21. THREE CHALLENGING OUTCROPS IN THE MARLBORO FORMATION, MASSACHUSETTS, USA

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July 9, 1997

Introduction

Three enigmatic outcrops in the Precambrian Marlboro Formation offer challenges for students who desire an exercise in critical thinking. These outcrops occur in plagioclase amphibolite in a small area in northeastern Massachusetts about 32 km (25 miles) north of Boston (Fig. 1 and Fig. 2) and are particularly interesting because of interbedded augen gneiss and cross-cutting granitic veins and masses that show puzzling relationships.
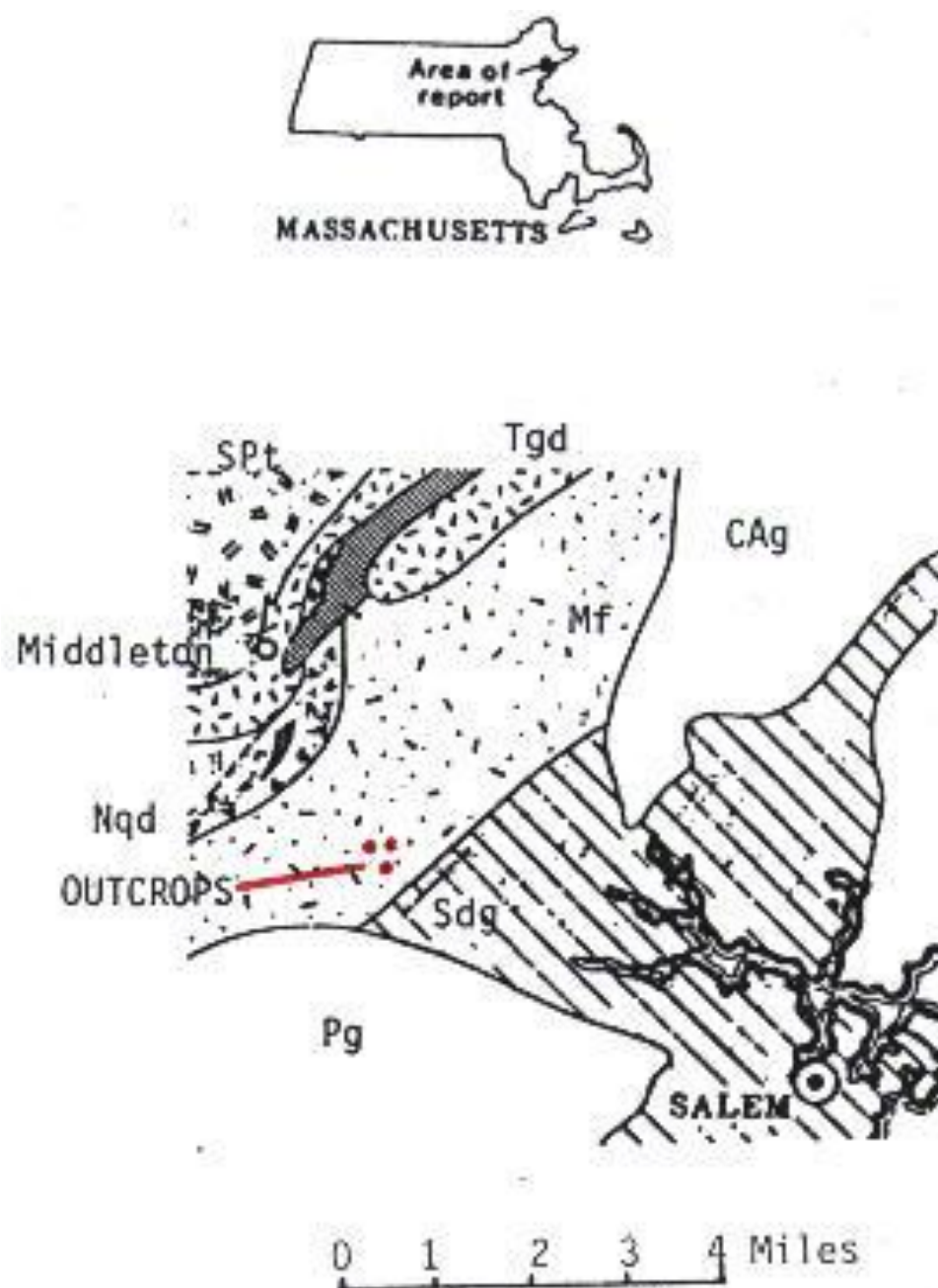
Fig. 1. Geologic map showing location of the undifferentiated Marlboro Formation (Mf) relative to the Cape Ann (CAg) and Peabody granite (Pg) bodies, the Salem diorite-gabbro (Sdg), the Newburyport quartz diorite (Nqd), Topsfield granodiorite (Tgd), and the Sharpners Pond tonalite (SPt). Sites of three enigmatic outcrops are indicated in three red dots. Map is modified from maps prepared by Toulmin (1964), Castle (1965), Dennen (1976), and Harrison et al. (1983).
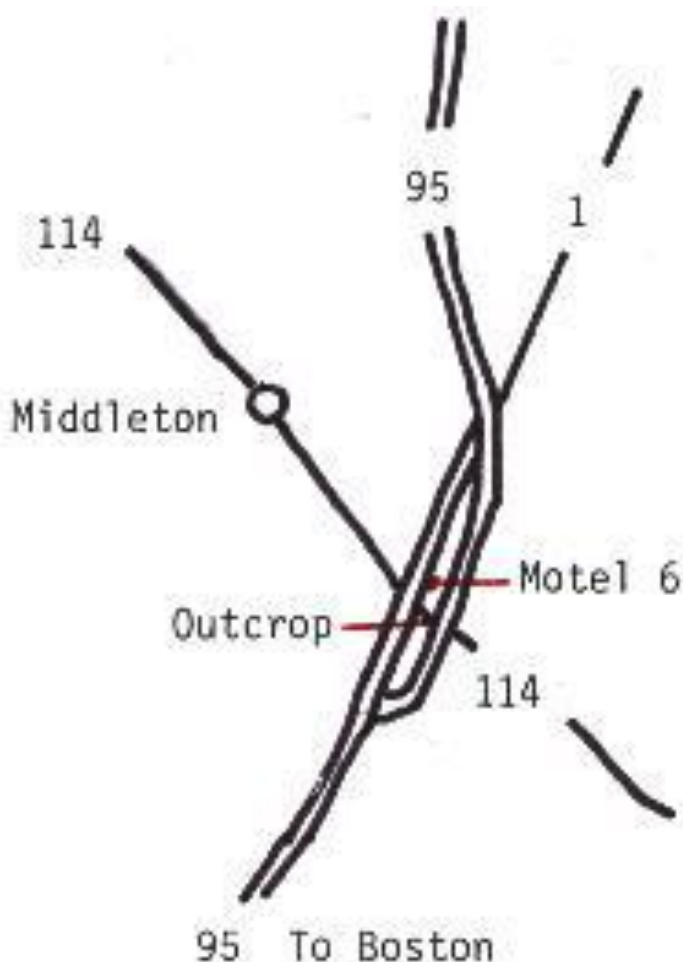
Fig. 2. Location of three amphibolite outcrops in Danvers, Massachusetts, on a portion of the Salem, Massachusetts, 7 1/2 Minute Quadrangle Map. Outcrop ONE is on the north side of Massachusetts 114 (Andover Street), west of and adjacent to the U.S. Route 1 (Newburyport Turnpike) overpass. Outcrop TWO is on the north side of Massachusetts 114 (Andover Street) between the south and north lanes of U.S. Route 95 overpasses. Outcrop THREE is behind the Brew House of Danvers, west of Motel 6, and accessed from the north-directed lanes of U.S. Route 1.

