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44. K-metasomatism and the origin of Ba- and inclusion-zoned orthoclase megacrysts in the Papoose Flat pluton, Inyo Mountains, California, USA

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Abstract

In the Papoose Flat pluton in the Inyo Mountains of California the orthoclase megacrysts are suggested to form by K-metasomatism because microfracturing of a few normally zoned plagioclase crystals channeled introduced K-bearing fluids to these places, thereby promoting K-metasomatism and localized growth to form the megacrysts. Isochemical recrystallization to produce the megacrysts from preexisting stressed orthoclase and plagioclase crystals is ruled out because the original relatively undeformed granodiorite of the Papoose Flat pluton contained only 8-13 vol. % orthoclase that could not have been reorganized into more than 19 vol. % orthoclase in the groundmass and megacrysts and because original biotite was insufficient to supply enough K. An outside K source is required. Si-metasomatism of biotite to form quartz would have supplied some of the K. Concentrically oriented plagioclase inclusions that occur parallel to Ba-K growth zones in the megacrysts are shown to be formed from primary groundmass minerals, some of which were broken into fragments but others were not microfractured. The occurrences of myrmekite inside the megacrysts, scalloped edges on all surfaces of many plagioclase inclusions, sodic rims on irregular plagioclase inclusions against outer surfaces of former faces of the orthoclase, and disoriented inclusions that are not parallel to growth zones provide evidence for the primary origin of the inclusions. Rare trails of inclusions through the megacrysts indicate that the megacrysts are porphyroblasts and not residual phenocrysts (porphyroclasts). Microcline replacements of plagioclase which occur at lower temperature in cataclastically deformed granite (micro-aplites) produce abundant myrmekite and recrystallized sodic plagioclase. Pseudo-aplites in strongly sheared zones result where nearly all plagioclase is replaced by microcline, and most biotite is replaced by quartz. Progressive non-isochemical K-metasomatism occurred in the pluton with increasing deformation from the initial orthoclase

appearance through the megacryst stage and then the final production of microcline. Orthoclase megacrysts in the wall rock Campito sandstone are shown to have a metasomatic origin similar to that found in the Papoose Flat pluton.

Introduction

The Papoose Flat (PF) pluton in the Inyo Mountains of California (Fig. 1) is one of the most studied plutons in California because of its petrology, interesting contact relationships with the deformed sedimentary wall rocks, and the controversy over how the pluton was emplaced (Dickson and Sabine, 1967; Sylvester et al., 1978; Brigham, 1984; Nelson, 1987; Dickson, 1966, 1994, 1995ab, 1996; Paterson et al., 1991; de Saint-Blanquat et al., 2001). The contact relationships and emplacement of the PF pluton are not discussed in this paper, and only a few of the many papers discussing these topics are cited above. Instead, the subsolidus history of this pluton is emphasized with particular interest on the Ba and K oscillatory zoned orthoclase megacrysts that contain concentric shells of tiny plagioclase, biotite, and quartz inclusions. Two hypotheses have been suggested for the origin of the megacrysts. Brigham (1984), de Saint-Blanquat et al. (2001), and Vernon and Paterson (2002) considered them to be of primary igneous origin, whereas Dickson (1996) suggested an isochemical recrystallization origin. However, on the basis of studies of textures in thin sections of samples of both rocks and isolated megacrysts collected throughout the PF pluton and in the wall rock Campito sandstone, these two hypotheses are questioned, and a third **non-isochemical metasomatic origin for the formation** of the megacrysts is proposed in the following sections.

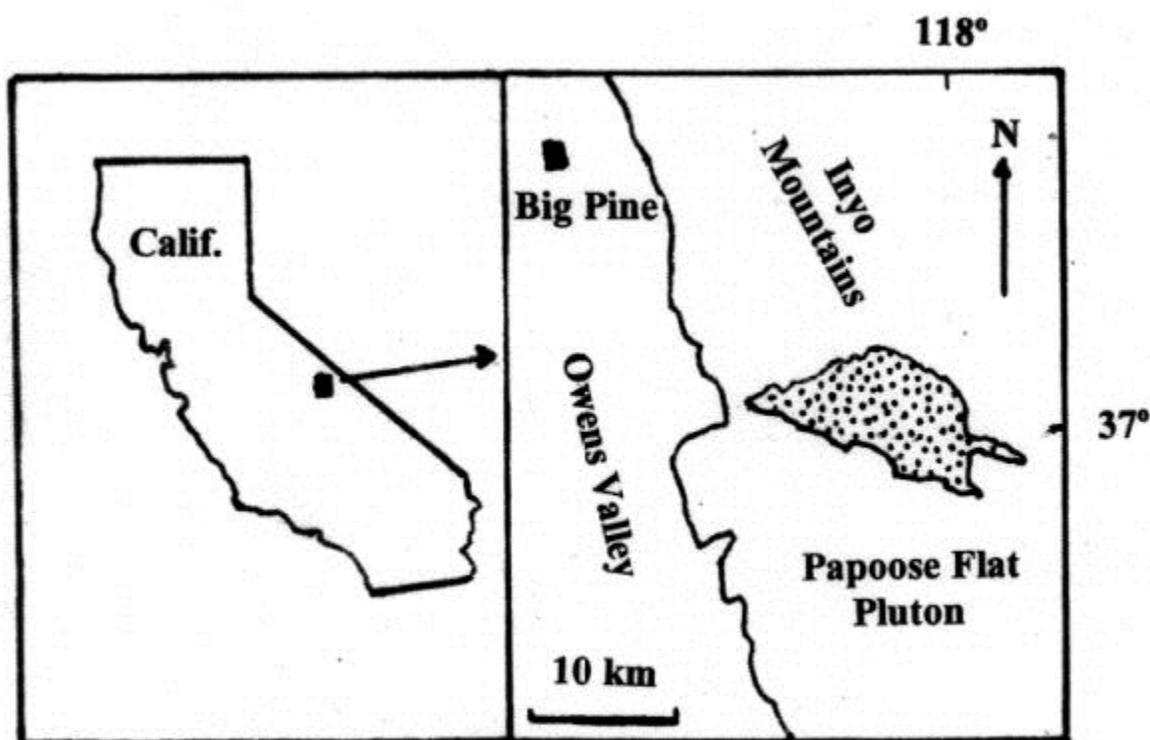


Fig. 1. Map showing location of the Papoose Flat pluton, Inyo Mountains, California, adjacent to Owens Valley and east of the Sierra Nevada Range (after de Saint-Blanquat et al., 2001).

Samples and thin sections

A suite of 72 thin sections of PF rocks was borrowed from Arthur Sylvester, and an additional 31 extra-large thin sections were made from rock samples that he provided from collections he made along the border of the PF pluton and in a north-south traverse across the middle of the pluton (Sylvester, 1966, 1969). Another suite of 59 thin sections was made from rock samples collected by Frank Dickson in a grid pattern throughout the PF pluton, and 45 thin sections were made from isolated megacrysts. Finally, an additional set of 15 extra-large thin sections was made from samples of the megacryst-bearing Campito sandstone collected by Brigham (1984), which were in the possession of both Frank Dickson and Arthur Sylvester.

Papoose Flat pluton petrography

Ross (1965) found that modes of eleven samples of rocks in the main PF mass averaged 42 % plagioclase (mean An₂₅), 33 % quartz, 19 % K-feldspar, and 6 % other constituents, most of which is biotite. Epidote, allanite, muscovite, apatite, magnetite-ilmenite, zircon, garnet (rare), hornblende (rare), and titanite (rare) are minor constituents. These modes do not include the megacrysts and plot in the granodiorite field near quartz monzonite. If the megacrysts were added, the composition is likely a quartz monzonite. The megacrysts are orthoclase although some have totally converted to microcline. They occur in almost all parts of the PF pluton and range up to 5 cm long, but most are from 1.0 to 2.5 cm long. Dickson (1995b and 1996) noted that many of these megacrysts, which normally have a monoclinic symmetry, have an outward triclinic symmetry. The triclinicity occurs because the (001) face with respect to the (010) face is tilted 1 to 4 degrees from the normal 90 degree angle. Dickson (1996) suggested that stress on the megacrysts might have caused the tilting.

Microstructures in the Papoose Flat pluton

In their study of the PF pluton, de Saint-Blanquat et al. (2001) mapped three different microstructure domains on the basis of characteristic textures (Fig. 2). These domains were labeled as (A) magmatic (coarse-grained with minimal deformation), (B) high-temperature solid state deformation (intermediate-grained and deformed), and (C) medium-temperature solid state deformation (fine-grained and strongly deformed). Generally, the greatest amount of deformation occurs in the western part of the pluton (domain C), where the quartz becomes polycrystalline ribbons, and the least in the eastern part (domain A). Domain (C) also forms a narrow rim around the edge of the pluton (not shown on Fig. 2) and stratigraphically overlies domain (B). Thus, both (C) and (B) once were on top of domain (A), resulting in rocks that were strongly deformed in the roof of the pluton before erosion removed them. Even so, localized areas of (B) occur in (A) and (C), and localized areas of (C) occur in (A) and (B), so that the relationships shown in Fig. 2 represent only a generalized pattern of gradual changes from coarse- to fine-grained microstructures. Thus, any kind of deformation can be found in all parts of the pluton.

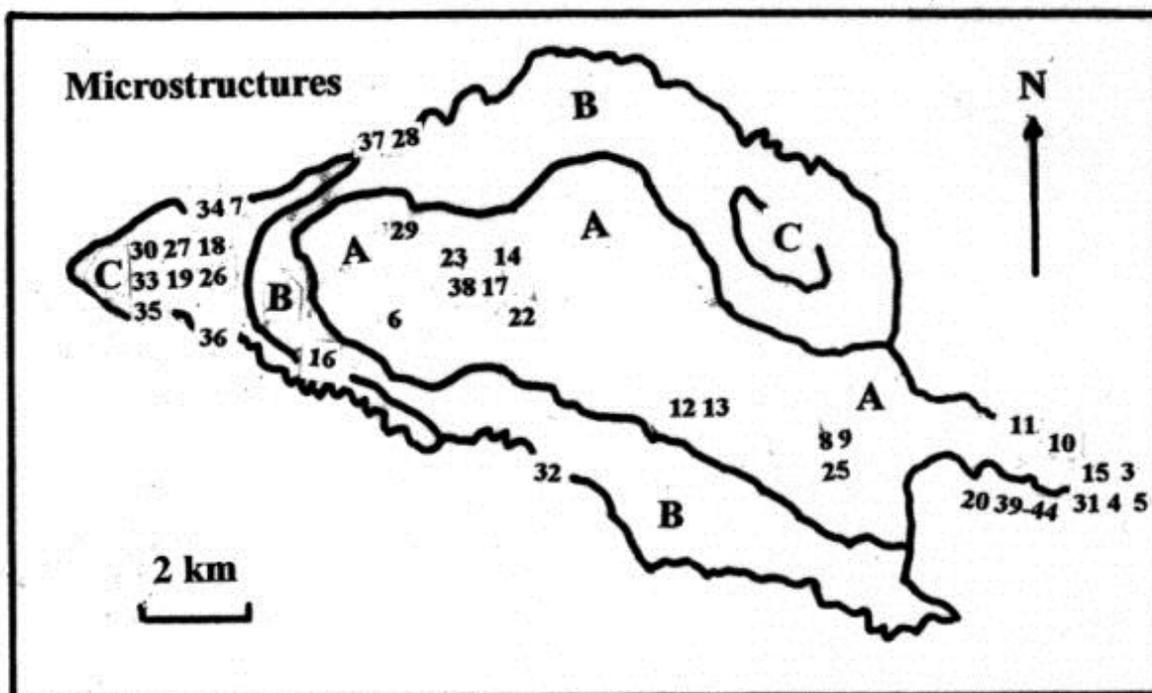


Fig. 2. Deformation domains in the Papoose Flat pluton (modified after Fig. 8 of de Saint-Blanquat et al., 2001). (A) magmatic, (B) high-temperature solid state deformation, and (C) medium-temperature solid state deformation. Numbers are figure numbers for the photomicrograph illustrations, and also indicating approximately where the samples were collected from which the photos were made in thin sections. Locations of Figs. 21 and 24 from the same sample in domain A are not shown, but are likely near sample 22. Note that because of late changes of the order of the illustrations in the text, Fig. 36 is now from a sample at site 39, Fig. 37 at 36, Fig. 38 at 37, and Fig. 39 at 38. The figure will be redrawn to correct this deficiency.

It should be emphasized here that the magmatic and subsolidus deformation that are described by de Saint-Blanquat et al. (2001) and which produced these three microstructure domains were not at temperatures in which cataclastic textures formed. The quartz grains do not exhibit strain with undulatory extinction, but demonstrate high-temperature dislocation mobility and grain boundary migration that resulted in triple junctions. The plagioclase crystals do not show bent albite-twin lamellae nor twisted mottled extinction. At the high temperatures in which these microstructures formed, flowage and annealing occurred that resulted in shape preferred orientations in which the elongated plagioclase crystals commonly contact each other in parallel alignments (synneusis). This high temperature flow

fabric also resulted in dynamic recrystallization of the quartz to produce ribbons and polycrystalline aggregates, lacking evidence of stress like that observed by Sylvester and Christie (1968) in quartzite wall rocks. Dynamic recrystallization of the plagioclase, however, did not occur because the crystals still retain their Na-Ca growth zones with relatively calcic cores and sodic rims. Nevertheless, superposed on this high-temperature flow fabric is a lower temperature brittle deformation that could have enabled the kinds of metasomatic reactions that are described hereafter. [Included in Fig. 2 are the figure number locations of the photomicrographs that are used in the article to show these relationships.]

Origin of the orthoclase megacrysts

In their discussion of foliation and lineation, de Saint-Blanquat et al. (2001, p. 982) indicated that the PF pluton has a ubiquitous magmatic *"foliation and associated grain-shape lineation, defined by the preferred orientation of **primary igneous** minerals, predominantly **feldspar megacrysts** and biotite. The foliation, which is variably developed in the center of the pluton, increases in intensity toward the pluton margin where the gneissic or locally mylonitic foliation is defined by a parallel alignment of micas, elongate plagioclase and **K-feldspar** grains, and plastically deformed quartz aggregates."* Because the orthoclase megacrysts are aligned parallel to the foliation, it may be assumed, nevertheless, that the megacrysts are primary (crystallized from magma) and oriented with the other minerals during plastic deformation. A magmatic origin for the megacrysts is questionable, however, because in the field the megacrysts (a) are found in both the pluton and the metasedimentary wall rocks, (b) cut pygmatic and aplite dikes in the wall rocks and in the pluton (Fig. 5 in de Saint-Blanquat et al., 2001, and Figs. 6 and 7 in Dickson, 1996), and (c) occur in mafic enclaves in the pluton (Dickson, 1996).

In opposition to Dickson's model, Vernon and Paterson (2002) suggested that the megacrysts are residual phenocrysts (porphyroclasts) and not porphyroblasts. These authors proposed (a) that the concentrations of megacrysts in the hornfelses (the Campito sandstone wall rocks) were derived from pegmatite dikes that had been strongly deformed, leaving behind xenoliths and xenocrysts of the pegmatites in the hornfelses, (b) that the megacrysts cutting pygmatic and aplite dikes can be explained by magmatic processes, and (c) that megacrysts in mafic enclaves can be explained by magma mixing. However, arguments (a) and (b) by Vernon and Paterson are based on field observations and not on thin section studies of the megacrysts, and argument (c) is based on evidence from other terranes and not on thin section studies of mafic enclaves in the PF pluton. These

arguments and others by Vernon and Paterson (2002) for a magmatic origin of the megacrysts are addressed later after analyses of textures and crystal relationships have been made. Nevertheless, the isochemical recrystallization and the non isochemical metasomatic models must be examined carefully to see if these offer a viable hypothesis.

The metamorphic isochemical recrystallization model

Dickson proposed that the Ba and K oscillatory zoned orthoclase megacrysts, with concentric-ally-aligned tiny plagioclase inclusions, formed at subsolidus temperatures by a metamorphic isochemical recrystallization process (not specifically designated by this name by Dickson but hereafter called the metamorphic model). In this model the formation of megacrysts results from geochemical self-organization that is controlled by internal reactions in a rock under stress (Ortoleva, 1994). In the stressed PF pluton, the primary minerals that became the orthoclase megacrysts are postulated to have recrystallized isochemically in response to imposed tectonic stress, and the heat released during this recrystallization caused dissolution of adjacent plagioclase crystals. This dissolution created a localized fluid from which dissolved plagioclase then renucleated on a growing face of the orthoclase megacryst. In this way the longer dimensions of the renucleating plagioclase crystals were aligned parallel to a former orthoclase face. During the growth of the orthoclase megacrysts, different concentrations of Ba and K precipitated in concentric zones, and all Ba and K were locally derived with neither element coming from outside sources. Different percentages of plagioclase, biotite, and quartz were renucleated in different sectors of the megacryst (Brigham, 1984). The orthoclase megacrysts were formed mainly by recrystallization of K-feldspar, plagioclase, biotite, and quartz which occurred in the same volume and composition as is present in each final orthoclase megacryst.

The assumptions that are made in this isochemical recrystallization model are (1) that unstressed primary PF rocks had more than 19 vol. % orthoclase (or other K-source minerals) in them prior to isochemical recrystallization which would produce the orthoclase megacrysts and groundmass microcline and (2) that dissolution and renucleation of plagioclase, biotite, and quartz were the only processes that produced the concentric, parallel-aligned, tiny inclusions of these minerals in the megacrysts. To test these assumptions, the mineralogical composition of unstressed primary PF rocks that lack orthoclase megacrysts are examined in areas in the pluton that represent pre-megacryst time, and then areas representing megacryst forming time and post-megacryst time are examined next.

Pre-megacryst time

The least stressed area in the PF pluton which could represent pre-megacryst time and which contains those minerals that formed during the intrusion and final crystallization of the PF magma occurs at the eastern end of the broad "feeder dike" that is part of domain (A) (Fig. 1). Modes of two thin sections indicate that the rock here contains about 54-69 % plagioclase, 19-29 % quartz, 3-5 % biotite, and 8-13 % orthoclase (Fig. 3). The plagioclase is albite- and Carlsbad-twinned and relatively sodic (oligoclase, mean An₂₅). It is seriate granular, consisting of (a) tiny, normally zoned crystals (0.1-1.0 mm wide) with narrow zones (cores An₃₅; rims An₂₀), (b) intermediate-sized, normally zoned crystals (1 to 5 mm wide) with broader zones, and (c) larger crystals (5 mm to 1 cm but locally up to 2 cm long), showing the broadest zones. Many of the early-formed orthoclase crystals are inclusion free and too small to develop any Ba-K zonation that is observed in the larger megacrysts. Others have inclusions, mostly in random orientation, but some are oriented parallel to a possible orthoclase face. All of these orthoclase crystals are interstitial and in a few places are bordered by myrmekite with extremely tiny, barely visible quartz vermicules (Fig. 4 and Fig. 5). Locally, the tiny orthoclase crystals penetrate and appear to replace adjacent plagioclase crystals, forming scallops or wedges. Some adjacent plagioclase grains are cut by veins of sodic plagioclase (Fig. 5 and Fig. 6). The myrmekite and scalloped margins suggest that at least some (if not all) the orthoclase was formed by replacement of plagioclase under subsolidus conditions (Collins, 1988; Collins and Collins, 2002b; <http://www.csun.edu/~vcgeo005/Nr43Temecula.pdf>).

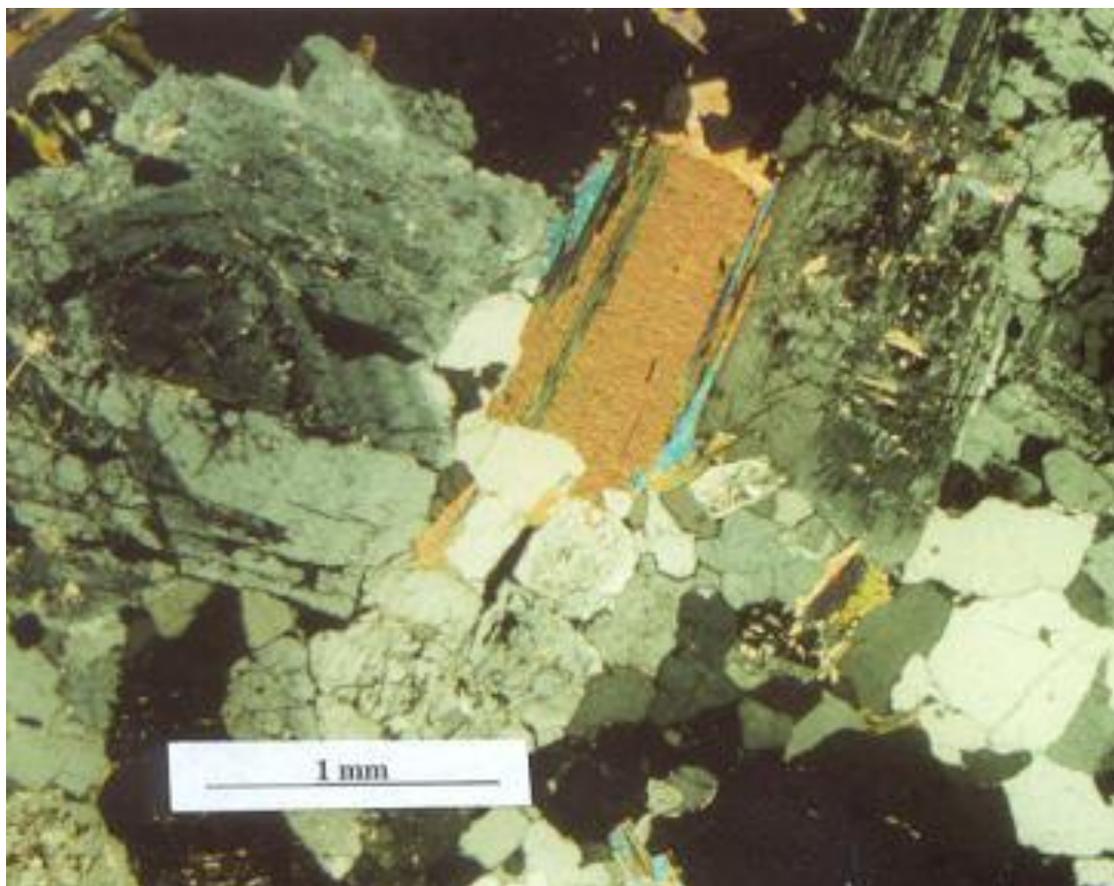


Fig. 3. Undeformed plagioclase, quartz, and biotite in granodiorite in the "feeder dike" at the east end of the Papoose Flat pluton.



Fig. 4. Tiny orthoclase crystal (light gray), replacing plagioclase (black, right and left sides; gray, bottom). Orthoclase forms wedges and scalloped boundaries against the plagioclase. Myrmekite with very tiny quartz vermicules (left side of orthoclase) forms a border against the plagioclase. Quartz (tannish gray; lower center); muscovite (brightly colored grains).

