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38. Modification of a magmatic tonalite to produce a megacrystal granodiorite by K-metasomatism, Monterey peninsula and northern Santa Lucia Mountains, California, USA

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Abstract

A megacrystal granodiorite, occurring in a pluton in the Monterey peninsula of California, is gradational south to quartz monzonite and then to tonalite and trondhjemite and southeast to granodiorite and then to tonalite. A primary magmatic origin for the pluton is indicated by normally zoned plagioclase crystals and by dikes that extend into biotite-hornblende quartz diorite southeast of Point Lobos and into biotite schists south of Carmel Valley Village. Plagioclase in the tonalite lacks zonation, but toward the northwest, the plagioclase becomes increasingly zoned in the megacrystal granodiorite. Therefore, the shallowest part of the original pluton must have been near Monterey. The tonalite is undeformed but progressively becomes cataclastically broken from the southeast toward the northwest. In less than one kilometer, broken plagioclase crystals are increasingly penetrated and gradually replaced by microcline, converting the tonalite into granodiorite. K-metasomatism first creates tiny microcline islands and veins in interiors of broken plagioclase crystals. Then, the microcline grows and engulfs plagioclase remnants and other groundmass minerals. Eventually, the microcline becomes megacrysts, some as large as 4 cm long. Wartlike myrmekite commonly borders the microcline. In formerly strongly-deformed zones, the microcline megacrysts locally have parallel alignment. Some megacrysts show concentric zonation and alignments of tiny plagioclase inclusions parallel to possible crystal faces of the microcline. Thus, the four facies in the pluton, tonalite, quartz monzonite, granodiorite, and megacrystal granodiorite, which seem to have formed by magmatic differentiation, are a result of cataclasis of a former trondhjemite/tonalite pluton in which some of the plagioclase has been replaced progressively by microcline.

Introduction

A plutonic megacrystal granodiorite (Mgd), trending northwest-southeast from the Monterey peninsula, is gradational south to quartz monzonite (Qm) and unmapped trondhjemite and tonalite at and near Yankee Point, and southeast to granodiorite (Gd) and tonalite (T) south of Carmel Valley Village (CVV; see Fig. 1). The quartz monzonite extends as dikes (Fig. 2) into wall rocks of biotite-hornblende quartz diorite (Qd; Fig. 1), and the tonalite extends as dikes into large biotite schist enclaves (30 m wide; not shown on Fig. 1). The gradational boundaries between these granitic facies are approximately located. An additional large area of the megacrystal granodiorite occurs in the city of Monterey, but it was not studied and is not shown on Fig. 1; see geologic map of Dibblee (1999).

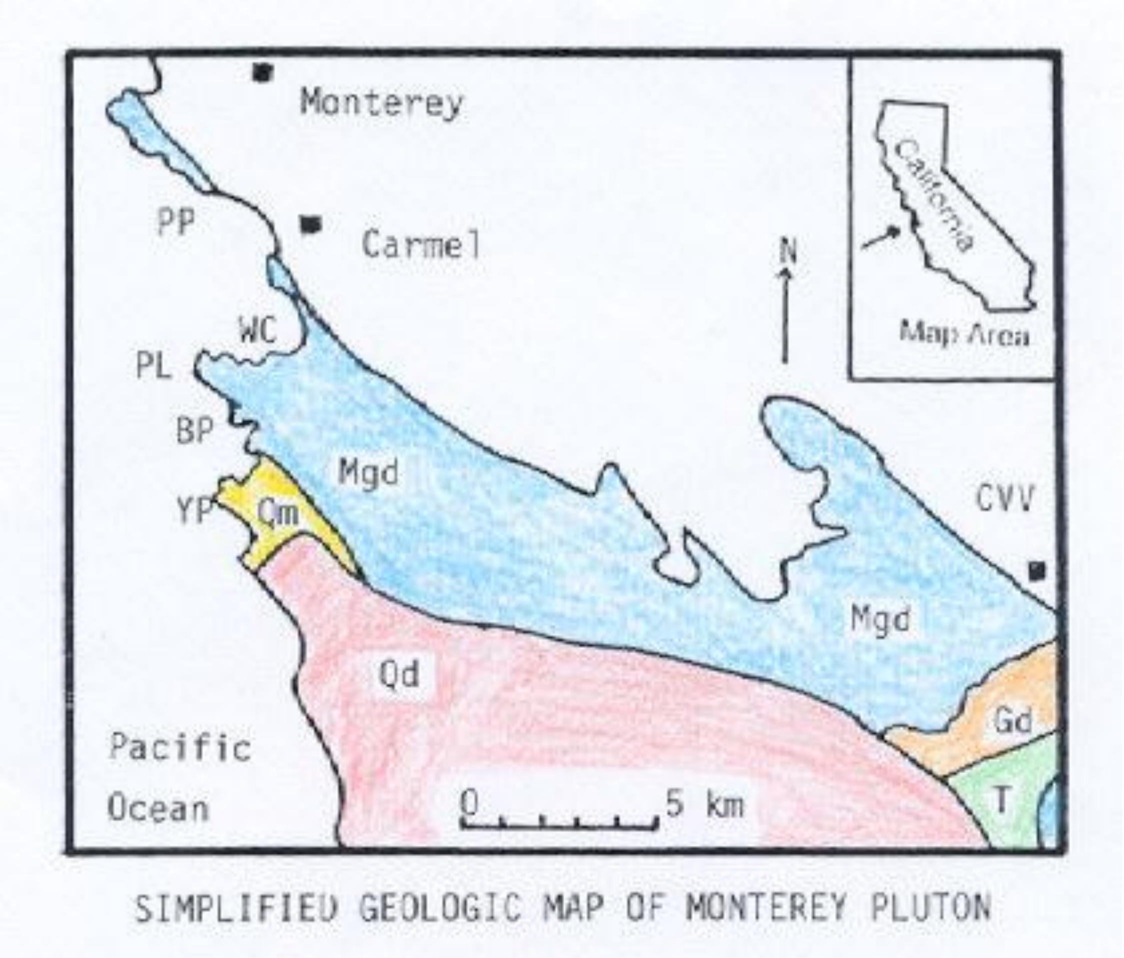

Fig. 1. Simplified geologic map (after Dibblee, 1999), showing location of the "porphyritic" (megacrystal) granodiorite of Monterey. Tonalite (T, green); granodiorite (Gd, orange); quartz monzonite (Qm, yellow); megacrystal granodiorite (Mgd, blue); quartz diorite (Qd, pink). Symbols: PP = Pescadero Point; WC = Whalers Cove; PL = Point Lobos; YP = Yankee Point; BP = Bird Point; CVV = Carmel Valley Village. Tertiary and Quaternary sedimentary rocks have been omitted.

Fig. 2. Dike of quartz monzonite (light colored) extending into biotite-hornblende quartz diorite.

The megacrystal granodiorite (Mgd) has spectacular exposures on wave-cut rocks along the Pacific coast near Monterey, California (Fig. 3 and Fig. 4). In some places local concentrations of megacrysts occur, but these are not separate pegmatite dikes (Fig. 5). Rare, but occasionally found, are concentrations of biotite in swirled schlieren (Fig. 6) in wave-cut rocks in the most western exposures of megacrystal granodiorite, southwest of Monterey in the west-facing coast, supporting a magmatic origin.

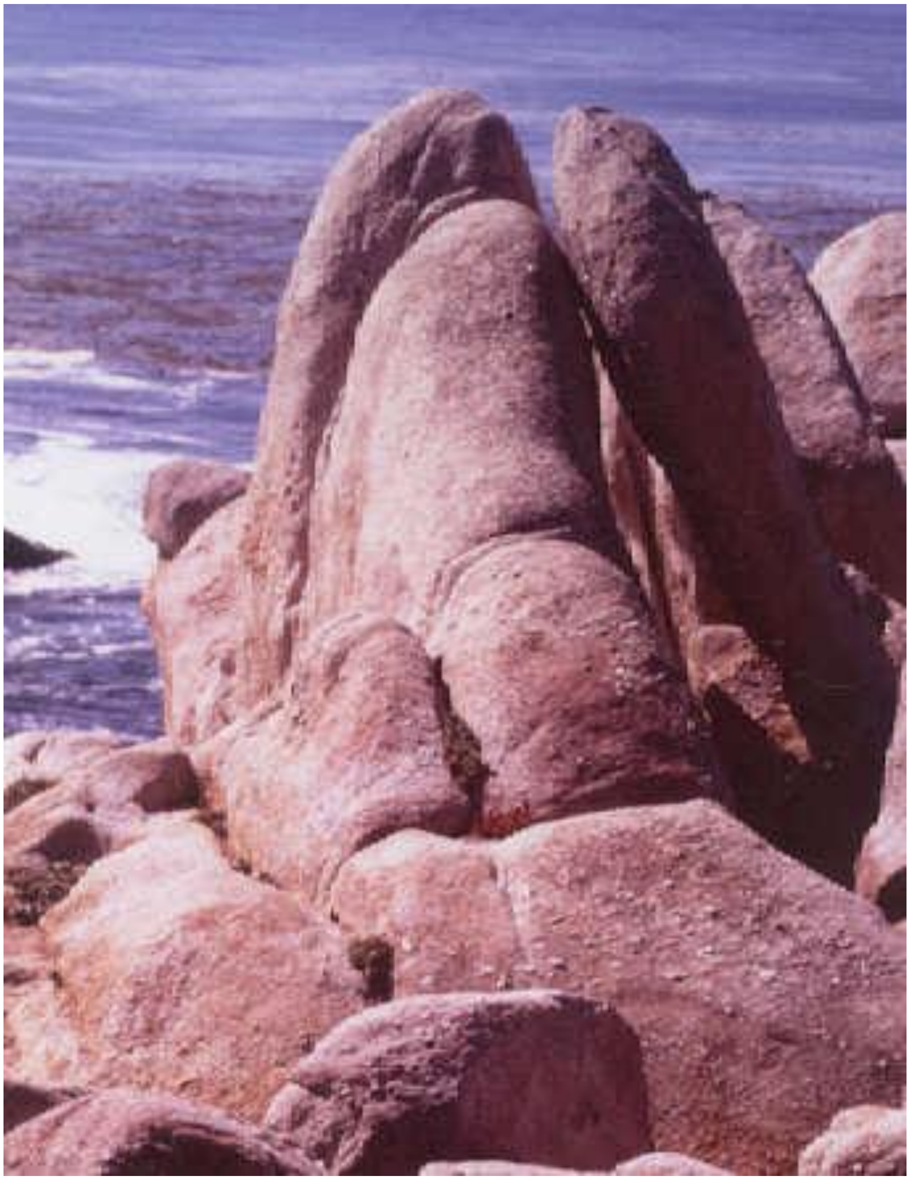

Fig. 3. Massive outcrops of megacrystal granodiorite along coast line of the Monterey peninsula. Larger crystals of microcline megacrysts (white; near bottom of photo) show alignment generally parallel to the coastline.

