Geological Society of America Supplemental File

Appendices to Accompany:

Camilleri, P. A., 2009, Growth, behavior and textural sector zoning of biotite porphyroblasts during regional metamorphism and the implications for interpretation of inclusion trails: Insights from the Pequop Mountains and Wood Hills, Nevada U.S.A.: Geosphere, v. 5, no. 3.

Preface

This document contains twenty appendices. Appendices 1, 2 and 5 provide additional discussion or documentation of information that is related to, but not the focus of, the paper and Appendices 3 and 4 provide additional data and details on material presented in the paper. The purpose of the remaining appendices (6-20) is to show photomicrographs of additional samples that were studied but not presented in the paper, especially the porphyroblasts that exhibit more subtle expressions of textural sector (TS) zoning or those where the presence of zoning is suggested but inconclusive. These specimens either did not have the right composition to leave an overt record of zoning or had inappropriate strain vs. growth rates. These observations can provide a point of reference that may help in recognition of textural zoning in biotite in other regional metamorphic terrains. Please note that microstructures of the post-zoning destructive phase are present in all samples (e.g., extension fractures, rotated inclusion trails, quartz $\pm$ biotite-filled strain shadows). All photomicrographs are in plane-polarized light unless otherwise indicated, and should be viewed in color for maximum resolution of subtle zoning patterns. Sample locations are listed in Figure 1 in the paper.

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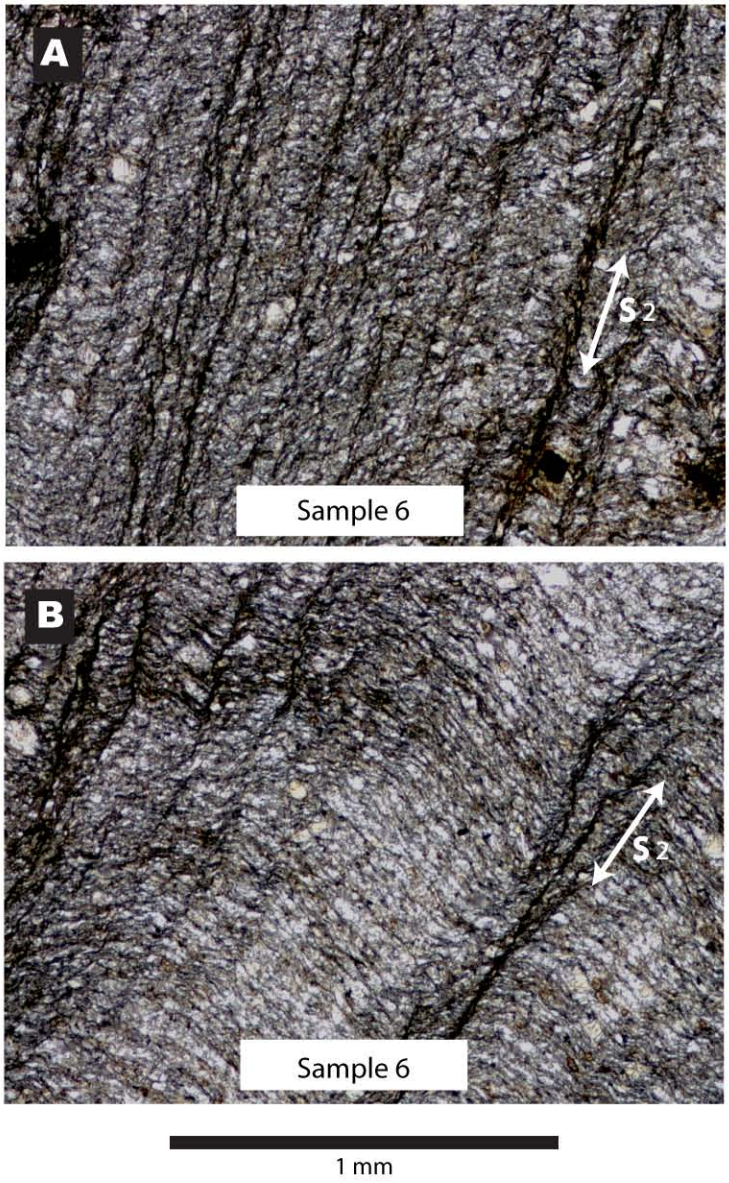
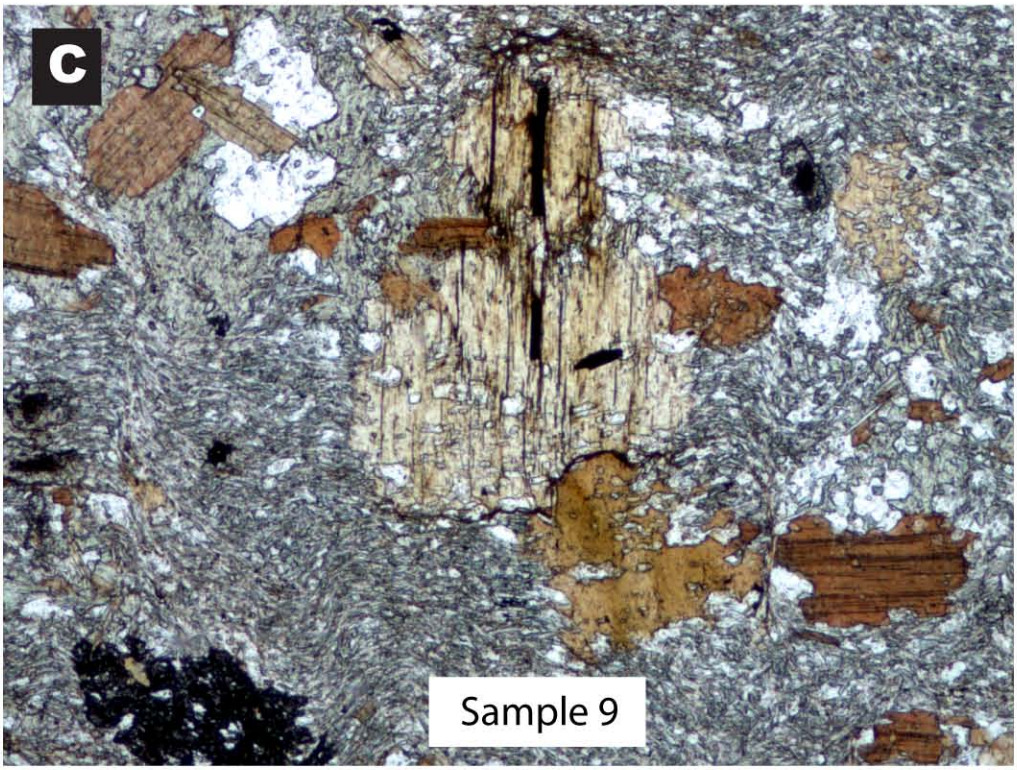
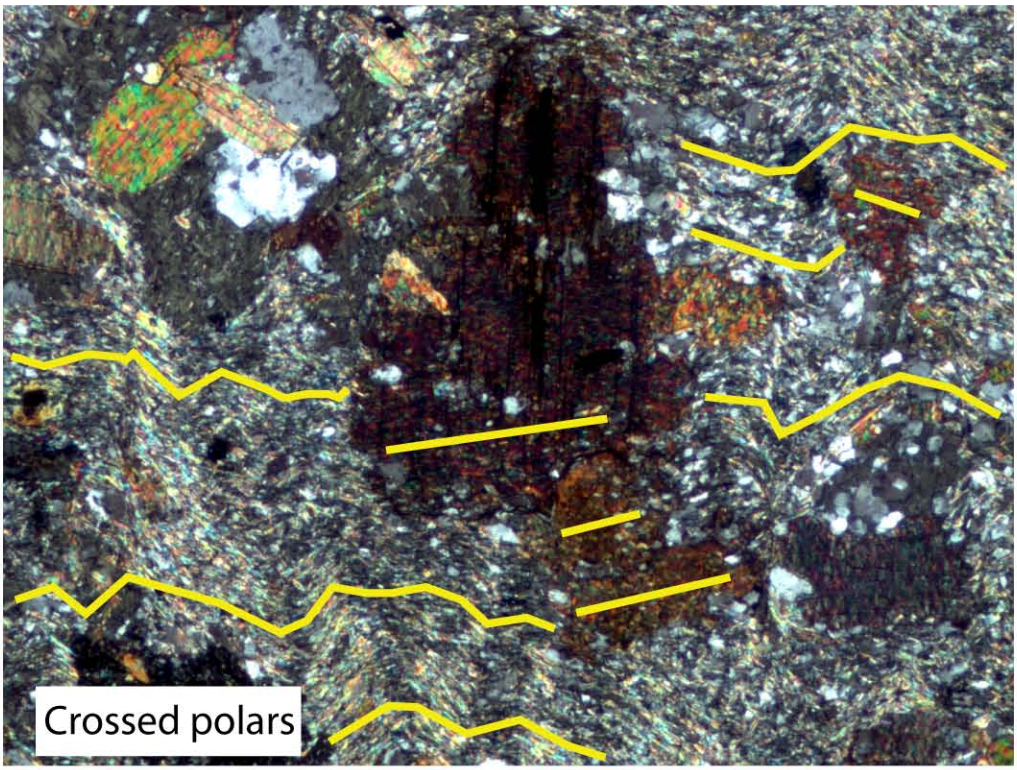
APPENDIX 1
S_2 (the Crenulation of S_1)
(Samples 6, 9, and WH 1b)