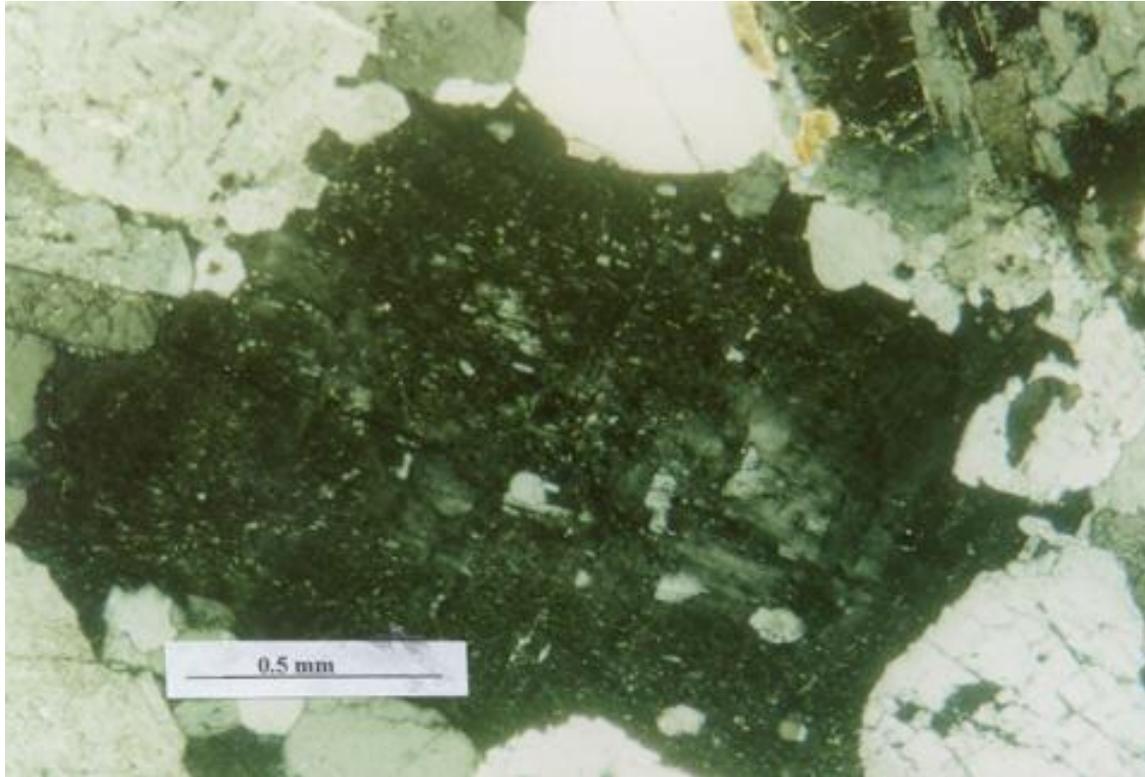


Fig. 5. Orthoclase (black) with tiny remnant plagioclase inclusions. The orthoclase forms scalloped edges against adjacent plagioclase crystals (light gray; right side and upper left). Plagioclase grain in upper left has veins of sodic plagioclase (barely visible) like that in Fig. 6. Myrmekite grains border the three orthoclase fingers (black) that project into the plagioclase (right side), but the tiny quartz vermicules are invisible in this orientation.

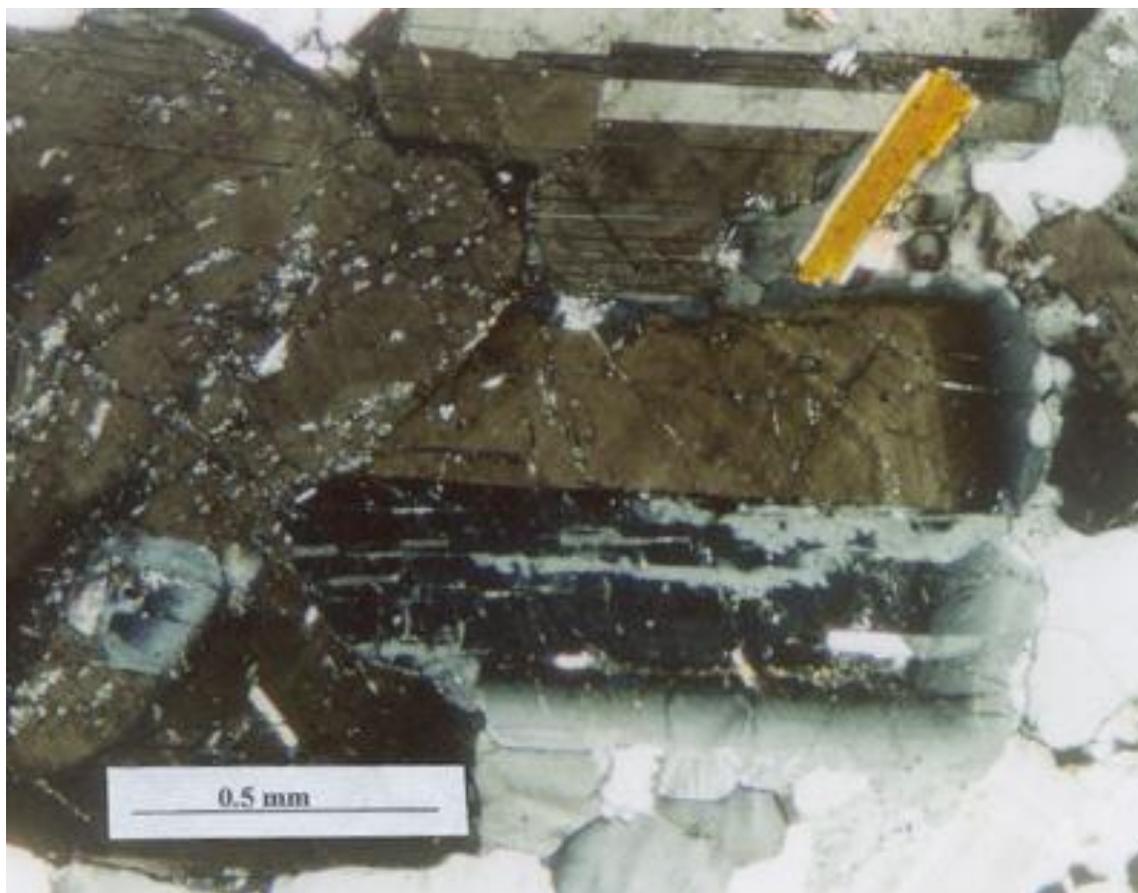


Fig. 6. Sodic plagioclase veins (light gray) cut microfractured, Carlsbad- and albite-twinned, and normally zoned plagioclase crystal. Quartz (white); biotite (brown).

Most of the evidence that post-magmatic deformation caused local microfracturing of some of the plagioclase crystals following solidification of the PF pluton has been destroyed by the recrystallization and replacement processes. Only by tracing unstressed-appearing orthoclase crystals through a transition back to "stressed" plagioclase crystals with microfractures would one be able to see the progressive changes between these two feldspars. A similar type of transition was examined by Sylvester and Christie (1968) in their studies of the conversion of stressed quartz grains (with undulatory extinction) in a sandstone to unstressed quartz grains (lacking undulatory extinction) in a quartzite adjacent to the PF pluton. Unfortunately, finding transitions between the two feldspars cannot be done because *no place exists in the pluton that is unaltered from when the pluton first completely solidified*. The only clue to the former conditions leading to the orthoclase formation is the presence of myrmekite (Collins, 1988; Hunt et al., 1992). Such a clue and the associated progressive changes between feldspars are

well demonstrated in a terrane near Temecula, California (Collins, 1997a; 1997b); Collins and Collins, 2002b).

On the basis of the studies at the Temecula site (Collins and Collins, 2002b), the wedges and scallops of orthoclase penetrating adjacent plagioclase and the myrmekite bordering the orthoclase in Fig. 4 and Fig. 5 can be used as evidence to claim that the tiny orthoclase crystals in the bulk of the PF rocks likely resulted from K-replacements of Na and Ca in microfractured plagioclase. In that case, the sodic plagioclase veins in plagioclase (Fig. 5 and Fig. 6) reveal sites where Na displaced by K moved into nearby brittle-fractured plagioclase crystals. Such albite-veined plagioclase crystals are common throughout the pluton, but they are particularly abundant in domain C. See also Fig. 10D in de Saint-Blanquat et al. (2001). Nevertheless, *because no place exists in the pluton that is unaltered*, it is impossible to determine whether some or all of the cores of the tiny orthoclase crystals were magmatically precipitated. If they were magmatic, however, they acted as nuclei sites for the overgrowths of the metasomatic orthoclase. In any case, **the amount of orthoclase in the unmodified plutonic rocks is limited to small volumes (8-13 vol. % or less), thus, suggesting that insufficient original orthoclase was present in the main body of the PF pluton for isochemical recrystallization to produce more than 19 vol. % orthoclase where the megacrysts are found.**

Megacryst-forming time

Studies of textures in thin sections of rocks in the eastern and central parts of the main PF pluton in domain (A) that are transitional to where the megacrysts first began to grow and increase in size, show that the cores of the smallest euhedral megacrysts contain orthoclase with no or few inclusions and no apparent zonation, just as is observed in many of the tiny orthoclase crystals in the feeder dike (Fig. 4 and Fig. 5). Therefore, the interpretation is made that the megacrysts nucleated on the earlier-formed magmatic and/or metasomatic orthoclase.

The growth of the metasomatic orthoclase crystals is dependent upon the ability of K-bearing fluids to reach the nucleation sites. Plastic conditions that created a flow fabric in all three domains, as reported by de Saint-Blanquat et al. (2001), are not favorable for maintaining an open fracture system for abundant hydrous fluid movements that could result in K-metasomatism, although minor movements of fluids are always possible. When the hot subsolidus PF rocks flowed plastically, annealing that healed the fractures and grain boundary migrations that adjusted for the stress on the crystals, likely simultaneously closed any avenues for abundant

hydrous fluid flow. Nevertheless, as the rocks cooled below plastic conditions, brittle fracturing could have occurred locally in some of the plagioclase crystals because the same stresses that caused a flow fabric would not necessarily cease as the pluton cooled. If so, at lower temperatures, these stresses produced brittle deformation (cataclasis) that allowed either microfracturing without rotation of fragments or granulation with translation of fragments or both. Under those conditions, avenues were kept open so that metasomatic fluids could be introduced and continue to move through the system. Evidence for such microfracturing are the albite veins that cut many of the plagioclase crystals (Fig. 6). Although cataclasis would be expected to produce undulatory extinction in the quartz, annealing at the high temperatures in which myrmekite and orthoclase replacement of plagioclase occurred would have recrystallized the quartz so that the undulatory extinction would disappear and not be seen, as also was observed by Sylvester and Christie (1968) in the wall rock quartzites.

(a) Growth of the orthoclase crystals and characteristics of the inclusions

Following formation of the first orthoclase crystals (Fig. 4 and Fig. 5), local cataclasis of the adjacent groundmass minerals could have occurred, causing breakage and granulation. This cataclasis would allow K-bearing fluids to come in, creating orthoclase overgrowths on the initial anhedral crystals. In that process these crystals gradually became euhedral and increased in size as the added orthoclase replaced most of the adjacent broken fragments (Fig. 7 and Fig. 8). The repeated cataclasis also helps to explain the crystal zoning of the tiny inclusions within the megacrysts (Fig. 9 and Fig. 10). As the crystal grows, most of the adjacent groundmass minerals are replaced by the orthoclase. Some, however, are not replaced or only partly replaced and become incorporated within the growing megacryst, forming **zones of inclusions** (parallel to the crystal faces) with each episode of K- and Ba-replacements. Each concentric zone represents another sequence of replacement and megacrystal growth.

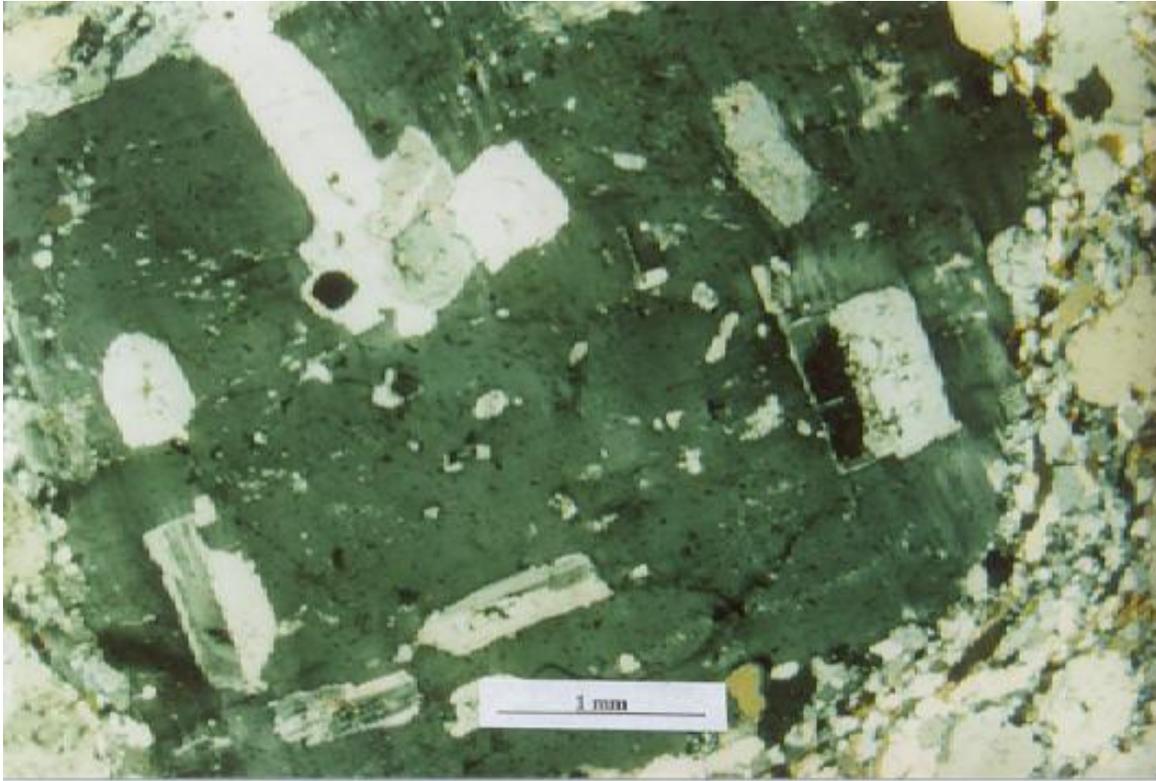


Fig. 7. Tiny orthoclase megacryst (gray), showing cataclasis of adjacent groundmass minerals. Some of the groundmass minerals have been strongly granulated. The orthoclase is partly converted to microcline along its outer boundary (right side) and shows a faint K- Ba zonation. Some tiny elongate plagioclase inclusions are oriented parallel to possible faces of the growing megacryst. One aggregate of plagioclase crystals projects from the edge of the megacryst toward its center. Biotite (black and brown) occurs as inclusions in the megacryst and as elongate crystals in the groundmass. Very tiny remnants of quartz and plagioclase fragments also occur inside the megacryst.



Fig. 8. Tiny Ba-zoned orthoclase megacryst (light gray) with strongly granulated boundary. One elongate plagioclase inclusion (left side) is parallel to the zoning and is about the same size as other plagioclase crystals in the granulated groundmass. Biotite (brown). In its outer border, the orthoclase encloses tiny granulated inclusions (left side and top right). Note that the orthoclase extends beyond corner (upper right) to penetrate and enclosed rounded inclusions and that this orthoclase is optically continuous with the main crystal and has not resulted from deformation or the orthoclase to form a "tail."

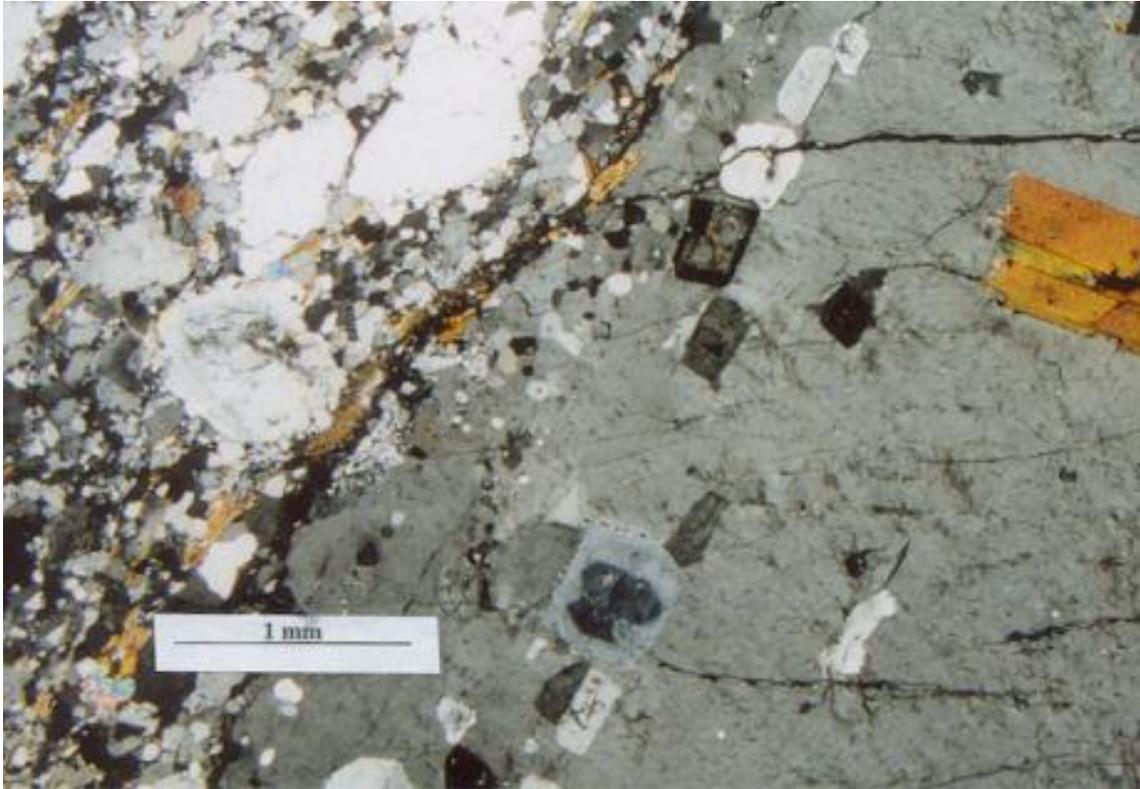


Fig. 9. Border of large orthoclase megacryst (light gray) near its corner, showing granulated groundmass minerals (left side). Quartz (white); plagioclase (light gray); biotite (brown). Tiny plagioclase inclusions show parallel alignment but some are slightly tilted. Some have an outer, sodic rim. Note that orthoclase grows around granulated groundmass minerals along the edge of the megacryst.

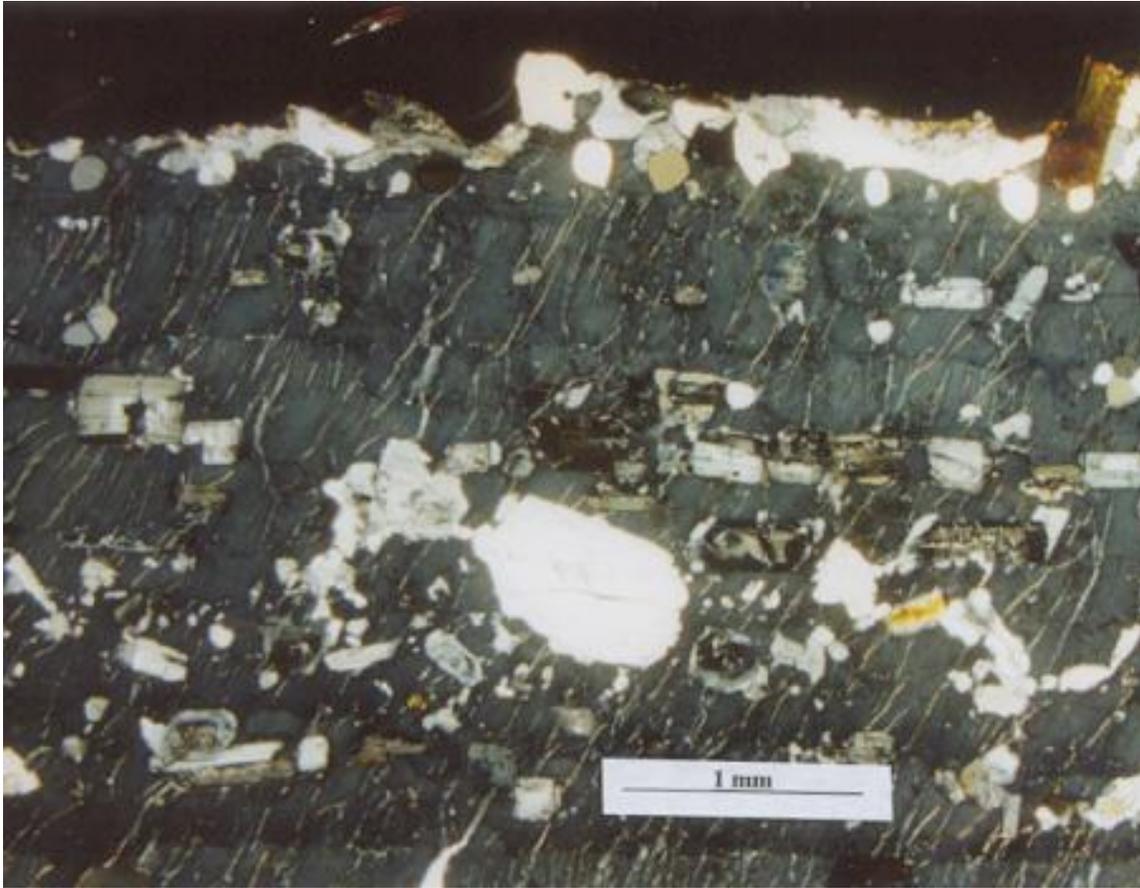


Fig. 10. Border of isolated large orthoclase megacryst (dark gray), showing remnants of granulated ground mass minerals. Black in top of photo is glass of thin section. Orthoclase projects into and around granulated groundmass minerals at the edge of the megacryst, and other former boundaries can be seen in the interior of the megacryst with disoriented fragments and tiny granulated remnant crystals. Some of these inclusions form a train of tiny crystals that are nearly in the same parallel alignment. Other crystals are strongly inclined to the zonation. Biotite (brown).

The final result, then, is an euhedral megacryst with concentric shells of tiny inclusions. Many of the plagioclase inclusions within the concentric shells are parallel to the Ba-K growth zones, but others are inclined or perpendicular. Also scattered within each zone are tiny rounded quartz and/or angular remnants of plagioclase (Fig. 11, Fig. 12, Fig. 13, and Fig. 14). Those plagioclase grains that do show alignment parallel to the crystal face might appear to have been chemically precipitated (Fig. 11) as suggested by Dickson (1996). However, some are **completely surrounded by an albite rim**, which is scalloped on all surfaces (Fig. 12, Fig. 15, and Fig. 16). A plagioclase crystal nucleating on a growing face of an

orthoclase crystal could not have scalloping on all surfaces or an albite rim adjacent to where it nucleated on the growing face. Thus, the renucleation model is negated for at least some of the plagioclase inclusions.

