. 2.12 (+)Q. No co-oriented albitization of K-feldspar was provoked by intense hetero-orientation albitization (Ab1′Ab2′). Naqin leucogranite
occurrence of the hetero-oriented albitization of K-feldspar.

These are actual facts that the authors have observed for years. We cannot see any other alternative explanation but to recognize that the processes of the two patterns of albitization took place and proceeded individually and independently, although they were all directed against K-feldspar and were created commonly by a sodic hydrothermal solution. There is no continuous or transition relation between them, although they are all generally called albitization of K-feldspar.

It may be inferred that their conditions of occurrence and the environments in which they were formed are probably quite different and they

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**Fig. 2.13** (+). No co-oriented albitization of K-feldspar was triggered by intense hetero-orientation albitization Ab'. Naqin leucogranite

**Fig. 2.14** (+). Albite clear rim in ordinary granite. Jiling granite, Gansu Province

**Fig. 2.15** (+). Albite clear rim keeps the same size after K-feldspar was completely co-orientedly albitized K(Ab). Sodium metasomatite in Jiling granite

**Fig. 2.16** (+). Swapped albite rows between two K-feldspars in Jiling granite, Gansu Province

**Fig. 2.17** (+). Swapped albite rows keep the similar width after K-feldspar was thoroughly co-orientedly albitized K(Ab). Sodium metasomatite, Jiling granite
should reasonably be distinguished and not be confused each other.

2.6.3 Albitization of Plagioclase

In early stage during hetero-oriented albitization, K-feldspar is easily replaced while most perthitic albite will remain in situ. Only a few tiny perthitic albite accompanied with K-feldspar might be replaced simultaneously, while whole euhedral plagioclase keeps its integrity and even maintains its zonal structure. At that time, plagioclase is fresh and unsericitized (Fig. 1.3) and co-oriented albitization of plagioclase does not occur.

After later alteration due to the introduction of either hydrothermal fluid or groundwater, plagioclase is partly or wholly blurred, sericitized, and transformed into albite with decreased An value, i.e., co-orientedly albitized.

In contrast, wherever plagioclase has been subjected to intense alteration, resulting in perfect co-oriented albitization, the early-formed clear albite rim and intergranular albite keep their original widths as before. So, intense co-oriented albitization of plagioclase also does not enhance the hetero-oriented albitization.

It indicates that the hetero-oriented albitization and co-oriented albitization of plagioclase took place separately and respectively.

Therefore, the formation conditions and environments of the two replacement patterns are different and not associated with each other.

The authors emphasize that it is reasonable and necessary to divide metasomatic phenomena into the above two patterns and to describe and treat them separately, rather than to confuse them, although their individual formation mechanisms and conditions are poorly understood so far.

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