The plagioclase amphibolite is medium grained and may be massive or foliated. It is dark because of abundant mafic minerals, including hornblende (20-55 vol. %), clinopyroxene (0-15 vol. %), and locally as much as 30 vol. % biotite. Plagioclase (39-72 vol. %) and quartz (1-20 vol. %) are additional primary minerals. Alteration products include epidote, muscovite, and chlorite. The

plagioclase is normally zoned and albite- and Carlsbad-twinned. Its composition ranges from andesine to sodic labradorite (Toulmin, 1964).

Outcrop ONE

The first outcrop, a road cut, in Danvers, Massachusetts (Fig. 3), contains layers of diverse rock types, including quartzo-feldspathic bands, augen gneiss, and fine- to medium-grained quartz- and biotite-bearing plagioclase amphibolites.


Fig. 3. Portion of outcrop ONE, showing plagioclase amphibolite layers and broken and lenticular plagioclase amphibolite fragments interlayered with augen gneiss and quartzo-feldspathic layers.

The augen gneiss consists mostly of microcline, plagioclase, and biotite, but it contains accessory amounts of quartz, hornblende, epidote, pyroxene, chlorite, and magnetite. The ellipsoidal augen (1 cm long) are primarily microcline, but

some are plagioclase. The plagioclase is strongly altered to sericite and clay, so not all textural relationships can be clearly seen here in thin sections. At the outcrop, some augen show a *distinct zonal structure* with thin light-colored rims and darker cores. X-ray diffraction patterns of the core and rim obtained by Toulmin (1964) show that in a single megacryst, the core is microcline and the rim is plagioclase having a composition about An_{30}.

Since 1964, the top of the outcrop apparently has been covered by vegetation and soil, but Toulmin sketched enigmatic relationships (Fig. 4) that occurred there which are worth considering. In this respect, reading Toulmin`s discussion of the Marlboro Formation (1964, pages A4-A9 and A67-A69) before examining the outcrop would be helpful. Similar relationships are still exposed in the present outcrop, but not exactly the same relationships as in the former exposed top. He noted that brittle plagioclase amphibolite layers appeared to be broken and separated (as in Fig. 3) and that the spaces between fragments seemed to be filled by inflowing augen gneiss that behaved plastically (Fig. 4). If flowage occurs, the relationships are enigmatic because augen adjacent to the blunt end of the plagioclase amphibolite show no evidence of flowage, and fragments of plagioclase amphibolite beyond the blunt end are not rotated or offset laterally toward the site of supposed flowage.
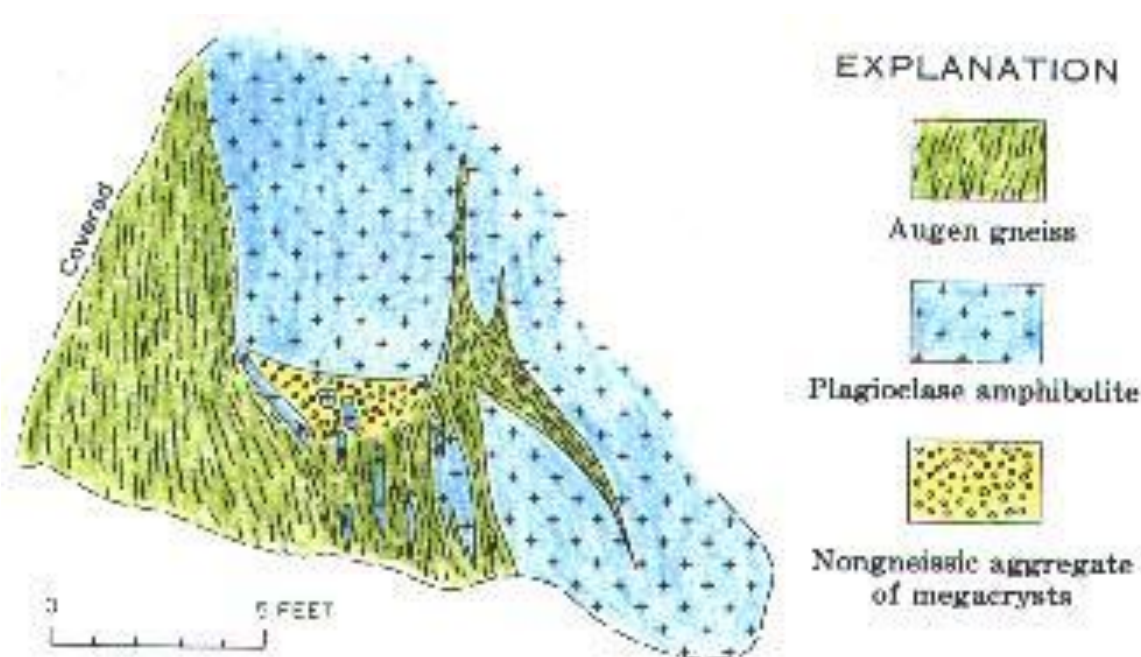
Fig. 4. Sketch of top of outcrop in the Marlboro Formation at intersection of Routes U.S. 1 and State 114, Danvers (Fig. 13, p. A-67, in Toulmin, 1964).

