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50. Plate tectonics, the segmented Laramide Slab, deformation, and large scale K- and Si-metasomatism

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Abstract

Deformation, caused by the down-going segmented Laramide Slab under southern California, created shear zones in the Sierra Nevada batholith, in the Mojave-Salinia arc segment, and in eastern California. In these shear zones, the plagioclase crystals in primary quartz diorite plutons were deformed and microfractured so that introduced K caused some of them to be replaced by K-feldspar. Broken mafic silicates were also replaced by quartz. As a consequence of the K- and Si-replacements, the quartz diorites in the shear zones were converted into metasomatic granodiorite, quartz monzonite, or granite. Myrmekite is a clue to the metasomatism. In other parts of the world where K is available and where primary mafic igneous rocks are sheared, K-metasomatism that produces K-feldspar and myrmekite can be expected.

Introduction

It is well recognized that the release of hydrous fluids from a subducting slab creates the rise of magmas that are emplaced as arc plutons in an overlying continental plate, such as happened to form the Sierra Nevada batholith (Billen and Gurnis, 2001; Ulmer, 2001). Once the plutons are emplaced, cooled, and solidified, however, the subduction of the oceanic slab does not stop. Its continued downward motion and any changes in angle of subduction can then have major structural effects on the overlying solidified plutons. Saleeby (2003) described the effects of segmentation of the Laramide Slab in southern California when thickening of the slab caused it to be more buoyant and change from a steep dip to a shallow dip under the region now occupied by the Mojave Desert. As this change in dip occurred, the overlying plutonic rocks in the Sierra Nevada batholith were sheared, creating the nearly vertical Proto-Kern Canyon-Sierra Crest shear zone and other shear zones parallel to it. The overlying plutonic rocks in the Mojave-Salinia arc segment and in eastern California were also sheared, producing multiple high angle reverse faults (Figs. 1, 2, and 4 in Saleeby, 2003). Subsequently, a thick portion of the shallow down-going oceanic slab was followed by a thinner slab, and the subducting slab again obtained a steep dip. Movements of the steeply subducting slab now caused the overlying plutonic rocks in the Mojave-Salinia block to again become sheared, this time forming low-angle, west-dipping, normal faults that crosscut the reverse faults and greatly increasing the degree of shearing. Blocks of the plutonic rocks were then extended westward and eventually, the Salinia block moved from its position in the Mojave Desert northward adjacent to San Francisco. Finally, uplift and erosion exposed the plutonic rocks in the Mojave Desert, the eastern California shear zone, and the Sierra Nevada batholith, enabling the plutonic rocks in the shear zones to be examined.

Generally, assumptions are made that after plutons have been emplaced and solidified, their compositions are fixed except for minor alterations. For example, while the shallow and steep subductions of the Laramide Slab were occurring, marine "wet" graywackes and basalts (schists) were carried down in a wedge on top of the subducting slab and underplated the overlying continental plutonic rocks. Saleeby (2003) noted that copious amounts of water must have continued to be released from both the underlying subducting oceanic Laramide Slab and from the underplated graywacke-basalt schists and that this water would have caused retrograde metamorphism of the overlying rocks after the rocks had cooled. This metamorphism presumably produced some green-schist-facies minerals at temperatures of 250-350 degrees C. Such retrograde metamorphism, however, would neither change the chemistry of the rocks (except for added water) nor their defining mineralogy that classifies them as granodiorites or diorite, for example. Mineral alterations and rise of fluids, however, should not be limited to the 250-350-degrees-C range and logically would be expected to occur also at higher temperatures but below melting conditions. On that basis, investigations need to be centered on the temperature range after solidification of the various magmas but before the green-schist-facies minerals.

The combination of extensive shearing in the Sierra Nevada and Mojave Desert area and the continued rise of abundant hydrous fluids at subsolidus temperatures could have permitted chemical and mineralogical changes in the overlying sheared plutons. In this temperature range, K becomes soluble and would readily move or diffuse in the hot hydrous fluids to cause metasomatic changes

(Orville, 1963; Collins, 1999; http://www.csun.edu/~vcgeo005/Nr36Experimental.pdf). The source of the K would be from the same Precambrian continental crust that melted to produce biotite in the primary relatively mafic rocks in the eastern parts of the magmatic arc. Additional K could come from "wet" micas and feldspars in the marine graywacke (schists) that were underplated beneath the overlying plutons. Silica is soluble over the whole temperature range and would have been available from these same Precambrian rocks and underplated schists.

The deformation, caused by the continental motions of the subducting slab, would have broken the overlying solid rocks in the plutons in the shear zones, cracking grain boundary seals and microfracturing crystals. Therefore, avenues existed through which hydrous fluids could flow and bring in dissolved K and Si. Some plagioclase crystals in the earlier emplaced diorite, quartz diorite, and tonalite could be slowly replaced by K-feldspar, which is more stable at lower temperatures (Orville, 1963), and some of the mafic silicates could be replaced by quartz. In that process, primary relatively-mafic plutonic rocks in the magmatic arc could be slowly and gradually converted over time into more granitic compositions. The following sections provide evidence of changes that occurred in the sheared plutonic rocks after they had solidified.

The Sierra Nevada

In the broad Proto-Kern Canyon fault zone near the Lake Isabella Reservoir (Fig. 1 and Fig. 2 in Collins and Collins (2004; http://www.csun.edu/~vcgeo005/Nr49Isabella.pdf) the shear zones in solidified diorite created an open system in which hydrous fluids moved upward and caused modifications of the rock.

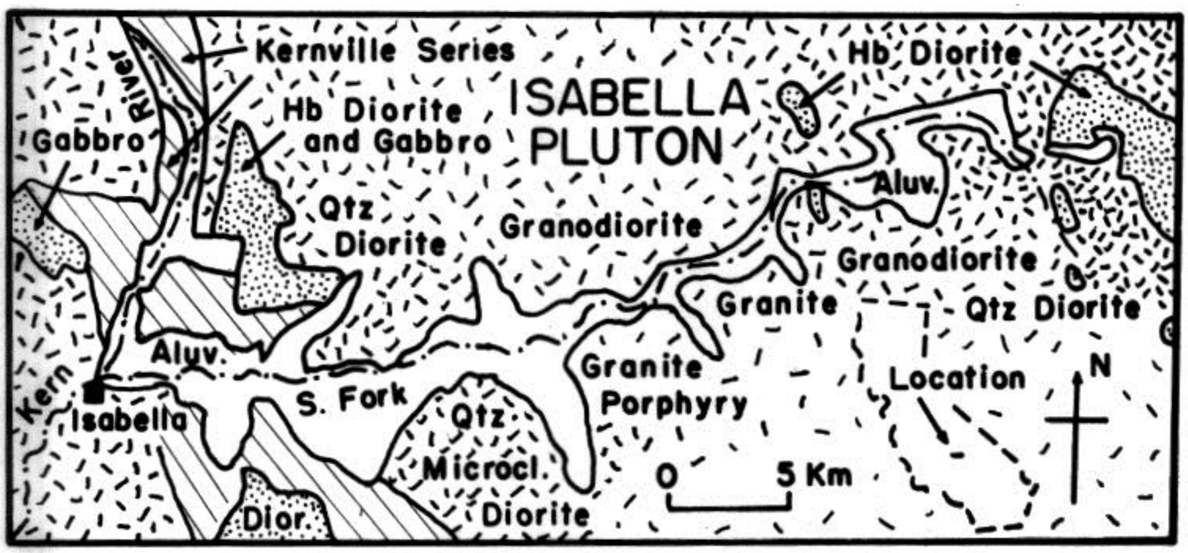

Fig. 1 in Collins and Collins 2004. Geologic map of the Isabella pluton, showing location of hornblende (HB) diorite and gabbro wall rock (Kernville pluton) and the Kernville metasedimentary series: see text. Modified after Miller (1931) and Miller and Webb (1940), keeping their generalized map pattern but emphasizing locations of different rock facies. The Proto-Kern Canyon-Sierra Crest fault zone extends northward in the Kern River valley west of the small diorite and gabbro pluton.