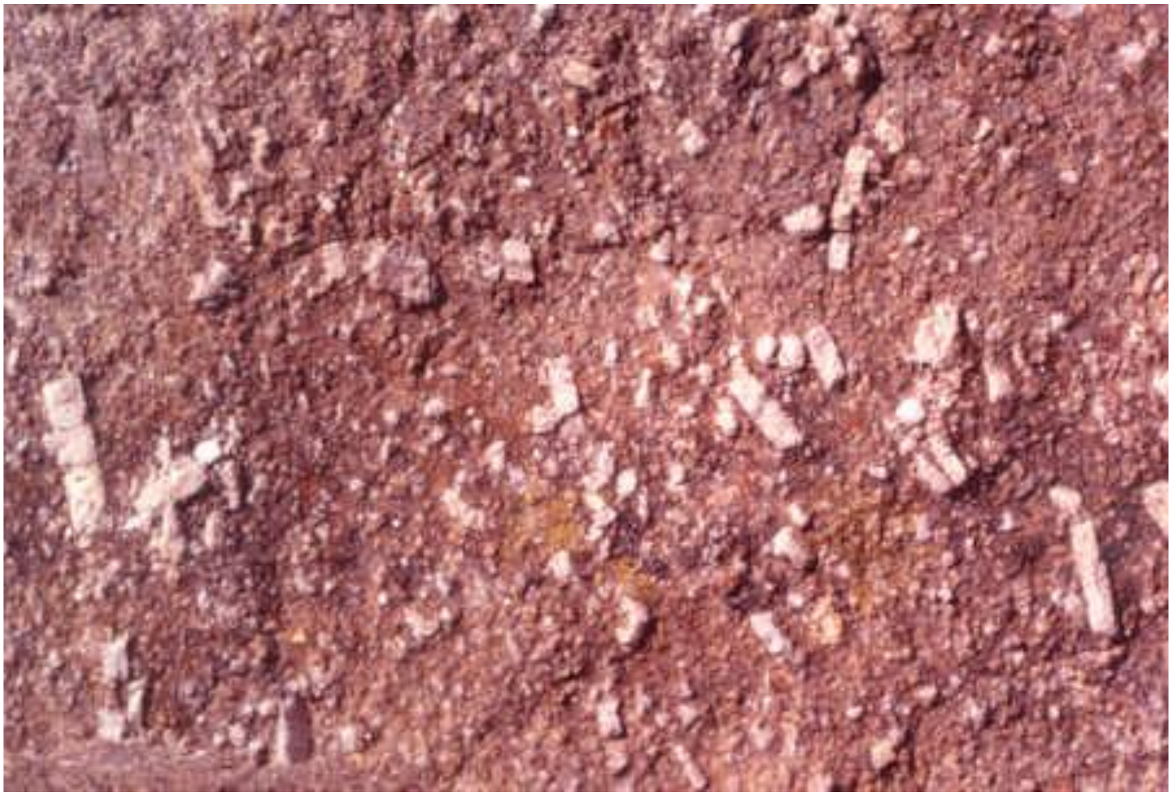

Fig. 4. Close-up of partly aligned megacrysts of microcline crystals. The largest crystals are as much as 4 cm long.

Fig. 5. Megacrystal granodiorite with local concentrations of megacrysts at Carmel Point, southwest of the city of Carmel (Fig. 1).

Fig. 6. Biotite-rich schlieren in west-facing, wave-cut exposures along the Pacific Ocean in the most western parts of the pluton, southwest of Monterey (Fig. 1).

The megacrystal facies has been studied by a number of investigators (Bowen, 1965; Compton, 1966; Wiebe, 1970; Ross and Brabb, 1973; Dibblee, 1999). All of these investigators support magmatism as the sole origin of the megacrystal granodiorite and refer to it as being "porphyritic." However, Wiebe (1970) studied a smaller area of megacrystal granodiorite southeast of the area shown on Fig. 1 and suggested that "K-feldspar appears to have replaced plagioclase in granodiorite" and that a quartz monzonite facies exhibits metamorphic recrystallization.

The gradual changes from a more mafic to more felsic rocks --- (a) tonalite through granodiorite and then to megacrystal granodiorite or (b) tonalite and trondhjemite (unmapped) through quartz monzonite to megacrystal granodiorite (Fig. 1) --- strongly suggest that the different facies in this pluton have been formed by magmatic differentiation. However, a parallel alignment of microcline crystals in megacrystal granodiorite at Whaler's Cove and Bird Point in Point Lobos State Reserve (WC and BP, Fig. 1) in the western part of this pluton is unusual (Fig. 7) and attracted my attention because in other localities where megacrysts have been similarly aligned, myrmekite is common, indicating that some K-metasomatism has occurred. See http://www.csun.edu/~vcgeo005/Nr6Waldoboro.pdf, http://www.csun.edu/~vcgeo005/Nr9Twenty.pdf, http://www.csun.edu/~vcgeo005/Nr22Ponanganset.pdf, http://www.csun.edu/~vcgeo005/Nr29Greece.pdf. Therefore, this study was initiated (1) to investigate the extent of the parallel alignment of the microcline crystals, (2) to determine if the megacrysts were bordered by myrmekite, and (3) to find out whether magmatic differentiation is the proper interpretation for the origin of the different facies in the pluton.

Fig. 7. Parallel alignment of microcline megacrysts in granodiorite at Whalers Cove, Point Lobos State Reserve, California (Fig. 1).

General relationships

The tonalite (T) south of Carmel Valley Village (CVV, Fig. 1) is biotite-rich (7-15 %), undeformed, and lacks any K-feldspar. The amount of K-feldspar in the pluton generally increases to the northwest as the tonalite grades to granodiorite and then to megacrystal granodiorite. The plagioclase in the tonalite is unzoned, but toward the northwest, zoning appears and becomes increasingly apparent (Fig. 8), suggesting (1) that the top of the pluton was formerly centered around Monterey and (2) that its deeper root was south of Carmel Valley Village. Where megacrysts first appear in the transition to the megacrystal granodiorite, the megacrysts have a random orientation. This applies to both transitions from quartz monzonite to the megacrystal granodiorite near Yankee Point and from the granodiorite to the megacrystal granodiorite south of Carmel Valley Village (Fig. 1). Only in a central band about 2 km wide at Point Lobos are there a few local zones (30 m wide) containing a strong parallel orientation of the megacrysts, and these zones generally trend northwest-southeast (Fig. 7).

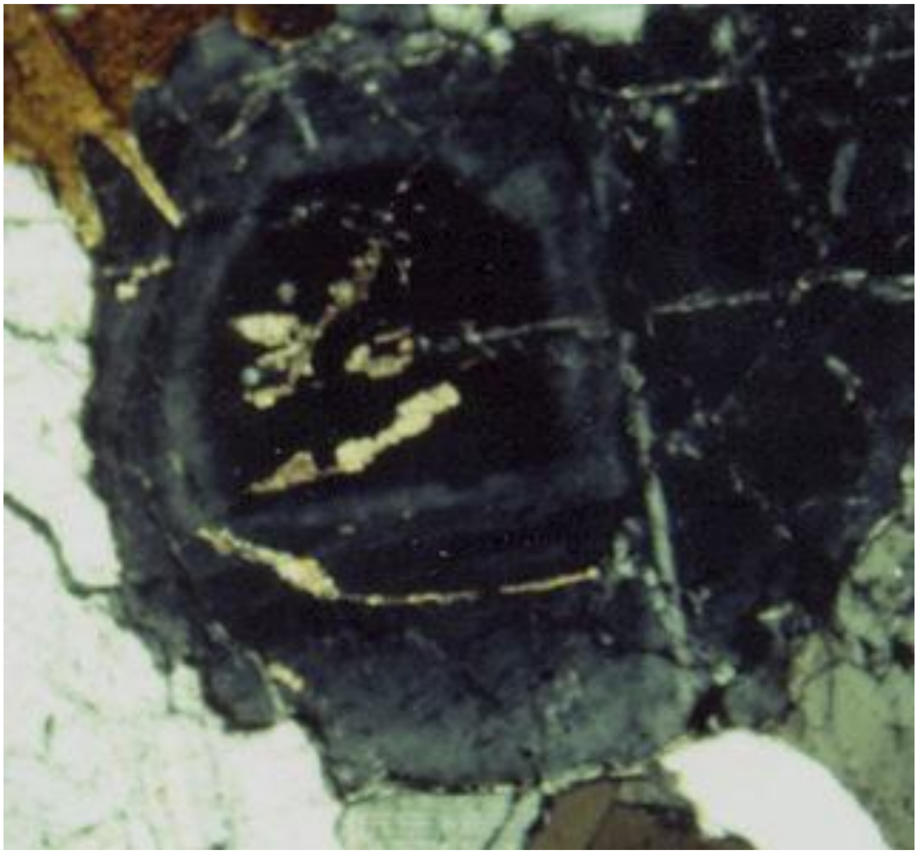

Fig. 8. Zoned plagioclase crystal; sericitized in core. Quartz (white); biotite (brown).

Changes across the transition zones in the different granite facies

Gradual mineralogical and textural changes occur across the transition zones. These changes are accompanied by cataclasis, which can be seen only in thin section. Generally, there is no evidence in the field for cataclasis or deformation.

Tonalite.

In the southeastern part of the pluton the biotite-rich tonalite (T, Fig. 1) is a medium-grained, hypidiomorphic, dark-gray rock and contains about 7-15 % biotite, 60-75 % plagioclase (An_{25-32}), and 15-25 % quartz. Generally, the tonalite is massive and undeformed (Fig. 9). Gradually, northwestward, the tonalite becomes increasingly broken by cataclasis (a cracking of plagioclase grains), and microcline begins to replace the interiors of broken plagioclase crystals in irregular veins and islands in random distribution (Fig. 10, Fig. 11, and Fig. 12).

Fig. 9. Outcrop showing oxidized and weathered biotite-rich tonalite.

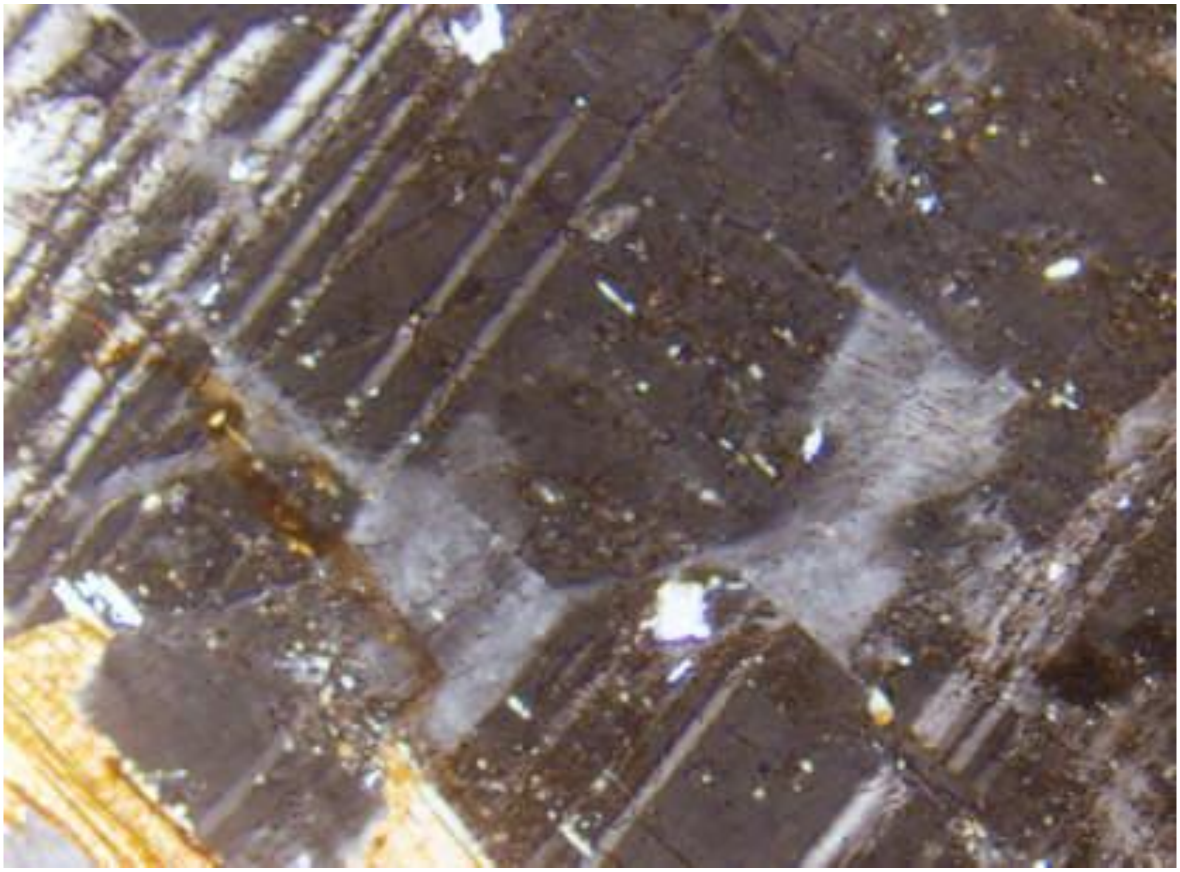

Fig. 10. Branched veins of microcline (light gray and white) extending into albite-twinned plagioclase (black).