The purpose of this appendix is to show that crenulation of S_1, which is related to minor structures associated with the Independence thrust, postdates growth of biotite porphyroblasts. The crenulation is generally a weak fabric (S_2) and it does not transpose S_1. The photomicrographs and associated line drawings show crenulated S_1 in chlorite, biotite and kyanite zone Cambrian Dunderberg phyllite or schist. The photomicrographs in (A) and (B) show examples of the crenulation in chlorite zone phyllite (sample 6). The photomicrographs in (C) and (D) show examples of biotite-zone biotite porphyroblasts with straight, inherited inclusion trails surrounded by crenulated matrix foliation, which indicates biotite grew before crenulation (sample 9). Yellow lines in the line drawings in (C) and (D) indicate traces of foliation in the matrix and inclusion trails in biotite. The photomicrograph in (E) is an example of crenulated kyanite zone schist from the Wood Hills (sample WH1b). Note the kinked biotite porphyroblast defining the hinge of a crenulation. The photomicrographs in (A-D) have the same scale.



APPENDIX 1 CONTINUED
S_2 (the Crenulation of S_1)
(Samples 6, 9, and WH 1b)





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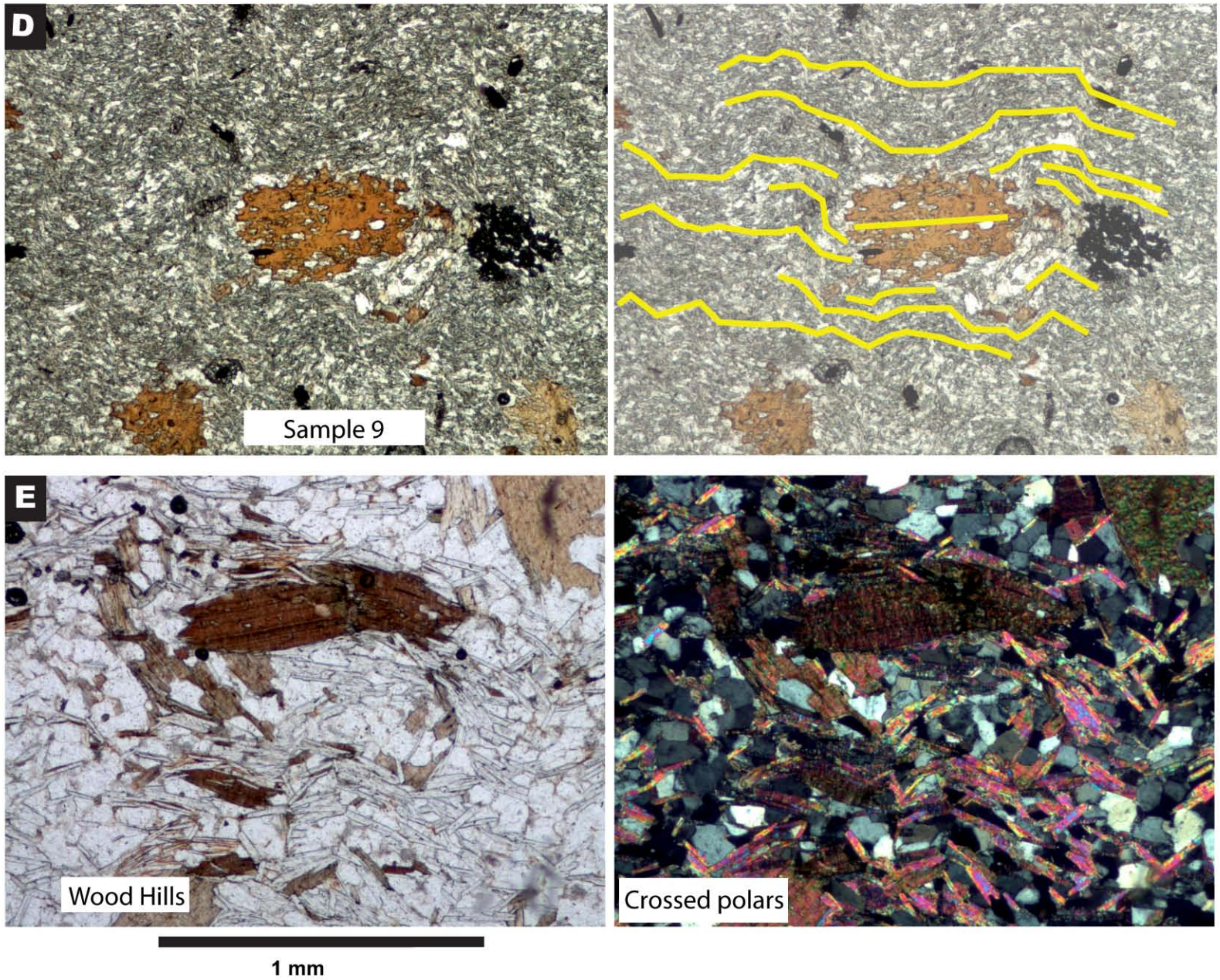
APPENDIX 1 CONTINUED
S_2 (the Crenulation of S_1)
(Samples 6, 9, and WH 1b)



APPENDIX 2

Significance of the development of extension veins that are sub-parallel to foliation in the chlorite zone

Chlorite and biotite zone metapelite in the Pequop Mountains contain extension veins that are typically a few millimeters to a few centimeters long and are parallel or at a low-angle to foliation. The veins are filled mostly with chlorite but may also contain quartz, plagioclase, and white mica. The development of these veins appears to have ceased before attainment of biotite zone conditions because the vein chlorite and adjacent matrix in biotite zone phyllite and schist has been, in part, replaced or overgrown by biotite porphyroblasts (see photomicrograph A in this appendix and the photomicrographs in Appendix 9, and Fig. 9B in the paper). The orientation of these veins is unusual in that such veins are commonly thought to form at a high angle to tectonic foliation, i.e., parallel to sigma one. However, according to Gratier (1987) "… it is well known that such tectonic veins are sometimes developed parallel to…cleavage planes". Gratier (1987) indicates that such rocks are anisotropic and probably have a tensile strength perpendicular to cleavage that is significantly less than the tensile strength of the rock in a direction parallel to cleavage. Consequently, when fluid pressure builds, fracture is likely to occur parallel to cleavage and hence normal or at a high-angle to sigma one (e.g., see Diagram 1 of this appendix and Fig. 4 of Gratier [1987]). By analogy, it is likely that the ~foliation-parallel veins in the chlorite zone in the Pequop Mountains formed in a similar manner with buildup of fluid pressure due to dehydration reactions accompanying metamorphism.