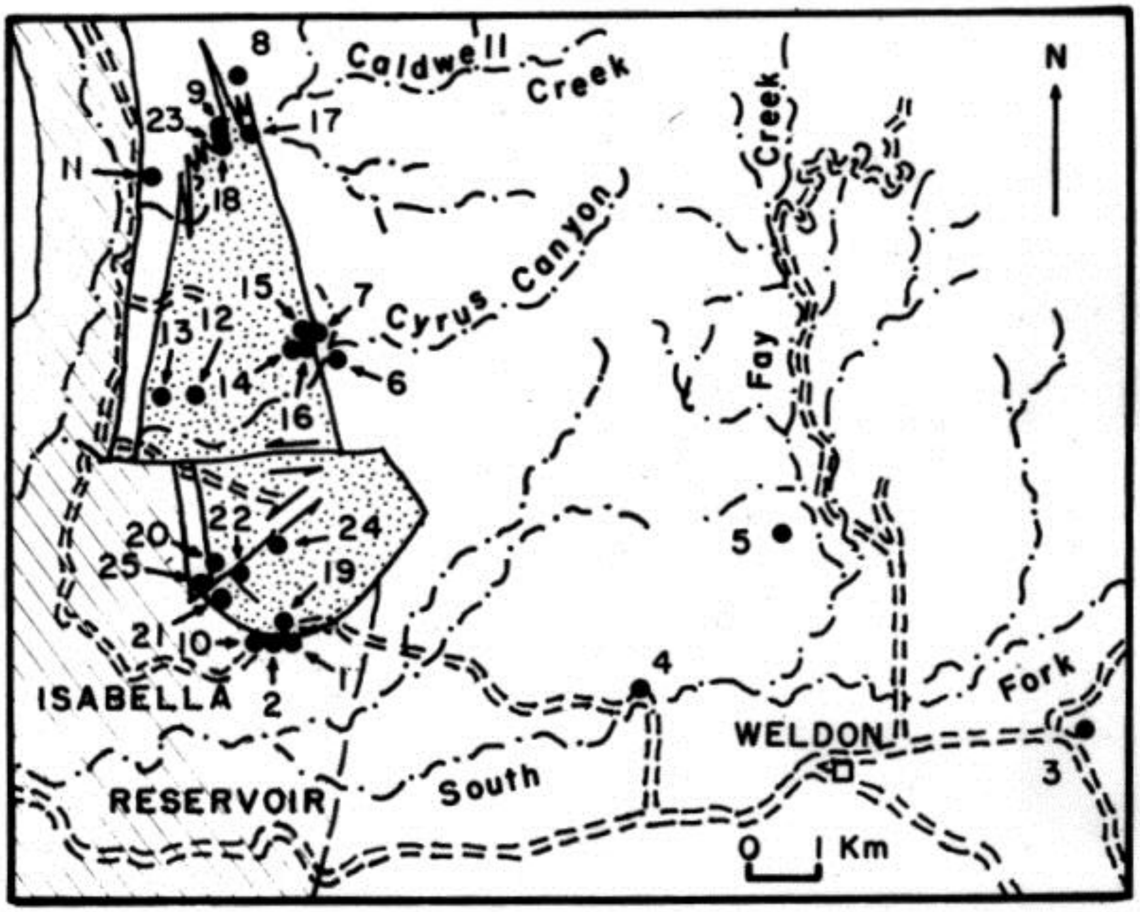

Fig. 2 in Collins and Collins 2004. Location map of chemically analyzed samples listed in Tables VI and VII in Collins (1988), but not discussed in this article. Slanted line area = Kernville metasedimentary series: dot pattern = diorite-gabbro of the Kernville pluton; unshaded = Isabella pluton. Outline of the Isabella Reservoir is not shown − only the general position.

Locally, gradational changes can be observed from unsheared hornblende-biotite diorite in the western border of the Isabella pluton (Fig. 1 in Collins and Collins, 2004) to increasingly deformed rock. Across 30 meters in a transition from unsheared to sheared rock (Fig. 4 in Collins and Collins, 2004), plagioclase first becomes microfractured, and gradually hornblende develops a partial quartz sieve texture. Farther along, microcline is observed replacing interiors of the microfractured plagioclase grains and then replaces some grains completely, changing the diorite into granodiorite because of the addition of the K-feldspar. Some microcline is bordered by myrmekite. Finally, where deformation is strongest, hornblende is totally replaced by quartz, and enough K-feldspar replaces plagioclase to convert the diorite into granite and even pegmatite. The conversion of diorite to granite occurs in such a short distance of 30 m in the Lake Isabella region because locally the shear zone has an S-bend which opens up the system for more extensive replacements. Granite is formed where the greatest angle of bend occurs (Fig. 4 and Fig. 5 in Collins and Collins, 2004). Because of volume losses, the replacements cause shrinkage whereas if the granitic dikes had been injected into the diorite an expansion would have occurred (Fig. 3). The replacements are also supported by whole rock and trace element chemical data and by changes in Rb and Sr isotopes (Collins, 1988; Collins and Collins, 2004).

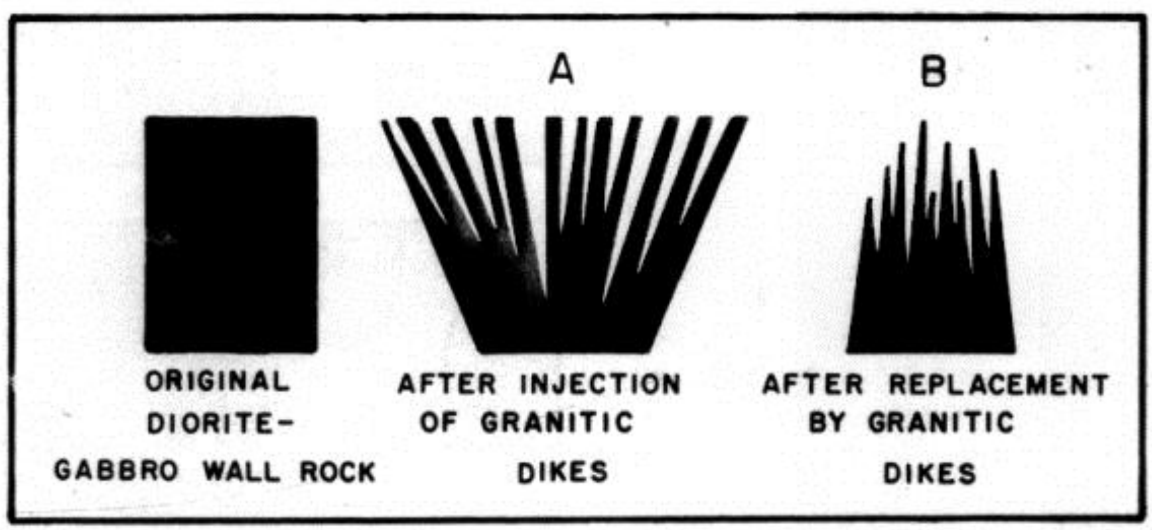

Fig. 3 in Collins and Collins 2004. Schematic of injection of granitic magma versus loss of volume during replacements.

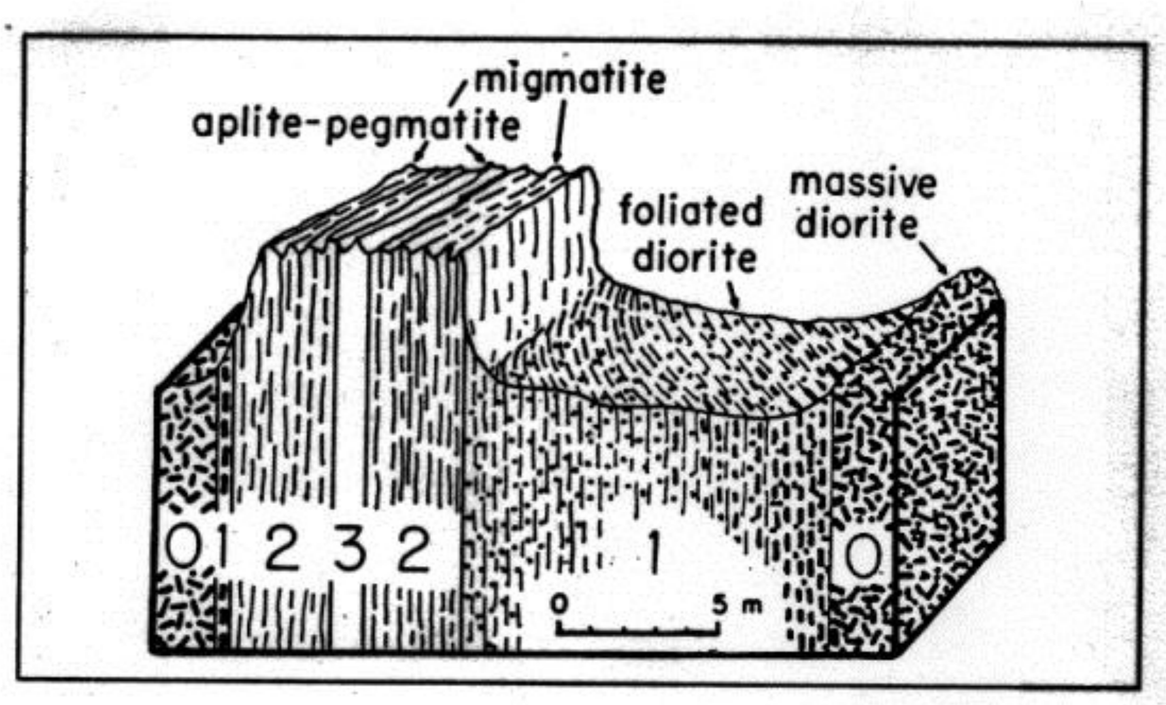

Fig. 4 in Collins and Collins 2004. Schematic diagram for mode of formation of migmatite and aplite-pegmatite dikes in the Kernville diorite-gabbro pluton, southern Sierra Nevada, California. Zone 0 = massive diorite; zone 1 = transition rocks; zone 2 = migmatite; zone 3 = aplite-pegmatite.