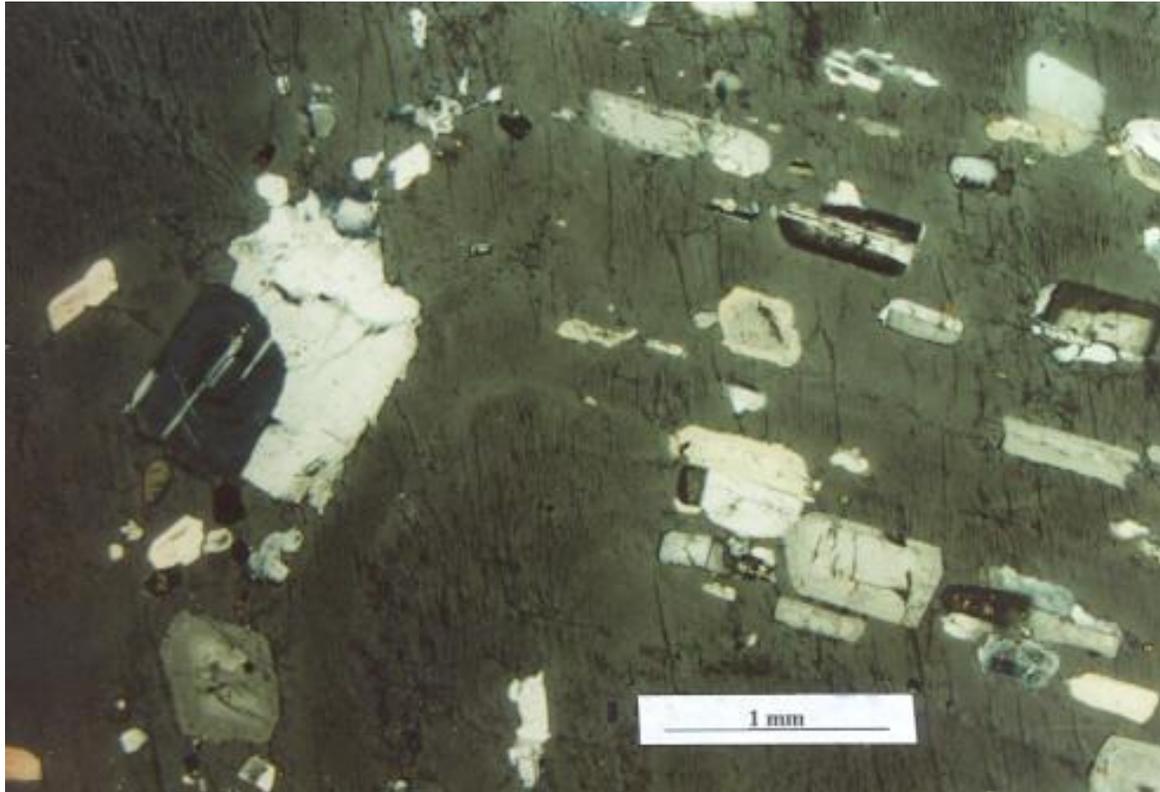


Fig. 11. Inner corner of a Ba-zoned orthoclase megacryst, showing well-developed concentric banding of tiny parallel plagioclase inclusions and change of orientation of the inclusions at the border. Inclusions generally disappear at the corner, but a few irregular tiny remnants occur in one of the layers at the corner (upper left). Many of the inclusions have sodic rims. At least one plagioclase inclusion coexists with an adjacent tiny plagioclase inclusion (black; center; about 1 mm above left end of scale) whose orientation is at right angles to the Ba-K layering.

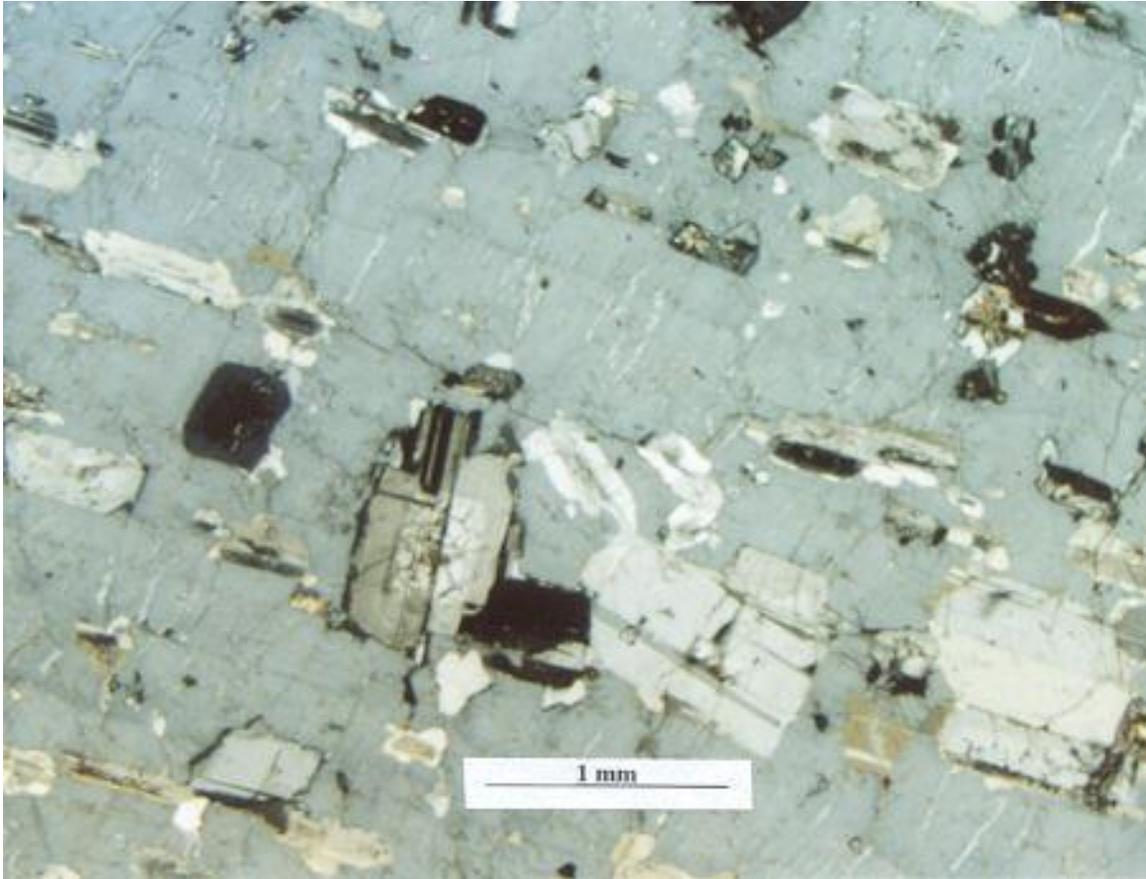


Fig. 12. Fig. Interior layers in an orthoclase megacryst (light gray), showing tiny plagioclase inclusions, generally aligned in concentric arrangement parallel to the Ba-K layers of the megacryst. Many of the inclusions are slightly tilted or strongly inclined to the layers and for many the outer albite rim is scalloped on all surfaces.



Fig. 13. Interior layers in an orthoclase megacryst (black), showing tiny plagioclase inclusions, generally aligned in concentric arrangement parallel to the Ba-K layers in the megacryst. Many of the inclusions are slightly tilted or strongly inclined to the layers. One plagioclase inclusion is strongly normally-zoned. Biotite (brown).

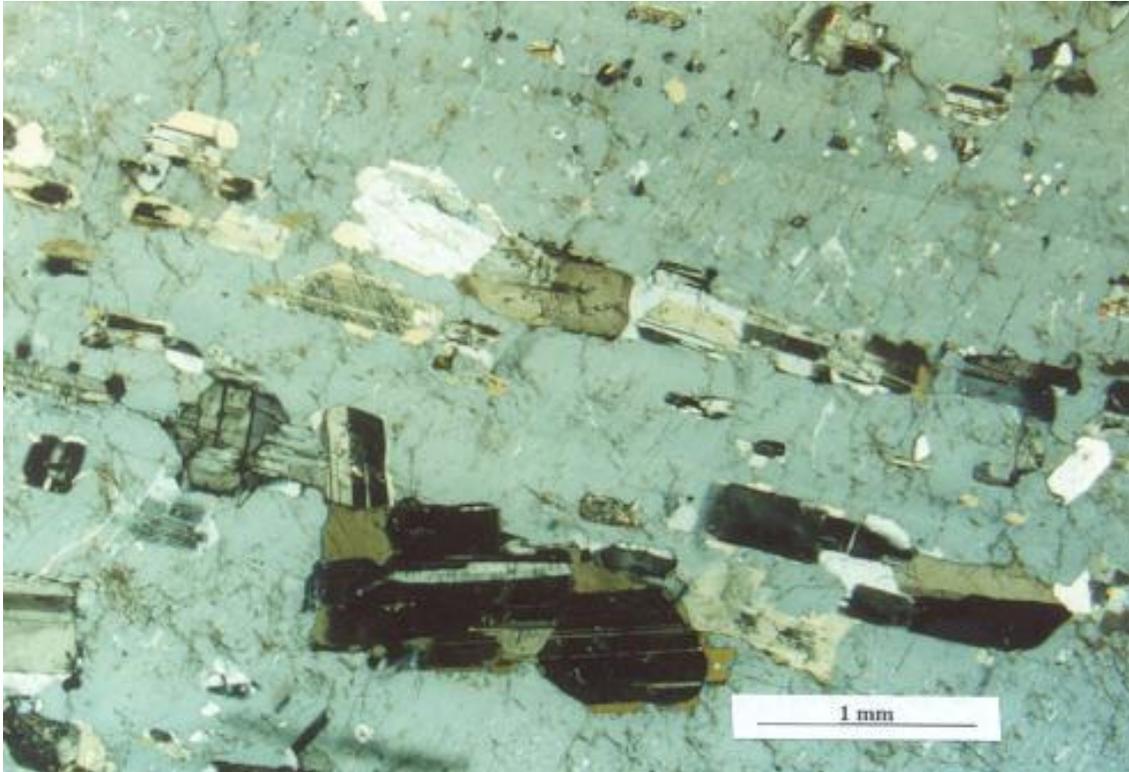


Fig. 14. Interior layers in an orthoclase megacryst (light gray), showing tiny plagioclase inclusions, generally aligned in concentric arrangement parallel to the Ba-K layers of the megacryst. Many of the inclusions are slightly tilted or strongly inclined to the layers. One band consists of a train of tiny quartz ovals (upper right).



Fig. 15. Border of large megacryst (light gray), showing relationships to groundmass minerals (right side). The orthoclase projects into and around granulated minerals smaller in size than in the adjacent coarser-grained groundmass. Many plagioclase inclusions in the orthoclase have scalloped borders. Five elongate plagioclase crystals (gray, white, black) in the groundmass have crystallized against each other in parallel alignment (synneusis) and are parallel to the zoning in the megacryst. Other crystals in the groundmass also show the same parallel alignments, but some are disoriented or at right angles (black).

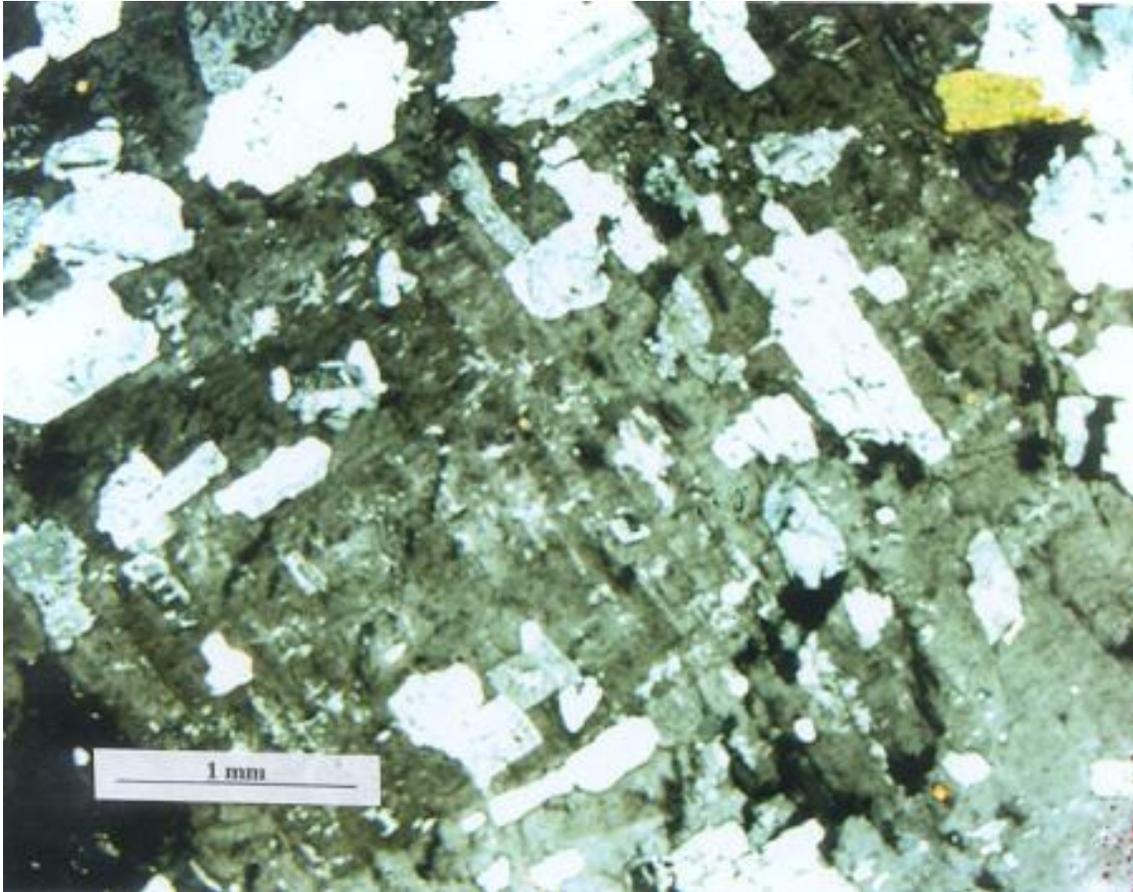


Fig. 16. Core of orthoclase megacryst (light gray), showing concentric Ba zones and concentric alignment of parallel plagioclase inclusions. A few inclusions are disoriented. Many have scalloped edges on all sides. Some inclusions are tiny oval quartz grains. Biotite (brown).

The parallel alignment of plagioclase crystals within the orthoclase megacrysts might rather be explained as a result of two factors: (a) original flow fabric of the groundmass minerals, and (b) preferential replacement of crystals that have an orientation at angles to the lattice of the growing orthoclase crystal. For example, as seen in Fig. 15 and Fig. 17, the alignment of many of the primary plagioclase crystals in the groundmass is parallel to the alignment of the plagioclase inclusions inside the megacrysts. During the replacement process, most of the strongly broken or disoriented groundmass minerals would be replaced, and only those whose lattices were parallel to the orthoclase lattice would be mostly preserved. Along the outer surface of a growing megacryst, broken grains still remain, delineating the extent of the orthoclase replacement (Fig. 15).

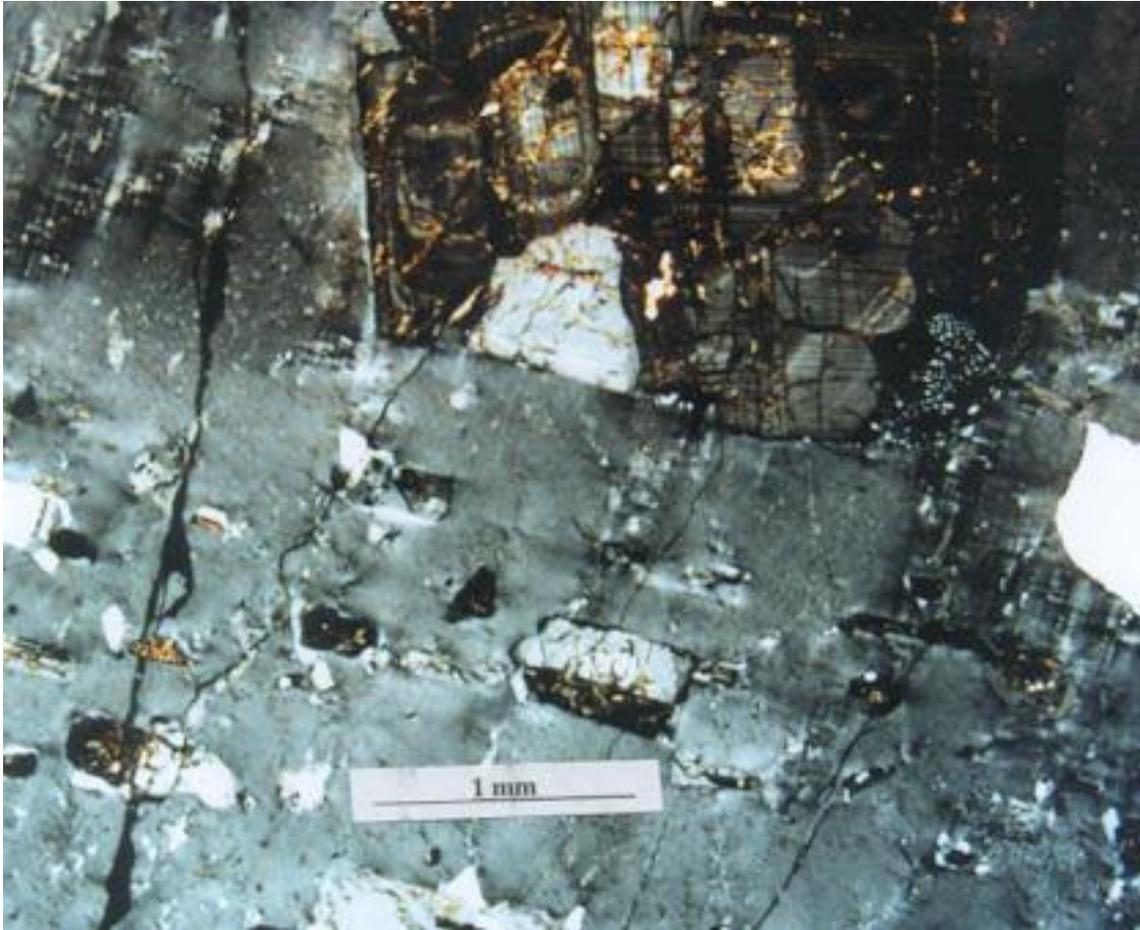


Fig. 17. The aggregate mass of normally zoned plagioclase crystals (top center) crystallized with their longer dimensions parallel to each other and are right angles to the inclusions in the megacryst. These crystals project into the orthoclase megacryst (light gray) from its edge but near the rectangular corner of the megacryst. Two plagioclase grains at the right corner of the aggregate mass adjacent to the myrmekite are parallel to the plagioclase inclusions. The myrmekite has very tiny quartz vermicules (black and white) and is in the right lower corner of the aggregate mass. Quartz (white; right side).

(b) Importance of biotite in the groundmass

The physical properties and abundance of biotite in the groundmass assert an important role in the formation of an orthoclase megacryst. Biotite has a hardness of 2.5-3.0 and planar cleavage. The primary rock has about 6 volume % biotite. When deformational forces are applied, the biotite easily cleaves, causing stresses upon adjacent plagioclase and quartz crystals. Microfracturing results, allowing avenues for K-bearing fluids to penetrate the original igneous rock and start the

replacement process. Because the orthoclase megacrysts have less than 1.0 volume % biotite as inclusions (Brigham, 1984), much of the former biotite must have been replaced. As the cleaved biotite disappears, continued stress caused more microfracturing of the adjacent groundmass minerals, many of which were replaced by orthoclase. Absence of biotite in the growing orthoclase crystal enabled additional strength, so most of the orthoclase megacrysts are not fractured except in post-megacryst time when some of the orthoclase crystals in domain (C) inverted to microcline.

The question still remains whether all megacrysts **crystallized before deformation** (magmatic model) or whether they **grew while deformation was occurring** (metasomatic model). It is agreed that the groundmass minerals anastomose around the megacrysts in deformed rock (Figs. 6 and 7, Vernon and Paterson, 2002). However, Fig. 18 shows a megacryst that **grew around remnants** of bordering anastomosing crystals, and the orthoclase of this megacryst **extends beyond the rectangular corner into the wedge of anastomosing grains** (Fig. 8, Fig. 18, and Fig. 19). This orthoclase overgrowth and extension from the corner provide evidence that the megacrysts grew while deformation was occurring, **not prior to deformation**. After a megacryst has completed its growth and temperatures have cooled sufficiently, continued deformation will cause a megacryst to be broken and produce groundmass minerals that anastomose around it (Fig. 10, Vernon and Paterson, 2002), but that breakage and continued anastomosing could occur if the megacrysts were formed either by magmatic or metasomatic processes.

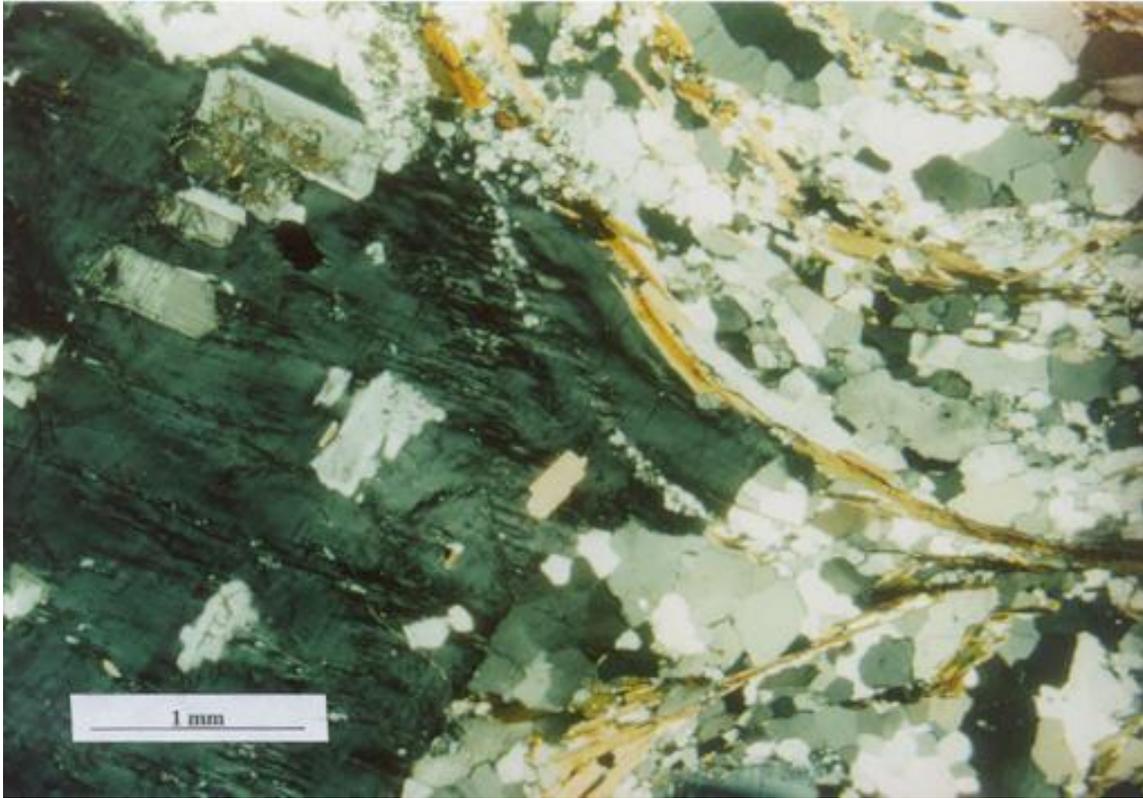


Fig. 18. Orthoclase megacryst (light gray) partly inverted to microcline, showing corner of the megacryst where the adjacent cataclastically broken groundmass minerals sweep around the top edge of the megacryst and split and sweep around the right edge of the megacryst. Larger biotite crystals (brown) are entrained parallel to the shear direction and form the upper boundary of the orthoclase. Below these biotite crystals is a train of tiny crystals that are remnants of a former shear plane that parallels these biotite crystals. This train is nearly continuous, but the orthoclase is not off-set by the shearing. The orthoclase extends into and has replaced minerals in the shear plane in the upper right corner of the megacryst. A myrmekitic inclusion occurs in the lower left (above the scale), but the quartz vermicules are not visible in this orientation. Quartz (white, gray, black) occurs on right edge of the megacryst.