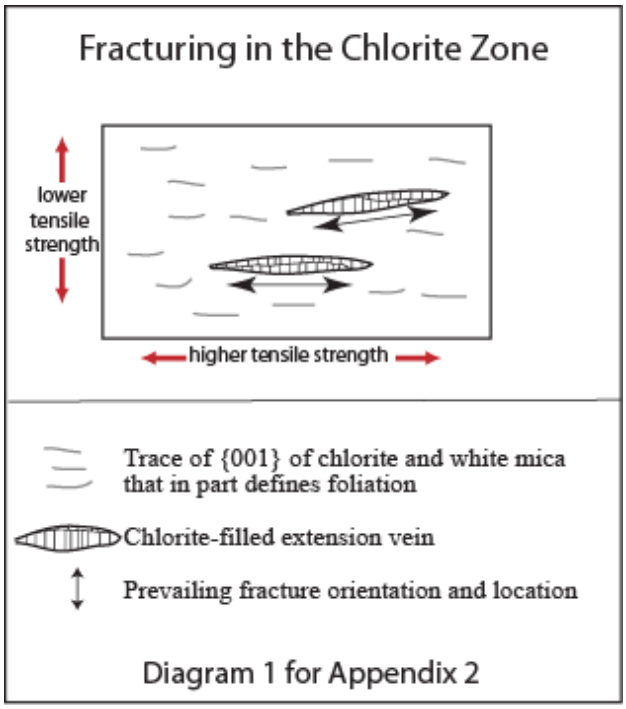
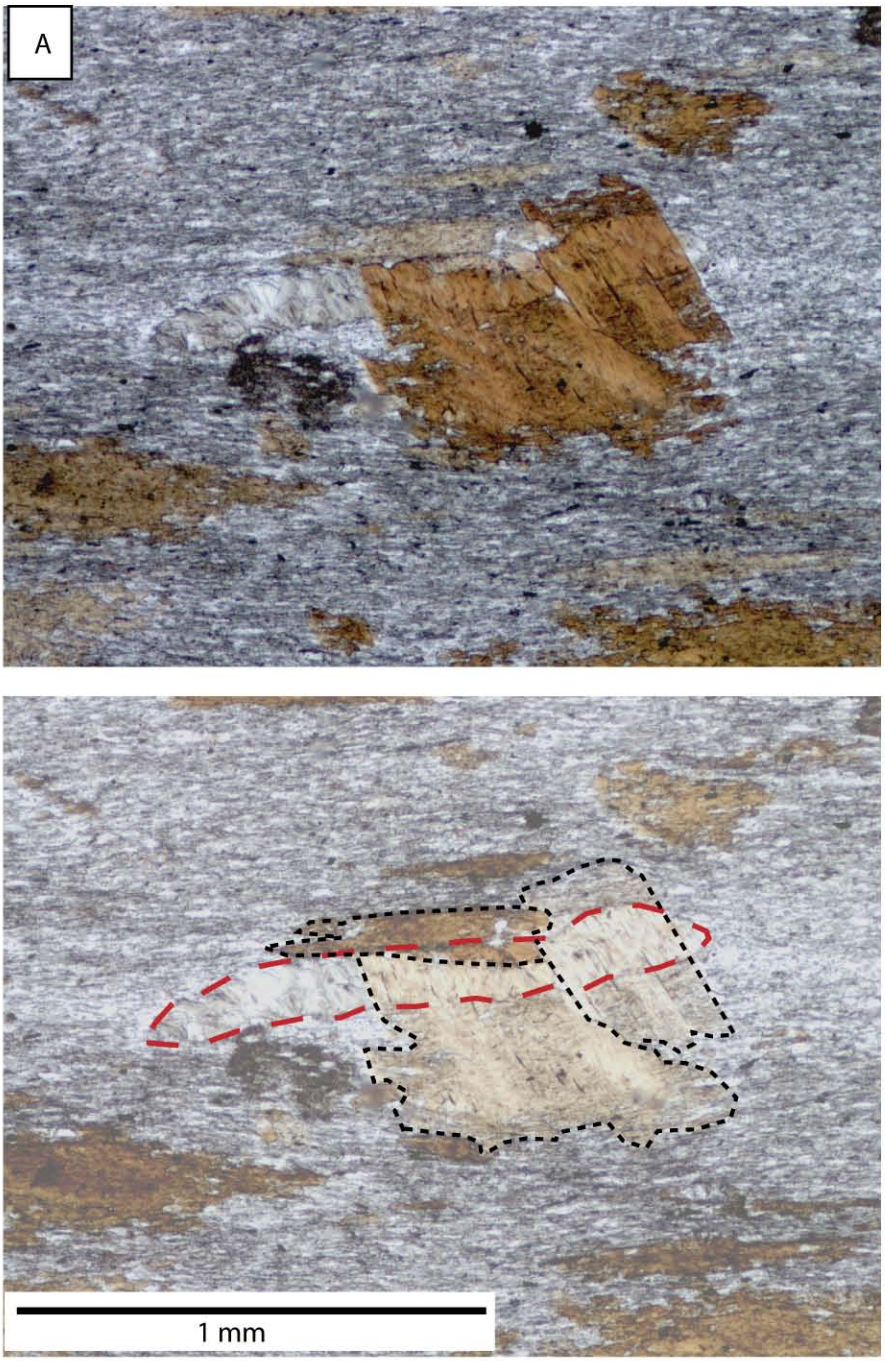


Diagram 1 for Appendix 2

Reference

Gratier, J.P., 1987, Pressure solution deposition creep and associated tectonic differentiation in sedimentary rocks, *in* Jones, M.E., and Preston, R.M.F., eds., Deformation mechanisms in sediments and sedimentary rocks : J. Geol. Soc. Lond. Spec. Publ. No 29, p. 25-38.