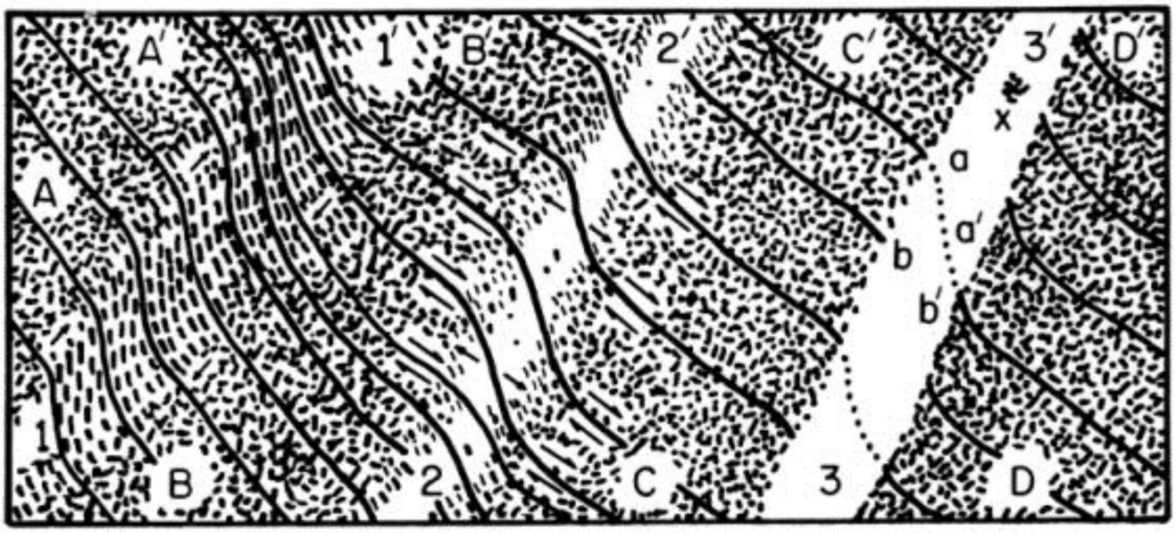

Fig. 5 in Collins and Collins 2004. Diagram showing theoretical stages in the formation of aplite and pegmatite dikes that replace diorite-gabbro wall rock. Areas between A-A', B-B', C-C', and D-D' represent the original massive diorite-gabbro with randomly oriented crystals. Area between 1-1' represents flexed rock in which shearing and cataclasis have oriented the crystals into parallel or sub-parallel alignment. Here the ferromagnesian silicates are partially replaced by quartz. Area between 2-2' shows differential movements parallel to foliation, which produce relatively low-pressure sites into which silica can move to replace the ferromagnesian silicates by quartz and into which K can move to replace zoned plagioclase to form microcline, myrmekite, and unzoned plagioclase. Migmatite can occur on either side of the 'dike,' but a central zone, where replacement is complete, is aplite or pegmatite. Remnant dark minerals show traces of the former flexed foliation. Area between 3-3' shows an aplite-pegmatite dike cutting across massive diorite-gabbro wall rock. A faint foliation is truncated by the granitic dike; layer b-b' appears to match up, however, a-a' actually connects equivalent layers. Island x is a remnant block of unsheared massive diorite-gabbro which remained as an enclave in the dike.

In other places in the Sierra Nevada shearing has occurred in plutons but not in just a narrow zone of 30 m. Instead, larger volumes are affected by the shearing, which opens the system just enough so that former primary diorite or quartz diorite can be converted to granodiorite. For example, in broad parts of the megacrystal Cathedral Peak pluton, plagioclase crystals are replaced in their interiors by K-feldspar (Fig. 5 in Collins and Collins, 2002a; http://www.csun.edu/~vcgeo005/Nr41Cathedral.pdf).

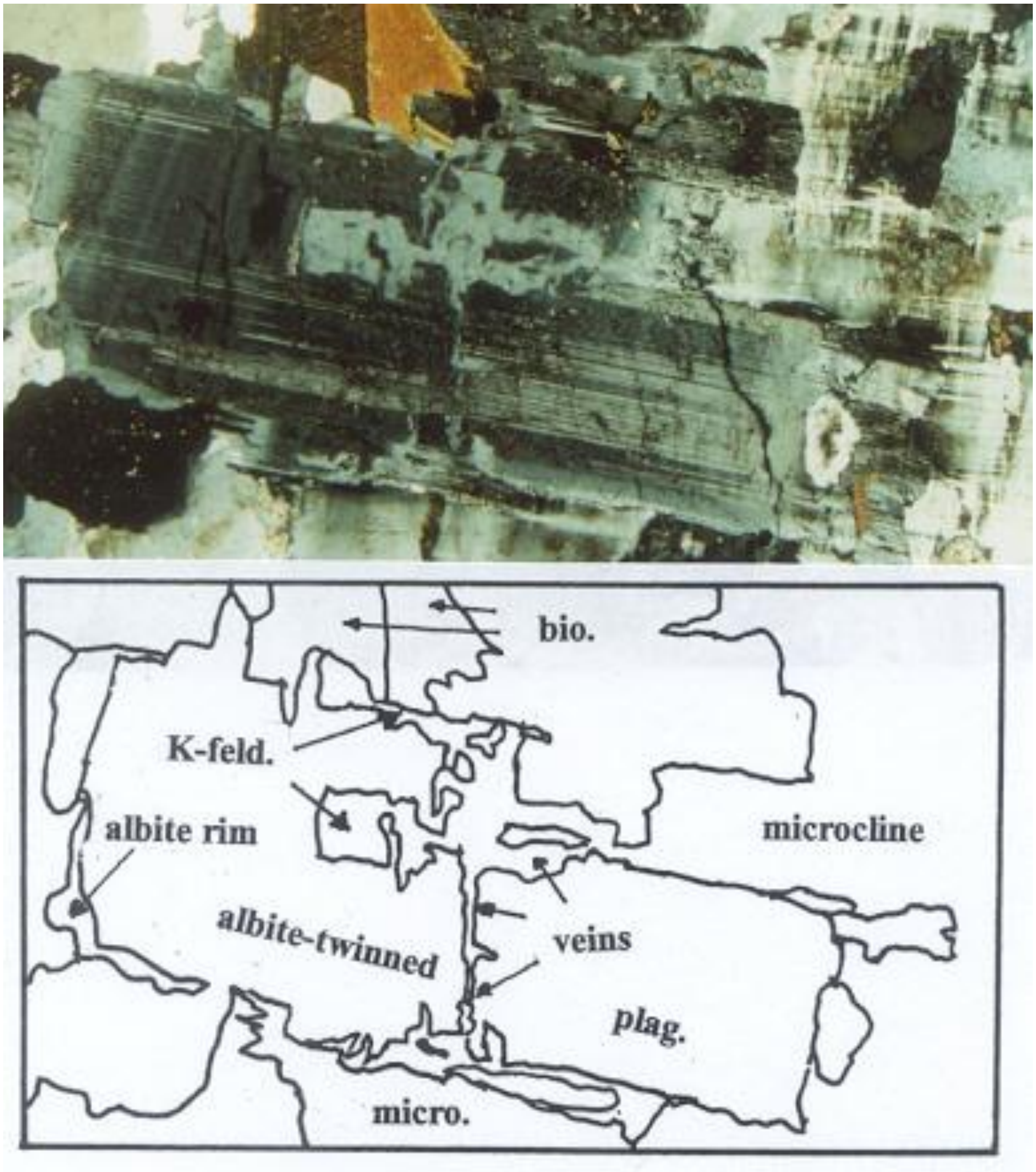

Fig. 5 in Collins and Collins 2002a. Veins of K-feldspar (center; light gray) in interior of albite-twinned, zoned plagioclase (black, light gray). Here, the veins crosscut the twinning and extend down to the edge of the plagioclase where veins also crosscut the twinning. From the center to the right, 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).

In areas of more intense shearing, the K-feldspar that was first in plagioclase interiors has grown by further replacements to become megacrysts (Collins and Collins, 2002a). Other examples include the Campers Flat, Wrights Lake, and Desolation Valley plutons, southwest of Lake Tahoe (Loomis, 1983; Collins, 2003). In these plutons K-feldspar replacements of plagioclase are common (Fig. 16 and Fig. 19 in Collins, 2003; http://www.csun.edu/~vcgeo005/Nr48Fallen.pdf).