Toulmin's (1964) hypothesis for the metamorphism of a sedimentary or pyroclastic original rock as a means of forming the augen gneiss and the relationships observed in the outcrop raise many questions for critical consideration. How does one explain the conflicting relationships that in one sense suggest plastic solid-flow behavior of the augen gneiss but in another sense suggest that the augen formed *in situ* without flowage of material from an outside source? Are the spaces between the amphibolite blocks truly former openings between separated blocks? Can the evenly bedded character of the augen gneiss (Fig. 3) be explained by processes other than sedimentation? Does the local high ratios of potassium, shown by abundant microcline and biotite, necessarily indicate admixtures of shaly material as Toulmin tentatively proposed? Why are megacrysts oriented in one area and not in the other?

Outcrop TWO

The second outcrop (Fig. 2) is a continuous, dynamited, fresh exposure of plagioclase amphibolite (more than 30 m long), containing masses and narrow stringers of pink granite. Portions of this second outcrop are illustrated in four long-shot photographs and five close-up pictures (Fig. 5, Fig. 6, Fig. 7, Fig. 8, fig. 9, Fig. 10, Fig. 11, Fig. 12, and Fig. 13.

Fig. 5. Light-pink granodiorite and black plagioclase amphibolite cut by two vertical drill holes. A close-up of the relationships is shown of the area just left of the right drill hole in Fig. 6.

Fig. 6. Light-pink granodiorite in stringers and isolated pink K-feldspar crystals in black plagioclase amphibolite. Where pink stringers are present, the plagioclase amphibolite is relatively biotite-rich.

Fig. 7. Light-pink granodiorite and black plagioclase amphibolite cut by a single vertical drill hole. The massive plagioclase amphibolite is primarily hornblende-rich; the lenticular black inclusions are relatively biotite-rich. A close-up of the lenticular inclusions in the center, left of the drill hole, is shown in Fig. 8.

Fig. 8. Close-up of black, lenticular, plagioclase amphibolite inclusions in pink granodiorite. Ghost remnants of plagioclase amphibolite with foliation parallel to the inclusions occur in the granodiorite.

Fig. 9. Pink granodiorite and black plagioclase amphibolite cut by a single vertical drill hole. A close-up of the pink granodiorite stringer, center, left of the drill hole is shown in Fig. 10.

Fig. 10. Close-up of pink granodiorite stringers in black plagioclase amphibolite. Ghost remnants of plagioclase amphibolite with foliation parallel to the inclusions occur in the granodiorite.

Fig. 11. Long shot of a portion of outcrop TWO, showing isolated augen in discontinuous stringers in foliated plagioclase amphibolite.

Fig. 12. Granitic rocks with unmatching walls of black plagioclase amphibolite. Feathered remnants of biotite or hornblende concentrations in the granitic rocks match compositions of plagioclase amphibolite along strike.

Fig. 13. Granitic rocks with unmatching walls of black plagioclase amphibolite. Feathered remnants of biotite or hornblende concentrations in the granitic rocks match compositions of plagioclase amphibolite along strike.

Superficial examination of rocks in this outcrop would suggest (1) that a granitic magma had been injected into fractures in the plagioclase amphibolite or (2) that anatexis had occurred in which partial melting had "sweated out" felsic components to form a migmatite. For critical thinking --- do the contrasting pink and black colors, the abrupt differences in mineral compositions, sharp contacts, and cross-cutting relationships fully support a magmatic origin for the granitic masses and augen? For example, is there any evidence that an introduced granitic magma has shouldered aside the plagioclase amphibolite wall rocks to make room for it? Did a granitic magma assimilate portions of the plagioclase amphibolite? Are there other possible explanations for the origin of these features?

Outcrop THREE

The third enigmatic outcrop (Fig. 2) is a relatively-unaltered, massive, plagioclase amphibolite (Fig. 14) which has variable composition. Some places are hornblende-rich; others are biotite-rich. Biotite-rich zones tend to contain coarser plagioclase crystals than hornblende-rich zones. Locally, the plagioclase amphibolite is deformed in lenticular patches (10 cm wide and 30 cm long) or sheared vertically to produce deformation zones, 10 cm wide. In the cataclastically deformed parts of the shear zones or patches, pink K-feldspar and white quartz nodules occur (Fig. 15). The shear zones show aligned augen that mimic the aligned augen in outcrop ONE (Fig. 3). Many of these pink K-feldspar crystals have white rims (Fig. 16), which in thin sections are seen to be composed of plagioclase and myrmekite; see later illustrations. Significantly, the deformed portions of the outcrop are primarily where the plagioclase amphibolite is biotite-rich rather than hornblende rich. More significantly, it is clear that the augen have developed in *modified portions of the plagioclase amphibolite* and did not form in distinct layers separate from the plagioclase amphibolite as would be expected if the augen were derived from a sedimentary or pyroclastic source rock.

Fig. 14. Outcrop of massive Marlboro plagioclase amphibolite behind the Brew House of Danvers west of Motel 6 on Route 1.

Fig. 15. Lenticular patch of deformed plagioclase amphibolite containing light-pink K-feldspar and white quartz nodules from a localized area in outcrop THREE (Fig. 14).

Fig. 16. Close-up photograph of Fig. 15, showing white rims on some of the pink-K-feldspar crystals.

Does the occurrence of K-feldspar megacrysts (augen) formed *in situ* in lenticular zones of deformed plagioclase amphibolite in outcrop THREE possibly explain the lenticular, supposedly plastically-flowed augen gneiss that fills hypothesized fractures in plagioclase amphibolite in outcrop ONE? Does the association of K-feldspar megacrysts with biotite-rich parts of outcrop THREE explain the abundance of biotite in the augen gneiss in outcrop ONE? Could the

occurrence of K-feldspar megacrysts in the 10-cm-wide sheared zone of plagioclase amphibolite in outcrop THREE explain the layered or banded appearance of augen gneiss in outcrop ONE?