APPENDIX 2 CONTINUED

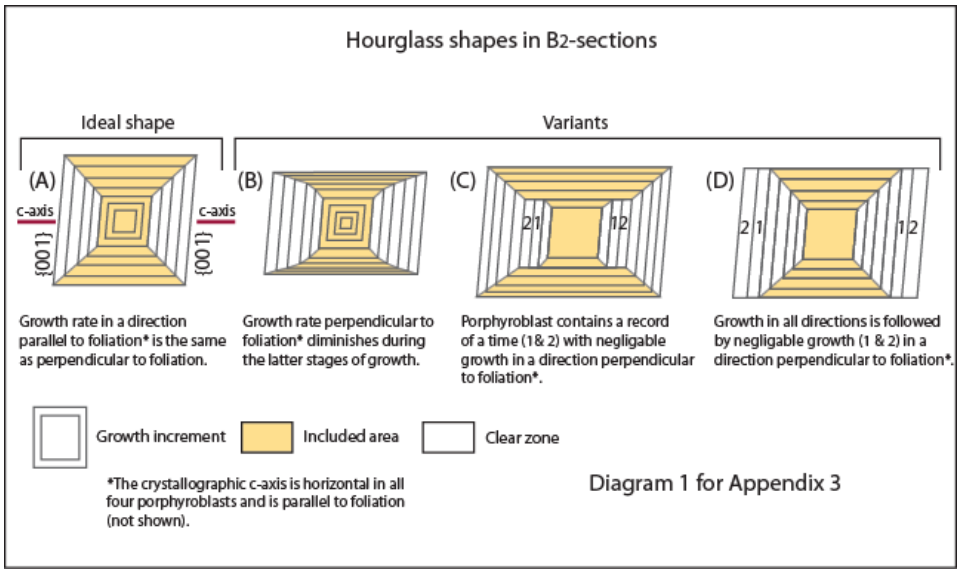


Photomicrograph and line-drawing of a chlorite vein partially replaced by three porphyroblasts with contiguous grain boundaries (sample 1a). The vein in the line drawing is outlined by a dashed red line and the porphyroblasts by dashed black lines. Note that biotite is clear where it has replaced vein chlorite and these clear zones are not a product of zoning. Biotite outside of the vein has sparse graphite inclusions (dark areas) and clear zones related to zoning. For example, clear zones in bottom left biotite porphyroblast outside the perimeter of the vein are related to zoning. Photomicrograph is perpendicular to foliation and parallel to lineation.

APPENDIX 3

Development of hourglass shapes that vary from ideal

Not all porphyroblasts in the Pequop Mountains have ideal zoning patterns such as depicted in Diagram 1A. For example, some porphyroblasts have evidence that growth was restricted in certain directions for a period of time or have evidence that tensile separation of matrix along {001} faces was uneven resulting in non-ideal zoning patterns. Growth restriction (or extremely slow growth) most typically occurred in directions perpendicular to foliation and in general is manifest by the extremities of clear zone-hourglass boundaries being arcuate rather than straight, which indicates a general slowing of growth rate perpendicular to foliation during the latter stages of growth (compare [A] and [B] in Diagram 1). However, in some cases growth restriction occurred for only a period of time resulting in straight clear zone-hourglass boundaries paralleling foliation for those increments (see [C] and [D] in Diagram 1). For example, local growth restriction perpendicular to foliation in some porphyroblasts appears to have been a result of growth being temporarily arrested when two porphyroblasts impinge (e.g., photomicrograph [B]), and in others it could be related to increased strain rate (± dissolution) relative to growth rate on the porphyroblast's margins that are parallel to foliation. The latter case is indicated by an increased density of graphitic inclusions bordering the clear zone (e.g., see areas above "a" and below "b" in photo [C]). In other cases, the cause of growth restriction is not apparent (e.g., see area above "c" in photo [C]) and may be related to impingement or interference with another porphyroblast(s) nearby or out of the plane of the thin section.



Some porphyroblasts have evidence that matrix separation did not occur along the entire length of the {001} faces resulting in an unusual hourglass shape. The porphyroblast in photomicrograph (A) is an example where matrix separated at the ends, but not in the center, of one of the {001} faces resulting in a perturbed hourglass shape; and photomicrograph (B) shows an example of a porphyroblast where matrix progressively stopped separating at one end of one of the {001} faces resulting in a reversal of slope for a part of the hourglass-clear zone boundary. The origins of these perturbations are not clear, but in the latter example it may be related to compression of part of the face by a neighboring porphyroblast(s) out of the plane of section, which could inhibit tensile separation. Because shape perturbations commonly do not affect all sides of the hourglass, it suggests that impinging or neighboring porphyroblasts perturb growth patterns locally on only one side or corner of the crystal, which attests to the heterogeneity of strain imposed by growing porphyroblasts.

Appendix 3

Development of hourglass shapes that vary from ideal

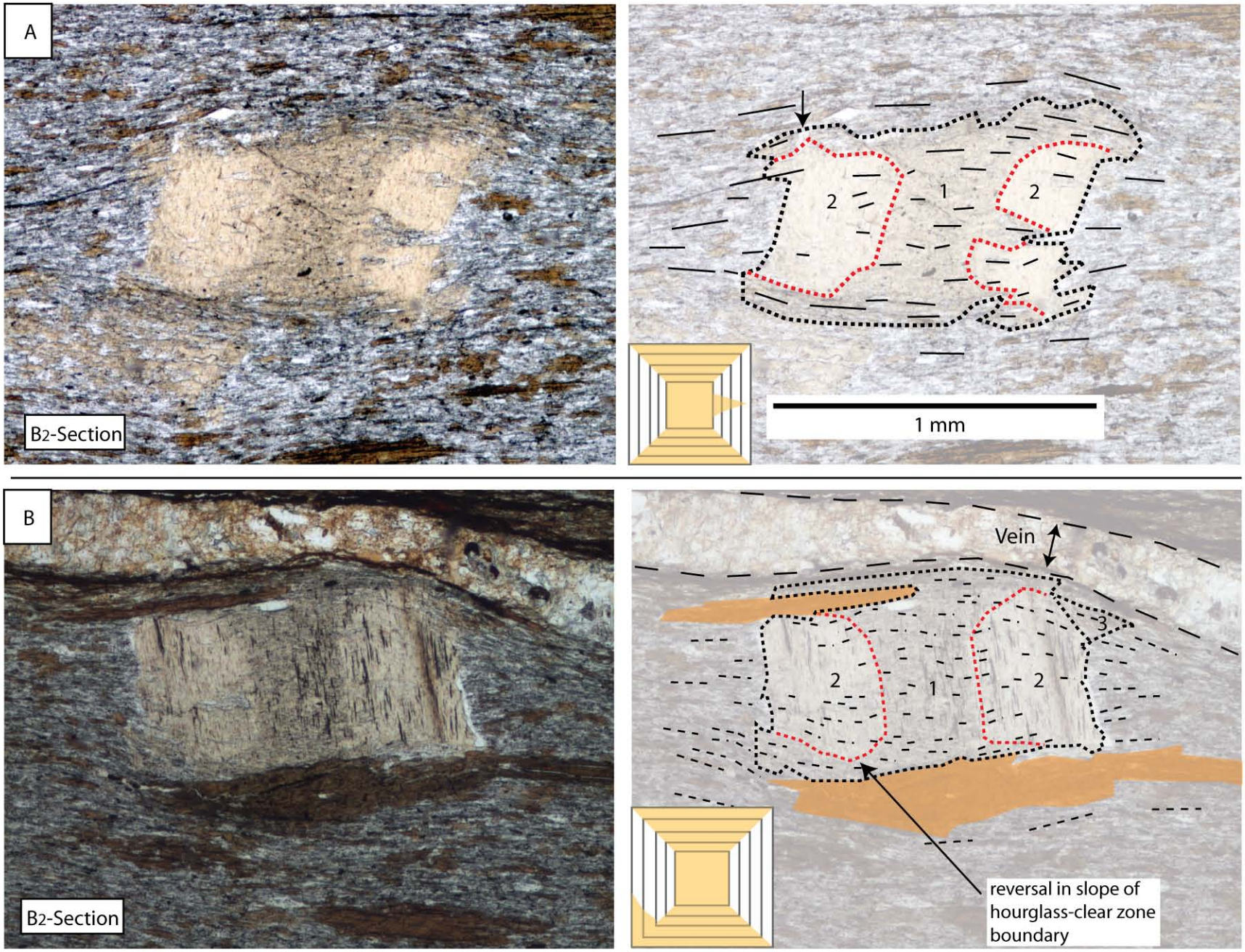
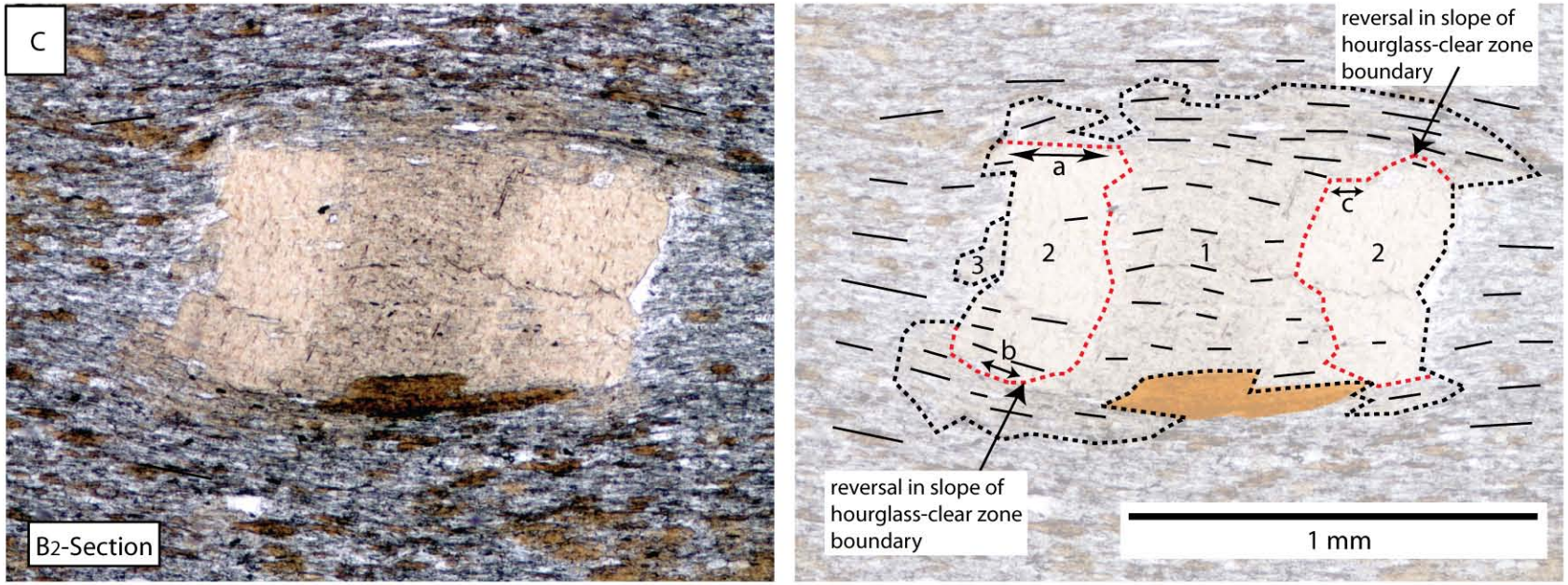