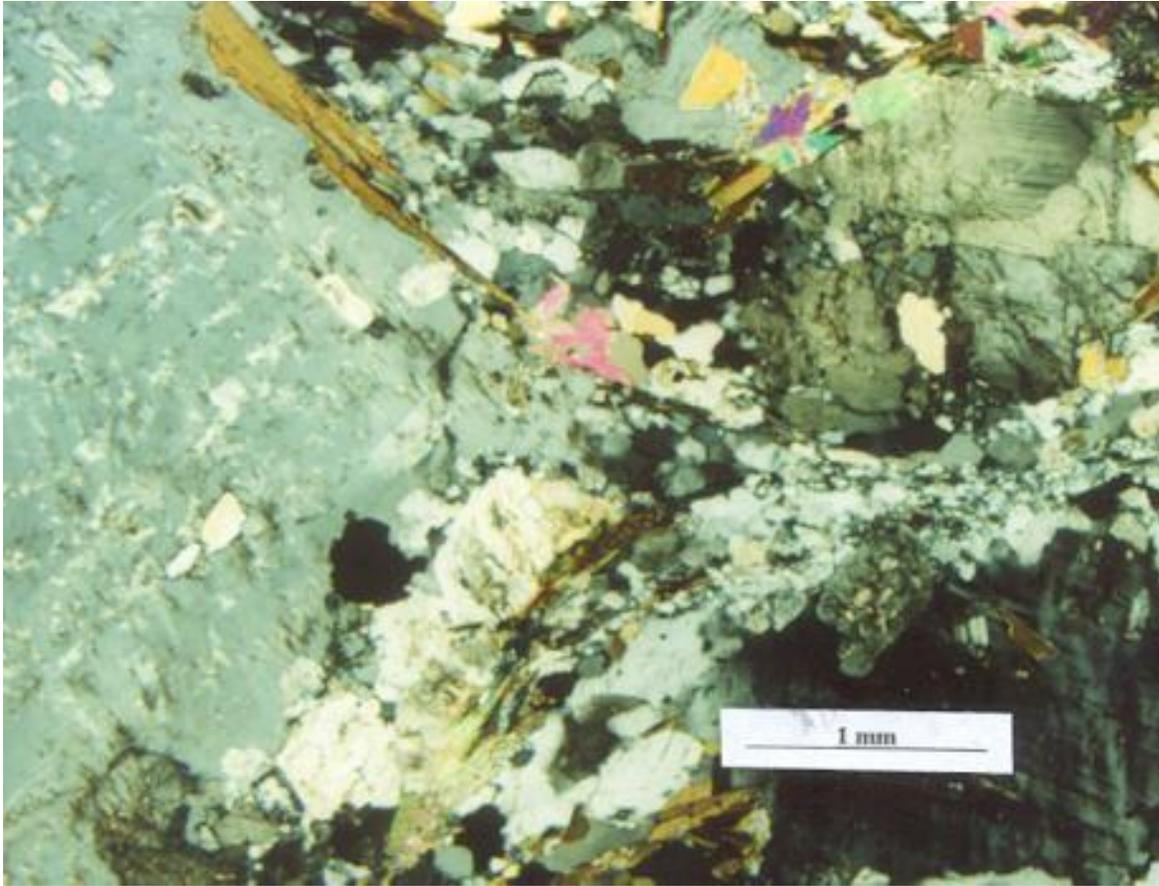


Fig. 19. Corner of orthoclase megacryst (light gray, left side) and granulated groundmass minerals anastomosing around the corner, causing elongated biotite and plagioclase grains to become aligned parallel to the faces of the orthoclase. Note that the orthoclase grew into the corner where the broken groundmass minerals split and divide and surrounded some of the broken groundmass minerals. The narrow black crystals that partly extend across the orthoclase at the corner are not in a fracture but quartz at extinction.

(c) Absence of inclusions on the (-201) face

In some megacrysts a corner is truncated by the (-201) face. Lattice spacing of elongated plagioclase crystals that were aligned parallel to that face would not be compatible with the lattice spacing of the orthoclase (-201) face. Such crystals would be preferentially replaced, thus explaining the paucity of crystals on that face or the corner where that face would develop (Fig. 11). Only when aggregates of unbroken plagioclase crystals occur are inclusions found, probably because K-bearing fluids could not reach their interiors or inner boundaries (Fig. 20 and Fig. 21).

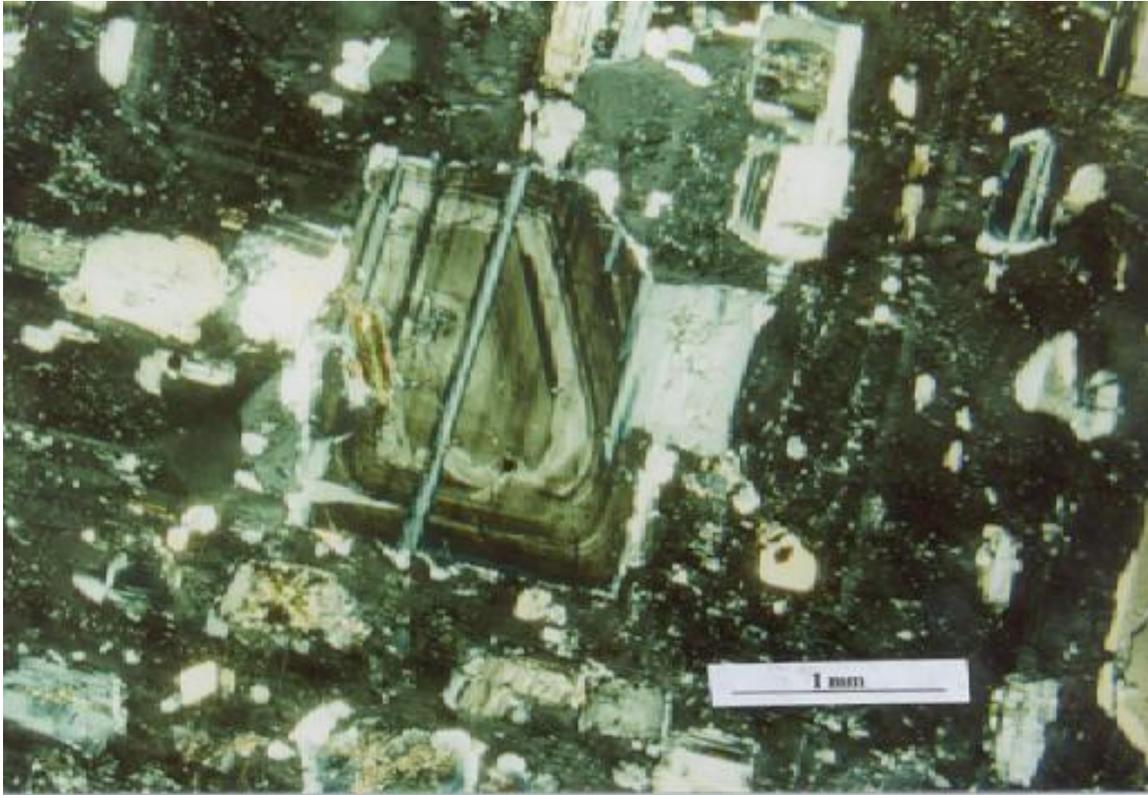


Fig. 20. Aggregate mass of plagioclase crystals that have crystallized with their longer dimensions parallel to each other. The aggregate occurs at an inner corner of the orthoclase megacryst (black). Tiny plagioclase inclusions extend in parallel layers on the right side and then change direction to become parallel to the lower edge of the aggregate (bottom left of photo). One inclusion is strongly normally-zoned. Some layers contain stringers of tiny plagioclase fragments and quartz ovals.

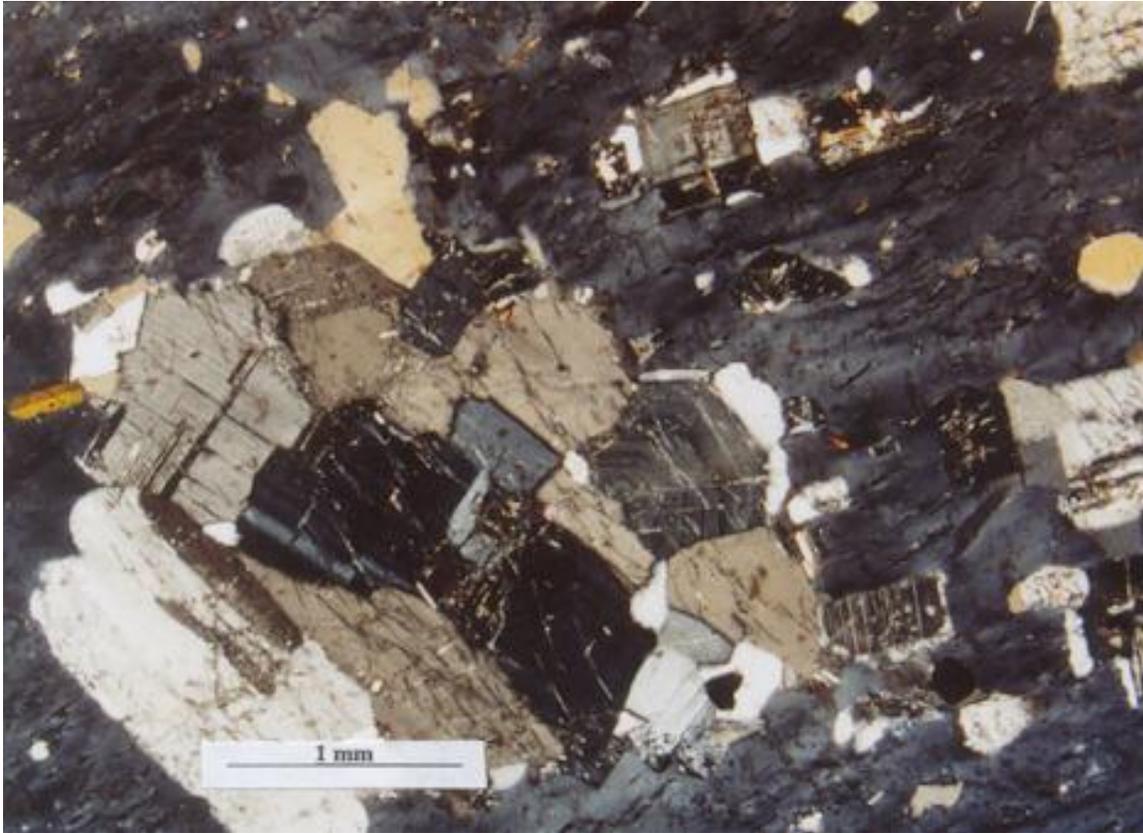


Fig. 21. Aggregate mass of plagioclase crystals at an inner corner of an orthoclase megacryst (black). Most of the crystals have lattices that are inclined to the Ba-K growth bands, but a few are parallel.

(d) Scarcity of quartz inclusions in the megacrysts

In the Papoose Flat granitic rocks, quartz is relatively abundant in the groundmass where orthoclase megacrysts are found. Ross (1965) reported 33 vol. % quartz in the average megacrystal granitic rock. Modal studies of the "feeder dike" show 19-20 vol. % quartz. In many parts of the Papoose Flat pluton, ribbons of quartz occur in the groundmass near or adjacent to the megacrysts, yet the coexisting orthoclase megacrysts **contain almost no quartz inclusions** (0.7 vol. %; Brigham, 1984). Such quartz inclusions that occur are mostly 0.1-1.0 mm wide and are notably **rounded or scalloped** (Fig. 9, Fig. 10, Fig. 13, Fig. 15, Fig. 17, and Fig 22), suggesting that **most of the primary groundmass quartz has been replaced by orthoclase**.

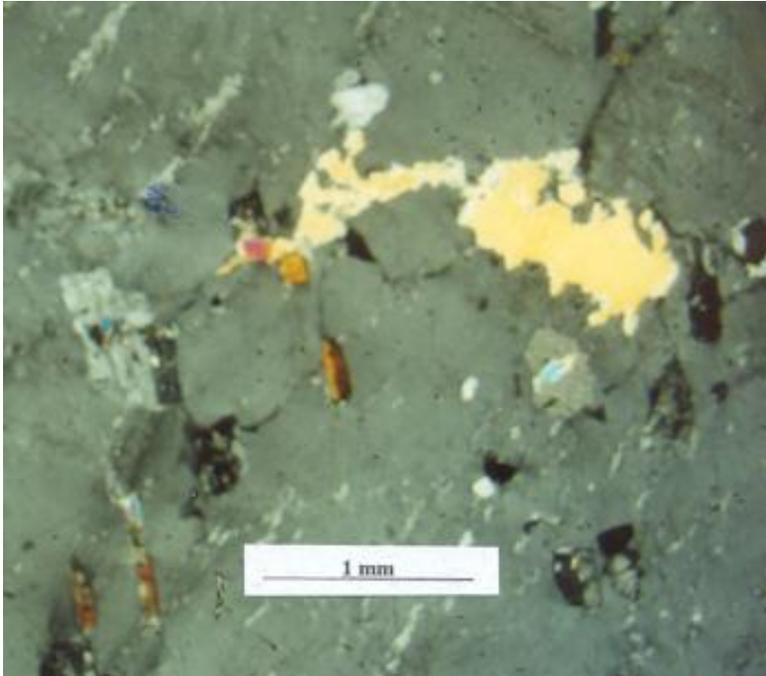


Fig. 22. Scalloped quartz inclusion (cream yellow) in orthoclase (gray) at interior corner of the megacryst.

The absence of quartz remnants as inclusions is logical because biotite and plagioclase being replaced do not have sufficient silica to provide the amount needed to form orthoclase that fills the same volume; see Appendix for calculations. As a result, silica is consumed, and little remains to form the partly replaced quartz inclusions. Nevertheless, some silica probably left the system in escaping fluids because silica is generally soluble in hot hydrous fluids.

(e) Why are the inclusions tiny?

The general tiny size of most inclusions in the orthoclase megacrysts is partly a reflection of the brittle deformation that is necessary for the K-replacements of the plagioclase crystals. Microfracturing of both large and small plagioclase crystals normally produces small fragments with many intersecting fracture boundaries. Therefore, where this closely spaced microfracturing allowed penetration by K-bearing fluids to replace some of these fragments by orthoclase, the remnant fragments that are not replaced will normally be small in size. As a result, **larger plagioclase inclusions are not found in the orthoclase megacrysts as would be expected if the orthoclase were crystallized in magma as phenocrysts.**

The further coexistence of tiny, equidimensional, strongly zoned, plagioclase grains (0.2-1.0 mm wide) with other plagioclase inclusions that lack such strong zonation (Fig. 12, Fig. 14, and Fig. 23), also lends support that all the inclusions are former primary groundmass minerals. The likely reason for the preservation of the tiny, strongly zoned crystals in the concentric zones is because these crystals are stronger (less likely to become fractured) than larger plagioclase crystals with broader Na-Ca growth zones. These larger crystals would have been more easily fractured into smaller fragments and then mostly replaced or **left as unzoned fragments**.

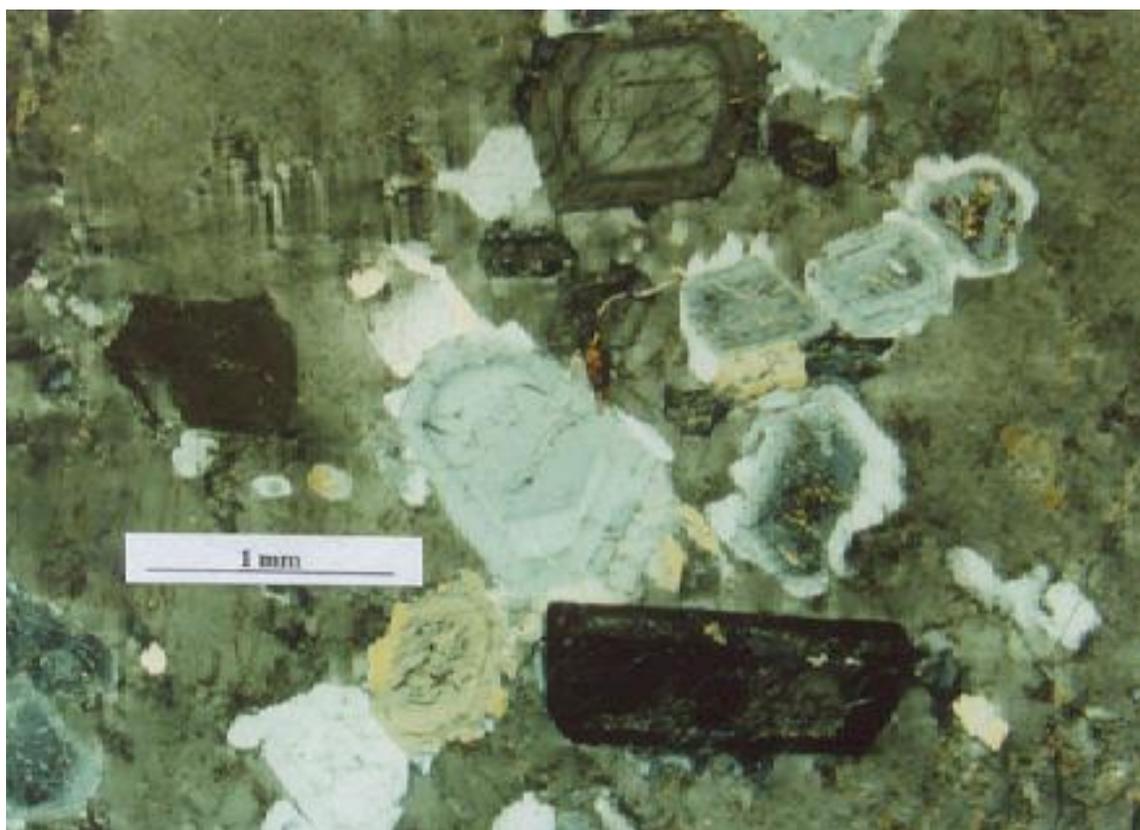


Fig. 23. Aggregate of disoriented, tiny, strongly normally-zoned plagioclase crystals in an orthoclase megacryst (dark gray) partly converted to microcline.

(f) Importance of myrmekite and the origin of the megacrysts

Wartlike myrmekite commonly forms on plagioclase crystals along the borders of the megacrysts where the plagioclase crystals project into the orthoclase (Fig. 17 and Fig. 24). Therefore, when wartlike myrmekite is found in **interior** parts of the megacrysts, either as modifications of larger grains or as isolated myrmekitic granules (Fig. 18, Fig. 25, and Fig. 26), the implication is that the interior

myrmekite grains once formed along the former faces of the growing megacryst (Collins, 1988). Moreover, in some places the myrmekite inclusions have their longer dimensions parallel to the Ba-K growth zones (Fig. 25), and, therefore, **they represent former aligned plagioclase crystals outside the megacryst** prior to their alteration and incomplete K-replacement by the orthoclase that overgrew them. This occurrence of myrmekite in cores, intermediate layers, and rims of the megacrysts is **not** consistent (1) with an origin by isochemical recrystallization because myrmekite does not form by renucleation. If myrmekite in the PF pluton formed by dissolution and renucleation, then either micrographic or granophyric textures of quartz-plagioclase intergrowths would be expected in which the plagioclase has a constant composition instead of myrmekite in which the plagioclase has variable Ca-composition proportional to the thickness of the quartz vermicules.

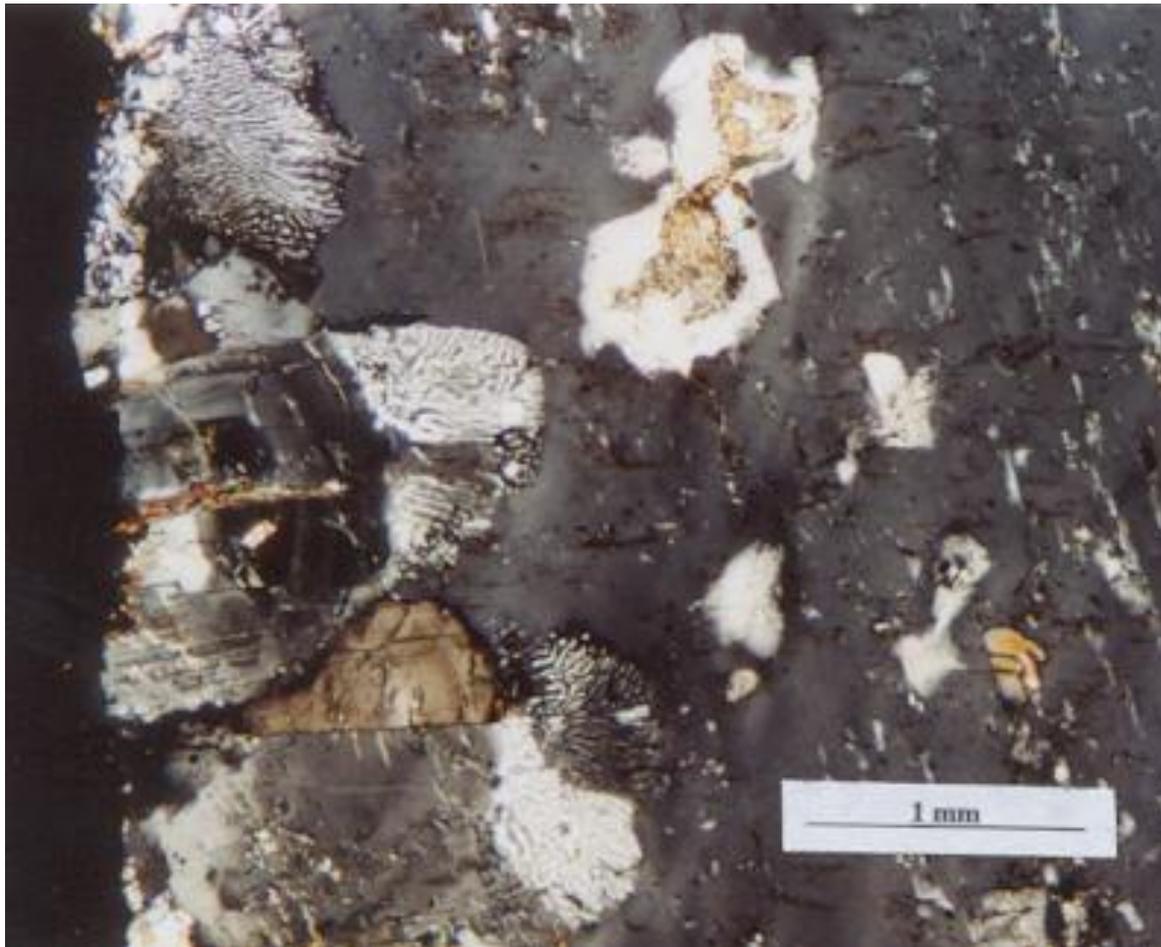


Fig. 24. Myrmekite with very tiny quartz vermicules along rim of orthoclase megacryst (gray). The myrmekite occurs primarily on plagioclase groundmass

minerals that project into the megacryst. Some plagioclase inclusions have strongly scalloped borders.



Fig. 25. Myrmekite forms an outer rim on a large, albite-twinned plagioclase inclusion that is strongly inclined to the Ba-K growth zones of the orthoclase megacryst (light gray). Four other elongated plagioclase inclusions (lower left quarter) and one plagioclase inclusion (white; above the large inclusion) is also myrmekitic. All these myrmekite grains are in the interior of the megacryst. Biotite (brown).