Thin section studies

Microscopic studies show that the pink granitic masses (outcrop TWO, Figs. 5-13) contain the same mineralogy as the plagioclase amphibolite except that (1) biotite, hornblende, and plagioclase percentages are less, (2) quartz percentages increase, and (3) K-feldspar appears and increases in abundance. In the narrow stringers, where the massive plagioclase amphibolite contains bent or broken grains, these deformed crystals contain irregular islands of K-feldspar (Fig. 17).
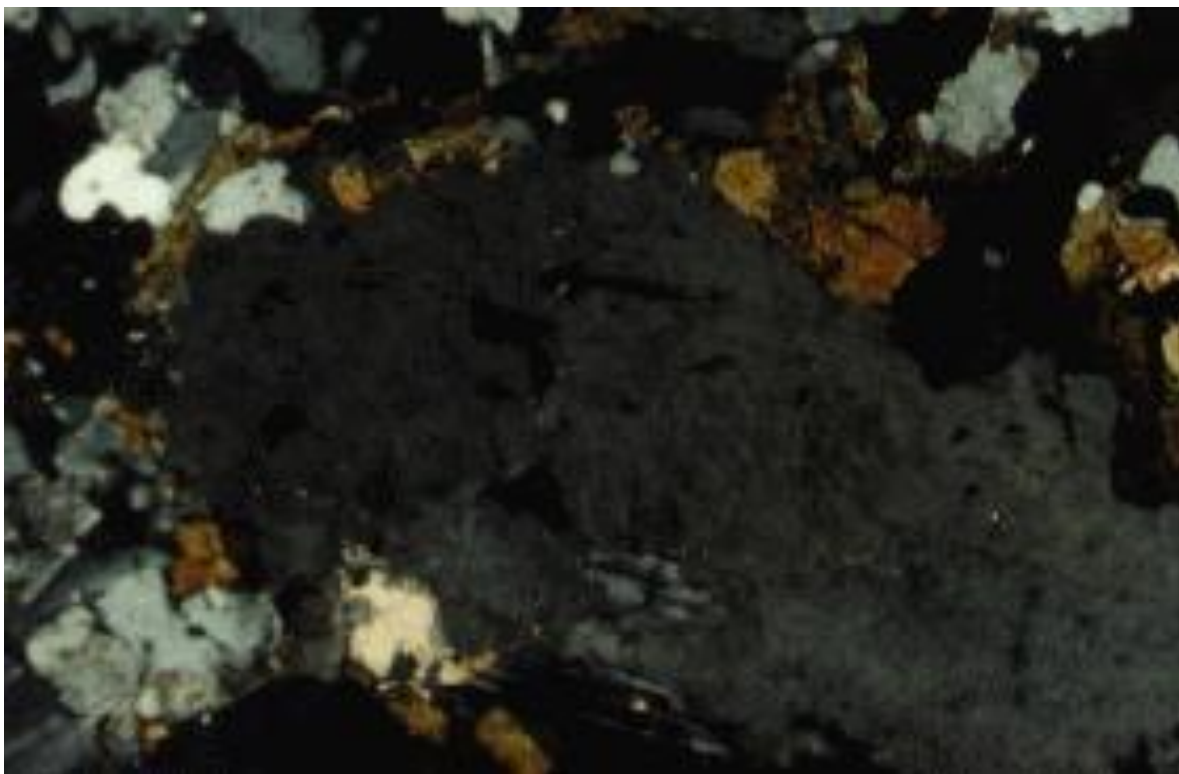

Fig. 17. Photomicrograph of deformed and fractured plagioclase in a plane of a granodiorite stringer in Marlboro plagioclase amphibolite in which the plagioclase has irregular islands of K-feldspar in the interior of the plagioclase crystal.

Surrounding the crystals are smaller grains of plagioclase, quartz, biotite, and hornblende in the plagioclase amphibolite wall rock of the stringer.

Gradually into zones of greater deformation, plagioclase crystals disappear and undeformed K-feldspar crystals occur containing fragments of plagioclase crystals which are in parallel optical continuity. Locally, the K-feldspar crystals are bordered by myrmekite with tiny quartz vermicules (Fig. 18 and Fig. 19).
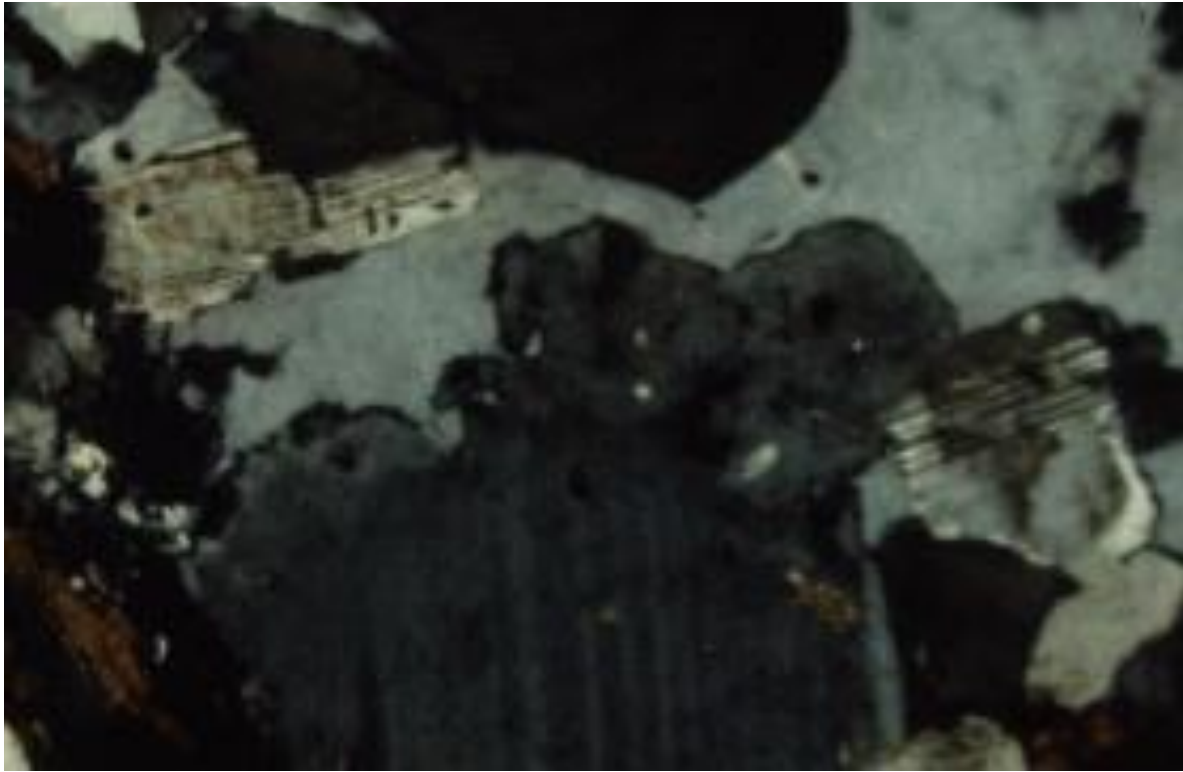