Figure caption on next page.

Appendix 3

Development of hourglass shapes that vary from ideal



Photomicrographs and line drawings of zoning patterns in B2-sections from sample 1g. View in all photomicrographs is perpendicular to foliation and parallel to lineation. Inclusion trails are defined primarily by graphite and are broadly convergent with the foliation surrounding the porphyroblast displaying a similar convergence. Biotite porphyroblasts that impinge on the B2-sections and have {001} at a low-angle to parallel to foliation are colored orange in the line drawings. (A) Example of a B2-section illustrating progressive partial tensile separation of matrix on the right {001} face during growth. Separation was inhibited in the center of this {001} face hence growth in this area proceeded by matrix replacement, which resulted in incorporation of inclusions. (B) Example of a B2-section where growth in a direction perpendicular to foliation was locally inhibited due to impingement of a neighboring biotite porphyroblasts (colored orange). Growth inhibition is indicated where clear zone boundaries parallel foliation in the top left and lower right corners of the porphyroblast. The vein overlying the porphyroblast is an extension fracture filled mostly with quartz, carbonate, and sparse biotite. The porphyroblasts in (A) and (C) are examples of porphyroblasts that have clear-zone boundary segments that parallel foliation. These segments indicate growth inhibition in a direction perpendicular to foliation that may be related to slow growth rate, which is suggested by a denser concentration of graphite adjacent to some clear zone boundaries that parallel foliation. It is also plausible that impingement or competition for nutrients with another biotite porphyroblast out of the plane of the thin section was a source of slow growth rate. The porphyroblast in (B), and to a lesser degree in (C), exhibit evidence of progressive partial tensile separation of matrix on the lower left and upper right corners of the {001} faces, which is indicated by a reversal of slope of the clear zone-hourglass boundaries. Arrows in all photomicrographs indicate positions of extension fractures filled with biotite and quartz. The letters "a", "b" and "c" in photomicrograph (C) are parts of clear zones (denoted by the double-headed arrows) that are referred to in the text. Diagrams in lower left corners of the line drawings in (A) and (B) show hypothetical growth increments that could produce the zoning patterns observed in the biotite porphyroblasts (see Diagram 1 for an explanation of symbols). The scale in (B) is the same as in (A).

APPENDIX 4

Extension fractures and the stress transfer mechanism: off-center extension fractures and modification of inherited inclusions