Fig. 11. Veins of microcline (black) extending along curved fractures and replacing a large crystal of albite-twinned plagioclase (light gray).

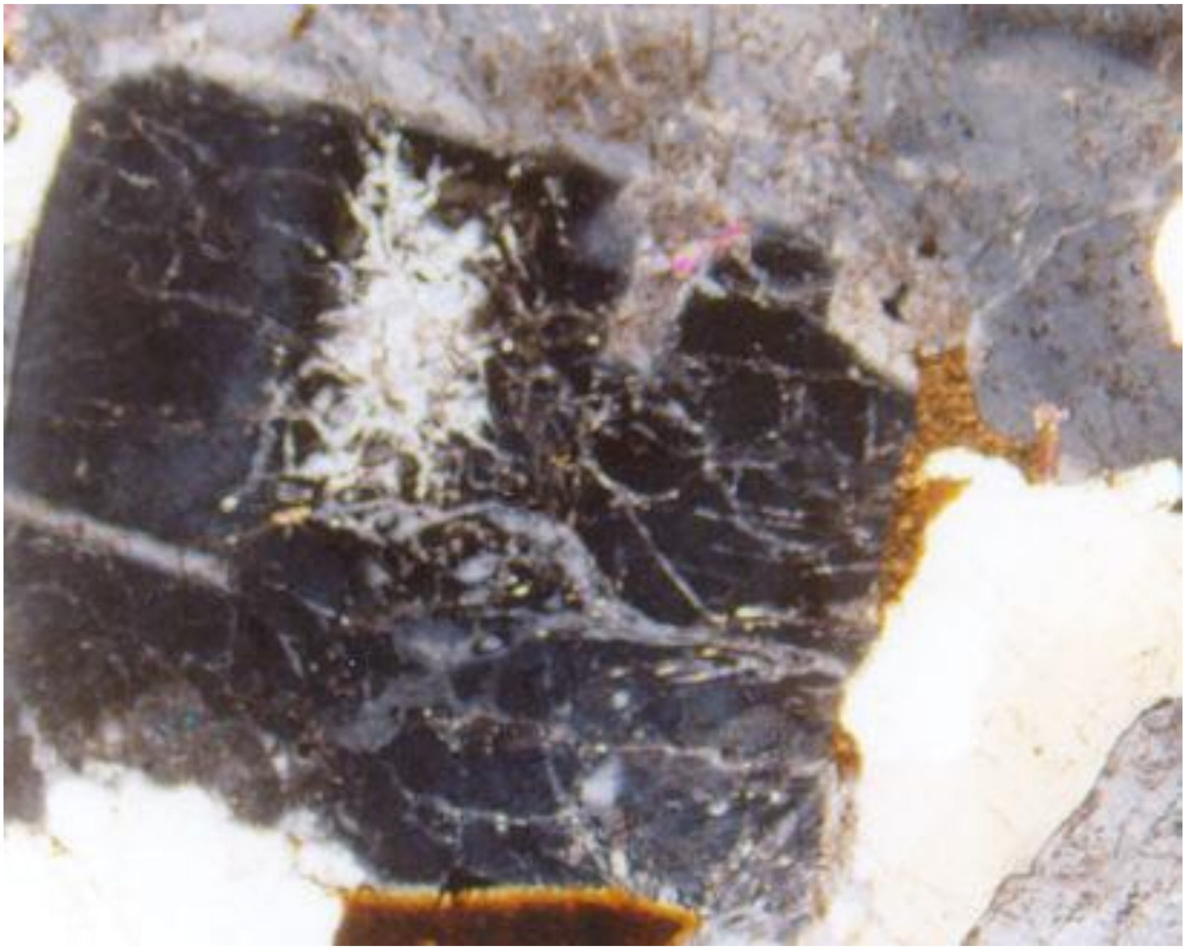

Fig. 12. Irregular branched veins of microcline (white and light gray) in albite-twinned plagioclase (black) and also extended into an adjacent plagioclase crystal (light gray; right side) along fractures. Quartz (white); biotite (brown).

Progressively northwest (but not uniformly everywhere), the microcline islands coalesce as the microcline increases in abundance. Here, the evidence for the cataclasis is eliminated in many places because the coalesced microcline is unbroken. As the coalesced microcline areas (as seen in thin section) increase in grain size, tiny islands of plagioclase occur locally and are in optical parallel orientation with them and/or with a larger plagioclase inclusion inside the microcline (Fig. 13).

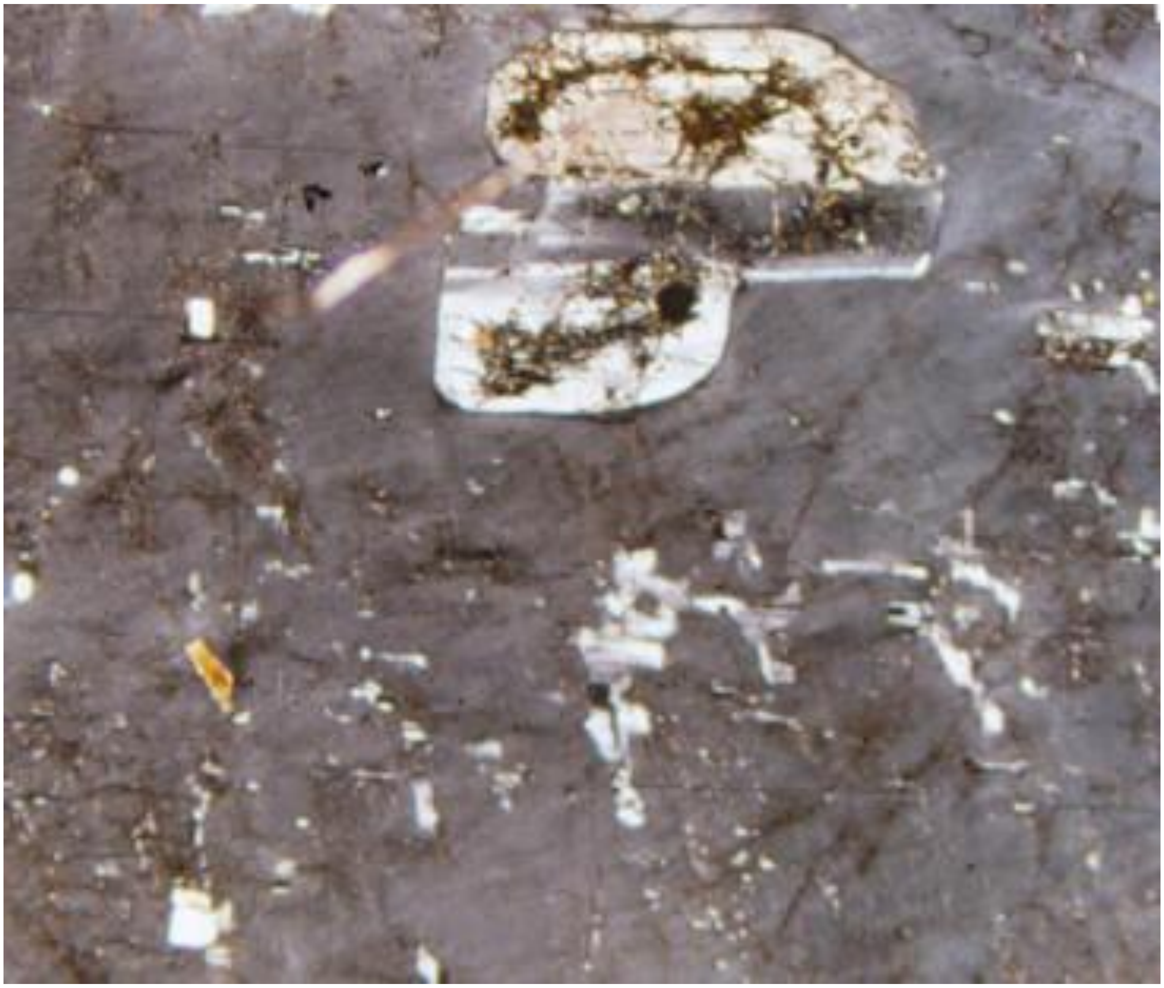

Fig. 13. Remnant islands of plagioclase (white; lower right) in parallel optical continuity occur in microcline (gray) below and altered, large, remnant island of albite-twinned plagioclase with rounded scalloped edges. Biotite (brown).

Farther northwest, where the microcline in veins and islands have coalesced and become larger crystals, myrmekite locally occurs with tiny quartz vermicules. The plagioclase of the myrmekite projects into the microcline but is optically continuous with a larger plagioclase grain outside the microcline (Fig. 14). Where myrmekite first appears in the transition, its volume is equal to or exceeds the volume of the coexisting microcline.

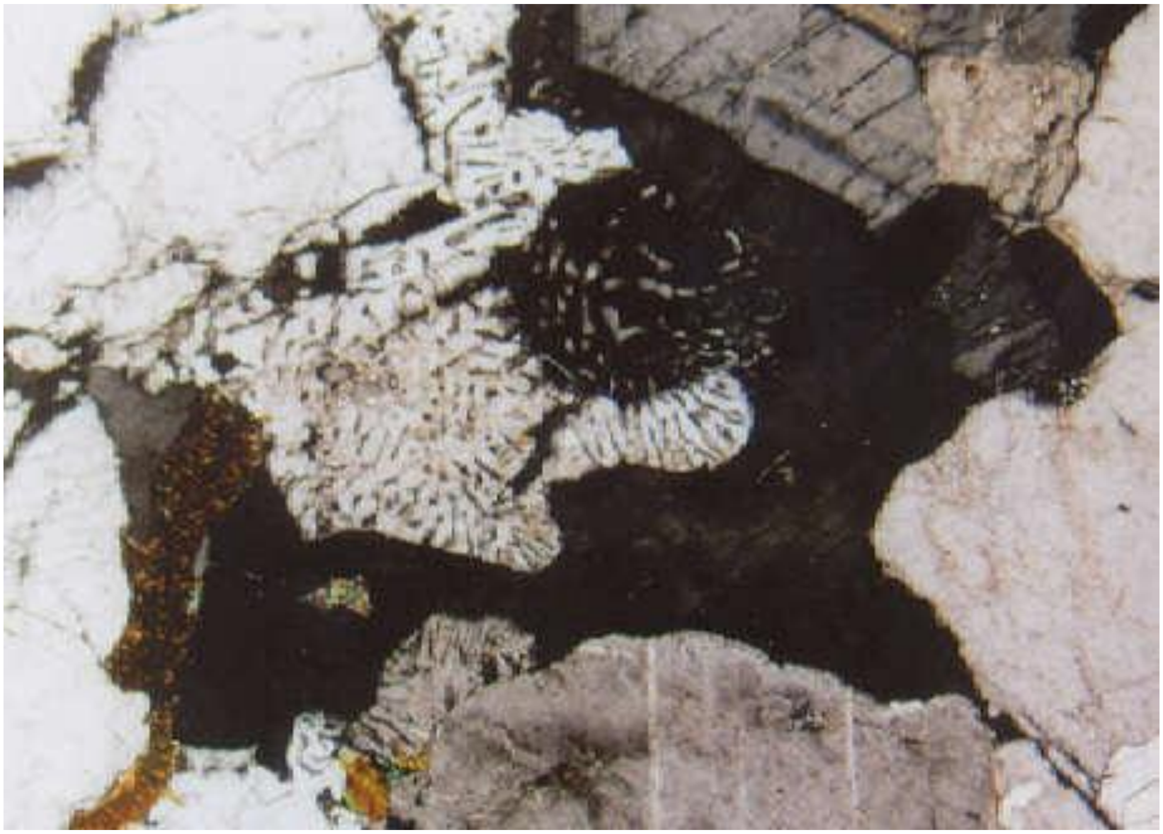

Fig. 14. Myrmekite (center, top and bottom) on borders of albite-twinned plagioclase (whitish gray and gray) and projecting into microcline (black). Microcline penetrates and replaces plagioclase along cracks.

Granodiorite.