Fig. 18. Photomicrograph of K-feldspar (gray and black, cross-hatch twinned) with remnants of plagioclase (tan) which extend through the K-feldspar in parallel optical continuity. Ground mass minerals consist of quartz (cream, gray, white), biotite (brown), hornblende (brown), and additional plagioclase (tan, gray). In hand specimen, this K-feldspar would appear as a tiny pink crystal in the midst of the black plagioclase amphibolite.
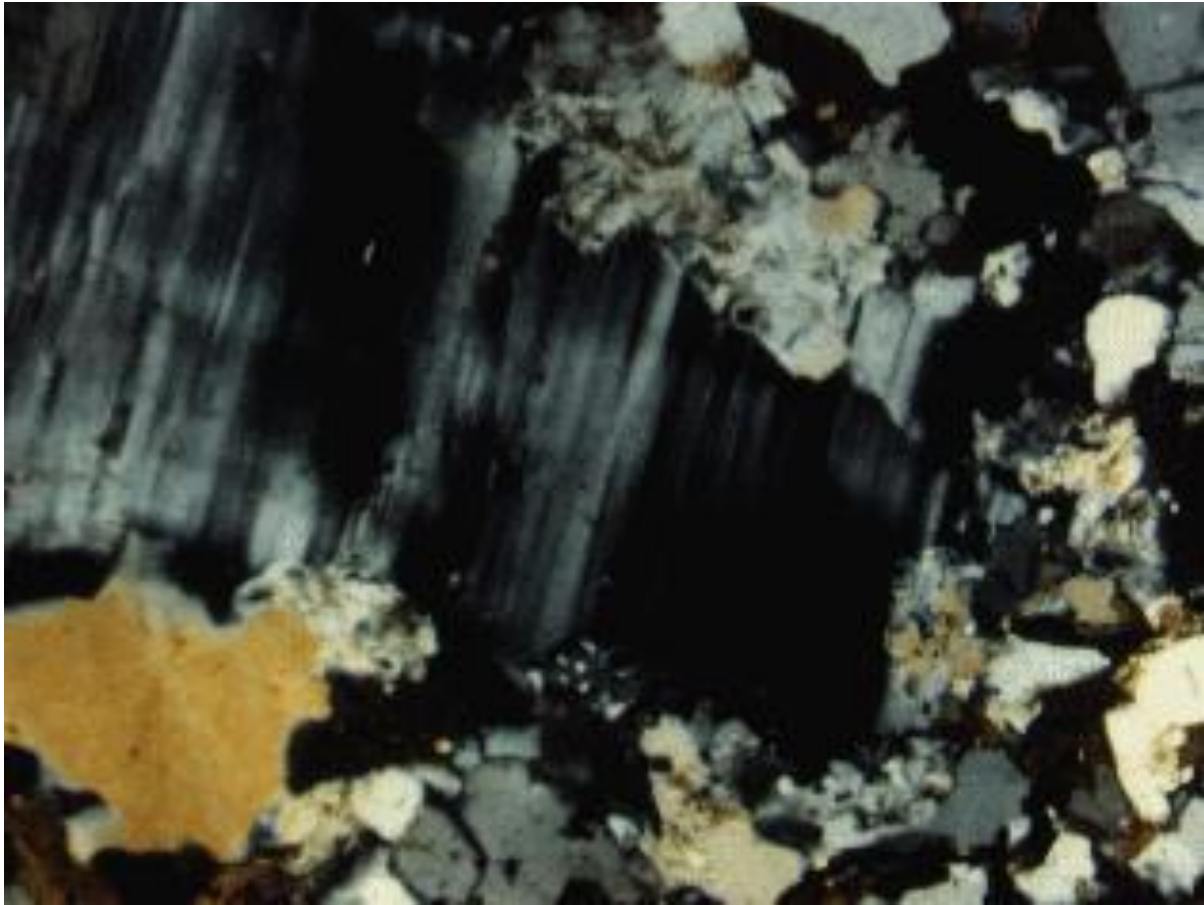
Fig. 19. Photomicrograph of isolated K-feldspar (black, gray, white, cross-hatch twinning) bordered by myrmekite in plane of granitic stringer in plagioclase. amphibolite. Ground mass contains smaller grains of biotite, hornblende, quartz, and plagioclase.

In the middle of the larger, pink, granitic masses between the black plagioclase amphibolite wall rocks (Figs. 5-13), the same kinds of features (e.g., islands of K-feldspar in interiors of deformed plagioclase crystals, myrmekite, etc.) occur. In feathered borders of the plagioclase amphibolite, as well as in the central parts of the granitic masses, K-feldspar penetrates plagioclase crystals (Fig. 20 and Fig. 21), and some penetrated plagioclase crystals are zoned like the zoned plagioclase crystals in the plagioclase amphibolite (Fig. 22).