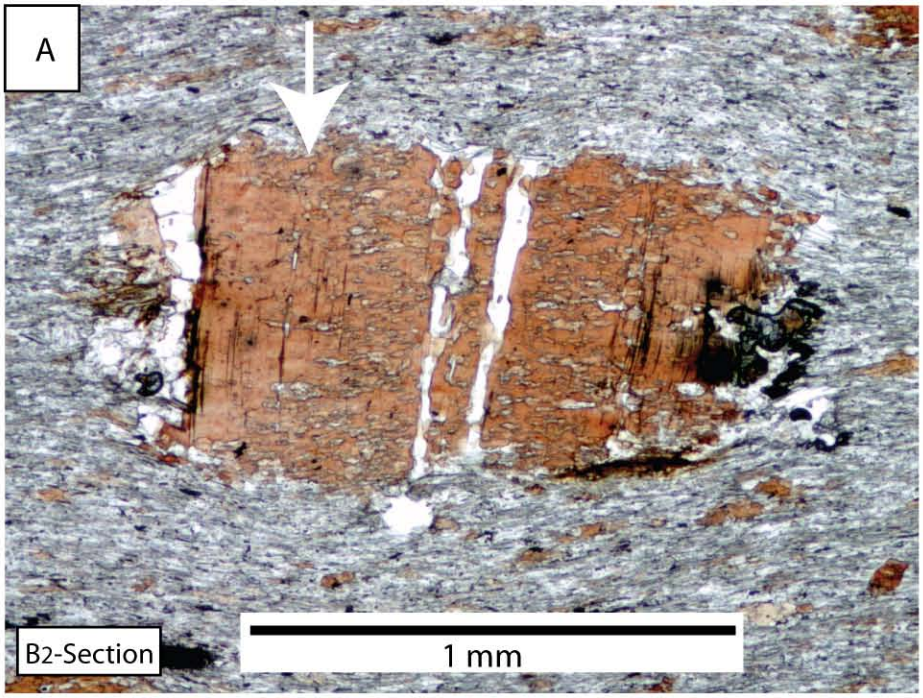
Off-center Extension Fractures

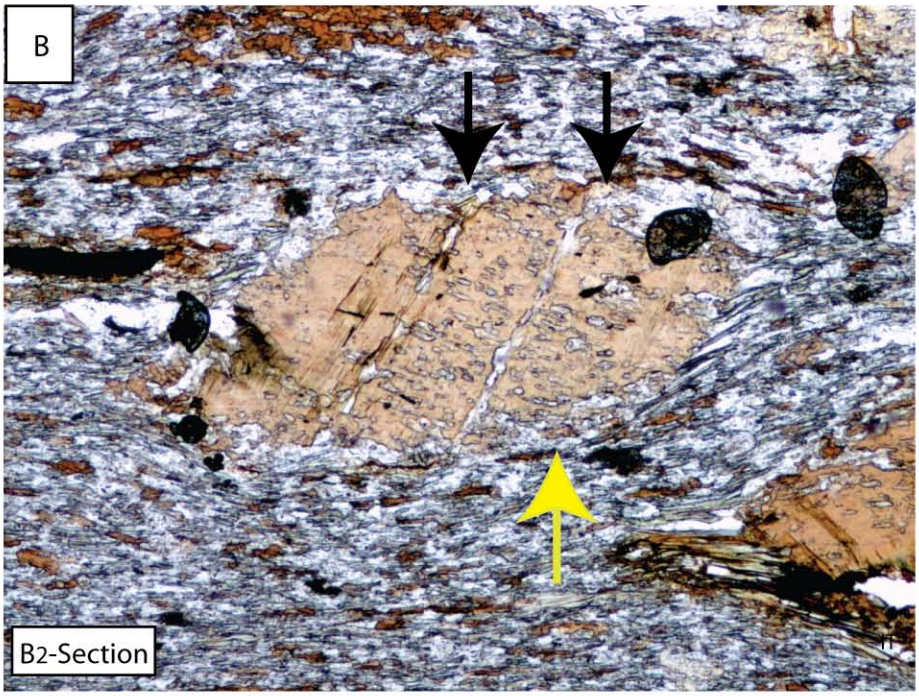
Porphyroblasts with {001} at a high angle to foliation in the Pequop Mountains commonly developed one to three {001}-parallel extension fractures during the destructive phase. These fractures are typically equally spaced with one fracture approximately in the center of the crystal (see Fig. 16 A-D in the paper). The stress-transfer theory was invoked to explain this characteristic distribution of fractures. According to this theory, stresses imparted to the rigid porphyroblasts by the ductiley flowing matrix result in development of tensile stress that is greatest at the mid-point of the mineral, and when tensile strength is exceeded a fracture develops in the center. Fractured segments will then continue to fracture at their midpoints until the length of a segment is below some critical length where stress cannot exceed the tensile strength of the mineral. The stress-transfer mechanism appears to be a plausible explanation of the consistency of the geometry and number of fractures observed in many biotite porphyroblasts. The theory, however, does not explain two fractures in the center (see photomicrograph [A]), two approximately equally spaced but off-centered fractures (see photomicrograph [B] and Fig. 12 C in the paper), or an off-centered single fracture (see Fig. 7A in the paper). These deviations may reflect the internal inhomogeneity inherent in zoned porphyroblasts or an unusual shape that alters stress distribution resulting in fracture in an unusual location. For example, two closely spaced fractures in the center of a porphryoblast may be the result of initial development and annealing of one fracture by growth of biotite (and quartz) that effectively altered the subsequent stress pattern, perhaps by increasing tensile strength at the location of the first fracture, resulting in development of another fracture in a nearby location. Porphyroblasts with two equally spaced fractures, none of which are in the center or those with one that is off center, are less common and occur in rocks where biotite comprises a significant volume of the rock and where it is not uncommon for two or more adjacent porphyroblasts to share a portion of a grain boundary. In this regard, neighboring porphyroblasts may have influenced stress distribution in a fractured porphyroblast because they are not truly suspended in a ductiley flowing matrix when they share boundaries with one or more porphyroblast.

Tensile Stress and Modification of Inherited Inclusions

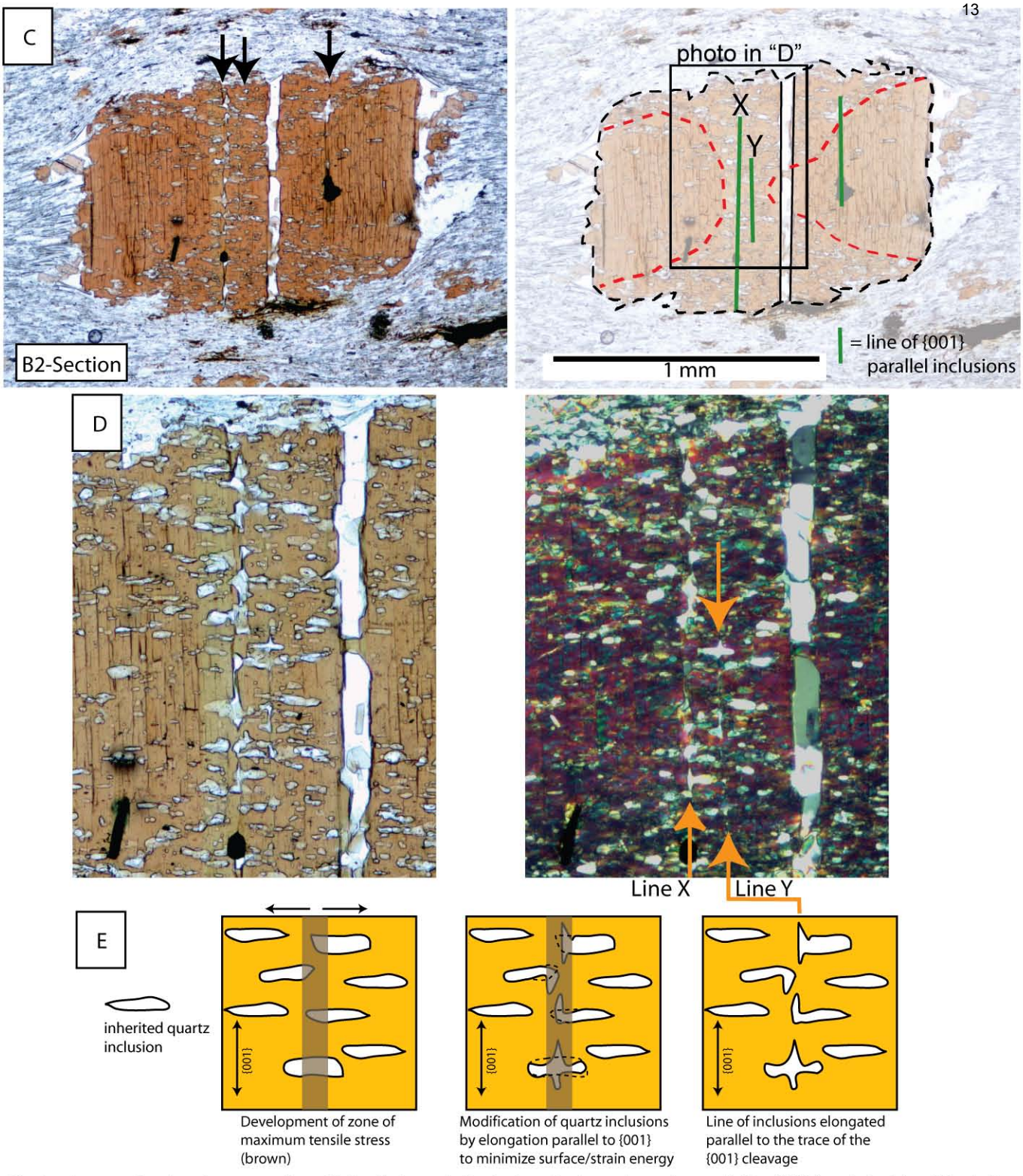
Minor growth of biotite in extension fractures occurred following fracturing, but more significantly, growth and fracturing has altered zoning patterns and resulted in development of false {001}-parallel inclusions. In fractures that mostly filled with biotite, quartz appears as elongated blebs parallel to {001} and therefore resembles inclusions (e.g., photomicrographs [B-D]). However, not all blebs of quartz that are elongated parallel to {001} may represent fracture fill. Some of the {001}-parallel quartz blebs occur along a zone where biotite in the zone has uniform extinction with the host (photomicrographs C-D). These blebs do not appear to be in a fracture that has any appreciable fill and many of them appear to be modified inherited inclusions elongate along {001} forming “T”, “t” or “L” shapes (e.g., see photomicrograph [D]). The zones of T-, t-, or L- shaped inclusions may represent former areas of significant tensile stress where failure did not occur but where stress-induced defects facilitated diffusion of impurities, i.e., the quartz in inherited inclusions. For example, this could have involved migration and elongation of the quartz in the tensile zone parallel to biotite’s {001} synchronous with migration of biotite to replace the displaced portions of quartz (e.g., Diagram E). Such a process would be driven, in part, by an attempt to minimize surface energy of quartz by aligning the quartz grain boundary parallel to biotite’s {001}, which is a lower energy boundary than perpendicular to {001}. This process may have preceded failure in porphyroblasts with large, filled fractures, but is not evident because of the presence of substantial fill. The interpretation that the zones of T-, t-, or L- shaped quartz inclusions are a result of stress induced modification of inherited inclusions rather than precipitation of quartz on the inherited inclusion on the fracture wall is preferred because there does not appear to be any tensile separation across the zones (e.g., line Y in Diagram E).