Still farther northwest from the tonalite (Fig. 1), the microcline crystals become larger and extend beyond the boundaries of the initially replaced plagioclase grain into the surrounding, diversely-oriented, groundmass minerals. Here, the microcline encloses and/or replaces adjacent broken groundmass plagioclase grains and other minerals, preserving their diverse orientations (Fig. 15). Where this greater abundance of microcline is found, the rock is now a granodiorite (Gd, Fig. 1). In these places, however, it is difficult, if not impossible, to distinguish the microcline from the plagioclase in the field in an outcrop (Fig. 16).

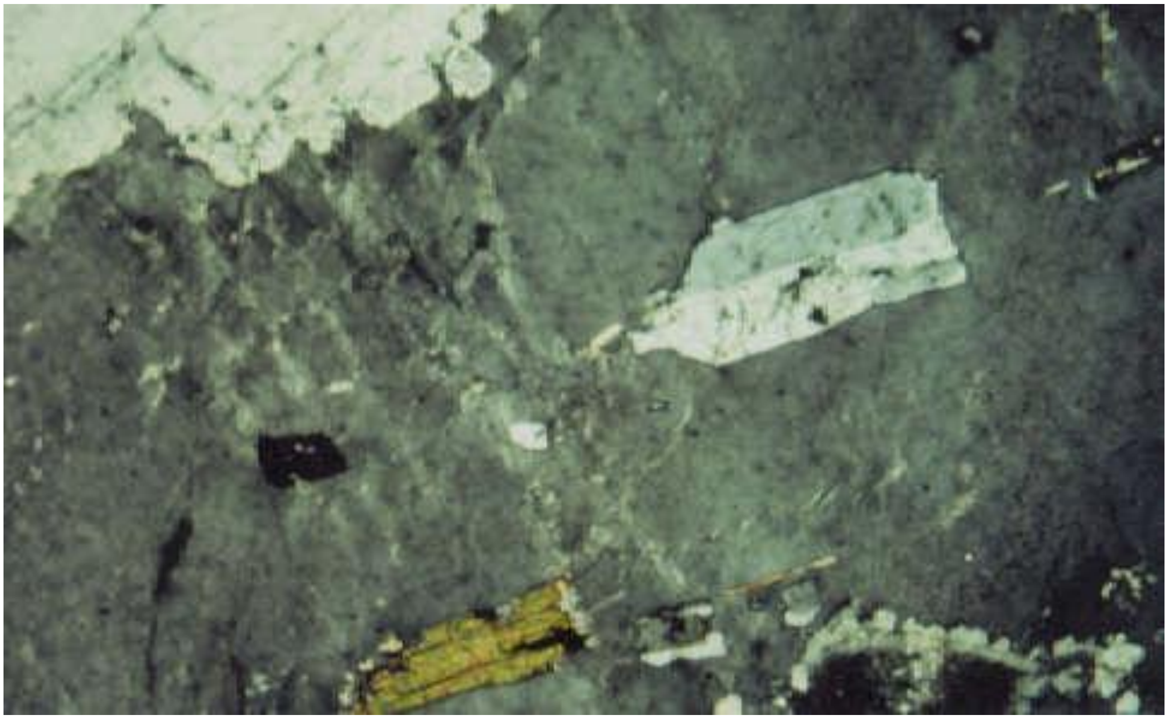

Fig. 15. Microcline (gray) with partly replaced plagioclase inclusions. One albite-twinned plagioclase inclusion (center; right) has relatively straight edges parallel to the microcline lattice. Two other plagioclase inclusions (upper left, white; bottom right, black and light gray) have lattices that are inclined to the microcline lattice and have scalloped edges.

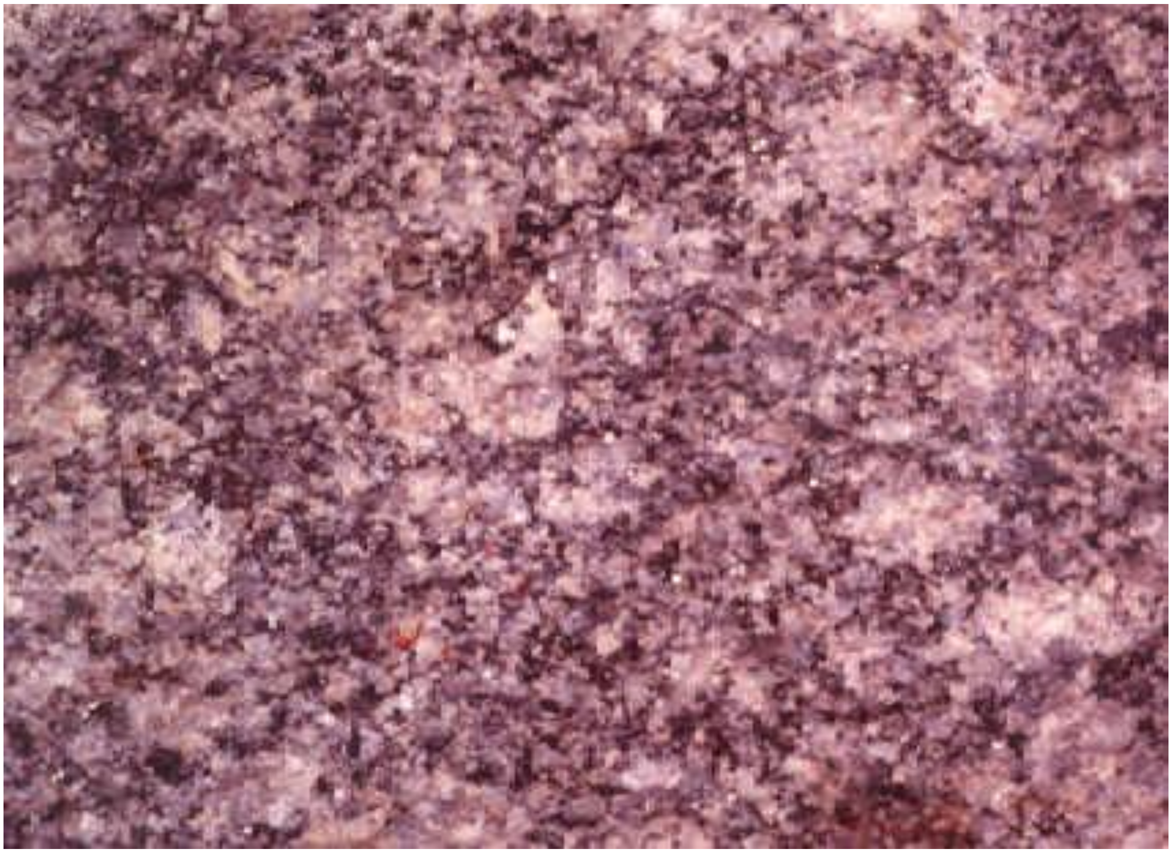

Fig. 16. Outcrop picture of biotite granodiorite.

Megacrystal granodiorite.

Still farther northwest toward Point Lobos and Monterey, the microcline crystals increase to 1-2 cm long, becoming visible in the field as separate randomly-oriented megacrysts in the rock (Fig. 17). The rock now becomes the megacrystal granodiorite (Mgd, Fig. 1). Continuing northwest (8-10 km), the microcline megacrysts gradually increase in size and become the largest (4 cm long) at Point Lobos and in the coastal area southwest of Monterey. At Point Lobos the larger megacrysts tend to be concentrated in broad planar zones trending northwest-southeast. The dominant minerals in the megacrystal granodiorite are microcline (5-20 %), biotite (3-5 %), quartz (10-20 %), and strongly zoned plagioclase (An_{24-28})(60-75 %). Magnetite, zircon, allanite, and titanite are accessories. Chlorite, epidote, and sericite occur as alterations.

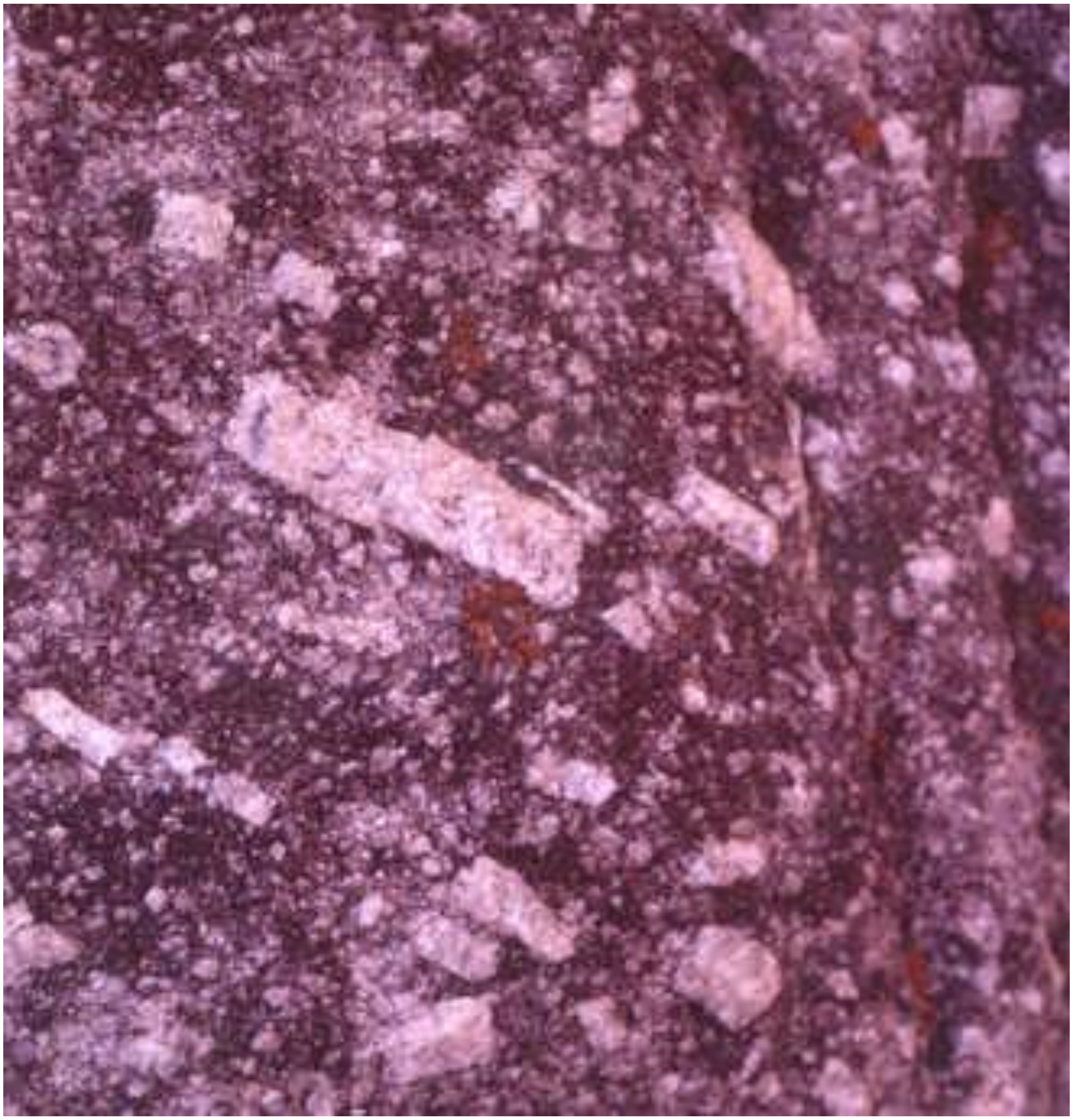

Fig. 17. Randomly oriented microcline megacrysts in megacrystal granodiorite.

In the field the microcline megacrysts appear euhedral with sharp borders (e.g., Fig. 4). In thin section, however, these crystals commonly have ragged irregular boundaries. Margins of the microcline megacrysts project into deformed plagioclase crystals, which are commonly bordered by myrmekite with tiny quartz vermicules (Fig. 18 and Fig. 19). Island remnants of the plagioclase occur in the microcline in parallel optical alignment with themselves or with an adjacent large plagioclase grain outside the microcline (Fig. 18 and Fig. 19). Some of the large microcline megacrysts with straight instead of ragged edges have remnants of plagioclase inclusions (Fig. 20) with veins of microcline extending into fractures in these inclusions.