Fig. 20. Photomicrograph of K-feldspar penetrating along fractures in plagioclase, forming scalloped boundaries.
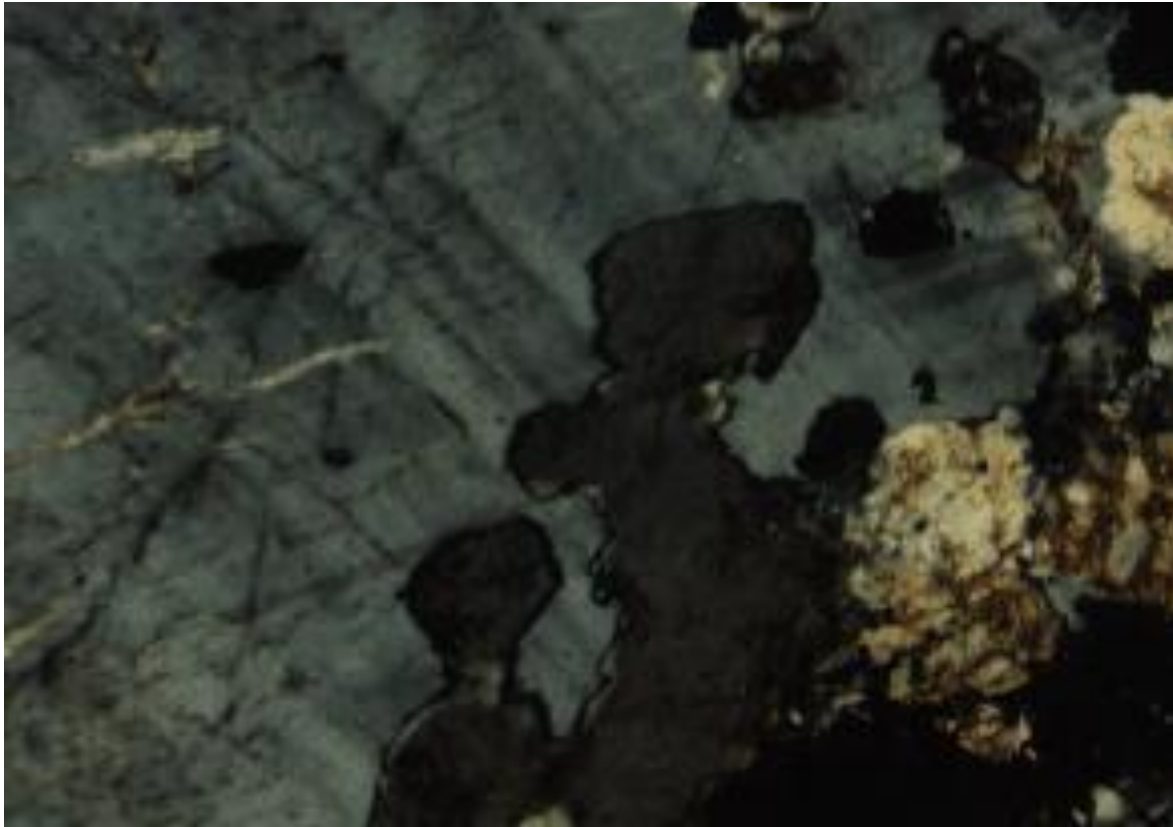
Fig. 21. Photomicrograph of K-feldspar penetrating along fractures in plagioclase, forming scalloped boundaries.
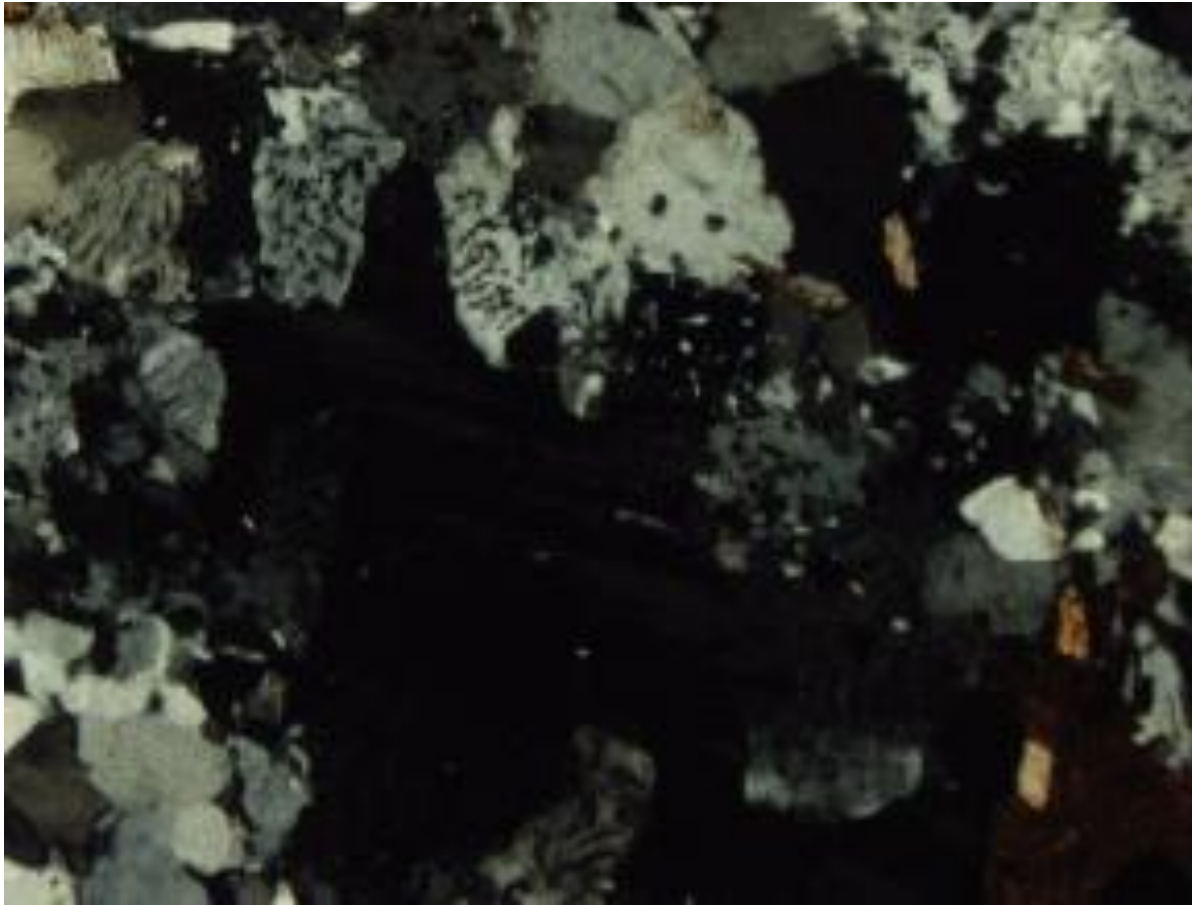
Fig. 22. Photomicrograph of myrmekite projecting into K-feldspar (black, top) and optically continuous with zoned non-quartz-bearing plagioclase (shades of gray, bottom) in granodiorite associated with the Marlboro plagioclase amphibolite.

Throughout the granitic masses in outcrop TWO, K-feldspar crystals occur that have remnants of scattered, broken, and/or deformed plagioclase crystals which are in continuous optical continuity (Fig. 23) or which are bordered by myrmekite (Fig. 24 and Fig. 25). The quartz vermicules in the myrmekite have the same sizes as that found in myrmekite (Fig. 19) associated with isolated augen in narrow stringers (Fig. 6 and Fig. 11).

Fig. 23. Photomicrograph of K-feldspar (shades of gray, cross-hatch twinning), enclosing bent and broken, albite-twinned, plagioclase islands which are in optical continuity (tan, rectangular, and black and gray).