APPENDIX 4 CONTINUED





Examples of zoned porphyroblasts with extension fractures filled primarily with quartz and biotite (from sample 16a). Black arrows on photomicrographs denote positions of fractures that are mostly filled with biotite. White arrow in (A) denotes line of {001}-parallel quartz "inclusions". Yellow arrow in (B) points to grain margin where a small amount of biotite has overgrown matrix following rotation. Dark bubbles in (B) are air bubbles in the thin section.



Photomicrographs showing examples of inherited quartz inclusions that are elongate parallel to {001} and sketches illustrating their possible origin. (C) Photomicrograph and line drawing of a foliation-normal, lineation-parallel zoned B2-section from sample 16a. This porphyroblast exhibits vertical zones (i.e., lines in two-dimensions) across which inherited inclusions appear to be, in part, elongated parallel to {001}. These lines occur to the left and right of the mostly quartz-filled extension fracture in the center, and their positions are shown in green on the line drawing and by black arrows on the photomicrograph. (D) Enlarged view of some of the lines shown in (C) in plane-polarized light and in crossed polars. (E) Diagram illustrating a possible origin of a line of {001}-parallel inclusions.

Appendix 5

Significance of non-coaxial component

During the biotite destructive phase, porphyroblasts in some samples developed a preferred, top-towards-the-west sense of rotation probably due to a small non-coaxial component of strain. The purpose of this appendix is to provide additional discussion of the non-coaxial component by putting it into a regional tectonic perspective. Diagrams 1 and 2 show structural and metamorphic reconstructions of the thrust footwall at the peak of metamorphism. These diagrams show the footwall lying beneath the Windermere thrust and an east-tapering wedge of thrusted Phanerozoic strata. During growth of biotite, including its destructive phase, the metamorphic rocks in the biotite zone in the Pequop Mountains and in the kyanite zone in the Wood Hills (areas shown in pink and blue in Diagram 1, respectively) comprised part of the footwall of this thrust (Camilleri, 1998). Tectonic burial and thermal weakening induced Barrovian regional metamorphism and attenuation of the footwall wherein the amount of attenuation increases commensurate with the increase in overlying tectonic load and metamorphic grade (see Diagrams 1 and 2).

Diagram 1. Cross section reconstruction of the footwall of the Windermere thrust showing distribution of metamorphic facies

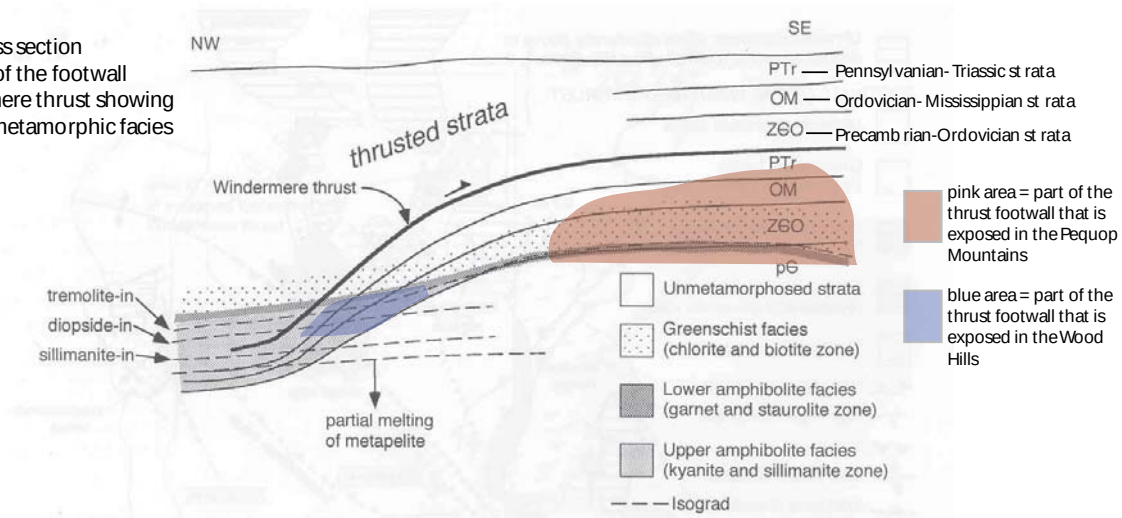
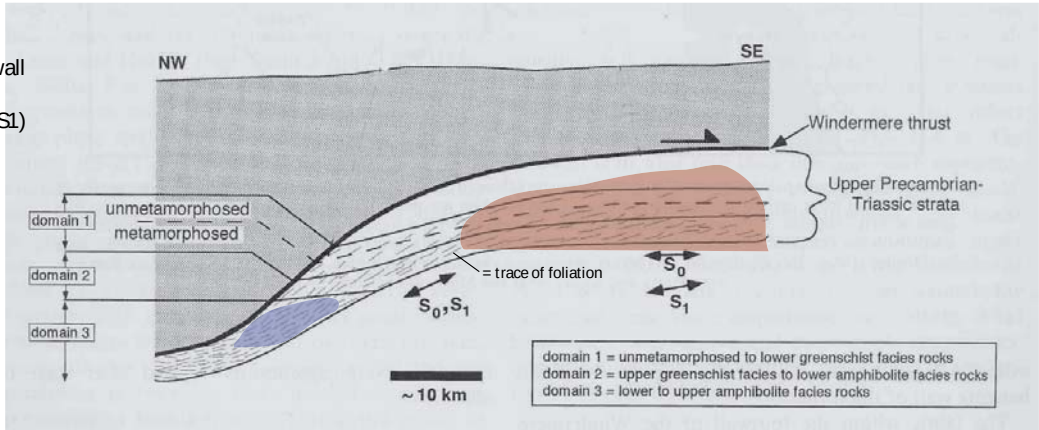