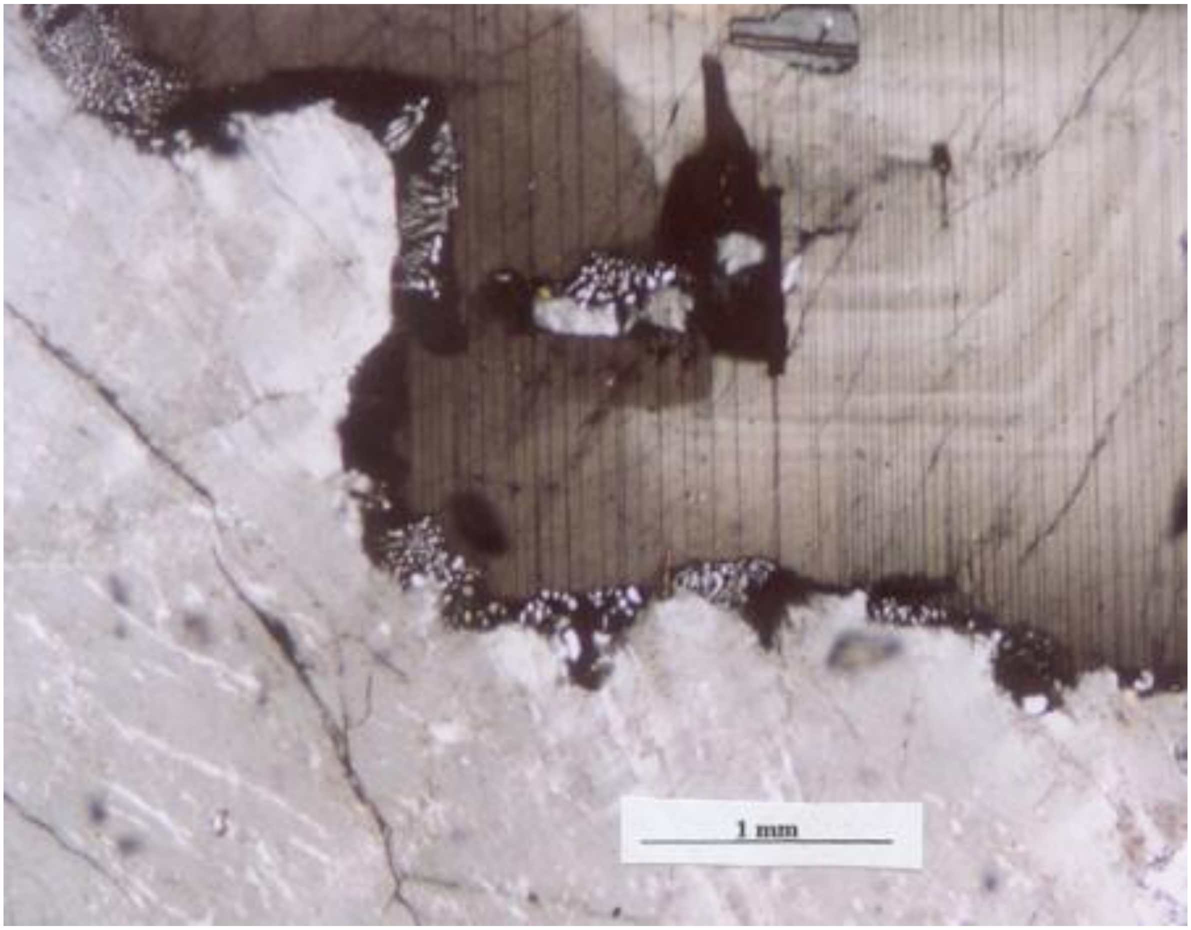

Fig. 16 in Collins 2003. K-feldspar (light gray; bottom and left side) replaces zoned and albite-twinned plagioclase (top). Rim myrmekite occurs on the border of the plagioclase against the K-feldspar. The K-feldspar and rim myrmekite transects the twinning and zonation in the plagioclase. K-feldspar bordered by rim myrmekite also replaces the interior of the zoned plagioclase crystal (left of center). Wrights Lake granodiorite, north of Wrights Lake and east of Fourth of July Flat. Thin section 173 from Loomis collection.

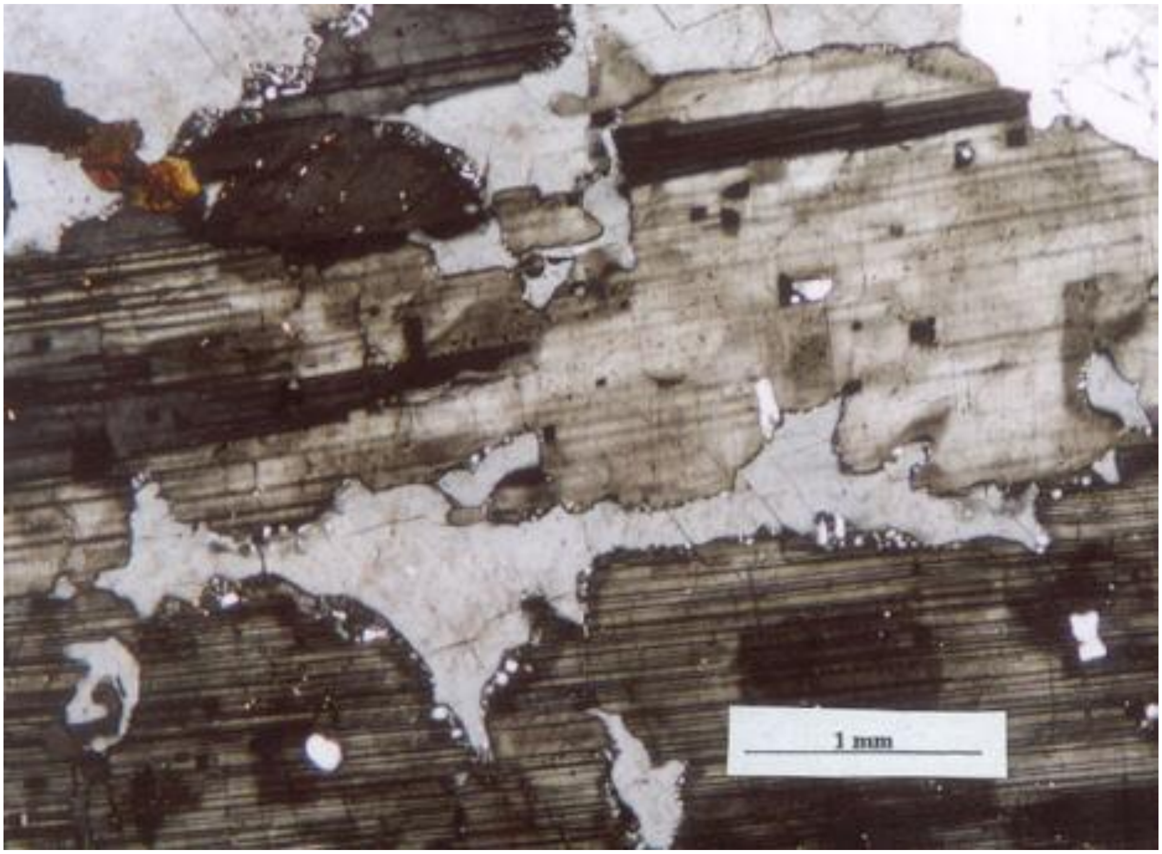

Fig. 19 in Collins 3. Large albite-twinned plagioclase crystal is replaced in its interior by large and small islands of K-feldspar (light gray), which locally are bordered by rim myrmekite. The K-feldspar also replaces the exterior of the plagioclase in the upper center and upper left side and is also bordered by rim myrmekite. Biotite (brown; upper left). Campers Flat granodiorite, 1.1 km southwest of Phipps Peak. Thin section 382 from Loomis collection.

Mafic enclaves are scattered throughout the Desolation Valley granodiorite. In places where deformation is strong, borders of the mafic enclaves are cut by poikilitic K-feldspar crystals that preferentially replace the fine-grained plagioclase in the enclaves. These cross-cutting K-feldspar crystals cannot be xenocrysts that resulted from magma mixing because (1) no plagioclase reaction rim occurs on the margin of the K-feldspar crystals, (2) the residual mafic crystal inclusions in the K-feldspar crystals match the mafic crystals in the enclaves in size and modal composition, (3) the mafic minerals in an enclave project into the K-feldspar at the contacts, and (4) *outside the zone of deformation*, none of the enclaves is cut by K-feldspar crystals (Loomis, 1983; Collins, 2003).

Mojave granitic rocks

Because of multiple episodes of shearing that occurred during early movements of the plutonic rocks on high-angle reverse faults and then later by extensional normal faults (Saleeby, 2003), other examples of former biotite-bearing diorites, quartz diorites, and tonalites in the Mojave Desert area can be observed to be strongly modified to more granitic compositions at subsolidus temperatures. One example occurs in the Twentynine Palms quartz monzonite (Rogers, 1955; Hopson, 1996; Collins, 1997f). Gradations occur across 100 m from unsheared hornblende diorite, containing little biotite, to deformed quartz monzonite, containing K-feldspar megacrysts. In the transition the K-feldspar replaces microfractured plagioclase crystals, (Fig. 7 and Fig. 8 in Collins, 1997f; http://www.csun.edu/~vcgeo005/Nr9Twenty.pdf).