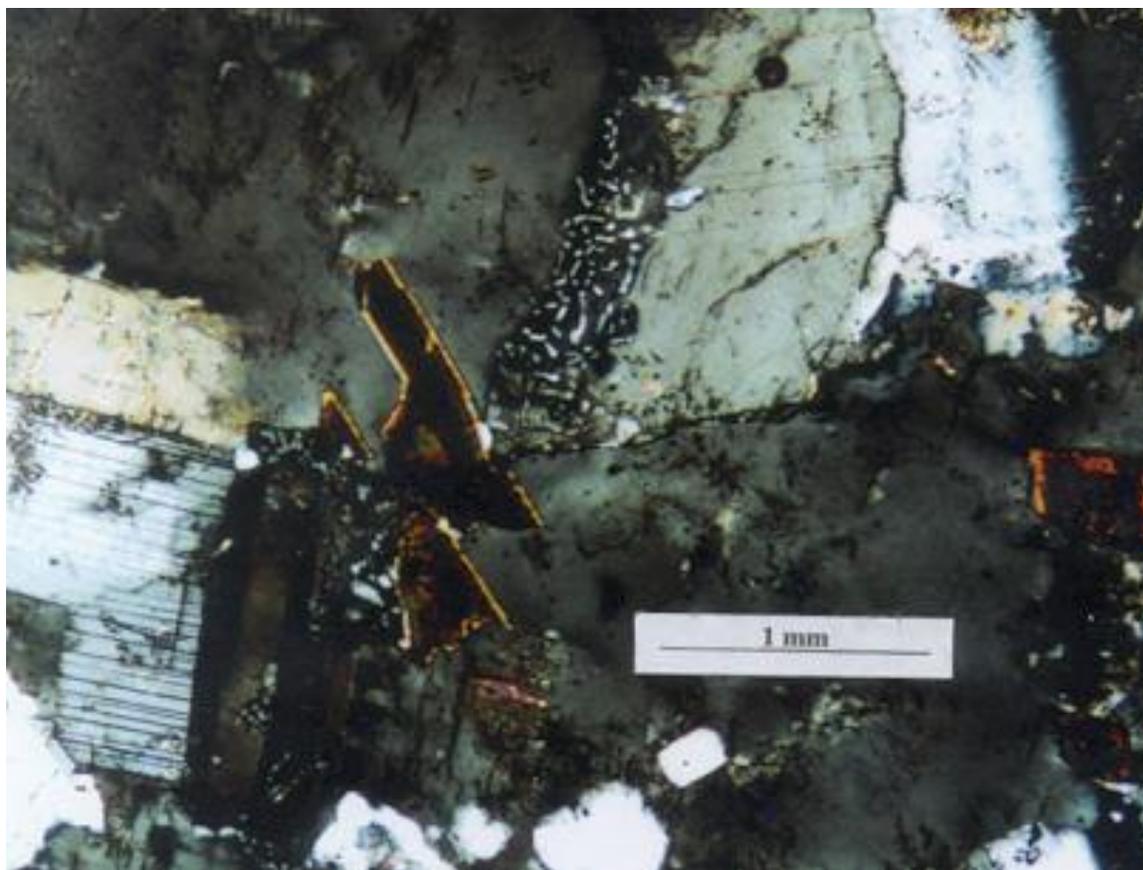


Fig. 26. Myrmekite in interior of an orthoclase megacryst (dark gray). Biotite (brown).

Vernon and Paterson (item 11, 2002) and Vernon (1991) pointed out that myrmekite is correlated with solid-state deformation and suggested that the myrmekite has formed by Ca- and Na-metasomatism along the "*margins of the megacrysts and/or along internal fractures,*" in the manner postulated by Simpson and Wintsch (1989). However, the illustrations provided by Vernon and Paterson (Figs. 11 and 12, 2002) show only fringe myrmekite and no examples of myrmekite forming along internal fractures. If Ca- and Na-bearing fluids had penetrated internal fractures in primary orthoclase phenocrysts in the PF pluton, then a continuous strip of myrmekite granules should occur on both walls of the fracture, as is observed in fractured primary orthoclase in Finland (Collins, 1997d), and **that has not been observed**. Moreover, the K-feldspar crystals in the terranes in California and Connecticut, in which Simpson and Wintsch (1989) assumed that the K-feldspar crystals were primary, have been restudied, and the K-feldspar crystals are actually secondary K-replacements of primary plagioclase in deformed rocks (Collins, 1997f, 1997g). Nevertheless, wartlike myrmekite in the **interiors** of megacrysts in the Papoose Flat pluton, which are not along internal fractures,

would be expected only with incomplete K-metasomatism of deformed primary plagioclase (Collins, 1988; Collins and Collins, 2002b).

(g) Different features in domain (C)

In domain C, the area of strongest deformation (de Saint-Blanquat et al., 2001), some orthoclase megacrysts have different features from what is found in orthoclase megacrysts in domains (A) and (B). Although many megacrysts in domain (C) have abundant parallel-aligned plagioclase inclusions in concentric zones throughout the megacrysts (Fig. 27), some have **no inclusions** in the inner 70 percent of the megacryst and sparsely distributed parallel and disoriented inclusions in the outer 30 percent (Fig. 28 and Fig. 29). Other megacrysts contain abundant inclusions that are arranged in concentric zones, but nearly all these inclusions are **randomly oriented** (Fig. 30 and Fig. 31).

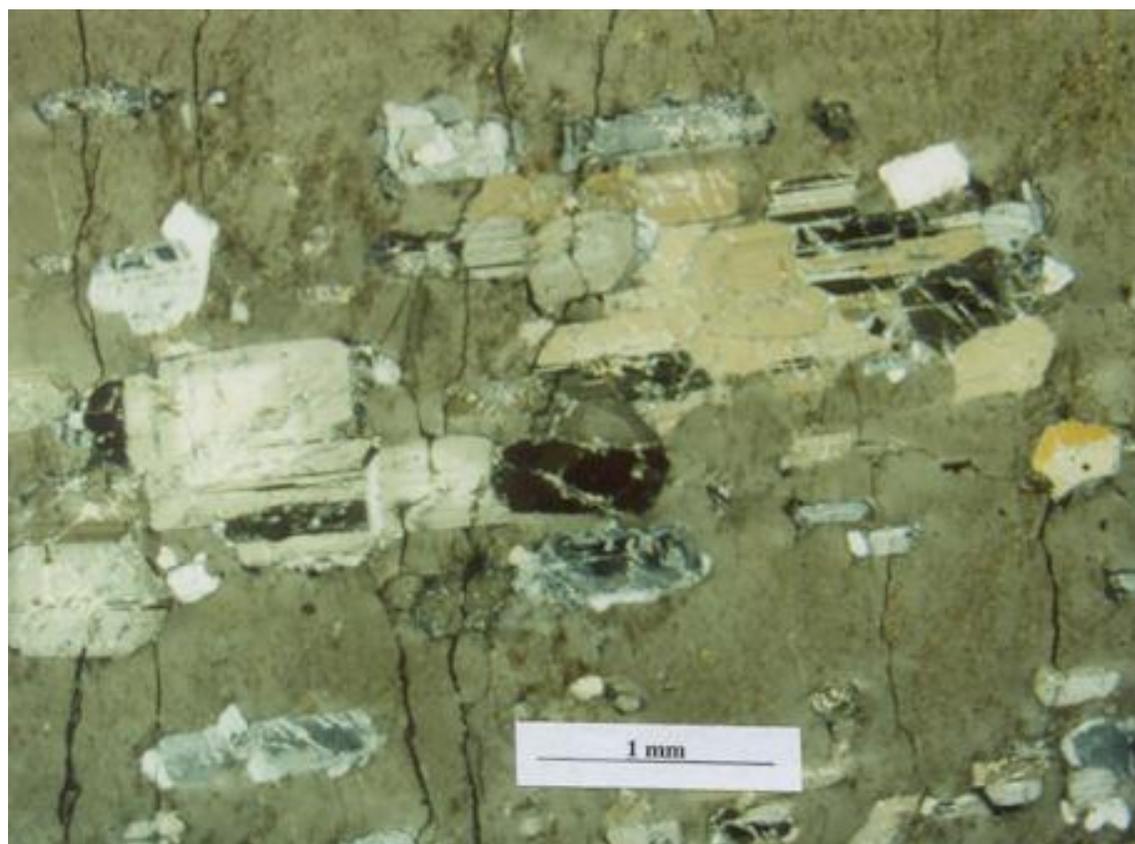


Fig. 27. Orthoclase megacryst (gray), containing an aggregate of parallel aligned plagioclase crystals, some of which show faint zonation. The plagioclase crystals in the aggregate are parallel to the scattered plagioclase inclusions which are parallel to the Ba-K growth zones. The aggregate is suggested to be a remnant of the flow fabric in the former groundmass that was enclosed by the growing

orthoclase crystal. Sample is from the south border of the east end of the pluton in the "feeder dike" near the metasedimentary wall rock.

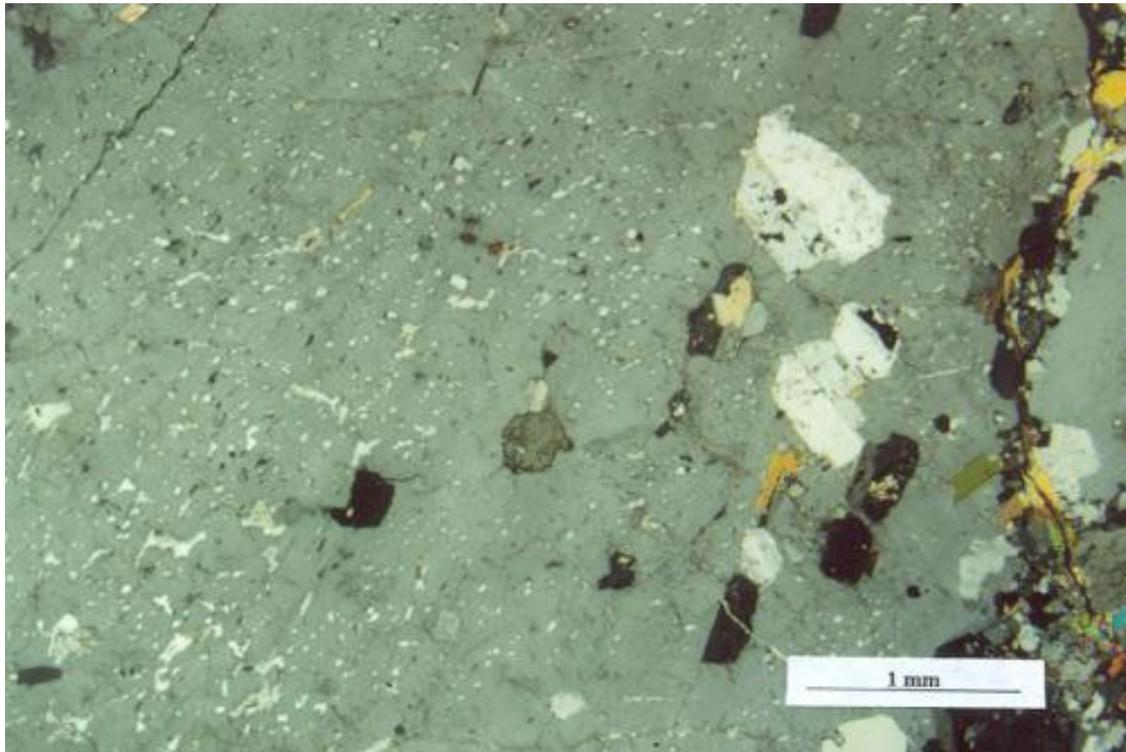


Fig. 28. Fig. Orthoclase (light gray), showing sparse plagioclase inclusions in Ba-K growth zones (left side), and the orthoclase megacryst lacks plagioclase inclusions beyond the left side of the photo to the core of the megacryst. Three of the plagioclase inclusions (white) have lattices that are inclined to the growth zones (right side). Edge of megacryst against granulated groundmass (far right side).

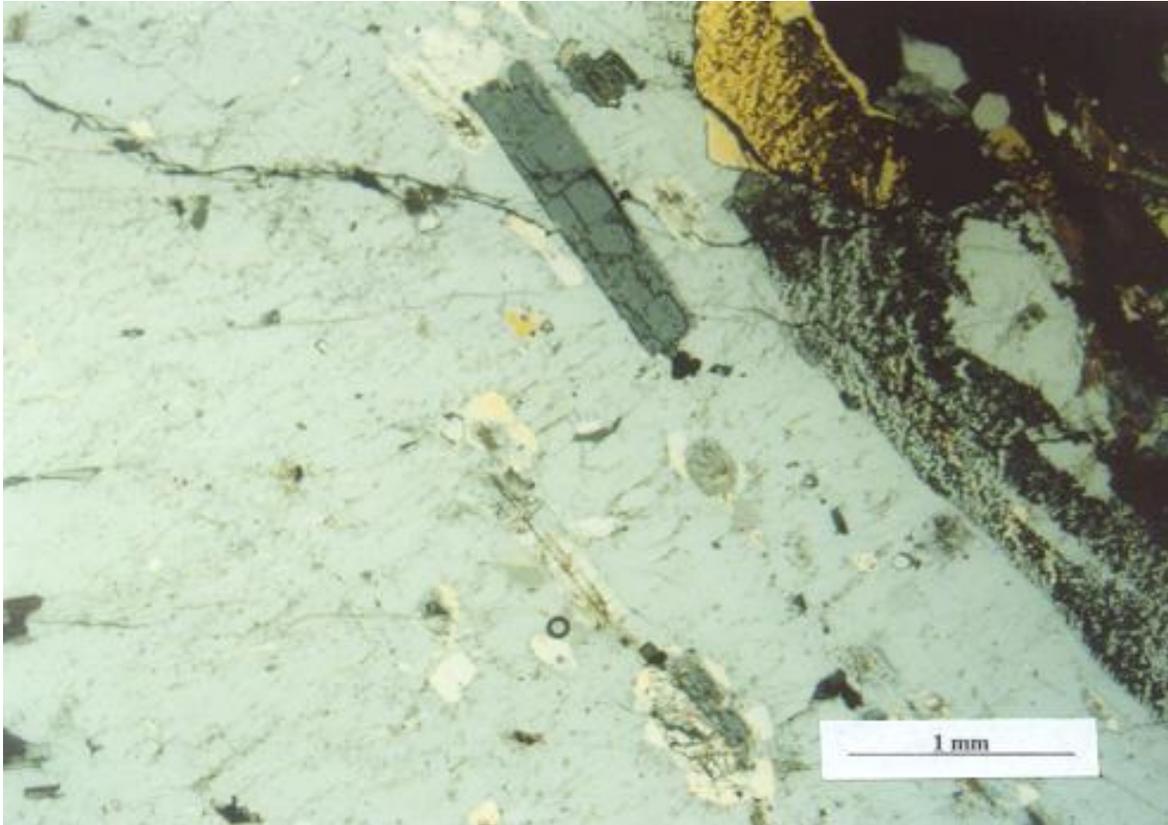


Fig. 29. Orthoclase (light gray), showing sparse plagioclase inclusions in Ba-K growth zones (left side). The orthoclase megacryst lacks plagioclase inclusions to the core outside of the photo (lower left corner). The plagioclase inclusions (white and gray) are zoned with outer sodic rims. Elongate crystal inclusion (dark gray; top, center) in the orthoclase is andalusite. Groundmass minerals are show in upper right. Irregular streams of granular dust (black) over quartz (yellow) and other dust (light gray) on groundmass minerals (black) are granules of grinding powder that did not get removed from the thin section before the cover slip was attached. Sample was collected in the granitic rock near the contact with andalusite-bearing metasedimentary wall rocks.

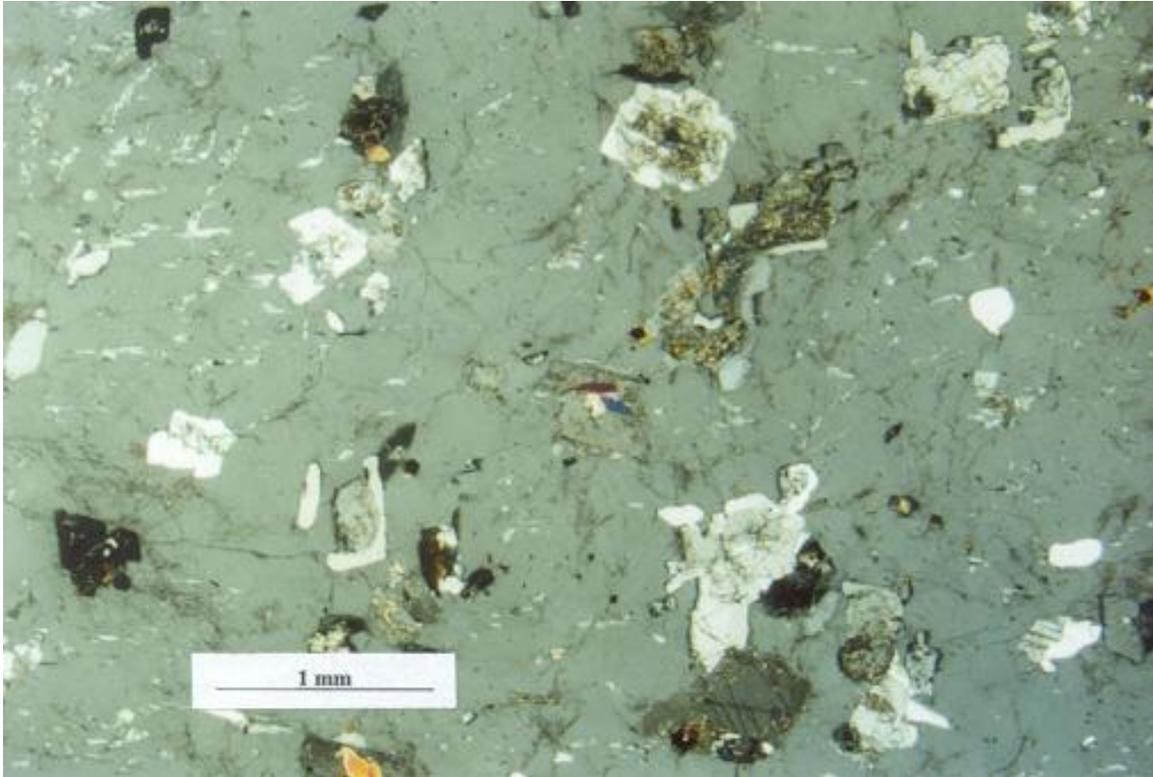


Fig. 30. Interior of orthoclase megacryst (gray), showing disoriented plagioclase inclusions along Ba-K growth zones that extend from upper right to lower left. None of the inclusions is aligned parallel to the growth zones.

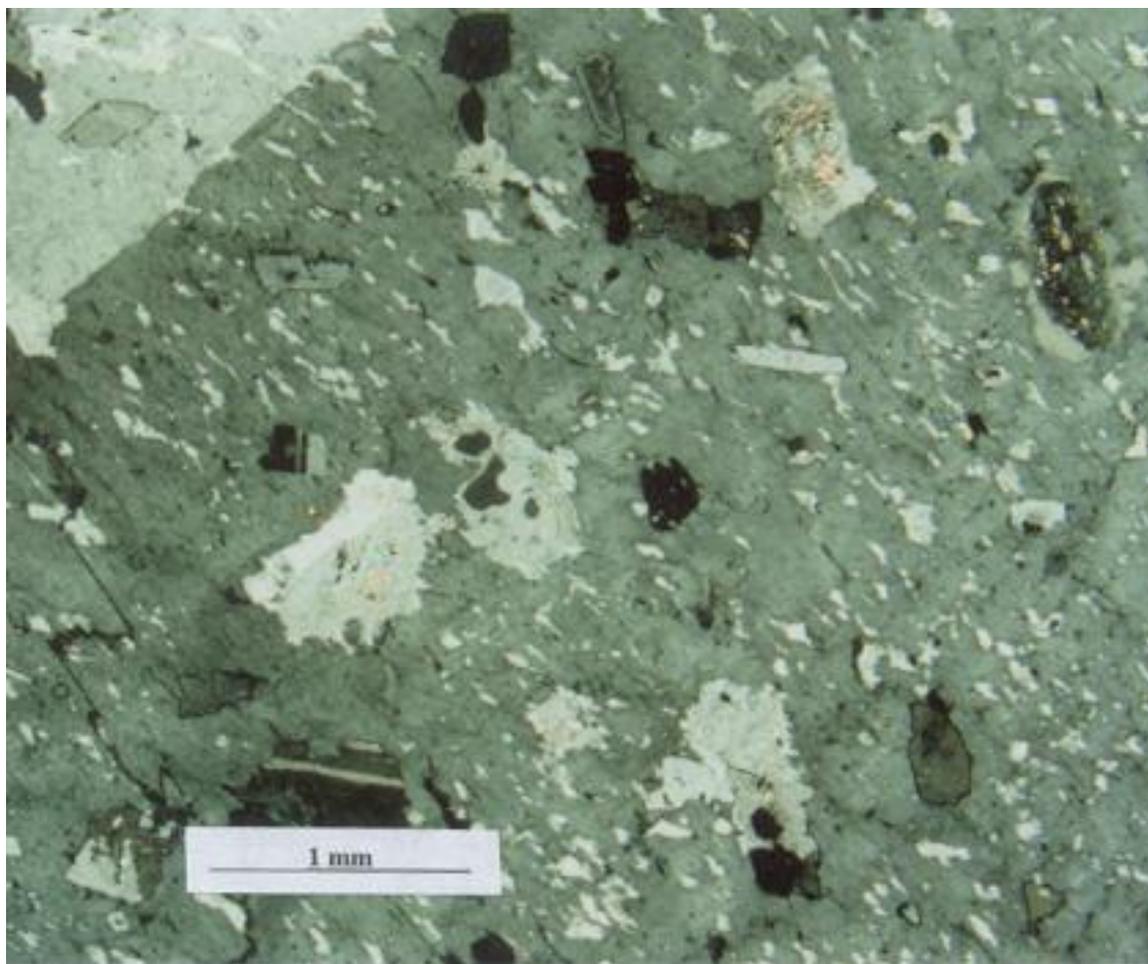


Fig. 31. Interior of Carlsbad-twinning orthoclase megacryst (light gray and dark gray), showing disoriented plagioclase inclusions along Ba-K growth zones that extend from lower right to upper left. None of the inclusions is aligned parallel to the growth zones, and many have borders that are strongly scalloped. Sample is from granitic rock near contact with metasedimentary wall rock.

In pre-megacryst and megacryst-forming time of domain (C), groundmass minerals were microfractured and broken, opening the system so that K-bearing fluids could enter, cause replacements, and produce orthoclase megacrysts. The absence, sparse amounts, or scrambled orientations of the plagioclase inclusions in the megacrysts resulted from the strong deformation of the groundmass minerals (the former crystallized granitic rocks) in domain (C). Broken and microfractured plagioclase crystals were either entirely replaced by orthoclase (inner 70 %) or mostly replaced (outer 30 %); Fig. 28 and Fig. 29. Moreover, the scrambled orientations of inclusions permitted many disoriented plagioclase fragments and crystals to be surrounded by orthoclase before they could be totally replaced (Fig. 30 and Fig. 31); see also Fig. 10 in Vernon and Paterson (2002). On the basis of

these observations, **if stress is the key factor** in the isochemical recrystallization model for causing plagioclase crystals to be dissolved and renucleated on faces of a growing orthoclase megacrysts, the megacrysts in domain (C), the area of strongest stress, should show the best developed concentric zones of parallel aligned plagioclase inclusions, and **that is not the case**.