Fig. 18. Carlsbad-twinned and zoned plagioclase crystal with speckled, sericite-altered core. Remnant end of the plagioclase crystal (center; right) occurs as an island in microcline (gray; right side) and is in optical parallel alignment with larger plagioclase crystal (left side). Myrmekite with tiny quartz vermicules occurs on corners of plagioclase projecting into microcline.

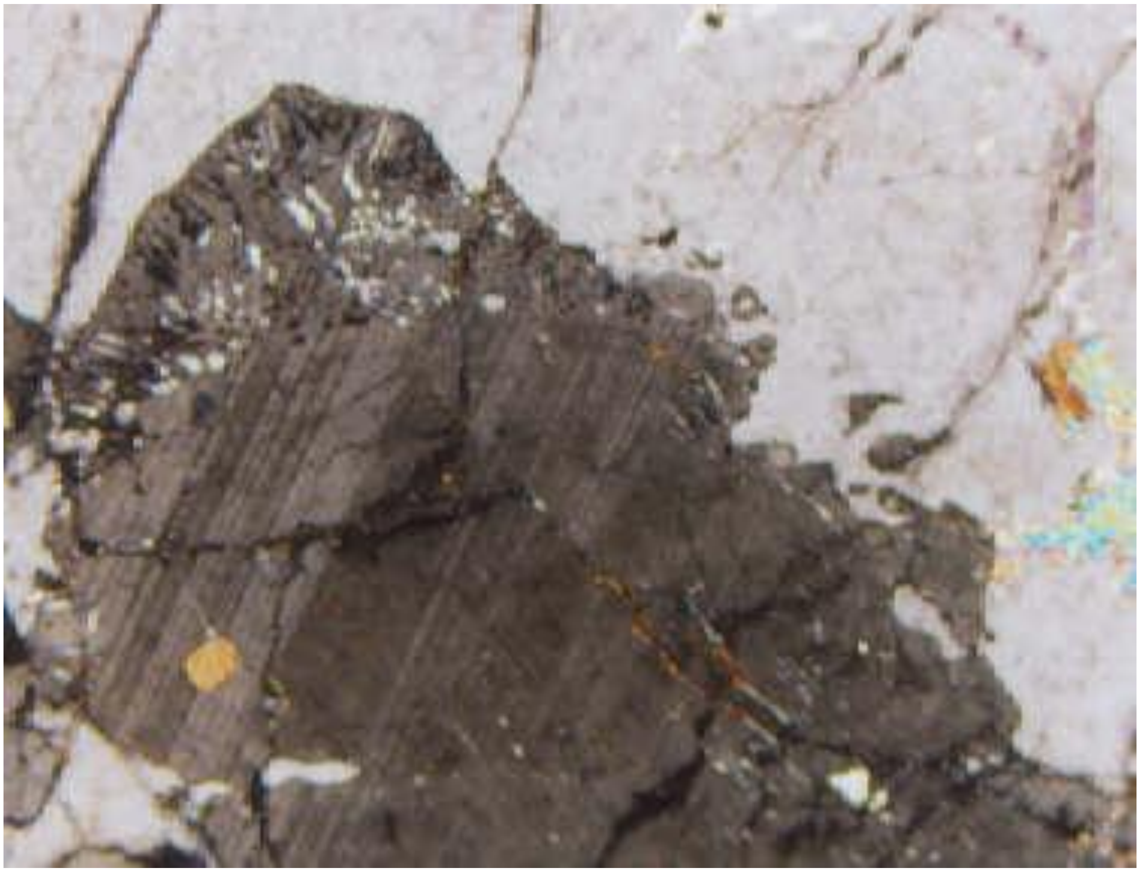

Fig. 19. Albite-twinned plagioclase (dark gray) is bordered by myrmekite and projects into a microcline megacryst (grayish white). Plagioclase of the myrmekite is optically continuous with the larger plagioclase crystal. Optically parallel islands of the plagioclase (gray; right side, center) are enclosed in the microcline (grayish white). Biotite (brown). Sericite alteration (blue).

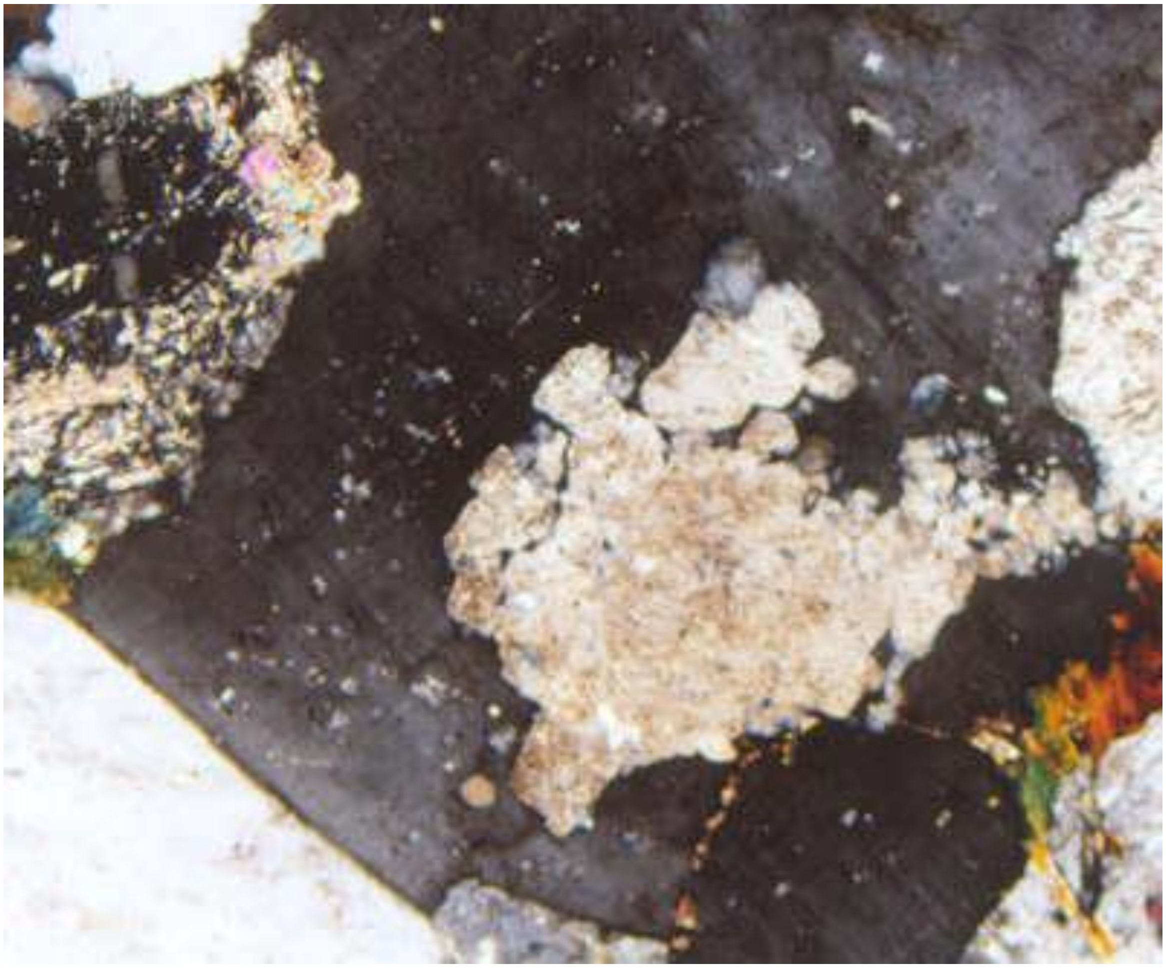

Fig. 20. Microcline megacryst (black) enclosing and projecting into a plagioclase island remnant (light tannish gray) along curved veins (former fractures; center). The veins have tiny microcline beads (center). One edge of the microcline forms a straight boundary (lower right).

In the transition from the granodiorite to the megacrystal granodiorite where the microcline crystals are about the same size as the adjacent groundmass plagioclase crystals, plagioclase inclusions are also found in the microcline. In these places the albite twinning and long edges of these plagioclase inclusions are mostly aligned parallel to the microcline lattice (Fig. 21). When the albite twinning in a plagioclase inclusion is inclined to the microcline lattice, the inclusion has irregular scalloped edges instead of smooth borders (Fig. 22). In a few places the plagioclase inclusions form rectangular outlines, like that found in a zoned plagioclase crystal (Fig. 8). In one such place, a myrmekite fragment is also enclosed (Fig. 23).

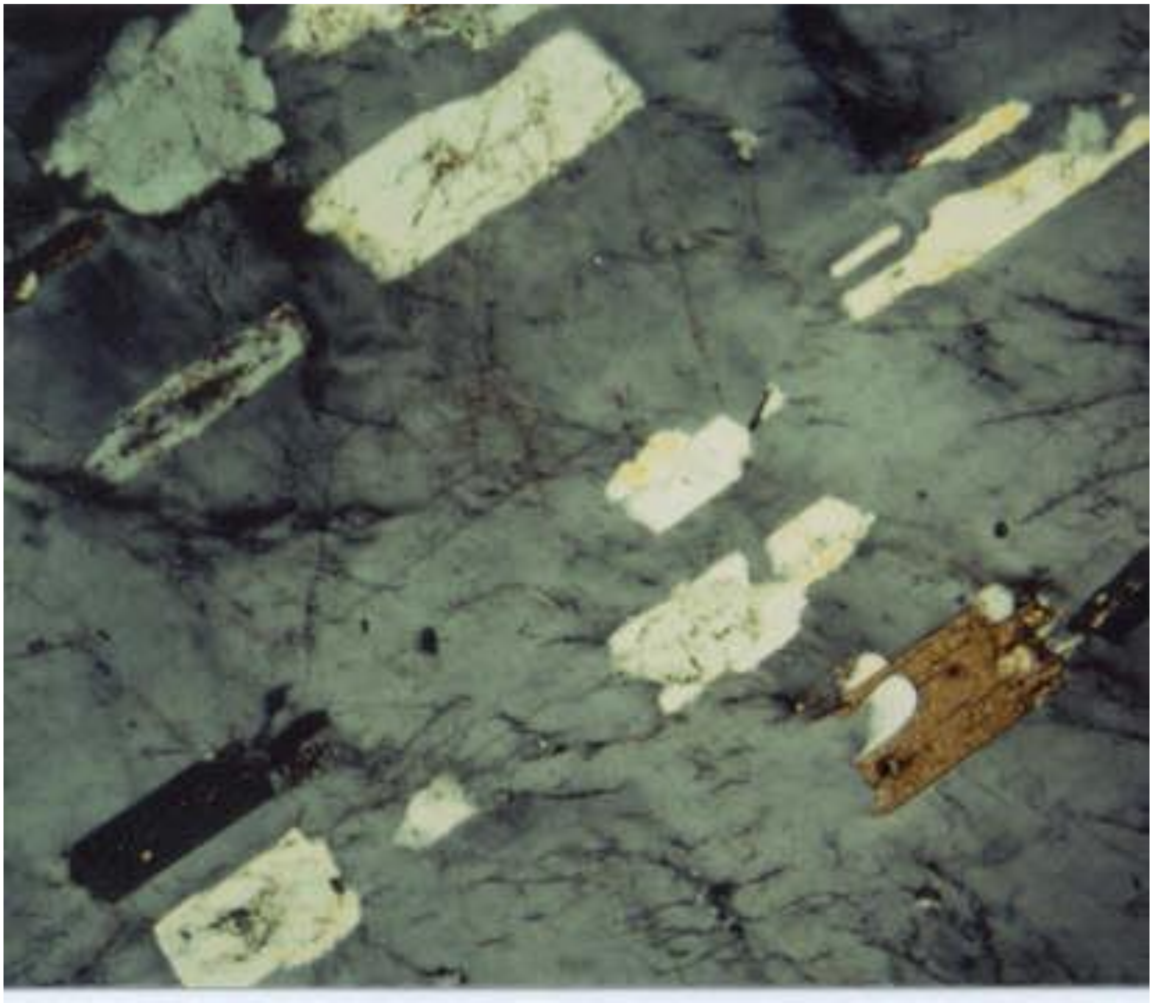

Fig. 21. Aligned inclusions of plagioclase crystals (white) and biotite (brown) in zoned microcline megacryst (light gray) in optical parallel orientation.