Fig. 24. Photomicrograph of K-feldspar (black) enclosing and bordered by aggregate masses of myrmekite.
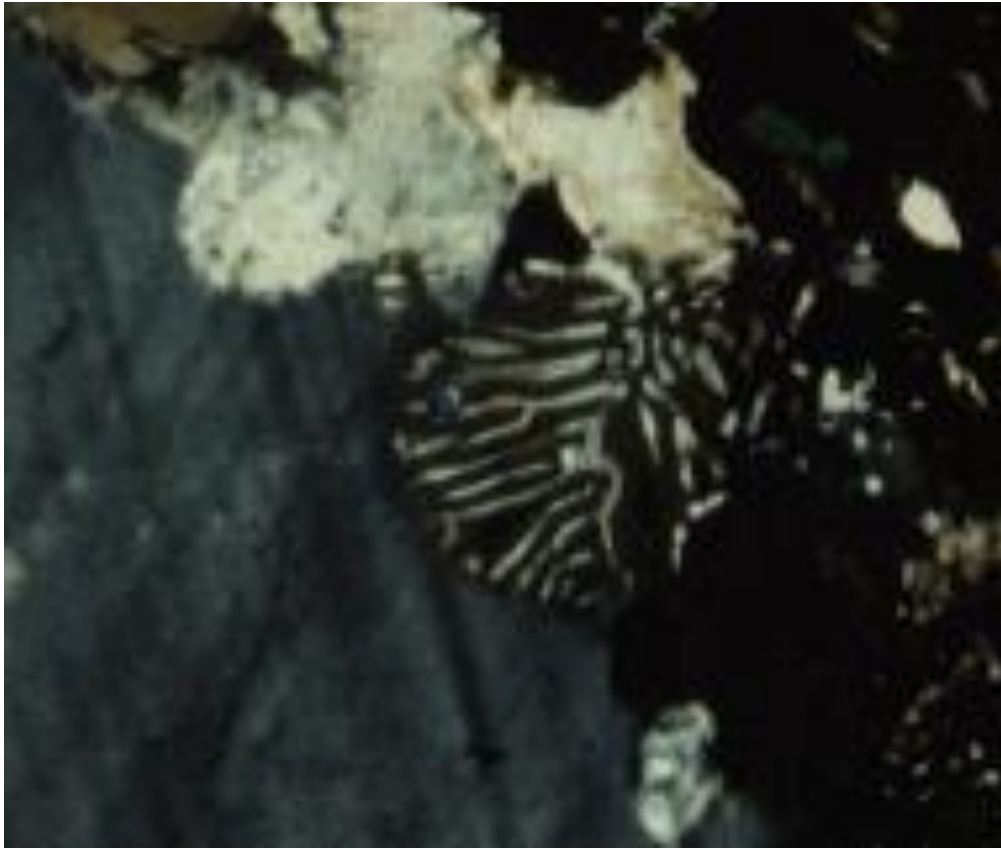
Fig. 25. Photomicrograph of K-feldspar (gray) bordered by myrmekite (tan and white).

The zonation of the feldspars with K-feldspar cores and plagioclase rims (Fig. 16) that occurs in outcrop THREE is the same as that reported by Toulmin (1964) at outcrop ONE, but Toulmin was unable to see what caused this zonation in thin section and resorted to X-ray studies. On close examination of the thin sections of the augen gneiss at outcrop ONE, the rims of the zoned augen consist of sericitized plagioclase grains and *sericitized myrmekite* whose quartz vermicules are the same size as in myrmekite bordering zoned K-feldspar crystals in outcrop THREE (Fig. 26).

Fig. 26. Photomicrograph of aggregate myrmekite grains bordering K-feldspar (gray) at outcrop THREE. Ground mass consists of quartz, plagioclase, biotite, and hornblende of adjacent plagioclase amphibolite.

In a few places biotite in zones of deformation contain a poorly-developed quartz sieve texture (Fig. 27) in outcrop THREE. Quartz sieve textures in biotite are absent in the undeformed plagioclase amphibolite in all three outcrops.
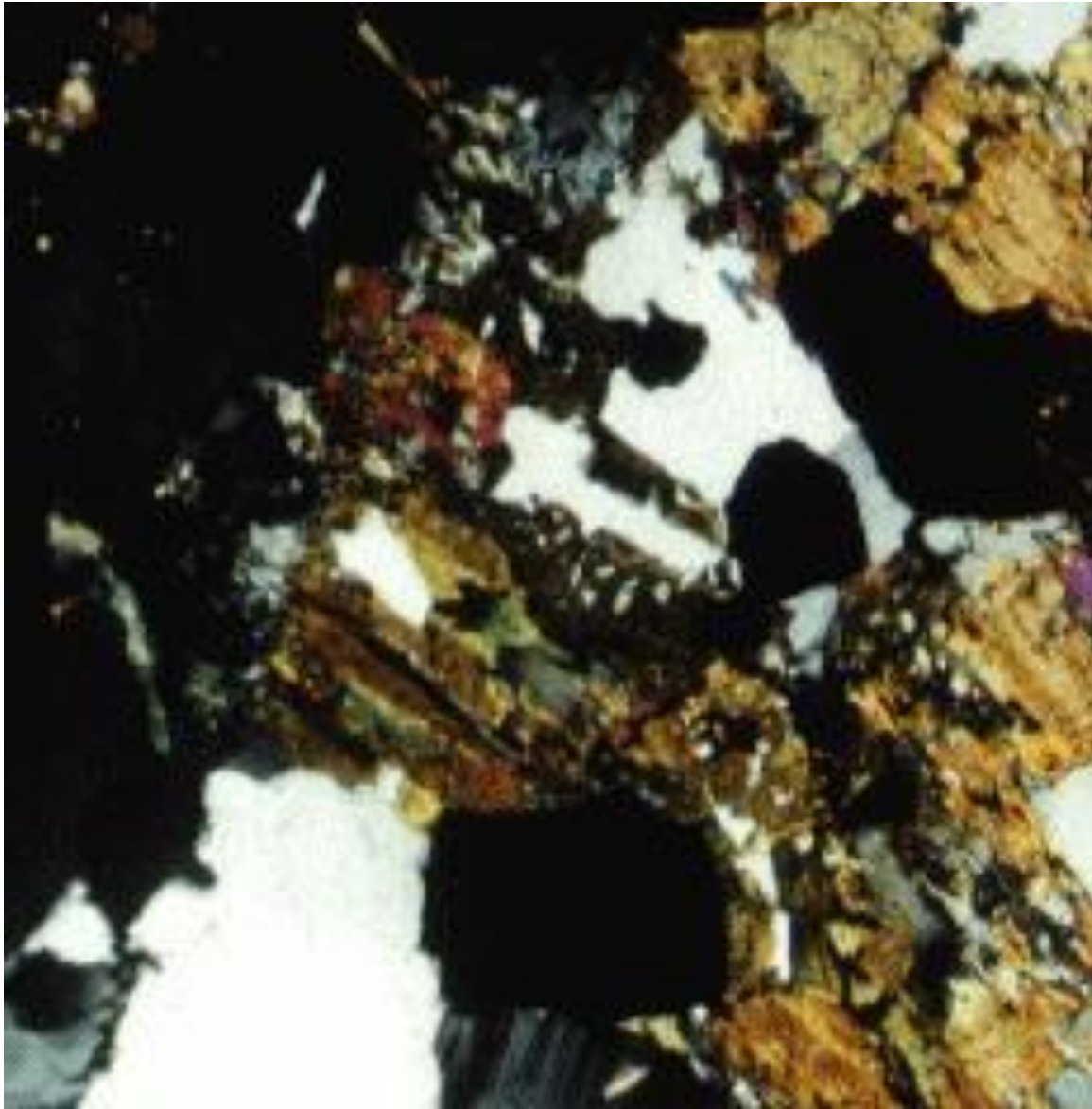
Fig. 27. Photomicrograph of quartz sieve textures in biotite in granitic masses in the Marlboro plagioclase amphibolite.