Another different feature of domain (C) is the relative abundance of orthoclase corner-extension replacements that are shown in Fig. 18, Fig. 32, and [Fig. 33](#) and which can be compared with those in domain (A) in Fig. 8 and Fig. 19. Corner replacements in domain (C), however, are more extensive with orthoclase extending as long prongs or fingers from a megacryst corner (Fig. 34 and Fig. 35). Moreover, even though some of the tails are slightly deformed (Fig. 34 and Fig. 35), the orthoclase in the single tails is not pulled apart into a train of separate fragments, as would be expected for former phenocrysts that have been deformed. In areas of strongest deformation, however, at temperatures below which orthoclase and microcline replacements occur, double tails on megacrysts are formed in which fragments are pulled apart in long trains (Figs. 8 and 9, Vernon and Paterson, 2002). Such tails can be expected where strong mylonitization at low temperatures occur, but these double tails do not necessarily make the deformed megacrysts into former phenocrysts.

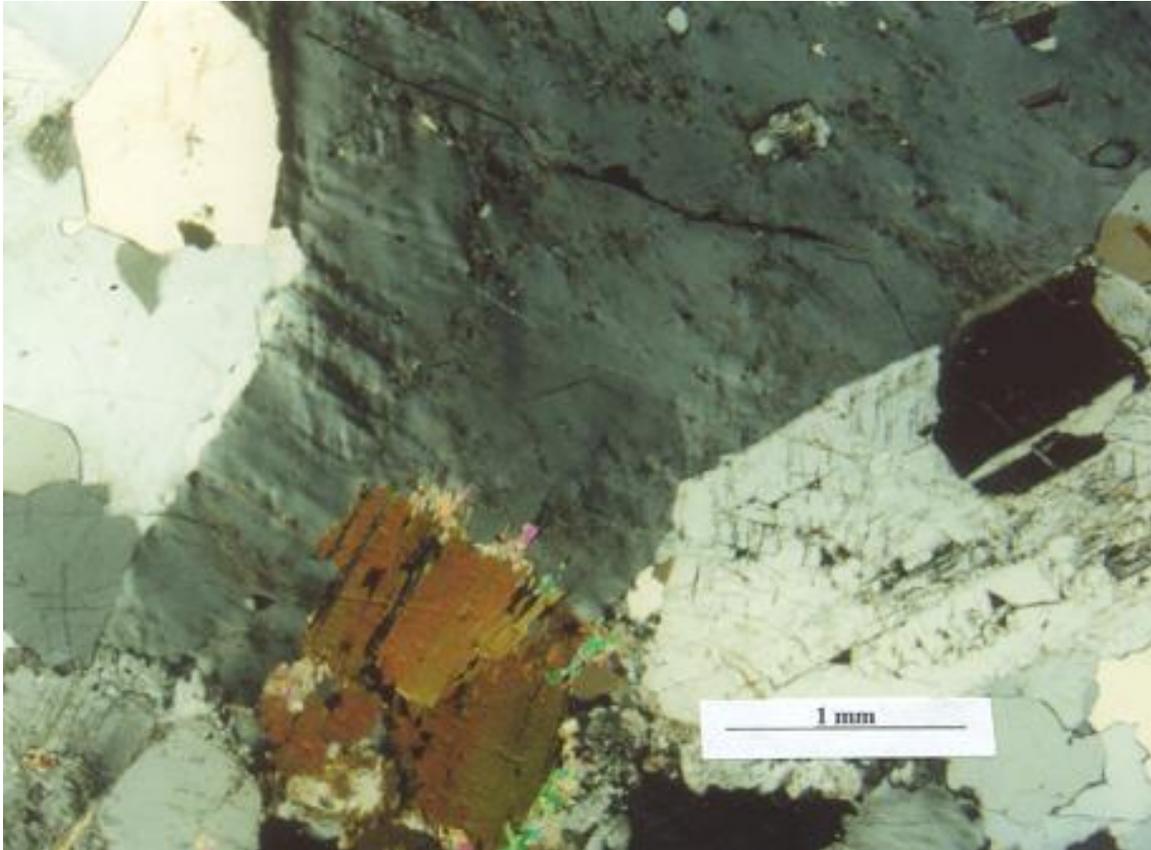


Fig. 32. Orthoclase megacryst (dark gray; top center) inverting to microcline and showing its corner (left of center) where the orthoclase extended beyond the corner (lower left) and replaced broken plagioclase crystals that surround biotite (brown). Sample is from south edge of the center of the pluton near metasedimentary wall rock.

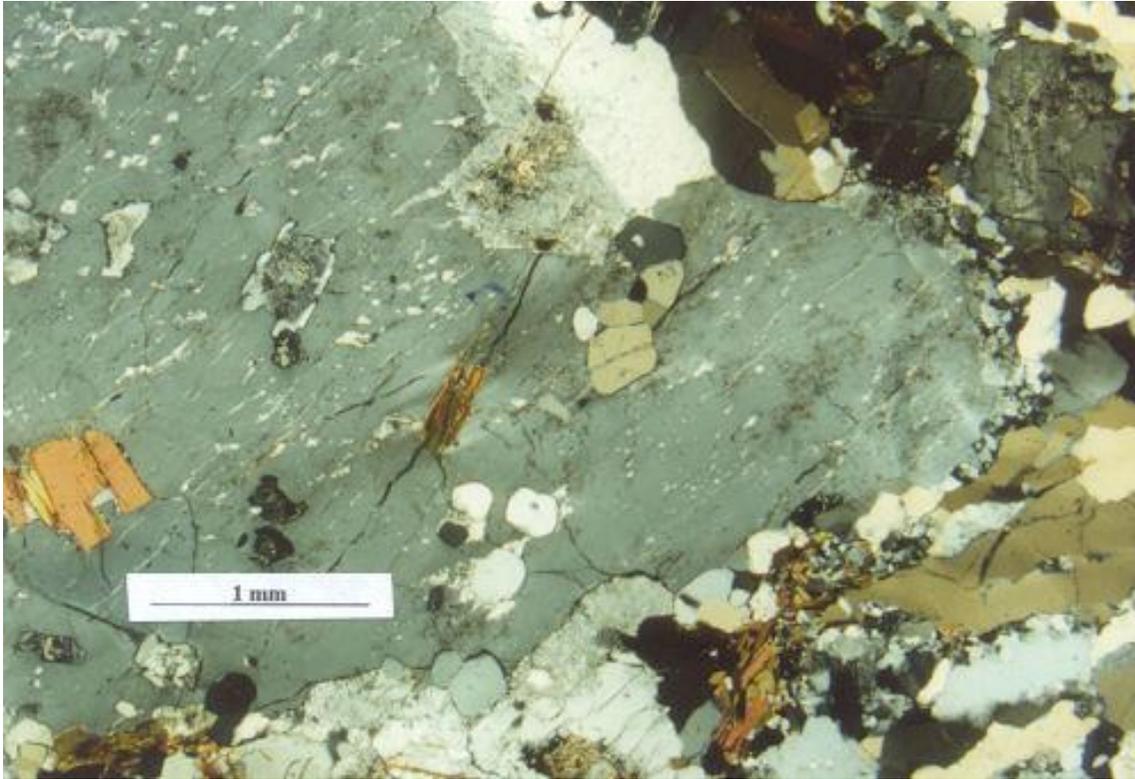


Fig. 33. Orthoclase megacryst (gray; left side), showing its corner (center) where the orthoclase continues as a bulbous extension beyond the corner into granulated groundmass minerals (quartz, plagioclase, and biotite; right side). All the orthoclase is optically continuous and shows no evidence of breakage (shearing) that would drag parts of the orthoclase into the groundmass.

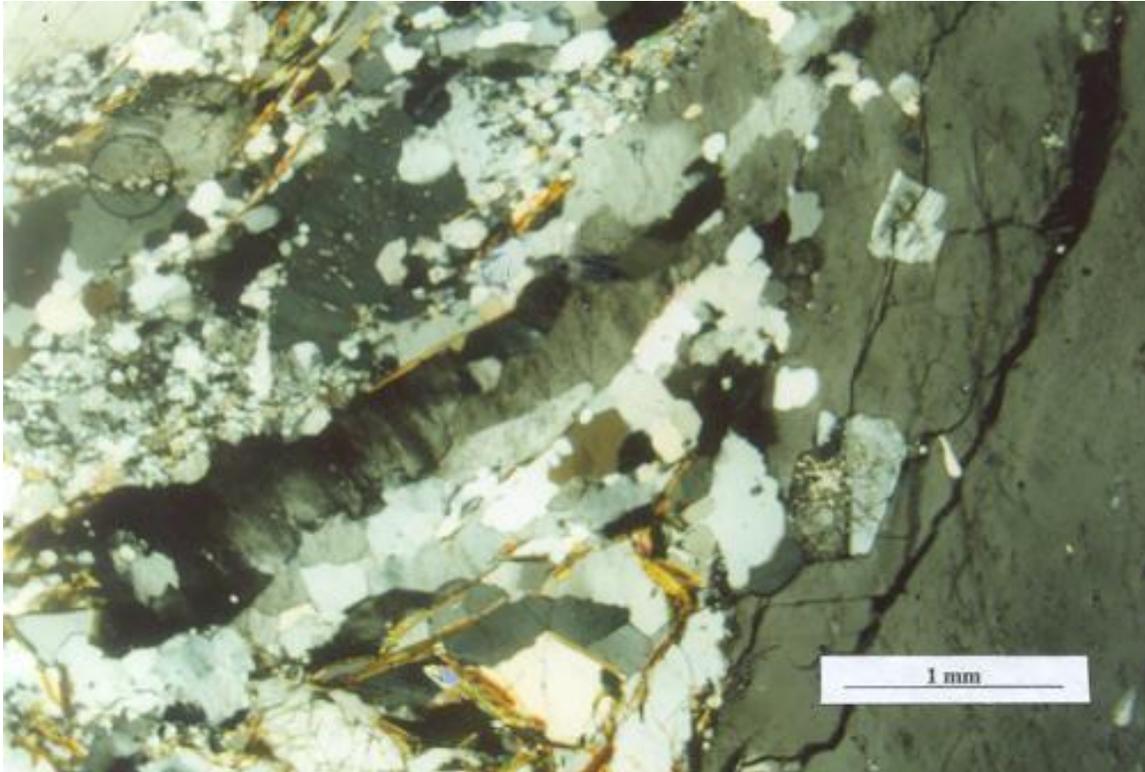


Fig. 34. Orthoclase megacryst (dark gray; right side), showing a narrow prong of orthoclase (dark gray and black) extending from near the corner of the megacryst into granulated groundmass minerals. Parts of the orthoclase in the extension are not optically continuous with the orthoclase in the megacryst, but most of the prong is.



Fig. 35. Corner of orthoclase megacryst (left side) with plagioclase inclusions. From the corner, orthoclase extends into granulated groundmass minerals in a contorted sinuous finger (toward the right). Part of the edge of the megacryst is broken as is the finger so that the orthoclase is no longer optically continuous in these places. The broken part has inverted to microcline.

Post-megacryst time

Superposed on this metasomatic history during megacryst forming time, however, is what happened in post-megacryst time. In post-megacryst time, deformation in all three domains (A), (B), and (C) continued during further upward movements of the solidified pluton, locally causing additional brittle deformation, not only breaking the groundmass minerals, but also earlier-formed megacrysts. The deformation was strongest in domain (C) and along the margins of the pluton as it also was during megacryst-forming time. In this stage, however, subsolidus temperatures were lower than the temperatures in which orthoclase megacrysts were formed. Where cataclasis was strong, locally, secondary quartz crystals were formed with euhedral outlines (Fig. 36). At the lower temperatures **microcline instead of orthoclase replaced interiors** of microfractured plagioclase grains, inheriting the albite twinning of the plagioclase as part of its grid-twinning (Fig.

37); see also Fig. 5 in Collins and Collins (2002a);
<http://www.csun.edu/~vcgeo005/Nr41Cathedral.pdf>.

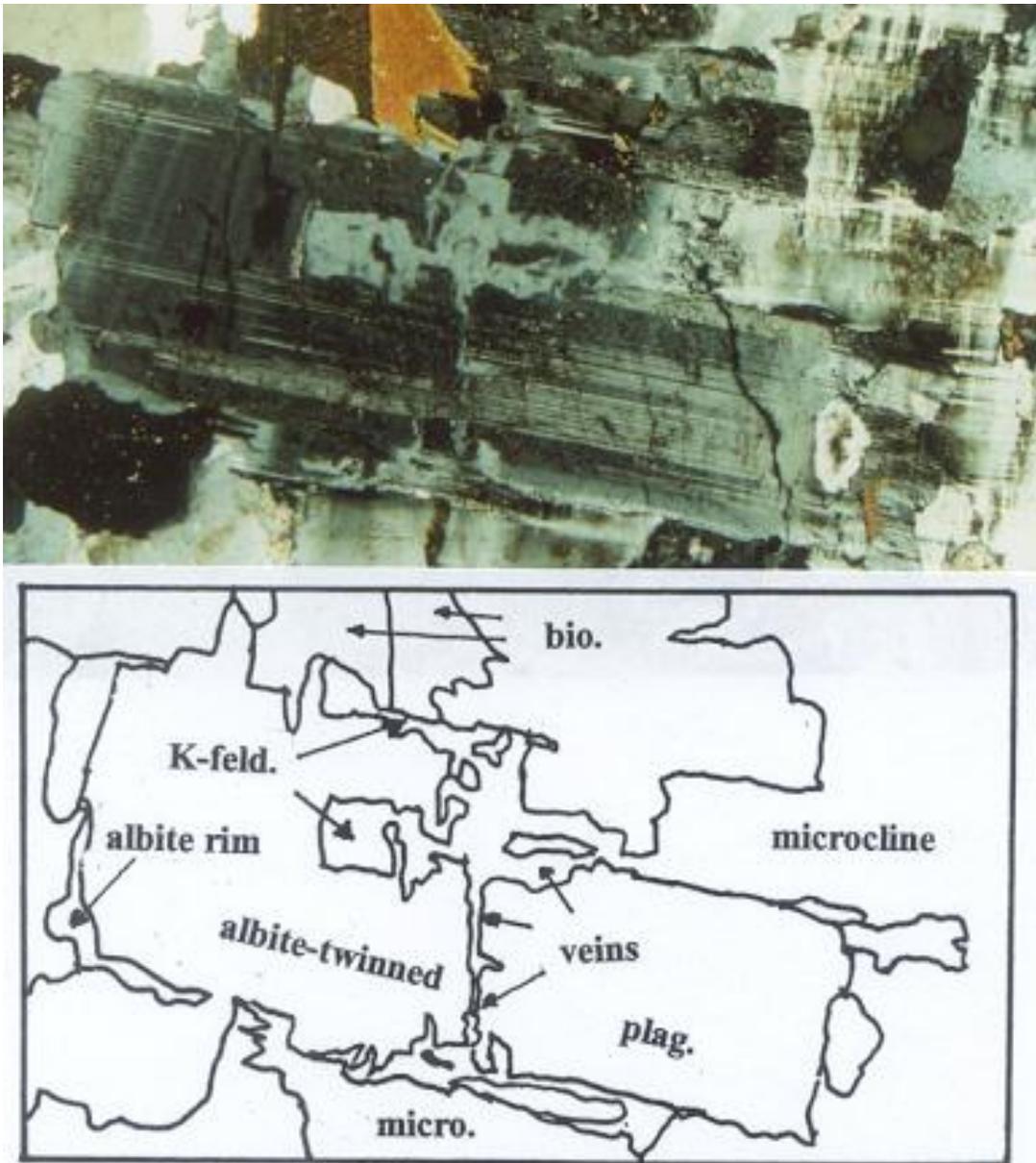


Fig. 5 in Nr41Cathedral.pdf. Veins of K-feldspar (center; light gray) in interior of albite-twinned, zoned plagioclase (black, light gray). Here, the veins crosscut the twinning and extend down to the edge of the plagioclase where veins also crosscut the twinning. From the center to the right, the light gray K-feldspar gradually changes to grid-twinned microcline at the end of the albite-twinned plagioclase crystal. One plane of the grid-twinning in the microcline is parallel to the albite twinning of the plagioclase. At left end of the plagioclase grain is an outer rim of albite, which is replaced by microcline at bottom center of the plagioclase. Biotite (brown); quartz (white, cream, gray).

Aggregates or isolated wartlike myrmekite grains with very tiny quartz vermicules are common where the microcline replaces the plagioclase (Fig. 38 and Fig. 39). The myrmekite, as shown in Fig. 39, cannot have formed by exsolution because the volume of myrmekite is much greater than could possibly exsolve from the volume of adjacent microcline.

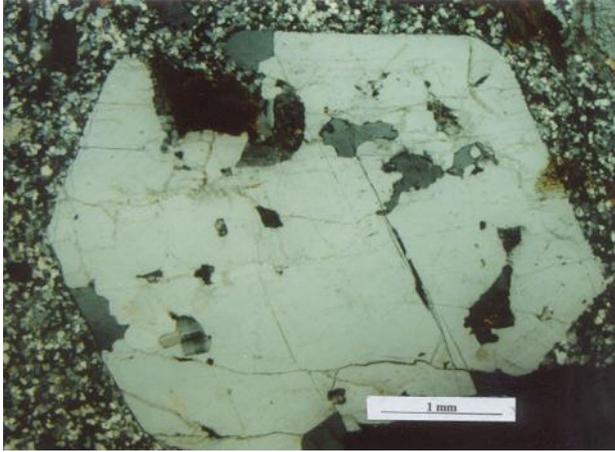


Fig. 36. Fig. 36. Euhedral quartz crystal in a strongly cataclastic groundmass. Note that this figure is from a sample at site 39 on Fig. 2 until Fig. 2 can be corrected.

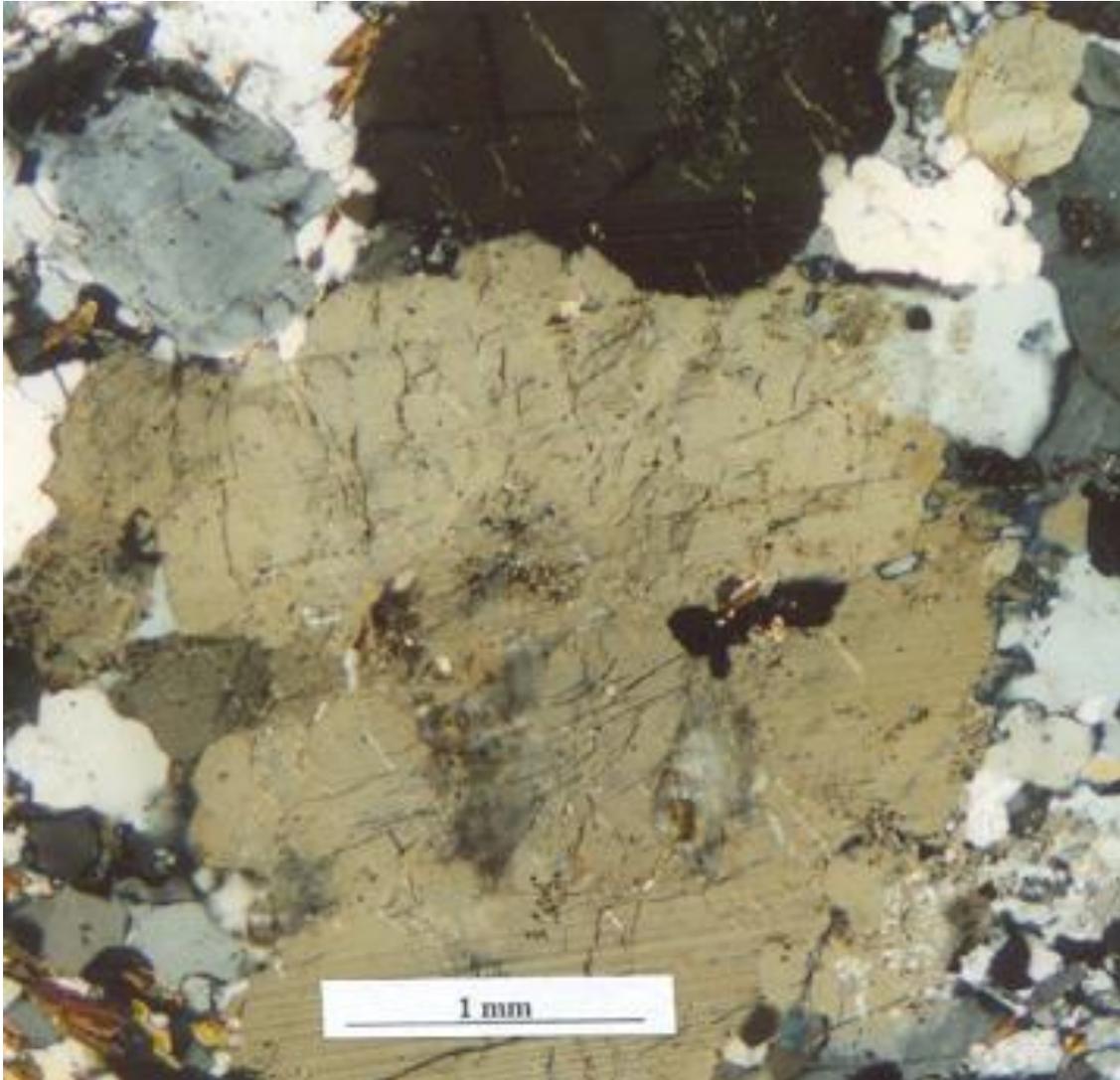


Fig. 37. Interior replacement of plagioclase (tan) by microcline (gray). The albite twinning of the grid-twinning in the microcline is in parallel alignment with the albite twinning of the plagioclase. Surrounding groundmass minerals show slight cataclasis and granulation. Note that this figure is from site 36 on Fig. 2 until Fig. 2 can be corrected.