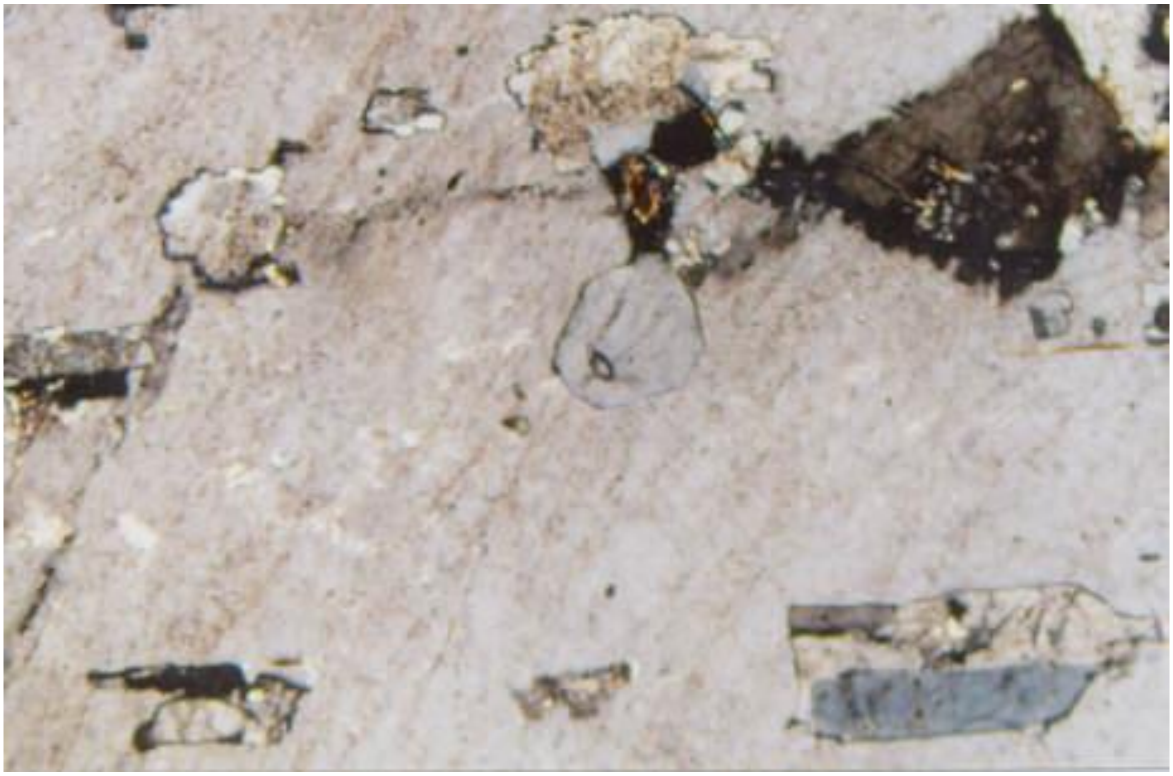

Fig. 22. Aligned inclusions of albite-twinned plagioclase crystals (bottom) in microcline megacryst (light gray; left to right) parallel to a possible crystal face in the microcline. Plagioclase inclusions (black and whitish gray) at the top have inclined lattices and exhibit scalloped edges.

Fig. 23. Possible remnant zoned plagioclase crystal (light gray, with rectangular outline) enclosed in microcline (black). Myrmekite occurs on former border.

Farther toward the northwest where the grain size of some of the microcline crystals gradually increases, the same relationships occur. Plagioclase inclusions have optical continuity with themselves or with larger plagioclase crystals outside the microcline. In the larger microcline megacrysts, however, the inclined plagioclase inclusions are greater in number than those which have parallel orientation. This would be expected because the plagioclase grains in the groundmass would have crystallized in random orientation in the magma, and, therefore, when these plagioclase crystals were engulfed by a growing microcline megacryst, rarely would they happen to have their lattices parallel to the lattice of the microcline. However, toward the northwest where the microcline megacrysts are as large as 4 cm long and have parallel alignment (Fig. 7), the plagioclase inclusions generally are smaller and more numerous, and those inclusions with parallel alignment are again more abundant than those with inclined lattices.

In many places, the edges of the large microcline megacrysts are bordered by aggregates of myrmekite grains that project into the microcline (Fig. 24). In these places the volume of the microcline megacryst is often more than 200 times greater than the volumes of the adjacent myrmekite grains, unlike what is observed at the first appearance of myrmekite.

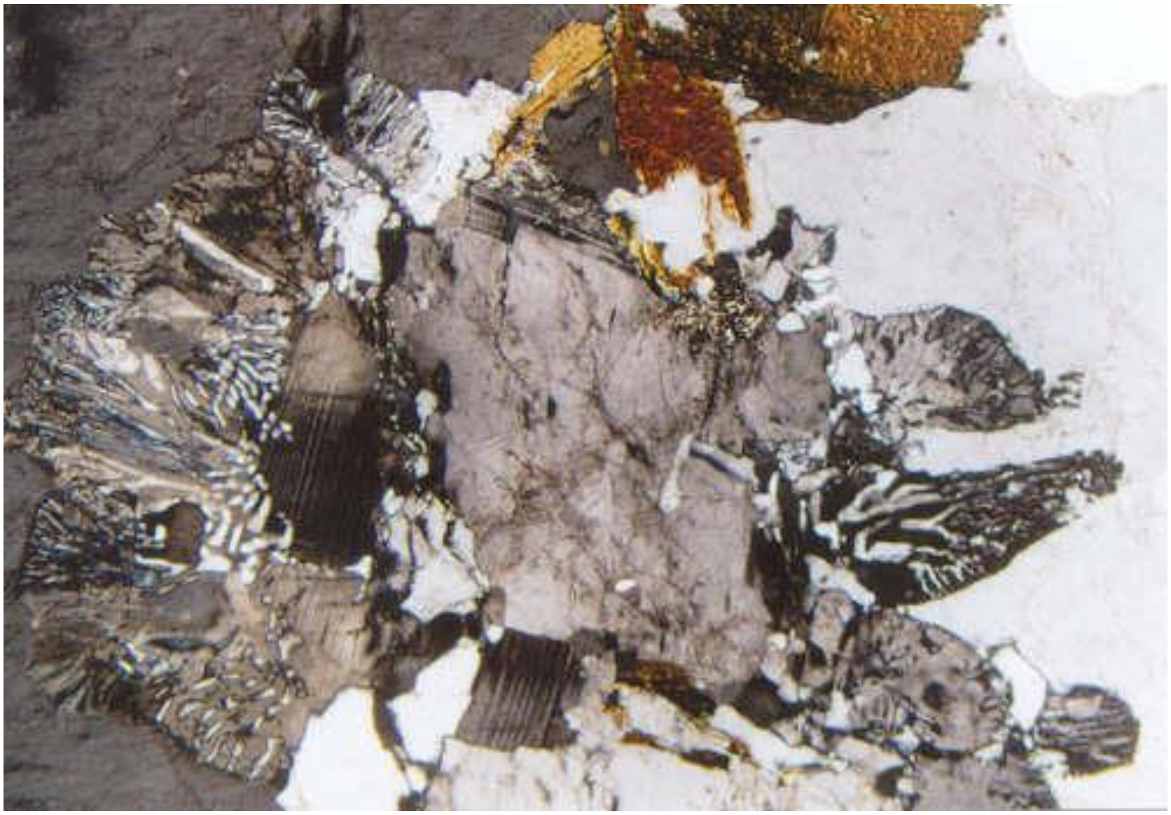

Fig. 24. Aggregate grains of myrmekite projecting into borders of microcline megacrysts (dark gray; left and upper left corner) and white (on right side). Albite-twinned plagioclase (light gray, center). Biotite (brown). Q uartz (white; upper right corner and bottom left edge of photo).

Finally, in the Point Lobos and Monterey area, the megacrystal granodiorite is a rock which looks magmatic (Fig. 25). It has a uniform composition, contains zoned plagioclase, has euhedral microcline megacrysts that look like phenocrysts, shows no evidence for cataclasis or deformation, and some of the microcline have Carlsbad twinning. It should be emphasized that much of the primary zoned and unzoned plagioclase crystals still remains in the rock, and, therefore, much of the original hypidiomorphic texture is preserved.

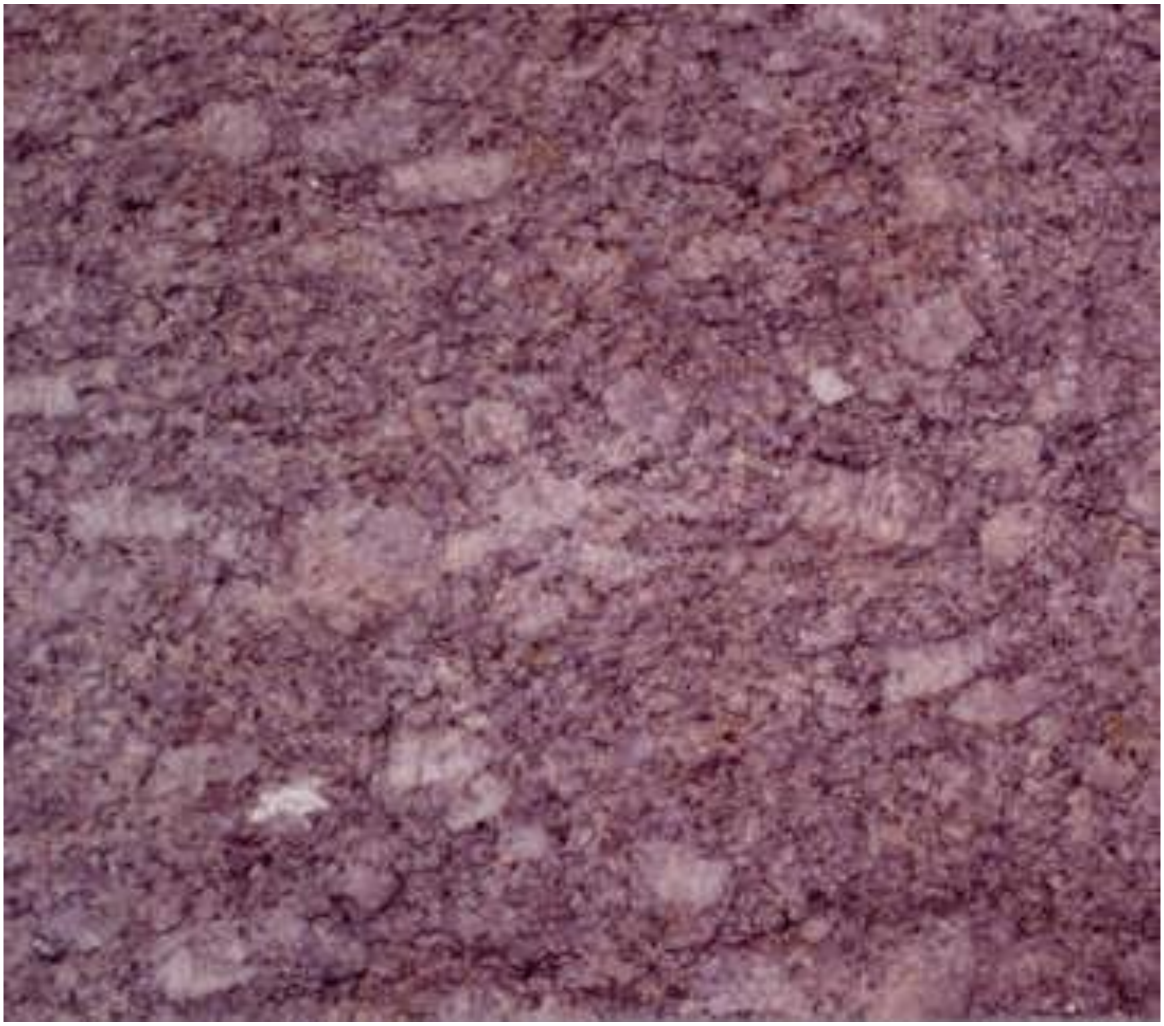

Fig. 25. Megacrystal granodiorite in which some of the microcline megacrysts are Carlsbad-twinned. (e.g., top left, center).