All three outcrops show the same kinds of deformed plagioclase crystals with interior islands of K-feldspar (Fig. 17, Fig. 18, Fig. 19,m Fig. 20, Fig. 21, and Fig. 22), remnant plagioclase crystals in K-feldspar with parallel optical continuity (Fig. 23), and similar myrmekite (Fig. 24, Fig. 25, and Fig. 26).

All of the textures observed in thin sections require critical consideration. What do the interlocking boundaries between K-feldspar and plagioclase indicate? Do the textures represent simultaneous crystallization of the feldspars? Do they

represent contemporaneous crystallization as in exsolution in perthites? If replacement is considered, is the pattern one of plagioclase replacing K-feldspar or K-feldspar replacing plagioclase?

Do the quartz vermicules in biotite represent symplectic reactions of K replacing orthopyroxene to form secondary biotite plus quartz or has primary biotite been replaced by quartz?

What is the significance of myrmekite? Is it a late-stage deuteric alteration of primary K-feldspar in a crystallizing granitic magma? Is it created by Ca- and Na-bearing fluids replacing primary K-feldspar? Is it the result of exsolution? Or is it the result of incomplete replacement of primary plagioclase by K-feldspar?

Finally, how do the mineral and textural relationships observed in the thin sections relate to the megascopic views of the structures and fabric in the three outcrops?

Further analysis of enigmatic relationships

Close inspection of outcrops ONE and TWO show that inclusions of the plagioclase amphibolite are not rotated (although some lateral displacement cannot be ruled out). This observation rules out physical injection of a viscous granitic magma in outcrop TWO and probably rules out extensive physical flowage of augen gneiss in outcrop ONE (Fig. 4) because the foliation in the fragments still retain parallel alignment with the foliation in plagioclase amphibolite along and across strike. Injection of magma is also improbable because many granitic stringers are so narrow that migration of a viscous silica-rich magma is unlikely and because some stringers consist of isolated, interrupted augen of K-feldspar (Fig. 11), which defy formation from an introduced melt.

Across the 30 m of exposure at outcrop TWO where the pink granitic rocks penetrate the plagioclase amphibolite, the walls of the plagioclase amphibolite do not match either in meter-scale relationships or dimensions of centimeters or less (Figs. 5-11). In other words, if the space that the granitic rocks now occupy were removed, the plagioclase amphibolite masses and fragments *would not fit back together* (Fig. 12 and Fig. 13). Thus, there is no evidence that the plagioclase amphibolite was shouldered aside by a granitic magma to make room for additional mass.

Many plagioclase amphibolite inclusions in outcrop TWO fade out or feather into the pink granitic rocks. Assimilation in a melt is an unlikely explanation for the "fading out" because the amount of mafic minerals in the granitic masses is insufficient to account for the volume of incorporated plagioclase amphibolite once supposedly occupying that same volume.

Anatexis can be ruled out because there is no evidence of a mafic restite that is left behind as more felsic components are melted and subtracted. This is true on a small scale as well as large scale. That is, there is no evidence for the migration of felsic materials from the plagioclase amphibolite that would produce a greater concentration of mafic components as a residue in the plagioclase amphibolite immediately adjacent to the supposed expelled felsic components in the granitic masses. Likewise, on a large scale, there is no apparent change in composition of the plagioclase amphibolite near the granitic rocks in comparison to compositions far from the granitic masses.

The formation of K-feldspar megacrysts (augen) only in zones of deformation in biotite-rich plagioclase amphibolite in outcrop THREE suggests that the K-feldspar is a secondary product associated with the deformation. It is likely, therefore, that the augen in outcrop ONE are not primary products of crystallization from magma or metamorphism of K-bearing shales or layered pyroclastic materials.

Where the feldspars have interlocking textures, it is the plagioclase which is broken or has deformed (bent) albite-twin lamellae and not the K-feldspar, and, therefore, it is clear that K-feldspar is younger than the deformation and has replaced the plagioclase. The progressive appearance of K-feldspar in interiors of deformed plagioclase crystals and the remnants of broken plagioclase fragments, having optical continuity, give further support for the K-metasomatism. The abundance of biotite (up to 30 vol. %) provides an ample source of K for the local K-metasomatism to produce the K-feldspar. Local metasomatism is obviously a more logical explanation for the development of isolated K-feldspar augen than is an origin by injection of magma.

The absence of orthopyroxene in the plagioclase amphibolite and local abundance of primary biotite suggest that the quartz sieve textures in the biotite are the result of replacement of biotite by quartz rather than the reaction of K-bearing fluids with orthopyroxene to produce biotite and left-over quartz.

Because K-feldspar must be secondary, the formation of myrmekite by exsolution from a high-temperature K-feldspar is not possible. Myrmekite formation by Ca- and Na-metasomatism is unlikely because it is K that is entering and removing Ca and Na from the deformed plagioclase crystals. Removal of Ca is incomplete in many places which causes myrmekite to be formed. See explanations in the first three presentations in this web site.

The replacement of plagioclase amphibolite by augen gneiss of granitic masses must be volume-for-volume because the broken and deformed crystals are generally replaced from their interiors outward. Nevertheless, such replacements need not be at constant volume because of density changes in the replacement minerals relative to the primary minerals and because more material (elements as ions) may be subtracted than introduced. A small, differential volume loss could cause the gentle bending of foliation around the broken blunt ends of unreplaced plagioclase amphibolite (Figs. 3-13).

The continuous layers of fine-grained quartzo-feldspathic rock in the plagioclase amphibolite (outcrop ONE), which essentially lack mafic components, can be explained as representing strong shear zones in which continued or periodic movements allowed intense (more complete) replacements. Coarse crystals would not have been developed there because of repeated granulation and recrystallization of the felsic residue as the mafic components were replaced progressively by quartz.

At any rate, outcrops ONE, TWO, and THREE are interesting because initial observations of the exposed relationships generally produce automatic reactions that granitic magma has intruded plagioclase amphibolite and that the plagioclase amphibolite contains interbedded metasedimentary or metavolcanic rocks. By using critical thinking, studying the outcrops closely, and looking at thin sections, students can reach alternative explanations. These outcrops are worthwhile places for students to study and observe what happens in a region affected by small-scale metasomatism.

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