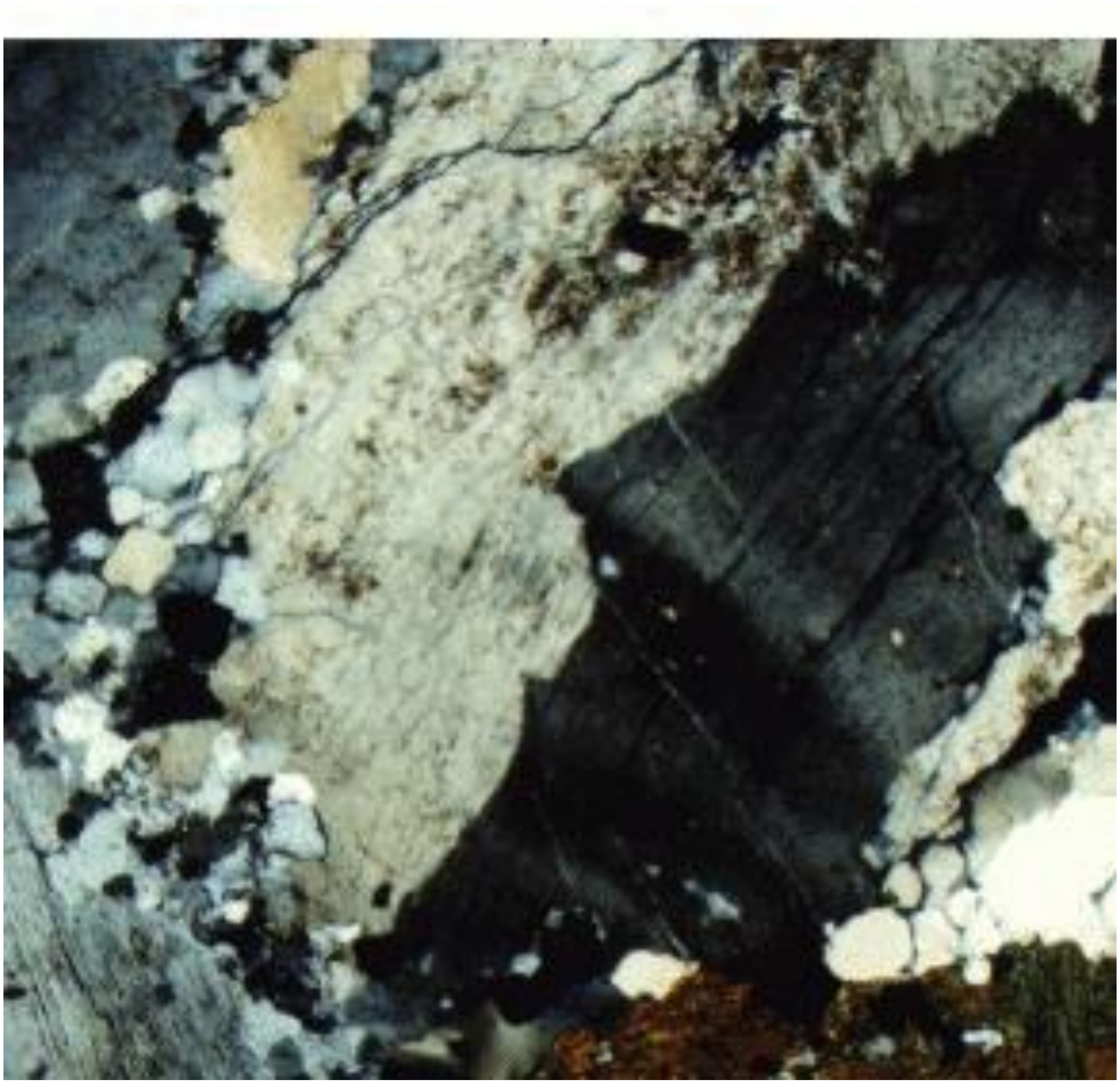

Fig. 7 in Collins 1997f. Felsic diorite, showing deformed (bent) Carlsbad- and albite-twinned plagioclase crystal (light and dark gray). Other large plagioclase crystals (left side have cataclastically broken grain boundaries. Hornblende crystal (brown, bottom) is adjacent to tiny grains of quartz (clear white). Microcline (light gray) is in earliest stages of replacement of deformed plagioclase and occurs as a few tiny irregular blebs just above the hornblende and quartz in the bottom part of the deformed plagioclase. Microcline is much less than 1 vol. % of the rock.

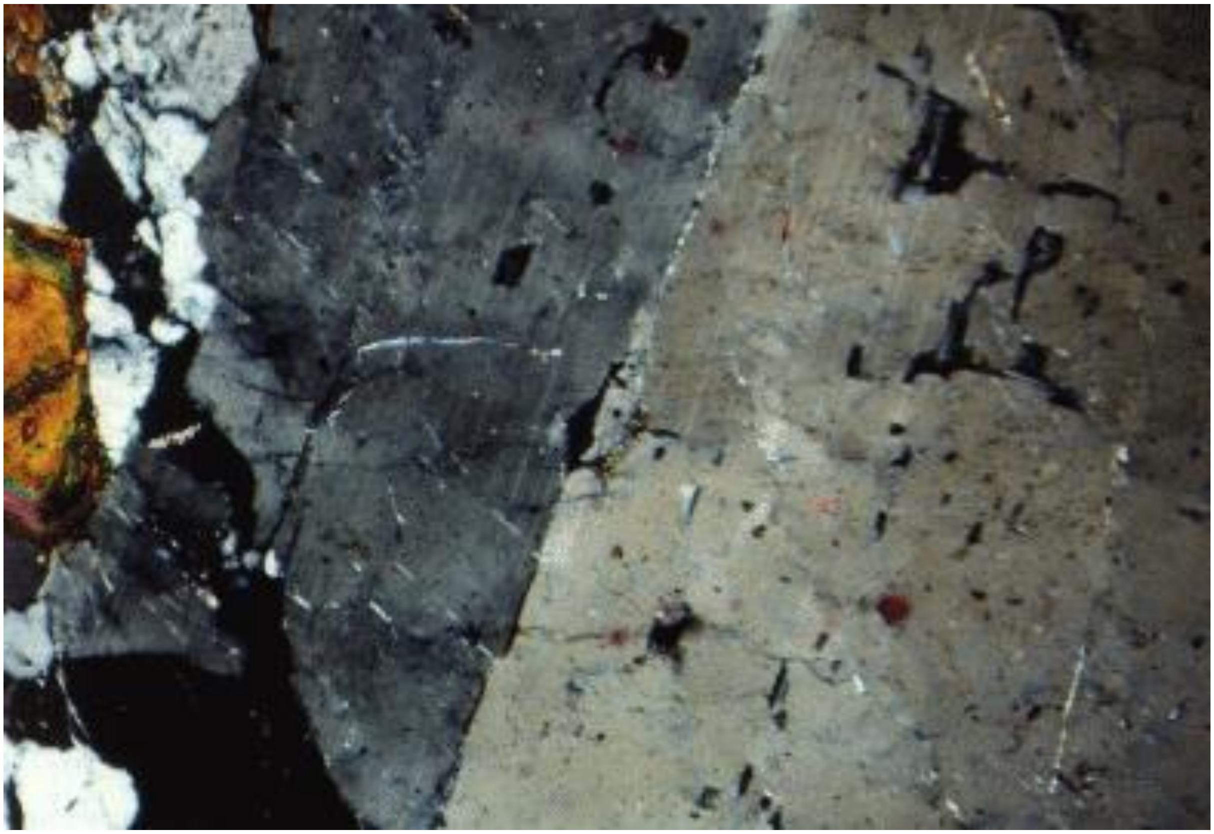

Fig. 8 in Collins 1997f. Felsic diorite, showing slightly deformed (fractured) Carlsbad- and albite-twinned plagioclase crystal (cream gray and gray), filling most of image. Tiny irregular islands and veinlets of microcline (black-gray) replace portions of both halves of the Carlsbad-twinned plagioclase crystal.

In final stages, tiny island remnants of plagioclase occur in the K-feldspar, and in some places the remnant plagioclase is myrmekitic (Fig. 10 in Collins, 1997f).

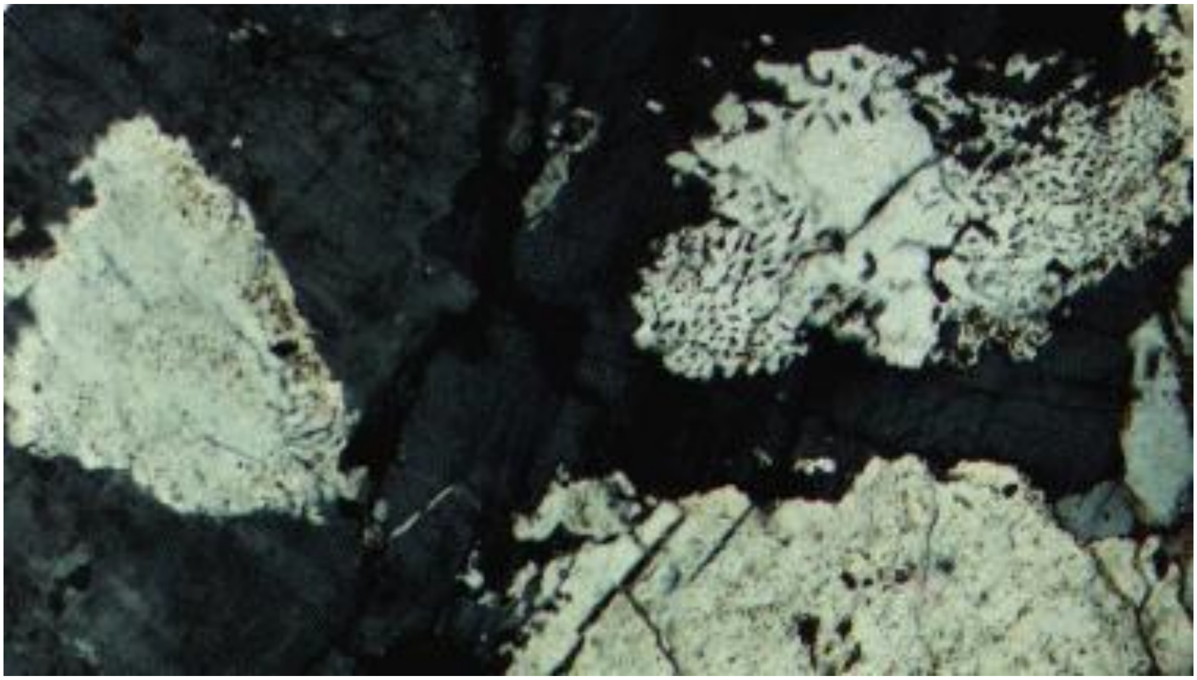

Fig. 10 in 1997f. Cataclastically-broken felsic diorite, in transitional rock between unaltered, undeformed, felsic diorite (Fig. 4 and megacrystal quartz monzonite (like that shown in Figs. 3 and 4). This photomicrograph was taken from a sample 10 m along strike from Fig. 4 Image shows a tiny portion of a less than 1-cm-long microcline crystal in earliest stage of becoming a megacryst (3 to 4 cm long). Microcline (dark gray; top and left) encloses, penetrates in veins, and replaces plagioclase (cream-gray, light gray). Large plagioclase islands are optically continuous with adjacent tiny islands (blebs) of plagioclase in microcline. Large plagioclase islands are locally myrmekitic, containing elongate-oval cross-sections of quartz vermicules (black to gray). Tiny biotite crystals (light tan) are poikilitically enclosed in plagioclase (bottom).

The general lack of biotite in much of the hornblende diorite strongly suggests that the K that went into the K-feldspar megacrysts had to be introduced from a deep source because the original magma was K-poor. The K-feldspar is not magmatic and must have been introduced after the shearing because the shear foliation planes in the groundmass crystals can be traced through the megacrysts *without any offset of the megacrysts*, the K-feldspar is absent in the groundmass in many places, and in some places cataclastically granulated groundmass minerals fill more than 50 percent of some of the megacrysts (Fig. 11 in Collins, 1997f).