Interpretations

Magmatism and K-metasomatism. In the field, the gradual changes from the relatively mafic tonalite to the more-felsic granitic facies, from bottom to top, in the Monterey pluton have most of the mineralogical and chemical characteristics typical of magmatic differentiation. Moreover, in a few places the Monterey pluton contains angular mafic enclaves that are fragments of the former solidified quartz diorite wall rocks. These enclaves were broken off and incorporated during intrusion of the magma that formed the pluton. Therefore, an initial magmatic origin of the original pluton is not in doubt. Nevertheless, a later K-metasomatism to produce microcline could have changed or modified the more mafic facies into the more granitic facies of the pluton.

t is obvious that the mafic enclaves in the pluton are wall rocks that were broken off by flowing magma when the wall rocks were totally solid and readily fractured. However, in the flowing magma carrying the enclaves, the early-formed plagioclase crystals floating in the magma or in a magma mush of crystals would not have been broken when the magma moved past the wall rocks because these crystals were surrounded by liquid (melt). In a liquid the pressure is equal in all directions, and cataclasis or shearing of floating crystals is not possible, nor would the enclaves be further sheared once they were enclosed in the liquid. Cracking of crystals occurs in solids free of liquid, just as cracking or fracturing of wall rocks to produce enclaves occurs in solids. Therefore, the tonalite of the Monterey pluton must have been totally solidified prior to deformation that caused the initial cracking of its plagioclase crystals.

***Origin of microcline megacrysts and their plagioclase inclusions*.**

On the basis that brittle deformation and cracking of crystals occurred in the tonalite of the Monterey pluton, avenues would have been created for K-bearing hydrous fluids to replace the plagioclase with microcline. These replacements would have occurred along the irregular fractures in the plagioclase, producing microcline in veins and islands (Fig. 10, Fig. 11, and Fig. 12). During gradual but incomplete replacement of the broken plagioclase, the coalescing microcline veins and islands from many centers of replacement would leave trapped tiny island remnants of plagioclase inside the microcline with parallel optical alignment with themselves and with other large plagioclase remnants (Fig. 13). Where a microcline crystal replaced and grew beyond the boundaries of the initial broken plagioclase crystal, it would enclose the diversely-oriented, groundmass plagioclase crystals (and other minerals). Therefore, many of the plagioclase inclusions in the growing megacrysts are remnants of many different groundmass plagioclase crystals and have random orientation. In some places the lattices of these remnant plagioclase inclusions are parallel with plagioclase crystals outside the microcline (Fig. 18, Fig. 19, and Fig. 20). Those enclosed, partly-replaced, plagioclase grains which happened to have their lattice orientations parallel to the microcline lattice are commonly replaced until their edges are nearly straight and parallel to the microcline lattice (Fig. 15, Fig. 21, and Fig. 22). In contrast, those enclosed, partly-replaced, plagioclase grains, which happened to have their lattice orientations inclined to the microcline lattice, are replaced with scalloped edges, and the microcline extends into them along fractures (Fig. 15, Fig. 21, and Fig. 22). These relationships must be common occurrences because both Schermerhorn (1956a) and Canon (1962, 1964) have also noted in other terranes that where microcline replaces plagioclase inclusions, those inclusions with inclined lattices have scalloped edges and those with parallel lattices have smooth, straight edges. Although orthoclase crystals growing in a magma could enclose earlier-formed plagioclase crystals as inclusions, the curved veins of microcline along former fractures in such inclusions (Fig. 20) are more characteristic of K-replacements of a broken, fully-solidified rock rather than forming the microcline by inversion from orthoclase crystallized from a magma in which fracturing of crystals would not have occurred.

***Alignment of plagioclase inclusions and megacrysts*.**

In the early stages of development of microcline megacrysts, some of the plagioclase inclusions are aligned parallel to the microcline lattice (Fig. 21 and Fig. 22). Toward the northwest, the size of the inclusions decreases. Those inclusions that are aligned parallel to the lattice have straight edges on their long dimensions, while those inclusions that are inclined to the lattice have ragged edges. In addition, the relative abundance of those inclusions not parallel to the microcline lattice first increase and then decrease in number as the size and alignment of the microcline megacrysts increase. Where the microcline megacrysts are in parallel alignment, the numbers of parallel aligned plagioclase inclusions reaches a maximum.

Alignment of megacrysts and inclusions can be explained in several different ways: (1) magmatic flowage, (2) plagioclase crystals nucleating on former faces of a growing K-feldspar crystal, (3) former orthoclase phenocrysts aligned because of rotation during cataclastic shearing, and (4) alignment because of K-replacement associated with cataclasis.

(a) In the Monterey megacrystal granodiorite, magmatic flowage is an inadequate explanation because the groundmass minerals are not wrapped around the megacrysts in parallel alignment. In addition, the inclusions are not all parallel to the direction of supposed "flowage." Many are at right angles to the flow direction but still parallel to the microcline lattice in the narrow ends of the megacrysts as well as in the mid-portions of the megacrysts.

(b) Nucleation of plagioclase crystals on former faces of orthoclase in magma or *re-nucleation* of replaced plagioclase on former faces of microcline or orthoclase formed by replacement of plagioclase is unlikely because such nucleated plagioclase crystals would be expected to be euhedral with rectangular outlines. Instead, the plagioclase inclusions in the microcline in the Monterey pluton have either jagged ends or scalloped edges. Moreover, whether nucleation occurred in magma or by re-nucleation during replacement, the same degree of perfection of alignment of all inclusions would be expected whether the microcline crystals were in parallel alignment or not. This is not the case. Maximum perfection of alignment occurs only when the microcline crystals are also in alignment.

(c) If the alignment of microcline megacrysts resulted from deformation of former orthoclase phenocrysts that were rotated by shearing to parallel positions, then the megacrysts should have the appearance of augen with associated S- and C-structures, and the groundmass minerals should show evidence of mylonitization, and that is not the case. In addition, such an explanation does not account for the alignment of the plagioclase inclusions in the microcline megacrysts. Furthermore, throughout the pluton there is no evidence for the presence of orthoclase.

(d) If the plagioclase inclusions were aligned because of structural control following solidification of the pluton, metasomatism that was facilitated by cataclasis could cause gradual changes from one area to another, and these changes would be related to the degree of deformation. And that appears to be the case.

Where the megacrysts first appear in the transition zone, they have random orientation. The formation of a particular megacryst depends on which randomly oriented plagioclase crystal happened to be cracked and was most open to K-bearing fluids that would enable growth of a microcline crystal to large size. Toward the northwest, the larger microcline megacrysts tend to have an approximate parallel alignment although many are not aligned (Fig. 3 and Fig. 4). Only locally do both small and large megacrysts have well developed parallel alignment (Fig. 7). Because the megacrysts form by replacement of cracked plagioclase crystals, those randomly oriented plagioclase crystals in the groundmass which happened to have their cleavage planes oriented parallel or nearly parallel to a northwest-southeast shear direction would have been preferentially broken, most open to K-bearing fluids, and would be most likely to grow and become the larger microcline megacrysts. By inheriting the northwest-southeast orientation of the cleaved lattices of the plagioclase crystals, the megacrysts also have this orientation (Fig. 3, Fig. 4, and Fig. 7). Unfortunately, the K-replacements and recrystallization that produced the megacrysts eliminate most of the evidence for the shearing and cataclasis, and, therefore, the whole process must be logically deduced.

Initially, where the larger megacrysts first appear, they are not aligned nor are the plagioclase inclusions in any particular alignment. Gradually toward the northwest, the plagioclase inclusions whose lattices were inclined to the megacryst lattice become less abundant, and those having parallel lattices become more frequent and smaller in size. This gradational change in plagioclase inclusion orientation is also associated with the greater tendency of the larger megacrysts to have parallel alignment. On the basis of increasing deformation with a northwest-southeast shear component toward the northwestern part of the pluton, a greater degree of cataclasis is inferred. Some of this breakage could also have resulted from the K-replacement process, itself. Volume adjustments because of different minerals being replaced in the surrounding groundmass could cause shrinkage. In turn, the shrinkage would result in cracking of the adjacent plagioclase grains. The cataclasis and continued shearing would keep the system open so that continued K-replacement by introduced fluids would be possible.

To help explain the decreasing size of inclusions and their alignment, a strong breakage in a northwest-southeast direction in the northwestern part of the pluton would increase the frequency in which smaller plagioclase fragments would be formed and also a greater frequency of fragments having a lattice parallel to that of the microcline lattice. Those fragments having parallel lattices tended to be preserved and incompletely replaced, whereas the remaining small fragments with inclined lattices were mostly replaced or had ragged scalloped edges (Fig. 21 and Fig. 22). In that preferential replacement process, fewer numbers of plagioclase inclusions with inclined lattices would remain in the megacrysts relative to the numbers of plagioclase inclusions with parallel lattices.

Another way to produce parallel alignment of plagioclase inclusions has been suggested by Smithson (1965) in his study of K-feldspar augen in strongly deformed gneisses in Norway. He proposed that former inclined broken plagioclase grains were recrystallized to re-align their lattices parallel to the K-feldspar lattice. The objection to this possibility occurring in the Monterey microcline megacrysts is the presence of adjacent plagioclase inclusions with inclined lattices having scalloped or irregular borders. If recrystallization is the cause of alignment of inclusions, why are not all broken plagioclase inclusions recrystallized with parallel alignment?

Surrounding the megacrysts with parallel alignment, the groundmass plagioclase crystals appear to be unbroken and retain their random orientation. This observation seemingly would cast doubt on any theory suggesting cataclasis, including the replacement theory. If cataclasis occurred, then the groundmass plagioclase crystals should also be broken, but they are not. However, if these plagioclase crystals were also broken, then fluids would have replaced them as well as the other plagioclase crystals. Na and Ca ions would be removed from plagioclase crystals being replaced by microcline. Ca would likely leave the system, but Na could now move into adjacent broken plagioclase crystals, forming a more Na-rich plagioclase devoid of cracks or evidence of cataclasis; see http://www.csun.edu/~vcgeo005/Nr43Temecula.pdf and Collins (1988). As a collaboration of this process, Smithson (1965) noted that where porphyroblastic K-feldspar augen, having oriented plagioclase inclusions, were formed in strongly deformed rocks, the "*recrystallization is so thorough that little to no trace of cataclasis remains in the rock*." On that basis, replacement and recrystallization of some formerly zoned plagioclase crystals in the Monterey pluton likely also occurred. Moreover, where quartz replaced biotite, where epidote was formed from released Ca and Al ions, and where broken primary quartz crystals were recrystallized, evidence for cataclasis of other minerals would also have been eliminated. Thus, the replacement and recrystallization processes destroy the evidence for cataclasis in the groundmass surrounding the microcline megacrysts. Once gone, this former cataclasis can only be logically interpreted by the cataclastically broken plagioclase grains that are preserved inside the microcline megacrysts.

Origin of myrmekite.

In Fig. 24, the volumes of the adjacent microcline megacrysts (extending beyond the field of view of the photo) are more than 200 times the volumes of the adjacent myrmekite grains. In that case, such myrmekite could have exsolved from a former high-temperature orthoclase crystal, which is the usual explanation for the origin of myrmekite. Because the adjacent microcline megacrysts show no evidence of cataclasis, it would be reasonable to assume that they were former primary orthoclase crystals from which exsolution occurred and, therefore, were former orthoclase phenocrysts. However, as is shown in the earliest stages of replacement (Fig. 10, Fig. 11, and Fig. 12), microcline is first formed in the interiors of broken plagioclase grains, and this microcline continues to grow and become the megacrysts. At no place is orthoclase observed. Moreover, in these earliest stages where the microcline first coalesces to form small crystals, myrmekite is found in a few places and has **relatively greater volume than the adjacent microcline** (Fig. 14).