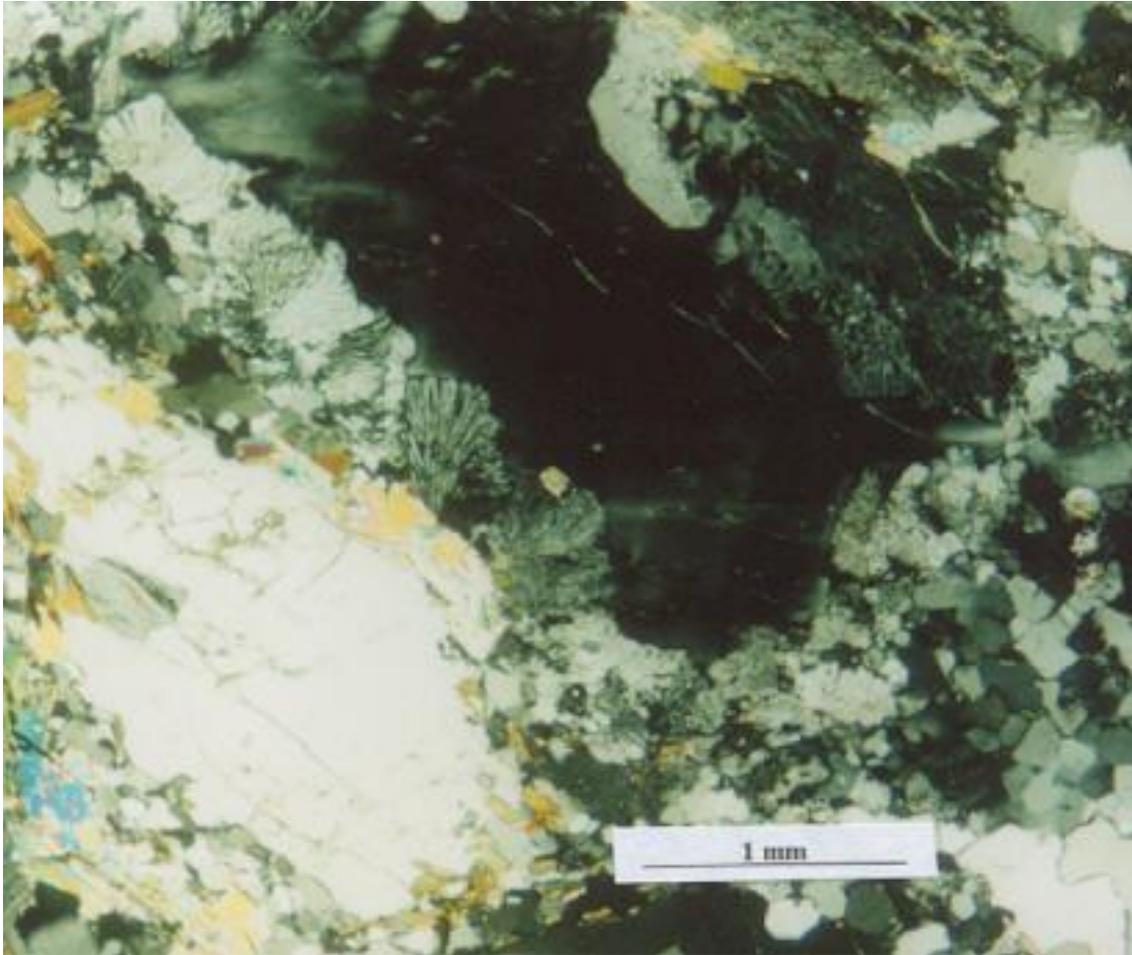


Fig. 38. Microcline (black) surrounded by an aggregate border of myrmekite granules with very tiny quartz vermicules. Muscovite (blue); biotite (tan); quartz (white, cream, gray); plagioclase (whitish; lower left quadrant). Note that this figure is from site 37 on Fig. 2 until Fig. 2 can be corrected.

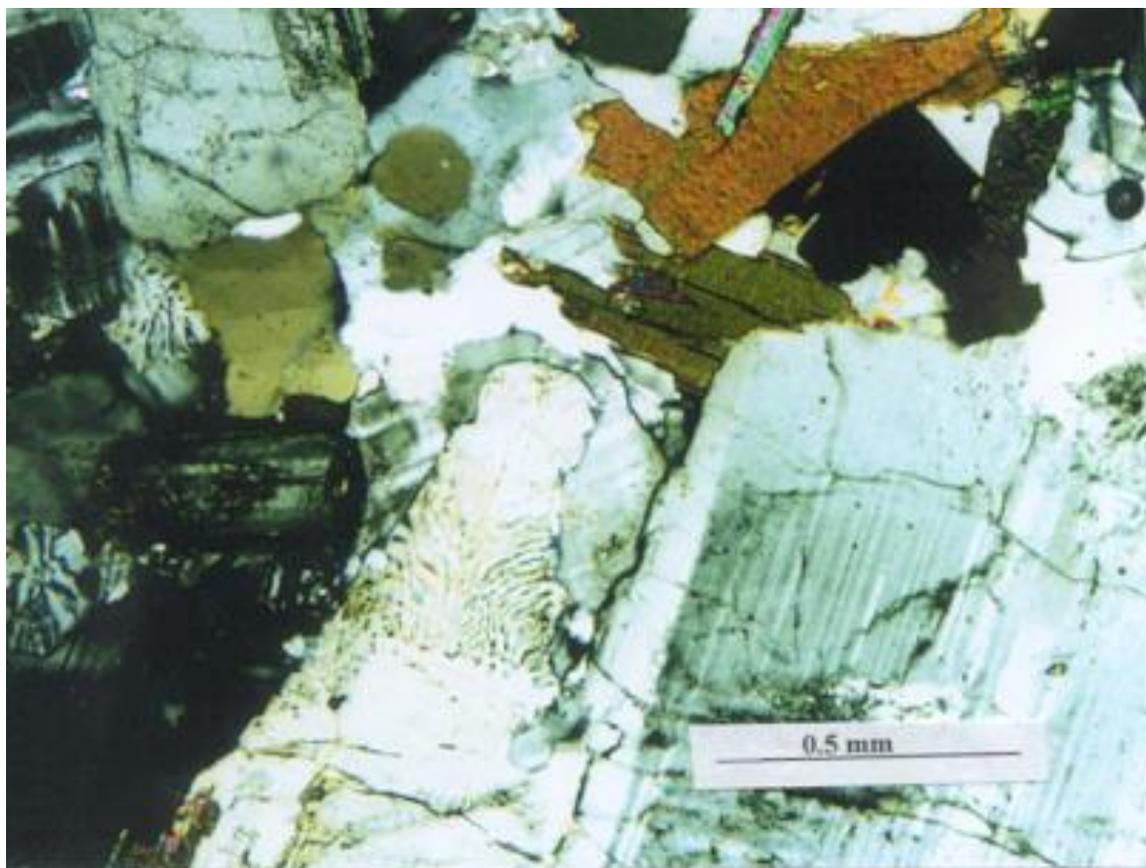


Fig. 39. Microcline (grid-twinning, gray) in upside-down U-shaped outline enclosing myrmekite that projects into the U and extends from non-quartz-bearing plagioclase (tan; bottom). Biotite (brown); albite-twinned plagioclase (light gray; lower right quadrant). Note that this figure is at site 38 on Fig. 2 until Fig. 2 can be corrected.

Ca- and Na-metasomatism of microcline to form the myrmekite (Vernon and Paterson, 2002), can also be ruled out because the myrmekite in the strongly deformed rock is found only on the rims of the microcline and never as double rows of microcline granules lining walls of fractures traversing broken microcline crystals.

In these same strongly deformed rocks, which contain earlier formed orthoclase megacrysts, progressive inversion to microcline has occurred proportional to the degree of deformation. Commonly, the orthoclase first converted to microcline along the outer border of the megacryst. Where the deformation is most intense, the orthoclase crystals are totally converted to microcline. Also in this area where microcline is present are a few, narrow, strongly sheared zones, which have the appearance in the field of leucocratic, fine-

grained aplite dikes. However, these zones are composed almost entirely of microcline and quartz. Nearly all the plagioclase was replaced by microcline, and most of the biotite was replaced by quartz, forming a pseudo-aplite, a product of metasomatic processes in a strongly sheared rock. In some of these pseudo-aplite dikes, orthoclase megacrysts are sheared off and imbricated, indicating that the orthoclase megacrysts had been formed prior to mylonitization (Fig. 15, Vernon and Paterson, 2002). However, the truncation does not necessarily make the orthoclase megacrysts magmatic in origin because orthoclase megacrysts formed earlier by metasomatism could also be sheared off. See also (Collins and Collins, 2002a) for similarly created pseudo-aplites in the megacrystal Cathedral Peak pluton.

Coexisting with the pseudo-aplites are real aplite dikes cutting through the granitic rock. Some of these dikes have orthoclase megacrysts that project across the aplite-granite contacts into the aplites, suggesting that the megacrysts grew later than the emplacement of the dikes. Vernon and Paterson (item 14, 2002), however, reported that in some terranes the aplite in the dike can be molded around megacrysts that project into the dikes, deflecting the flow layering, giving evidence that the aplite dikes were younger than the megacrysts. In the PF pluton, however, such molding and deflection of flow layering are not apparent from their illustration (Fig. 16, Vernon and Paterson, 2002). The foliation in the aplite abuts the megacryst or extends past the megacryst with no deflection. Therefore, Dickson's (1996) assertion that the megacrysts have formed by replacement is better supported.

A consistent, on-going, K-metasomatic, subsolidus history for the PF pluton

The evidence shows that **K-metasomatism was an on-going process throughout the whole subsolidus history of the PF pluton (pre-, during-, and post-megacryst time), and increased in intensity as the temperature decreased and the deformation increased.** All parts of the pluton were subjected to varying degrees of cataclasis, but annealing, recrystallization, and replacements in domains (A) and (B) concealed much of this slight or locally strong cataclasis (Collins and Collins, 2002b). The later on-going strong cataclasis at lower temperatures in domain (C) is an overprint on the earlier cataclasis and replacements that occurred at higher temperatures.

Orthoclase megacrysts in the adjacent wall rock Campito sandstone (arkose)

Because of the penetration of the Campito sandstone by both aplite and pegmatite dikes that extend from the PF pluton and because of the presence of orthoclase megacrysts in the Campito sandstone near these granitic dikes, it is logical to assume that the megacrysts grew from magmatic fluids that accompanied these dikes. Because these **pegmatite dikes contain magmatic orthoclase crystals**, Brigham (1984) and Paterson and Vernon (1995) used this as evidence that the orthoclase megacrysts in the Campito sandstone had a magmatic origin, also, and suggested that the megacryst-bearing zones are "*dykes, from which melt has been strained during intense deformation*". However, those orthoclase megacrysts that occur in clusters in the Campito sandstone **differ from the orthoclase crystals in the pegmatite dikes** crystallized at the eutectic and contain the same replacement characteristics described earlier for the orthoclase megacrysts in the pluton. If the clusters and isolated crystals of orthoclase in the Campito sandstone were xenoliths and xenocrysts of broken pegmatite orthoclase crystals dragged into strongly deformed Campito sandstone, as was also suggested by Vernon and Paterson (2002), then evidence of that deformation should be seen in the adjacent Campito sandstone groundmass, and **that is not the case**. Moreover, xenocrysts of orthoclase formed at the eutectic in a pegmatite should not contain tiny inclusions of strongly zoned plagioclase inclusions like that found in the Campito sandstone. Furthermore, in many places Ba- and K-zoned orthoclase megacrysts with tiny, concentrically-zoned plagioclase inclusions occur **completely isolated in the Campito sandstone** with no apparent connection to any magmatic dike that extended from the pluton into the sandstone. Therefore, it must be assumed that these megacrysts in the Campito sandstone formed by K-metasomatism under subsolidus conditions and were not magmatically derived.

On that basis, an earlier history of magmatism occurred at temperatures above the solidus in which the wall rocks were hot and plastic but allowed intrusion of magma along fractures. Plastic flow in the wall rocks caused extreme thinning of the stratigraphic section around the west half of the pluton, which is exhibited by pinch and swell in the beds, as well as folding of beds containing the aplite and pegmatite dikes. Dynamic recrystallization textures were also created in the quartzites and other rock types (Sylvester and Christie, 1968; Morgan et al., 1998). During this time of high-temperature plastic flow, fluids were being squeezed out of the wall rocks as clay minerals and chlorite were converted to biotite (+/- andalusite +/- cordierite near the pluton contact; de Saint-Blanquat et al., 2001), releasing some water in the process. Because K was being fixed in the biotite, it was not a time in which biotite was being replaced by quartz to release the K to make the orthoclase megacrysts. Under these tight, plastic, metamorphic conditions, it is illogical that K-bearing fluids could have entered such rocks to

produce the megacrysts. This time of high-temperature plastic deformation and medium to high grade metamorphism, however, was followed by a later history in which the wall rocks and the pluton had cooled below solidus temperatures, and upward movements of the pluton caused brittle fracturing in the pluton as well as in the wall rocks. The brittle fracturing permitted K-bearing fluids to enter and cause metasomatic orthoclase to form. Further evidence for this metasomatism, as provided by thin section studies, is given in the following paragraphs.

Thin section studies of the Campito sandstone

The Campito sandstone, which contains the orthoclase megacrysts, is primarily a former arkose that now is composed of fine-, medium-, and coarse-grained layers, consisting of mostly quartz, plagioclase, and biotite with some layers entirely composed of quartz as would be expected in a sandstone. Locally, K-feldspar is found in the Campito sandstone (Sylvester, written communication, 2002), but at least it is generally absent in the sandstone near the orthoclase megacrysts (Fig. 40). Most of the plagioclase consists of unzoned fragments, but some are tiny, strongly normally zoned crystals similar to that found in the pluton.

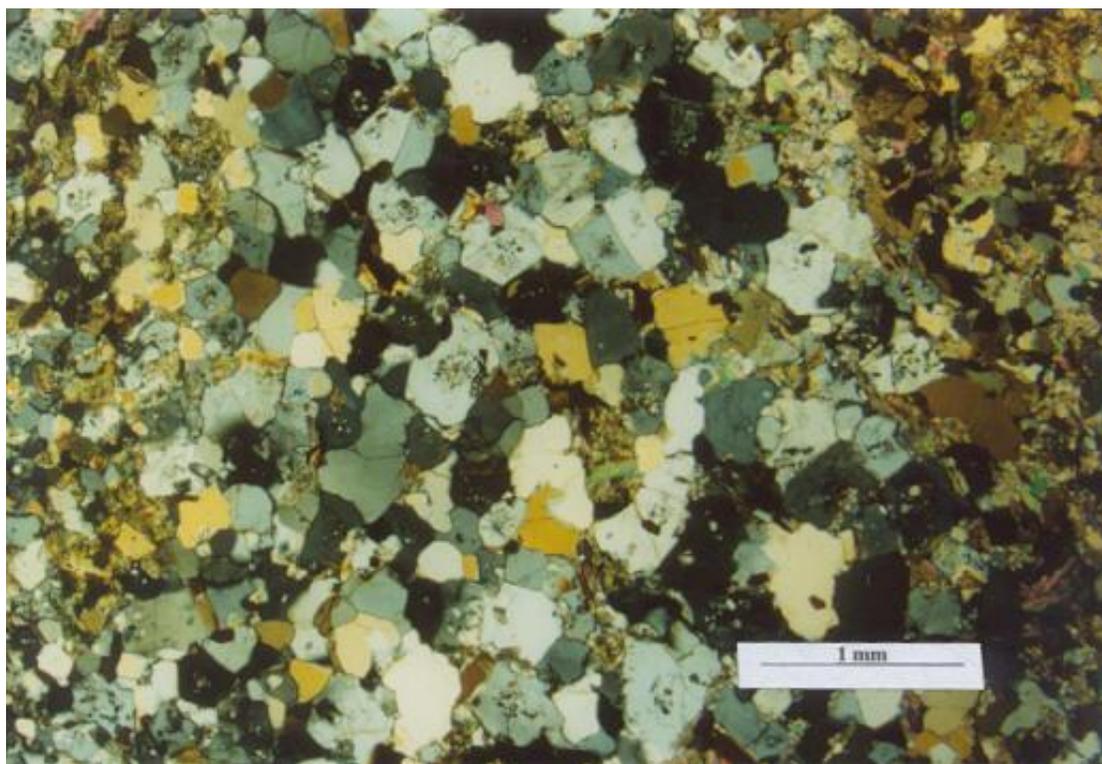


Fig. 40. Campito sandstone (arkose), containing quartz, plagioclase, and biotite. A coarser layer extends through the center of the photo.

Adjacent to some of the orthoclase megacrysts, but in the arkose, a few narrow quartz-orthoclase veins (2-4 mm wide) are found. Such veins are an anomaly in the arkosic sandstone because there would be no physical reason why flowing water could sort orthoclase and quartz grains into separate layers (or veins) from a source area that is producing layers consisting primarily of plagioclase, quartz, and biotite grains in the adjacent rock. The existence of myrmekite associated with these orthoclase grains strongly suggests that former medium- to coarse-grained arkosic layers were deformed, microfracturing the plagioclase grains and allowing K-bearing fluids to be introduced (Collins, 1988). Where K-bearing fluids replaced the plagioclase in the veins, all evidence of cataclasis is destroyed except for the presence of myrmekite, and, therefore, no microfracturing or evidence of cataclasis is seen in the veins or in the adjacent Campito sandstone (Fig. 40, Fig. 41, and Fig. 42).

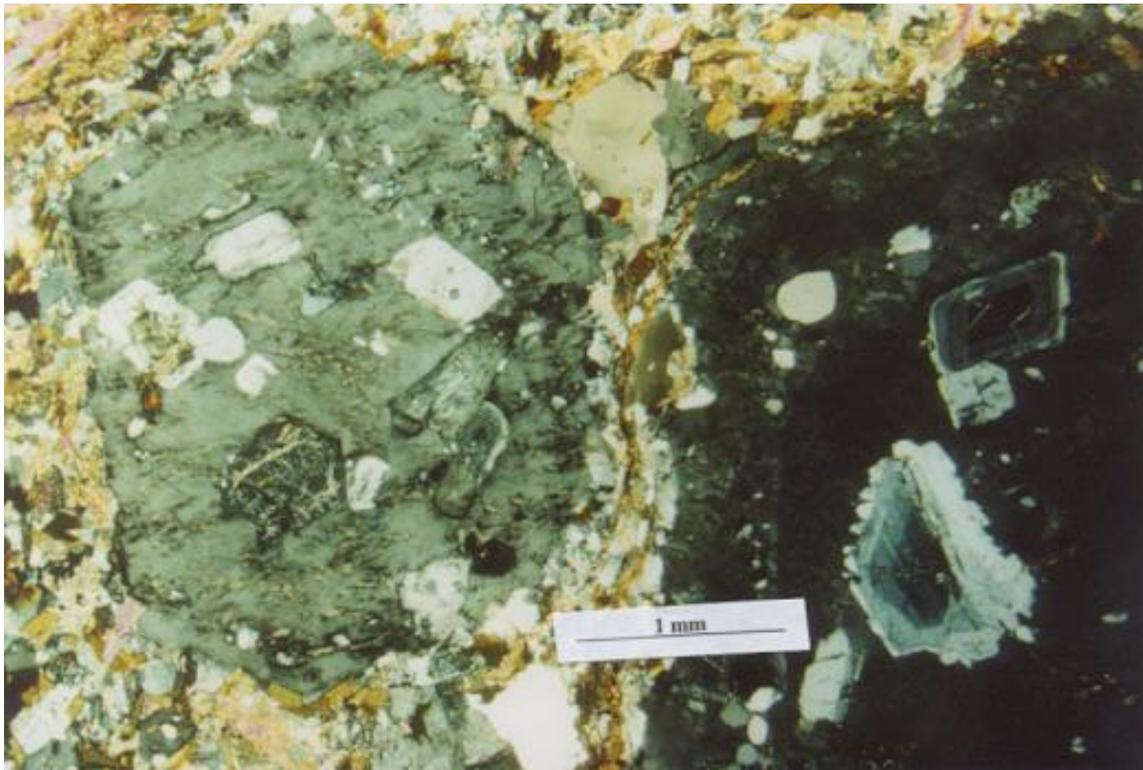


Fig. 41. Two tiny incipient orthoclase megacrysts (light gray and black) in early stages of replacement of the Campito sandstone. Remnants of the adjacent Campito sandstone occur inside the megacrysts, including one plagioclase grain with strong normal zoning.

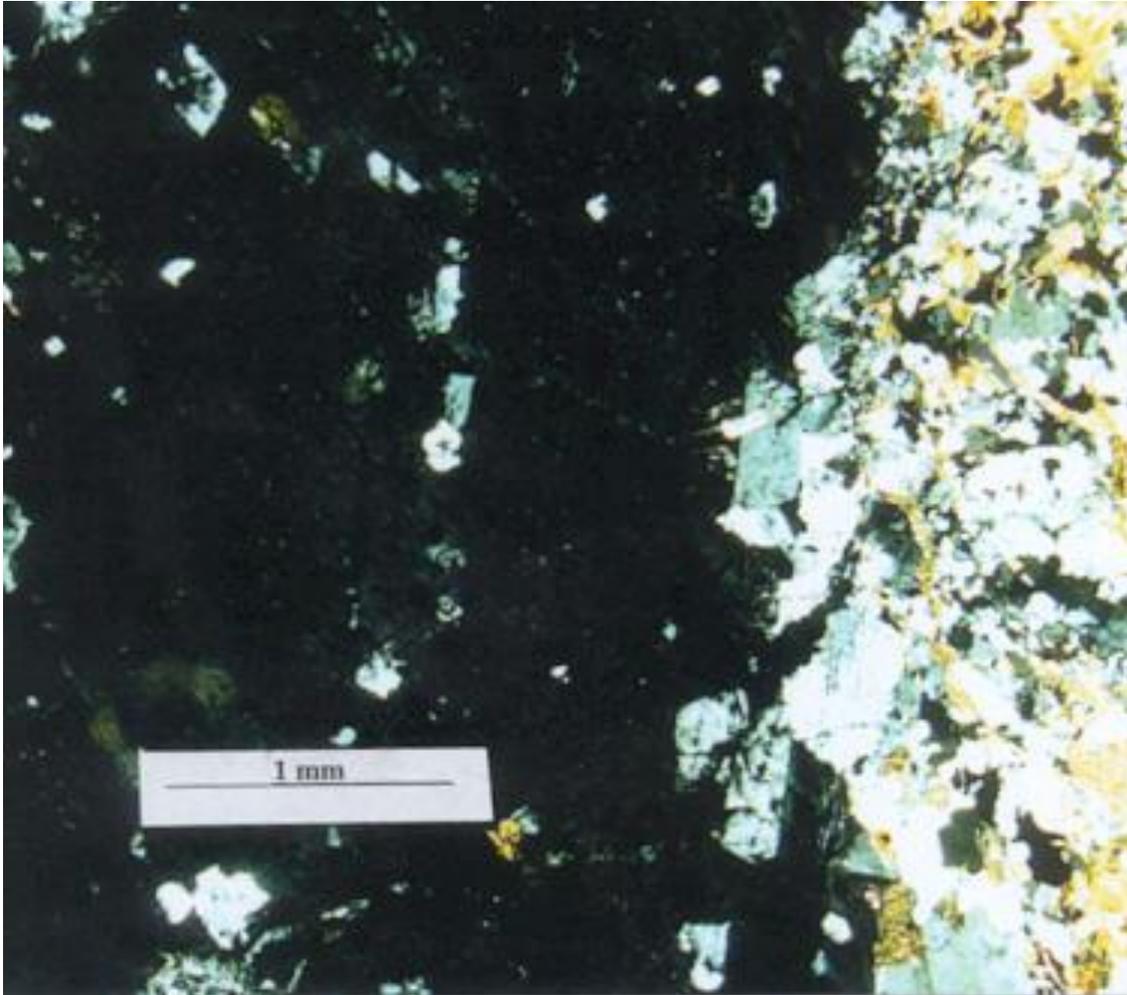


Fig. 42. Border of an orthoclase megacryst (black) against fine-grained Campito sandstone. Tiny plagioclase fragments (light gray) that occur in the sandstone in parallel alignment with the Ba-K zoning in the orthoclase project into the orthoclase and continue as isolated parallel inclusions. Remnant tiny fragments of the Campito sandstone also occur scattered in the megacryst. Biotite (brown).

Replaced layers in the sandstone could have been coarser grains, which became microfractured, allowing avenues for fluid movement. The finer-grained, adjacent, unbroken arkosic bands would have been denser and harder, preventing fluids from penetrating. At any rate, the microfractured parts of the medium- to coarse-grained plagioclase-quartz-biotite patches in the Campito sandstone would have been modified to form orthoclase megacrysts in essentially the same way as in the deformed PF pluton. Similar cataclastic borders, incorporation of granulated groundmass minerals, and preservation of grains with parallel orientations are found (Fig. 20, Fig. 41, Fig. 41, Fig. 43, and Fig. 44). Tiny strongly zoned plagioclase crystals, both inside the megacrysts and in the adjacent groundmass

(Fig. 43), preclude the orthoclase megacrysts from being xenocrysts of former orthoclase crystals that were broken loose and dragged from a pegmatite into the Campito sandstone, as claimed by Vernon and Paterson (2002). Tiny, rapidly crystallizing, zoned plagioclase crystals would not be found in orthoclase in a pegmatite crystallizing at eutectic conditions.