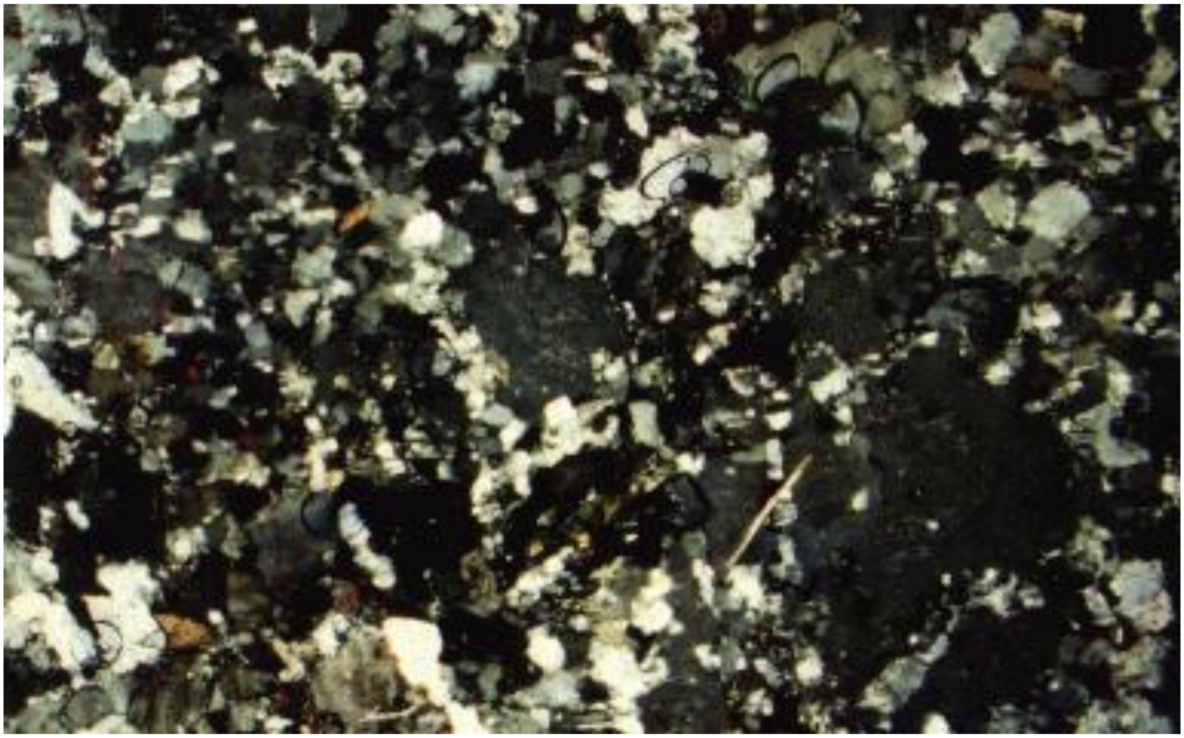

Fig. 11 in Collins 1997f. Tiny portion of a microcline megacryst (dark gray), 2 to 3 cm long, in Twentynine Palms quartz monzonite. Megacryst contains more than 50 vol. % fragments of quartz and plagioclase (gray and white) and a few tiny euhedral sphene crystals (brown), all remnants of a cataclastically deformed diorite. Hornblende is absent and presumably replaced by quartz and/or microcline. In hand specimen, the megacryst looks like one of those shown in Figs. 3 and 4 of Collins 1997f and gives no outward clue that it contains abundant inclusions. In most megacrysts, inclusions are less abundant (5 to 20 vol. %).

Eastern California shear zone

In eastern California several north-south shear zones extend from the Mojave Desert south to Mexico. Among them is the Santa Rosa mylonite zone (Simpson, 1984; Simpson and Wintsch, 1989) where plagioclase in deformed tonalite and quartz diorite has been replaced by K-feldspar (Collins, 1997i; http://www.csun.edu8/~vcgeo005/Nr12SantaRosa.pdf.). Near Palm Springs and Anza-Borrego, California, the primary igneous rocks, prior to replacement by K-feldspar contain relatively sodic plagioclase (An_{20}) so that little to no myrmekite is formed, or else the quartz vermicules are so tiny that they are visible only under high power magnification (Fig. 5 and Fig. 7 in Collins, 1997i; http://www.csun.edu8/~vcgeo005/Nr12SantaRosa.pdf.).

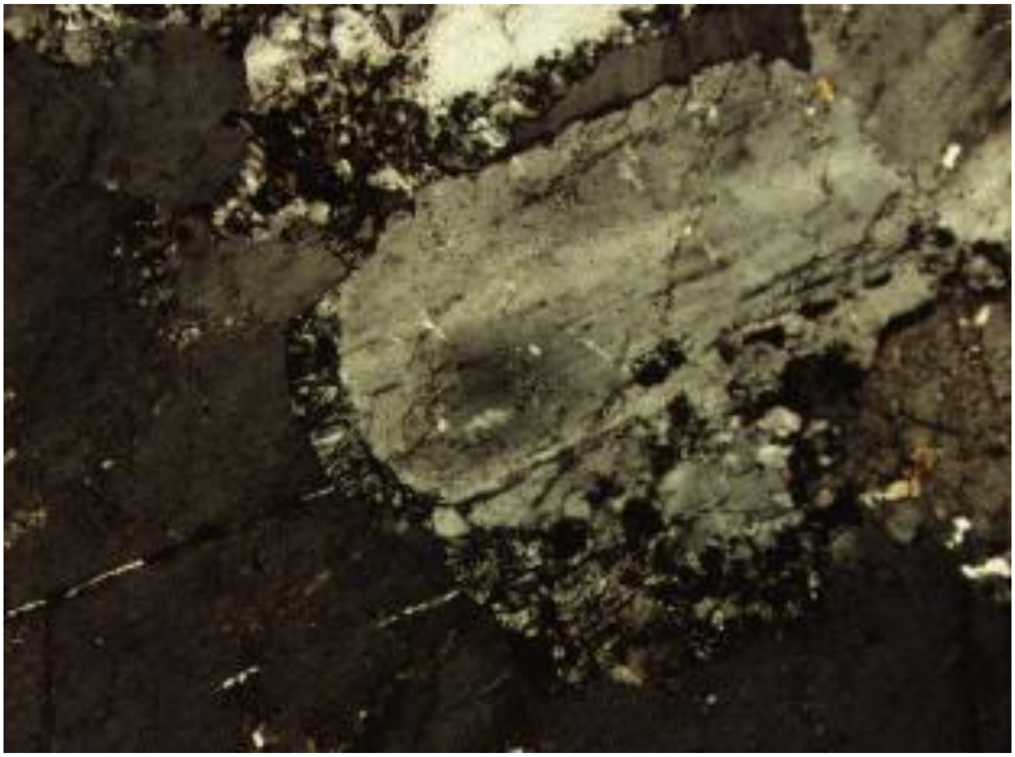

Fig. 5 of Collins 1997i. Myrmekite on the borders of an enclosed plagioclase crystal (light gray) inside a K-feldspar crystal (dark gray). Rock has not been mylonitized.

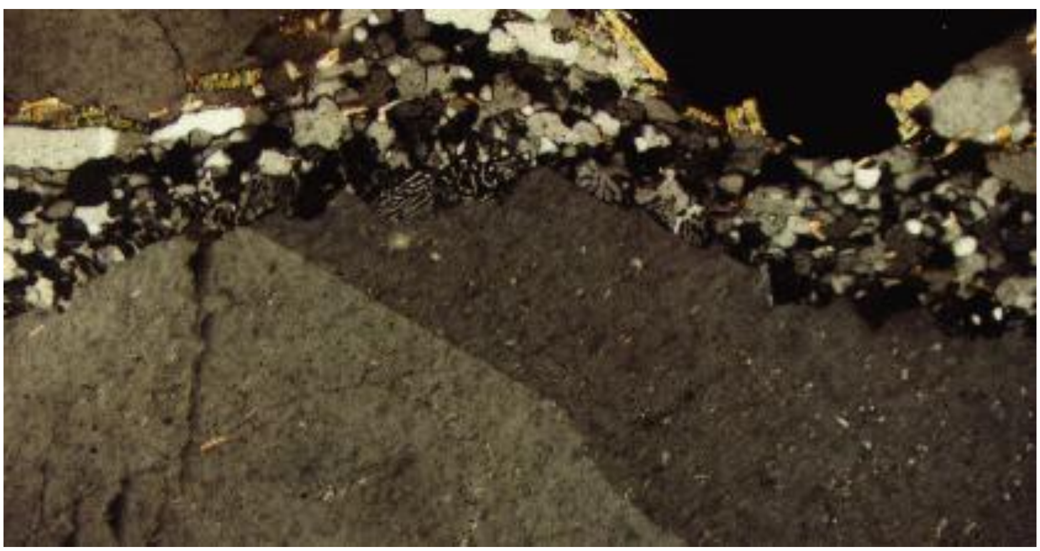

Fig. 7 of Collins 1997i. Carlsbad-twinned K-feldspar megacryst (light gray) bordered by myrmekite with tiny quartz vermicules and enclosed in a granulated ground mass of quartz, plagioclase, and biotite

The Salinia block

An example of progressive cataclasis of a biotite-rich tonalite and conversion to megacrystal granodiorite at subsolidus temperatures occurs in the northern Santa Lucia Mountains and then west toward Monterey, California. Undeformed biotite-rich tonalite can be traced from the eastern part of the pluton through a transition westward where crystals in the tonalite become broken and where K-feldspar first begins to replace the plagioclase (Fig. 10 in Collins, 2001a; http://www.csun.edu/~vcgeo005/Nr38Monterey.pdf).