As determined experimentally, the amount of dissolved Ca in a former high-temperature K-feldspar crystal cannot exceed 16 wt. % (Carmen and Tuttle, 1964). If this maximum amount of Ca were dissolved in the adjacent volume of microcline (or orthoclase) in Fig. 14 and it exsolved along with the necessary Si, Al, and O to produce myrmekite, the volume of myrmekite that could have been produced would have been only about *14 % of the volume of the adjacent microcline*. Instead, the volume of myrmekite **is equal to or exceeds** the volume of the adjacent microcline (Fig. 14). Therefore, this myrmekite **cannot have formed by exsolution** and must have been formed during the K-metasomatic and deformational processes that affected the quartz-free plagioclase on which the myrmekite is attached (see Collins, 1988; Hunt et al., 1992; http://www.csun.edu/~vcgeo005/Nr1Myrm.pdf; http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf).

Because similar myrmekite is found scattered throughout the granodiorite facies beginning with its first appearance where microcline also first appears (Fig. 14), it is logical that all myrmekite in the pluton must have been formed the same way. However, the degree of cataclasis affects the relationships of the myrmekite to the microcline and the associated quartz-free plagioclase. (1) Where the plagioclase was deformed by only slight cracking, the myrmekite is optically continuous with and part of quartz-free plagioclase while projecting into adjacent microcline (Fig. 14). (2) Where greater cataclasis was present, the microcline grew beyond the initial plagioclase grain that was replaced and enclosed myrmekite that was once on the borders of the original cracked plagioclase crystal (Fig. 23). Finally, (3) where cataclasis was very strong and was associated with the development of parallel-aligned megacrysts, the myrmekite now consists of aggregate grains, some of which are no longer optically continuous with adjacent quartz-free plagioclase (Fig. 24). Thus, myrmekite is not only a clue to the former cataclasis and replacement of the primary rock, but its relative size and relationship to adjacent grains are also a clue to the degree of cataclasis.

The myrmekite inclusion inside the microcline (Fig. 23) is also important because its presence as an inclusion is a clue that the microcline host cannot have been former orthoclase that crystallized from magma. In magma, if quartz and plagioclase exsolved from a growing orthoclase crystal while it was still growing and enclosed the myrmekite, the quartz and plagioclase at melt temperatures would either have coalesced to form separate quartz and plagioclase crystals or crystallized simultaneously in micrographic or granophyric textures. In such textures the coexisting plagioclase would have had a uniform composition, but that is not the case in myrmekite. In myrmekite the plagioclase has gradual changes in composition which correlate with the volume (width) of the adjacent quartz vermicules (Collins, 1988).

All of these relationships illustrate that to understand the full origin of microcline and its associated myrmekite, one must study more than the single outcrop and observe the transition from the megacrystal granodiorite to where the megacrysts and microcline disappear.

Carlsbad-twinned microcline.

Carlsbad twinning is common in orthoclase crystallized from a melt, and this twinning can be inherited by the microcline that inverts from the orthoclase. However, as in other localities, Carlsbad twinned microcline megacrysts can form by replacement in the interiors of former, cracked, Carlsbad-twinned plagioclase crystals without first forming orthoclase; see http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf and http://www.csun.edu/~vcgeo005/Nr3Myrm.pdf.

Quartz monzonite.

In the area closer to the Pacific Ocean, mapped as quartz monzonite (Qm) near Yankee Point (YP, Fig. 1), similar transitional textural replacements in deformed rocks (like those in Figs. 5-24) occur from (unmapped) trondhjemite and tonalite (plagioclase An_{24-31}) to quartz monzonite, and then to granodiorite with randomly-oriented megacrysts, and then to megacrystal granodiorite with strongly parallel-oriented megacrysts at Point Lobos (Fig. 7). Thus, in the quartz monzonite area (Fig. 1), deformation also controls the first appearance and formation of microcline megacrysts. Even the quartz monzonite dike cutting the quartz diorite (Fig. 2) has been slightly deformed, and cracked plagioclase crystals have been replaced by microcline and myrmekite. These relationships are consistent with the hypothesis that megacrysts throughout the pluton are not localized sites of orthoclase phenocryst growth in magma but are microcline metacrysts formed by K-metasomatism.

Wall rock biotite-hornblende quartz diorite modifications.

If large-scale K-metasomatism is a valid hypothesis, then it should be expected to cut across rock boundaries, and this is what is observed in the wall rock biotite-hornblende quartz diorite (Qd, Fig. 1 and Fig. 2), south of the quartz monzonite and megacrystal granodiorite of Monterey. This quartz diorite is generally undeformed, but local cataclasis (cracking of grain boundary seals) has allowed some broken plagioclase grains to be replaced in their interiors by microcline islands. Here, also, small microcline crystals (1-2 mm wide) and myrmekite are formed in less than 0.5 percent of the rock. *The volume of the* *associated myrmekite exceeds the volume of the adjacent microcline* (as in Fig. 14). These relationships support the concept that K-metasomatism of biotite-rich plutons is a common phenomenon, following solidification, provided that deformation permits introduction of fluids to facilitate the breakdown of biotite to release the K.

Oscillatory zoning in the megacrysts.

Dickson (2000, written communication), who has also studied the Monterey K-feldspar megacrysts, reported that on stained slabs the megacrysts have "hour glasses" of selected groundmass minerals and oscillatory zoning. If the K-feldspar megacrysts had formed initially as orthoclase that crystallized from a cooling magma, oscillatory zoning would be less likely. Instead, Ba ions would be enriched in the cores, because at high temperatures, Ba ions tend to crystallize before K ions and, as the temperature drops, become less abundant toward the rims. Therefore, orthoclase crystals tend to be Ba-zoned from cores to rims rather than show oscillatory zoning. During K-metasomatism, however, the microcline megacrysts in the Monterey rocks would crystallize at nearly the same relatively-low temperature as the crystals grew from cores to rims. In that process, both Ba and K ions would be brought in continuously in fluids at this low temperature as they are subtracted from biotite being replaced by quartz. Because slight differences in Ba- and K-concentrations in these fluids would occur from time to time, oscillatory zoning is what should be expected.

Triclinicity of the microcline.

Triclinicity of the microcline in the megacrysts is logical because the microcline replaces triclinic plagioclase (Wyart and Sabatier, 1956). Therefore, the microcline triclinicity in the Monterey pluton need *not* result from the secondary inversion from *former orthorhombic symmetry* in primary high-temperature orthoclase. For further discussion of this topic, see Collins (http://www.csun.edu/~vcgeo005/Nr26Controversy.pdf, http://www.csun.edu/~vcgeo005/Nr36Experimental.pdf, http://www.csun.edu/~vcgeo005/Nr37Overlooked.pdf and Orville (1958, 1962).

Conclusions

There is no doubt that the trondhjemite and tonalite of the Monterey pluton had an earlier magmatic origin. The normally zoned plagioclase crystals must have crystallized from a rapidly crystallizing melt. The general absence of zoned plagioclase crystals in the tonalite in the southeastern area and the increasing degrees of zonation in plagioclase toward the northwest imply that what is now the megacrystal granodiorite in and around Monterey, crystallized near the former top of the pluton. The tonalite in the southeastern part must have been the facies that initially crystallized throughout most of the pluton, although the top may have been a trondhjemite. After final crystallization of the pluton, deformation of the early-formed facies permitted rising, K- and Si-bearing, hydrous fluids to move through and modify the trondhjemite and tonalite by K-and Si-metasomatism, converting them to quartz monzonite, granodiorite, and megacrystal granodiorite, depending upon the degree of cataclastic breakage and the available K and Si ions. In that process, much (but not all) of the biotite was replaced by quartz, thereby releasing K and water to facilitate the K-metasomatism. A distant mantle source of the K ions is not necessary, although some K released from biotite in the pluton could have migrated upward to be concentrated at the top of the pluton. The K moved into cracked plagioclase crystals to form microcline, which locally grew in size, engulfing and replacing groundmass minerals to form megacrysts. Where deformation and shearing was strong, plagioclase crystals whose cleavage planes were aligned parallel to the plane of shearing were the ones which were initially or most often slightly cracked and replaced by microcline. In this way the microcline inherited the lattices of plagioclase crystals all having the same parallel orientation, and, as a result, many of the growing microcline megacrysts also were approximately parallel. During the shearing and volume adjustments that occurred where microcline crystals were formed, the granulation of weakened adjacent plagioclase crystals whose lattices were inclined to the plane of shearing created many small fragments some of which were parallel to the lattice of the growing megacryst. As the microcline grew in size from the initially replaced plagioclase, the microcline engulfed these fragments. Where the lattices of small broken grains happened to be parallel to the megacryst lattice, these grains tended to be incompletely replaced, while other grains whose lattices were inclined tended to be more completely replaced. This preferential replacement resulted in a zonal arrangement of plagioclase inclusions in the megacrysts.

The microcline megacrysts increase in size and abundance from the southeast to the northwest likely because the degree of cataclasis increased toward the northwest, and, thus, the system there became more open to fluid movements. Possibly, the cataclasis and K-metasomatism that produced the various granitic facies in the Monterey pluton occurred when the Salinas block containing this pluton was in the early stages of being transported northward along right-lateral strike-slip faults to its present position. The replacement origin of the microcline megacrysts means that the "porphyritic" granodiorite is not a true porphyry containing phenocrysts of orthoclase but the result of K-metasomatism.

Nevertheless, the dikes that extended from the pluton and penetrated the wall rocks, the enclaves of the wall rocks, the swirled schlieren characteristic of flowing plastic magma, and much of the hypidiomorphic texture are magmatic features that are retained during the replacement processes. Therefore, the magmatic tonalite and trondhjemite have changed or evolved into different mineralogical compositions after their emplacement and total solidification.

Other studies of microcline megacrysts

K-feldspar megacrysts lacking zoning and those with concentrically-oriented tiny plagioclase inclusions in rings have been studied by many different investigators. Suggested origins are either ***magmatic*** (Frasl, 1954; Cannon, 1964; Hibbard, 1965; Booth, 1968; Emmermann, 1969; Smith, 1974a, 1974b; Vernon, 1986, 1989; and Smith and Brown, 1988) or ***metasomatic*** (Drescher-Kaden, 1948; Schermerhorn, 1956a, 1956b, 1961; Marmo, 1958; Stone and Austin, 1961; Smithson, 1965; Augustithis, 1973; and Dickson, 1996). For those megacrysts considered by the above authors to be ***magmatic***, the K-feldspar is either microcline or orthoclase. For those megacrysts considered to be ***metasomatic***, the K-feldspar is usually microcline. Dickson (1996), however, considers the orthoclase megacrysts in the Papoose Flat pluton to be metasomatic; and Collins finds that orthoclase bordered by myrmekite in the Cooma pluton in Australia is metasomatic (http://www.csun.edu/~vcgeo005/Nr27Cooma.pdf). Also, microcline bordered by myrmekite which converted to orthoclase in the Popple Hill gneiss near the Adirondack massif is considered to be metasomatic (http://www.csun.edu/~vcgeo005/Nr28Popple.pdf).

Although progressive development of the microcline megacrysts in the Monterey granodiorite in cataclastically altered trondhjemite and tonalite supports a metasomatic origin for their formation, this situation does not necessarily serve as a model for other localities. Each terrane containing K-feldspar megacrysts with oriented, tiny, concentric plagioclase inclusions needs further study to see whether the characteristics are more consistent with K-metasomatism or magmatism.

Other examples that are consistent with K-metasomatism include the megacrystal granite in the Waldoboro complex in Maine (http://www.csun.edu/~vcgeo005/Nr6Waldoboro.pdf), the megacrystal quartz monzonite at Twentynine Palms in the Joshua Tree National Park (http://www.csun.edu/~vcgeo005/NrTwenty.pdf, the megacrystal parts of the Ardara pluton in the Donegal granites (http://www.csun.edu/~vcgeo005/Nr10Donegal.pdf), the Ponaganset augen granitic gneiss in Rhode Island (http://www.csun.edu/~vcgeo005/Nr22Ponanganset.pdf), the megacrystal Kavala granodiorite in northern Greece (http://www.csun.edu/~vcgeo005/Nr29Greece.pdf), the augen granite gneiss in the Bill Williams Mountains of Arizona (Collins, http://www.csun.edu/~vcgeo005/Nr33BillW.pdf), and the megacrystal Bergell granite in the Swiss Alps (Wenk, 1982; Blanckenburg, et al., 1992; Schmid, et al., 1996).

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