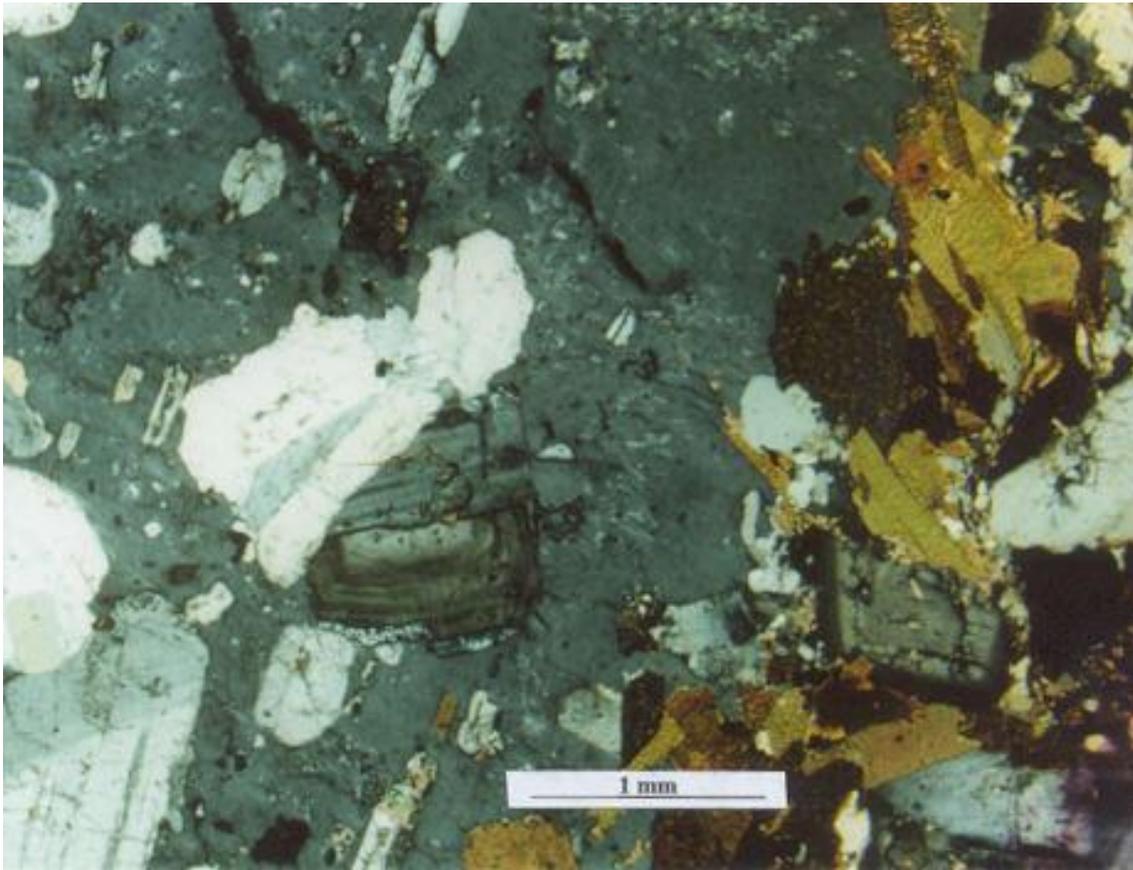


Fig. 43. Border of an orthoclase megacryst (dark gray) against medium-grained, biotite-rich Campito sandstone. Some larger plagioclase inclusions (light gray, cream) in the megacryst are inclined to the Ba-K layers but are the same size as similar grains in the Campito sandstone. A strongly normally-zoned plagioclase inclusion in the megacryst is about the same size as a strongly normally-zoned plagioclase grain in the adjacent sandstone. Many of the plagioclase inclusions show scalloped edges.

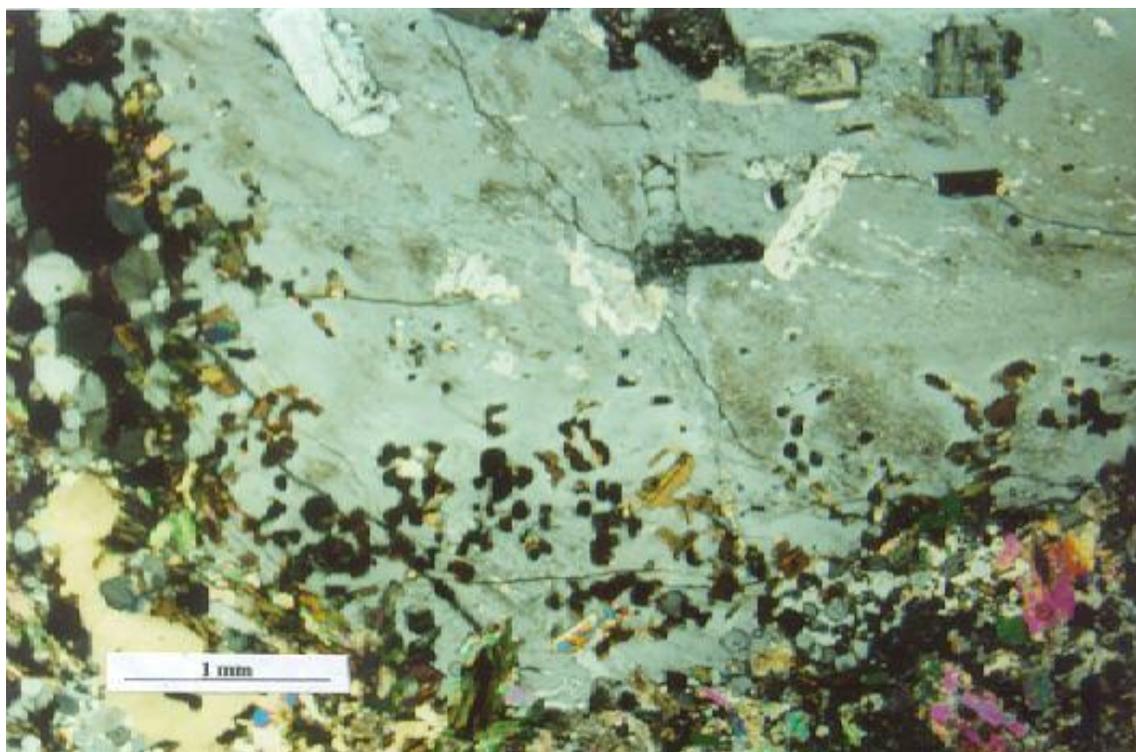


Fig. 44. Orthoclase megacryst (light gray) in Campito sandstone, showing remnant biotite grains of the sandstone enclosed in the border of the megacryst. Tiny plagioclase inclusions aligned in the megacryst are the same size as plagioclase grains in the sandstone. Some of the inclusions are inclined to the Ba-K concentric layers in the megacryst.

Because the adjacent arkose contains little to no K-feldspar where the orthoclase megacrysts are found, the orthoclase megacrysts cannot represent places where isochemical self-reorganization of stressed minerals in the arkose occurred to produce the megacrysts. There is neither sufficient original K-feldspar nor biotite in the arkose to supply the K needed in the volumes occupied by the megacrysts. Therefore, as in the PF pluton, some K must come into the arkose from outside sources to create the megacrysts. Moreover, the occurrence of orthoclase megacrysts in both the arkose and the PF pluton can be expected because **introduced K-bearing fluids should be able to cross geologic contacts and cause K-replacements on both sides of the contact.**

Even though abundant quartz (25 vol. %) is present in the surrounding arkose (Fig. 40, Fig. 41, and Fig. 42), scarcity of quartz inclusions in orthoclase megacrysts in the Campito sandstone is likely due to incorporation of SiO₂ from the quartz into the orthoclase composition as plagioclase and biotite are replaced by the orthoclase.

Other general observations

Because continued stress is apparent throughout the history of the PF pluton, particularly under subsolidus temperatures, it is not surprising that some orthoclase megacrysts were skewed to change their monoclinic symmetry into a triclinic symmetry, tilting a normal 90 degree angle by 1 to 4 degrees (Dickson, 1995b). This tilting may have been caused in part by differential replacements in the groundmass minerals from place to place, not only where plagioclase is replaced by orthoclase or microcline, but also where biotite is replaced by quartz. On that basis, side pressures on a megacryst need not have been the same from one end of a crystal to the other and could have deformed the crystal lattice.

The source of Ba cannot be determined in the Papoose Flat pluton because nearly all of the pluton has been modified by plastic and brittle deformation and by chemical replacements. Therefore, the source minerals from which the Ba could have been derived have all been altered by losses of Ba. The Ba (+2) ion is about the same size as the K (+1) ion in biotite and has the same chemistry as the Ca (+2) ion in plagioclase. Therefore, the replacements of Ba-bearing biotite by quartz and the replacements or recrystallization of plagioclase to form relatively more-sodic phases could have released the Ba that was precipitated in the orthoclase megacrysts. It is equally impossible to tell where Ca and Al displaced by Ba and K have gone because insufficient secondary epidote, calcite, or other Ca- and Al-bearing minerals occur in the pluton into which these elements could have gone. Presumably, the displaced Ca and Al were carried out of the pluton by through-going hydrous fluids.

Somewhat remarkable is the general absence of epidote (a calcium and aluminous silicate) in the granitic rocks of the PF pluton, except for the outer margin adjacent to aluminous and calcareous metasedimentary wall rocks. Abundant epidote would normally be expected as a hydrous alteration of biotite and plagioclase in rocks as strongly deformed as occur in the PF pluton, and **it is rare**. The explanation is that the Al, released from destroyed biotite and plagioclase, is consumed by combining with both Si from quartz and introduced K to make orthoclase in the megacrysts, and none is left over to combine with Ca to make epidote. Only where contamination from aluminous metasedimentary rocks along the pluton margins is there enough Al available to make epidote, and there, some of the Ca is supplied by the calcareous wall rocks. The paucity of epidote also provides evidence as to why Ca- and Na-metasomatism of the supposed primary orthoclase phenocrysts to produce fringe myrmekite, as proposed by Vernon and Paterson (2002), is not possible. The extra Al is not available to

produce the relatively calcic plagioclase in the myrmekite, and **Ca is leaving the system, not being added to it.**

In some zoned orthoclase megacrysts, one of the alternating bands of Ba-rich to Ba-poor layers appears to eat into an inner band, seemingly dissolving out part of that band while precipitating its own composition (e.g., Fig. 3 in Dickson, 1996; oral communication, 2002). Because each band represents the outer surface of the growing megacryst at one time, it is logical that a former unreplaced plagioclase grain, abutting against a growth zone on the border of the orthoclase crystal, once occupied this site where it was later replaced. This former bordering plagioclase grain could have been microfractured during continued deformation of the rock and replaced by the adjacent outer band, filling in the space where the inclusion once existed.

Are the orthoclase megacrysts residual phenocrysts (porphyroclasts)?

Vernon and Paterson (2002) allege that the "*igneous microstructures and structures resulting from solid-state deformation, indicate that K-feldspar megacrysts in deformed granite of the Papoose Flat pluton are residual phenocrysts, not porphyroblasts.*" As shown throughout previous sections, the igneous microstructures (the flow fabric and synneusis) are recognized. The local parallel alignments of orthoclase megacrysts in these microstructures and in schlieren or near comb layering, however, are not due to magmatic flowage that aligned the megacrysts but result from replacements of parallel aligned plagioclase, biotite, and quartz. Thereby, the megacrysts inherited the igneous microstructures. Also, although in final stages the orthoclase megacrysts are deformed, such deformation occurs after the metasomatic formation of the orthoclase megacrysts and, therefore, is not necessarily evidence that the megacrysts were former phenocrysts.

Furthermore, the suggested criteria "*crystal shapes, simple twinning, zonally arranged euhedral plagioclase inclusions, oscillatory compositional zoning, and local occurrences in microgranitoid enclaves*" are not necessarily evidence of an igneous origin (Roddick, 1982). Simple twinning (i.e., Carlsbad twinning) in K-feldspar is not common in metamorphic gneisses, but Carlsbad twinning is common in plagioclase in the Papoose Flat pluton, and this twinning can be inherited where orthoclase replaced a Carlsbad twinned plagioclase crystal; see also, Fig. 6 in Collins (1997c; <http://www.csun.edu/Nr3Myrm.pdf>) and Fig. 8 in Collins (1997c; <http://www.csun.edu/~vcgeo005/Nr9Twenty.pdf>).



Fig. 6 in Nr3Myrm.pdf. This photomicrograph shows a remnant zoned plagioclase crystal in the massive, pink, Cape Ann granite several meters from the contact with the Salem diorite. The plagioclase is Carlsbad-twinned and has a weathered, sericitized calcic core. This crystal is similar in size and shape to Carlsbad-twinned plagioclase crystals in the diorite. At its right end, the plagioclase crystal and calcic core is truncated by K-feldspar that inherits its Carlsbad twinning from the former plagioclase.



Fig. 8 in Nr9Twenty.pdf. Felsic diorite shows slightly deformed (fractured) Carlsbad- and albite-twinned plagioclase crystal (cream gray and gray) that fills most of image. Tiny irregular islands and veinlets of microcline (black-gray) replace portions of both halves of the Carlsbad-twinned plagioclase crystal.

Although some plagioclase inclusions are euhedral, many (if not most) are not euhedral and are **scalloped**, indicating that they were in the process of being replaced rather than nucleating from magma on a former face of a growing orthoclase phenocryst. The oscillatory Ba-K zoning can equally well be created by many pulses of introduced metasomatic fluids with differing Ba and K contents as it could be caused by magmatic processes.

These authors also offer the following additional criteria to support their phenocryst model:

"Evidence of solid-state deformation of the megacrysts (which is consistent with their existence prior to mylonitic deformation) includes marginal recrystallization and neocrystallization, microcline twinning, marginal replacement by myrmekite, and recrystallization/neocrystallized 'tails'. Evidence of porphyroblastic growth, such as overgrown inclusion trails, is absent. This appears to be the situation in most felsic augen gneisses and mylonites."

There is no doubt that solid state deformation has caused some orthoclase megacrysts to be recrystallized as microcline, and even to be fragmented in strong shear zones where pseudo-aplite dikes were formed, but this recrystallization and strong deformation do **not** make the orthoclase megacrysts into phenocrysts. Zonally arranged wartlike myrmekite in cores and intermediate zones in unfractured megacrysts preclude the myrmekite from forming by Ca- and Na-metasomatism. It is agreed that the megacrysts are **not porphyroblasts** in which inclusion trails of broken plagioclase, biotite, and quartz grains would be overgrown **during an isochemical solid-state metamorphic recrystallization process**. The absence of these inclusion trails in the megacrysts occurs, however, because in most places the broken plagioclase, biotite, and quartz grains are replaced by orthoclase. Nevertheless, in a few places such inclusion trails exist in the megacrysts (Fig. 18). **Therefore, the megacrysts are "porphyroblasts" that were formed by metasomatic processes.**

Finally, suggesting that the orthoclase megacrysts are phenocrysts of magmatic origin is inconsistent with the relative distribution of the megacrysts. In the standard magmatic model, the core of the pluton is the last to crystallize, and the late crystallization there is supposed to produce large crystals of orthoclase at or near the eutectic. Yet, the greater concentrations of orthoclase megacrysts are **found at and near the border of the Pappoose Flat pluton** (Fig. 1, 17, and 19, Vernon and Paterson, 2002), where the magma would be expected to first solidify, **not last, as in the core of the pluton**. Moreover, the greater concentrations of megacrysts are in places where the host granitic rocks are more strongly deformed, particularly the border of the pluton, suggesting a correlation with deformation rather than the eutectic. Also, the general non-aligned orientation of the megacrysts, as reported by Vernon and Paterson (2002) and Paterson et al. (1991), even in the strongly deformed margins of the pluton, suggest that the megacrysts formed mostly after the deformation occurred and did not form in magma crystallizing as phenocrysts prior to the deformation.

A non isochemical metasomatic model for the origin of the megacrysts

Collins (1997e, 2001) and Collins and Collins (2002a) found that K-metasomatism of a few, microfractured, normally zoned plagioclase crystals in tonalite or diorite in the Cathedral Peak, Monterey, and Twentynine Palms plutons produced microcline megacrysts in myrmekite-bearing granodiorite or quartz monzonite. Extensive K-metasomatism of normally zoned plagioclase crystals that were all subjected to strong cataclasis in a quartz diorite near Temecula, California, however, failed to produce any microcline megacrysts in myrmekite-bearing

granite (Collins and Collins, 2002b). The explanation for these differences is that where only a few normally zoned plagioclase crystals were deformed and replaced, introduced K was concentrated in a few nucleation sites and, consequently, the metasomatic microcline grew to become megacrysts. Where all normally zoned crystals were cataclastically broken and altered, all metasomatic microcline crystals competed for the introduced K, and none could grow large in size. This same relationship carries through to the PF pluton. Only a few of the normally zoned plagioclase crystals were cataclastically deformed and replaced, thus resulting in the formation of orthoclase megacrysts.

Conclusions

In comparison to the magmatic model proposed by Vernon Paterson (2002), which has many problems, the origin of the orthoclase megacrysts is best explained by local K-replacements of microfractured, primary, normally zoned plagioclase crystals while leaving other groundmass, unfractured, primary, normally zoned plagioclase crystals mostly unreplaced. The tiny, parallel aligned, plagioclase inclusions in concentric zones in the megacrysts, occurring as either broken fragments or unbroken euhedral to subhedral crystals, are also best explained as being inherited from alignments that occurred in the primary flow fabric or resulting from cataclasis that caused re-alignments of plagioclase crystals parallel to margins of growing megacrysts.

Reasons why a non isochemical metasomatic model is better than an isochemical recrystallization model (Dickson, 1996) for explaining the origin of the orthoclase megacrysts in the PF pluton include the following.

1. Because the initial, relatively unstressed solidified rock in the PF pluton contained little orthoclase (8-13 vol. % or less), *not enough primary orthoclase existed in the original granodiorite for this orthoclase to be isochemically recrystallized to form volumes greater than 19 vol. % in a megacrystal quartz monzonite*. This lack of sufficient K is true even if the first orthoclase were totally magmatic. Moreover, there is insufficient K available in the original biotite (less than 6 vol. %) to account for the amount of K in the volumes of orthoclase in the megacrystal rocks, if the local primary biotite were used as a source of some of the K. For every cubic centimeter of orthoclase, about 1.29 cubic centimeters of destroyed biotite are required to supply the needed K. On that basis, although some K in the orthoclase megacrysts can be supplied from biotite replaced by quartz in the local volumes, much of it must have come from other, likely deeper, sources so

that the primary K-feldspar-poor granodiorite could have been converted into the megacrystal quartz monzonite.

2. Myrmekite inclusions in the cores, interior layers, and rims of orthoclase megacrysts must have formed under subsolidus conditions because such quartz-plagioclase intergrowths do not crystallize from a melt and cannot have formed by renucleation. The alignment of myrmekite inclusions must have existed prior to the overgrowth of an orthoclase megacryst.

3. Sodic rims on all sides of most of the elongate plagioclase inclusions could not have formed if relatively calcic seeds for these inclusions were renucleated on a growing orthoclase face. These inclusions rimmed by sodic plagioclase must be remnants of primary groundmass minerals.

4. The tiny inclusions of strongly normally zoned, equidimensional plagioclase with sodic rims match the size and appearance of strongly normally zoned, equidimensional, primary plagioclase grains in the groundmass and must be former primary grains that were surrounded by the growing orthoclase as other adjacent groundmass minerals were replaced.

5. Scalloped edges commonly occur on all surfaces of many plagioclase inclusions. Scalloping on surfaces of the plagioclase inclusions facing the core of a megacryst indicates that the plagioclase that became the inclusion did not renucleate on smooth faces of a growing orthoclase crystal. Because plagioclase inclusions that are unscalloped on inner faces do not look any different from those that are scalloped on inner faces, it is logical that they all have a common groundmass origin without renucleation, particularly when parallel inclusions interlock with scalloped inclined or perpendicular inclusions.

6. Extension of orthoclase beyond the rectangular corner of a megacryst into broken groundmass minerals that split and divide by flowage around the corner indicates that the megacrysts formed in an open system controlled by the local deformation.

7. Megacrysts in domain (C) lacking inclusions, containing sparse inclusions, or with most inclusions having random lattice orientations along Ba-K growth zones are inconsistent for a model in which **all** megacrysts are supposed to contain abundant parallel-aligned inclusions that are formed by dissolution and renucleation. These abnormal features, however, are consistent with a non isochemical metasomatic model.

8. The preservation of less than 0.7 vol. % of tiny, rounded or scalloped quartz grains in and along many of the Ba-K growth zones in the megacrysts suggests that primary quartz was dissolved and utilized in the formation of the orthoclase. If many, tiny, stressed, magmatic orthoclase crystals once occupied the volume now filled by a megacryst and merely dissolved, renucleated, and grew as one large crystal with Ba-K oscillatory zones, then the many tiny orthoclase source crystals would have had already enough silica in their lattices and would not need to consume silica in order to grow as one large crystal. Thus, a megacryst formed by an isochemical recrystallization and renucleation process **should contain abundant quartz inclusions** that were once interstitial quartz coexisting with former magmatic orthoclase, plagioclase, and biotite, and **that is not the case**.

9. The production of additional K-feldspar (microcline) bordered by aggregate myrmekite in domain (C), as indicated by interior replacements of plagioclase by microcline, is more in harmony with a non isochemical metasomatic process involving the introduction of K-bearing fluids than with the recrystallization model in which the process of megacryst formation was envisioned to be entirely isochemical.

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Appendix

The disappearance of some of the quartz in the megacrysts during orthoclase replacements is logical for two reasons:

(1) Some of the quartz is consumed because groundmass plagioclase (oligoclase-andesine; density 2.67 g/cc), which is partly replaced by orthoclase, has about 60 wt. % SiO₂ (1.60 g/cc), and the coexisting biotite (density, 3.0 g/cc), which is mostly replaced, has about 35 wt. % SiO₂ (1.05 g/cc). In contrast, orthoclase (density, 2.56 g/cc) has 64.7 wt. % SiO₂ (1.66 g/cc), and, therefore, the biotite and plagioclase being replaced do not have sufficient silica in them (1.60 g/cc and 1.05 g/cc) to provide the amount needed to make orthoclase (1.66 g/cc) that fills the former volumes of replaced biotite and plagioclase. On that basis, some of the needed extra silica to make the orthoclase likely came from the quartz that disappeared.

(2) Orthoclase has only 18.5 wt. % Al_2O_3 (0.47 g/cc) whereas the plagioclase being replaced has about 25.3 wt. % Al_2O_3 (0.68 g/cc) and biotite has about 24.4 wt. % Al_2O_3 (0.73 g/cc). Thus, where biotite and plagioclase are replaced by orthoclase, more Al_2O_3 than can fit into the replacement orthoclase in the same volumes is displaced, and this Al_2O_3 in combination with introduced K (K_2O) would cause more of the quartz to disappear as Al_2O_3 and K_2O combined with SiO_2 in the quartz to produce additional orthoclase. Therefore, for these two reasons, **quartz would tend to disappear in volumes now occupied by the orthoclase megacrysts.**