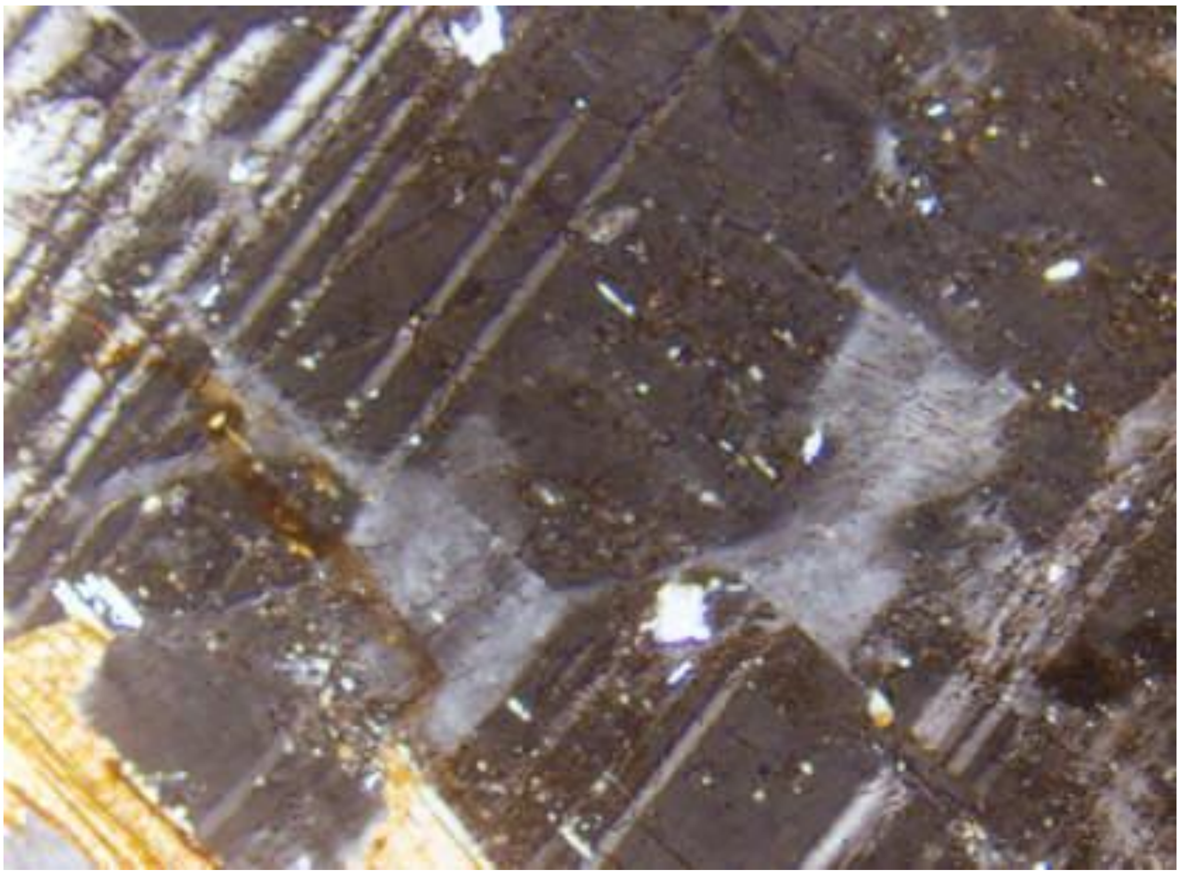

Fig. 10 in Collins 2001a. Branched veins of microcline (light gray and white) extending into albite-twinned plagioclase (black).

From there, the progressive metasomatic modifications extend westward across 17 km to Monterey, where the K-feldspar crystals grew to become megacrysts bordered by myrmekite (Fig. 14, Fig. 18, and Fig. 19 in Collins, 2001a).

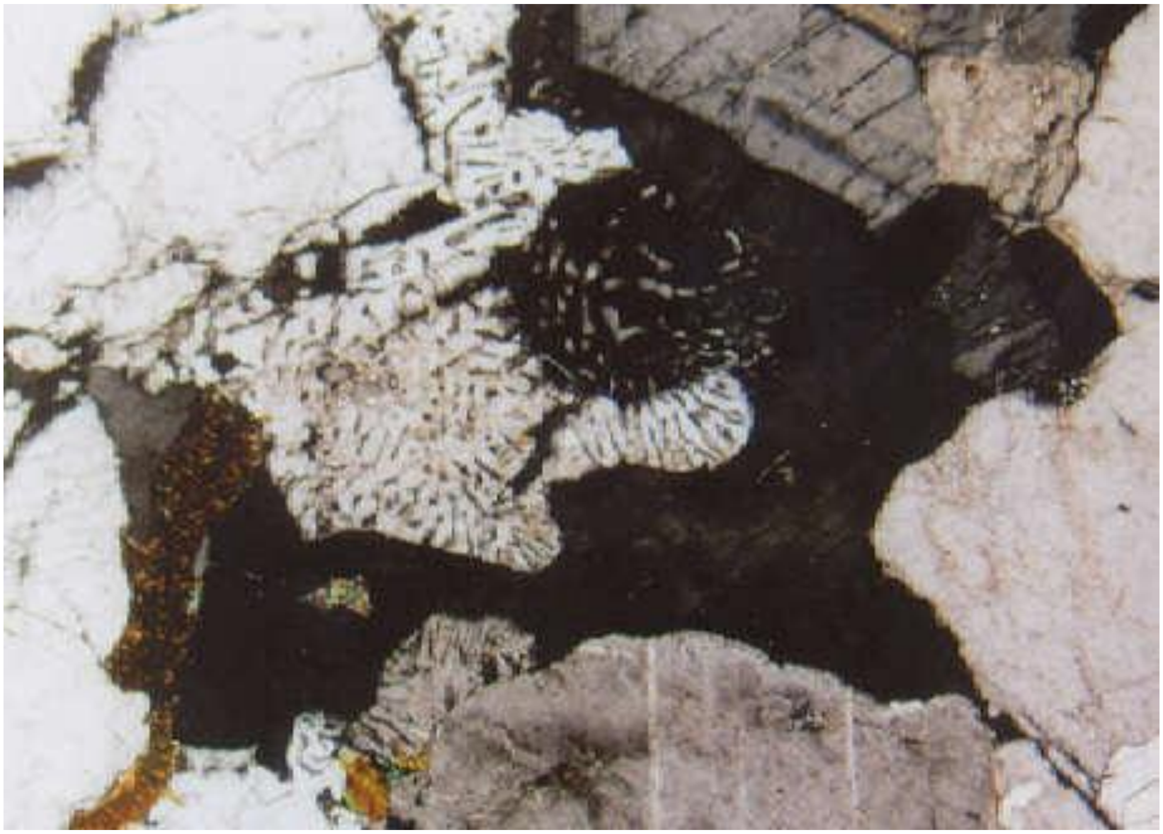

Fig. 14 in Collins 2001a. Myrmekite (center, top and bottom) on borders of albite-twinned plagioclase (whitish gray and gray) and projecting into microcline (black). Microcline penetrates and replaces plagioclase along cracks. (Note that the volume of myrmekite exceeds the volume of the adjacent microcline and cannot have formed by exsolution of Ca and Na from the microcline.)

Fig. 18 in Collins 2001a. 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.

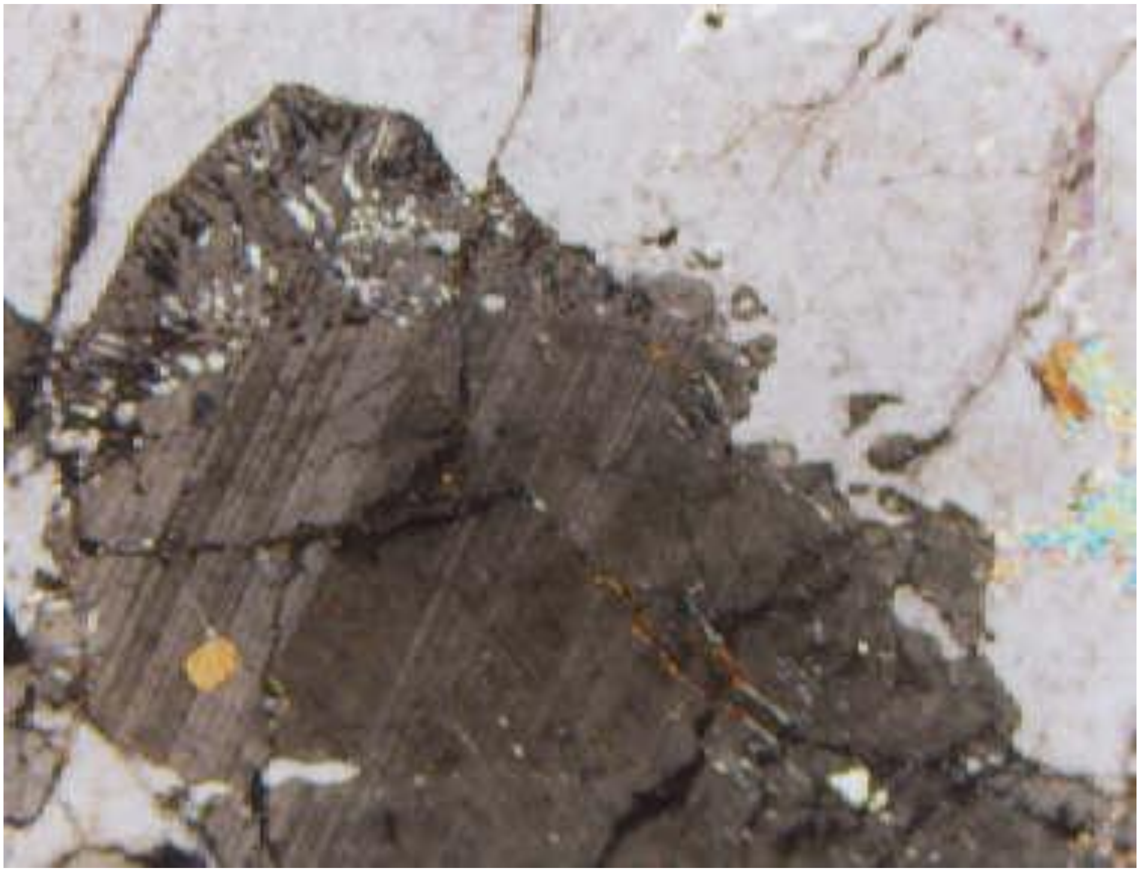

Fig. 19 in Collins 2001a. Albite-twinned plagioclase (dark gray) is bordered by myrmekite and projects into a microcline megacryst (grayish white). Plagioclase of the myrmekite is optically continuous with the larger plagioclase crystal. Optically parallel islands of the plagioclase (gray; right side, center) are enclosed in the microcline (grayish white). Biotite (brown). Sericite alteration (blue).

At Whaler's Cove on Point Lobos, K-feldspar megacrysts are aligned along a possible former shear plane (Fig. 7 in Collins, 2001a), but in most places the megacrysts have a random orientation, and each megacryst assumes the orientation of the original plagioclase crystal which it replaced and grew beyond its original boundaries. Similar myrmekite-bearing megacrystal granodiorites can be traced in the Salinia block to areas north of San Francisco at Point Reyes.

Fig. 7 in Collins 2001a. Parallel alignment of microcline megacrysts in granodiorite at Whalers Cove, Point Lobos State Reserve, California.

Discussion

Other investigators have attempted to assess chemical changes and flow processes in shear zones, including Selverstone et al., (1991), Dipple and Ferry (1993), and Ring (1999), and the results of their studies clearly show that elements freely move in fluids in shear zones. Also, investigations have been done where K-feldspar has formed by large-scale magmatic replacement processes involving the exsolution of magmatic-hydrothermal fluids (e.g., the Cornelia pluton near Ajo, Arizona; Wadsworth, 1968, 1975), but in such places the K-replacements have been from the outside of plagioclase grains inward rather than from the interior of microfractured plagioclase crystals outward, and in these magmatic-metasomatic rocks, myrmekite has not been formed (Collins, 1997m). Circulation of heated meteoric water can also result in large-scale K-replacements, but the K-feldspar (adularia) is not associated with myrmekite and occurs with low-grade metamorphic mineralogy (Duffin, 1989; Duffin et al., 1989; Liu et al., 2003). A deep source from a dehydrating subduction zone is the more logical explanation for the fluids that produced the metasomatic rocks in the Sierra Nevada, Mojave Desert, and Salinia areas rather than from either the exsolution of magmatic-hydrothermal fluids or from local heating of circulating meteoric water.

Conclusions

Although it is commonly believed by granite petrologists that no granitic bodies of plutonic scale can be formed by K- and Si-metasomatism, the petrographic and whole rock and trace element chemical evidence against this belief is extensive (Collins, 1988, Collins, 2004). Electron microprobe studies of plagioclase crystals in the process of being replaced, high-resolution scanning electron images of individual altered grains, and cathodoluminescent studies of polished thin sections that reveal unsuspected microfractures produce the kinds of convincing evidence for the K-metasomatism that cannot otherwise be seen by just using the petrographic microscope (Collins, 1988, 1997bcd; Collins and Collins, 2002b; Collins and Collins, 2004). Such K-replacements by exchange of ions in fluids in deformed and broken crystals at subsolidus temperatures are not only possible but also *demonstrated by experimental work* (Orville, 1963; Collins, 1999).

The process of K- and Si-metasomatism is not "*granitization*." Granitization was supposed to have occurred as the result of *solid-state diffusion* to change sedimentary or plutonic igneous rocks into granite and is obviously not possible. Solid-state diffusion cannot occur through tens or hundreds of meters of solid rock because rates of elemental diffusion in solids are too slow and because the solid rock offers no easy means for ion exchange. On the other hand, during K-metasomatism, replacement occurs by means of fluids moving through microfractures in sheared rock, and the only distance of solid-state diffusion that is necessary is commonly less than 1 mm, *half the width between microfractures*.

Because the minerals in the granitic rocks that are formed by metasomatic processes are stable at both subsolidus temperatures and temperatures just above the solidus, both metasomatic and magmatic granitic rocks will inevitably have nearly the same mineralogical and chemical compositions. Moreover, the metasomatic granitic rocks will have inherited the hypidiomorphic textures and igneous structures from the original magmatic rocks and appear as if they had a magmatic origin. One difference is that the K-replacement processes disrupt the Rb-Sr systematics, enriching the rocks in Rb and depleting them in Sr, which helps to explain "errorchrons" that are obtained from samples in many granitic bodies

(Collins, 1988; Collins and Collins, 2004)). Generally, the U-Pb systematics in zircons is not affected, although younger overgrowths on the zircon crystals will likely be produced.

Of course, not all granite and granodiorite plutons in the Sierra Nevada batholith are metasomatic in origin. Only those whose parent rocks have been extensively sheared at subsolidus temperatures and modified by K- and Si-replacement processes are metasomatic. In the Mojave Desert, deformation, causing shearing of the original relatively mafic plutons, was so strong and closely spaced that only a few of the original more mafic plutons remain unmodified, and these contain hornblende and pyroxene which are not as readily sheared as those containing abundant micas (Collins, 1997a; 1997j; Miller et al., 1996, 1997).

If plate tectonics cause deformation, shearing, and large-scale K- and Si-metasomatism in overlying solidified arc-related plutons in California, then such should also be expected in other arc-related plutonic systems. An example includes the Coast Plutonic Complex of British Columbia where primary, relatively mafic, plutonic rocks have been extensively sheared and now contain secondary K-feldspar. See Roddick (1965) for illustrations of progressive stages of interior replacements of plagioclase by K-feldspar. He also described many of the same kinds of replacement textures that are found in the deformed plutons of the Sierra Nevada batholith. Although Roddick did not report myrmekite in this study, he indicated that it is present (written communication, 2004).

Because of extensive upward flow of hydrous fluids released above the Laramide Slab and from down-going wedges of wet schists that underplate the continental plutons, the volumes of fluids that are needed to transport available K and Si are certainly adequate for the task of causing large-scale metasomatism. Because the K- and Si-replacements of mafic plutonic rocks are concentrated in and near shear zones generated by the segmented Laramide Slab in southern California and because such replacements are not found where deformation is not present, the correlation between deformation and metasomatism is strongly supported. Recrystallization of the minerals while the replacements were occurring commonly eliminates much of the evidence for the original cataclasis and microfracturing, but myrmekite can provide the clue that this cataclasis was once present. The Ca, Mg, Fe, and Al atoms that would have been displaced by K and Si have moved upward with escaping fluids. Deep erosion (5 to 20 km) has removed the overlying rocks into which these elements could have gone.

Applications to other terranes

Although plate tectonics is one means of causing deformation and open systems in which metasomatism can occur, it is not the only mechanism. The following are other kinds of structural environments in which large-scale K-metasomatism has modified the compositions of former relatively more-mafic igneous rocks.

a. Shear zones along fault systems.

A good example of K-replacements along a fault system occurs on the west side of the Main Donegal granite in northwestern Ireland where microcline replaces microfractured plagioclase (Collins, 1997g). Another example occurs in the eastern side of the Waldoboro granite pluton in Maine where K-feldspar megacrysts replace both the granite and its metasedimentary wall rocks (Barton and Sidle, 1994; Collins, 19o7e), A third example occurs in the Ponaganset gneiss in a fault zone extending along the eastern border of Connecticut into Massachusetts (Collins, 1997l).

b. Limbs of tightly folded anticlines.

The tight folding of layered igneous rocks in nearly isoclinal anticlines causes layers in the limbs of the folds to slide past each other and microfracture the plagioclase. In this process the cataclasis opens the rocks to fluid movements so that K-feldspar replacements of the plagioclase are common. Examples include the Gold Butte anticline in Nevada (Collins, 1997h), the Wanup pluton in Canada (Collins, 2001b), and the Split Rock Pond anticline in the Dover magnetite district of New Jersey (Collins, 1969, 1997k).

c. Rims of diapiric plutons.

Because of the continued diapiric rise of some plutons after solidification, former, relatively more-mafic rims are strongly deformed and sheared, allowing K-bearing fluids to move through the rocks and create K-feldspar megacrysts. A magmatic model would predict that the K-feldspar megacrysts would form in the core of the plutons where slow cooling would be expected to produce coarse crystals and where late-stage K-rich melts would accumulate. Instead, the K-feldspar crystals are fine-grained or absent in the core and are coarse-grained and present in deformed parts of the rim. Examples include the Vrådal pluton in Norway (Sylvester, 1964; study in progress) and the Ardara pluton in northwest Ireland (Collins, 1997g). Pitcher and Berger (1972) and Pitcher et al., (1987) described the decalcification of the plagioclase that precedes and accompanies this K-metasomatism in the Ardara pluton. Other examples of diapiric plutons in which

K-feldspar megacrysts are concentrated in the rims or in zones of strong deformation include the Papoose Flat pluton (Collins and Collins, 2002c) and the Birch Creek pluton in the White-Inyo Mountains of California (Barton, 2000).

d. Metamorphic core complexes.

Igneous rocks in nearly horizontal detachment sheets that occur in metamorphic core complexes are commonly mylonitized and granulated (Davis et al., 1980). In these sheared places K-bearing fluids commonly modify the igneous rocks by the addition of secondary K-feldspar. Examples occur in the Bill Williams Mountains in Arizona (Collins, 1998) and in several granitic bodies in the Whipple Mountains and the Parker Dam granite in California (Podruski, 1979).

See also http://www.csun.edu/~vcgeo005/index.html and Collins (1988) and Hunt et al., (1992) for other examples.

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