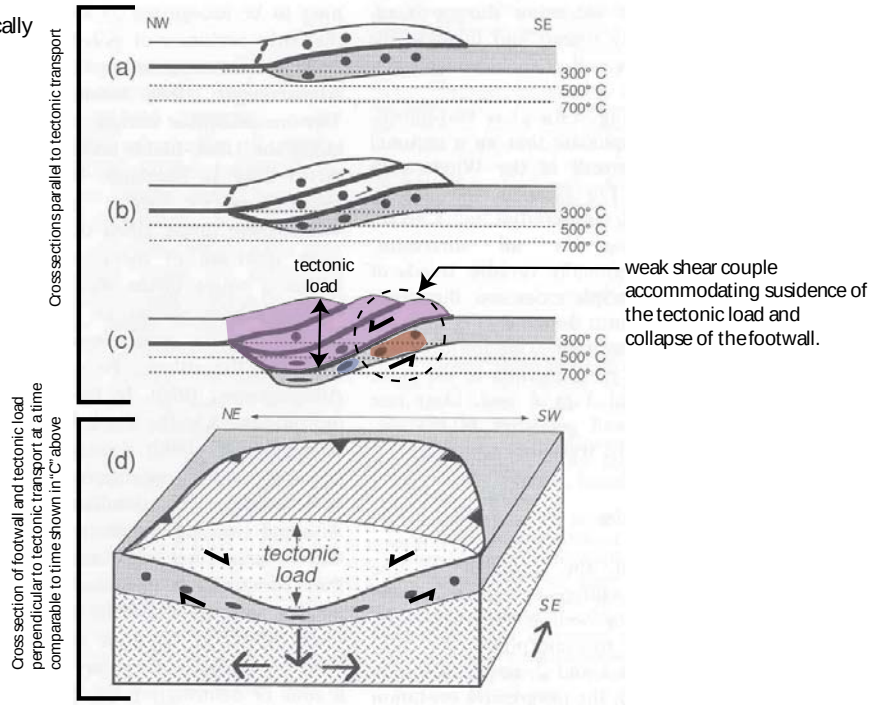
Diagram 2. Cross section reconstruction of the footwall of the Windermere thrust showing trace of foliation (S1)



The cross-sections shown in "a-d" in Diagram 3 schematically illustrate the evolution of the footwall. The cross sections in "a-c" show progressive loading, heating, and attenuation of the footwall under bulk coaxial strain wherein strain is highlighted by progressive flattening of strain ellipses. The cross section in (c) shows the footwall at the peak of metamorphism and at a time when biotite in the Pequop Mountains was likely in the destructive phase. In this scenario, the most logical origin of the top-towards-the-west non-coaxial component of shear during this time frame is that it is a product of development of a weak shear couple induced by subsidence of the tectonic load on the ductiley extending footwall (com-

pare cross sections “c” and “d” in Diagram 3 for a three-dimensional perspective of this phenomenon). This shear would have been partitioned between domains of largely coaxial deformation. Alternatively, this non-coaxial component may be localized, i.e., restricted to the Pequop Mountains, and simply reflects partitioning of a bulk coaxial strain.

Diagram 3. Cross sections in A-C schematically illustrate progressive loading, thermal weakening, and straining of the footwall of the Windermere thrust. Progressive loading occurs by emplacement of thrust sheets; cross sections are shown parallel to tectonic transport. The block diagram in D represents a cross sectional view perpendicular to tectonic transport at the same time as represented in the transport-parallel cross section shown in C.

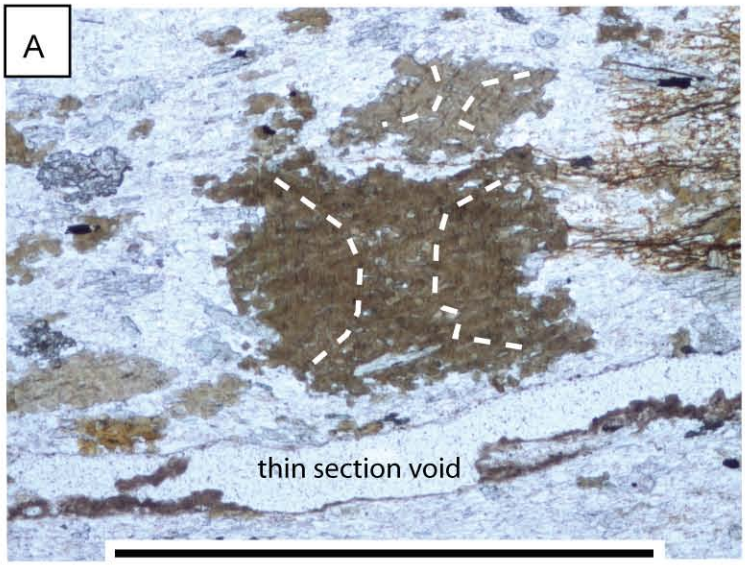


Diagrams 1-3 are modified from: Camilleri, P.A., 1998, Prograde metamorphism, strain evolution, and collapse of footwalls of thick thrust sheets: a case study from the Sevier hinterland, U.S.A.: Journal of Structural Geology, v. 20, p. 1023-1042.

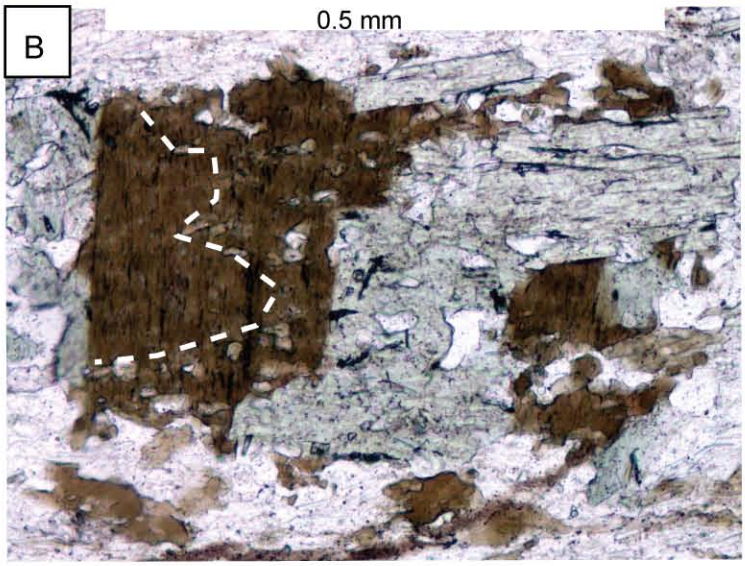
APPENDIX 6
(samples 1d, 1e, and 1f)

This suite of samples contains some biotite porphyroblasts that have been pseudomorphed by chlorite ± carbonate minerals. Chlorite does not appear to have inherited the orientation of the biotite host because replacement is characterized by laths of chlorite with a diversity of crystallographic orientations. The replacement of biotite with chlorite post-dates the biotite destructive phase because relict extension fractures are evident in the pseudomorphs. The photomicrographs in (A-B) show B2-section porphyroblasts from sample 1d. Most porphyroblasts in this sample are not pseudomorphed by chlorite (e.g., porphyroblast in photomicrograph [A]) but some have been partially pseudomorphed (e.g., porphyroblast in photomicrograph [B]). Inclusion trails in the large porphyroblast in photomicrograph (A) indicate no apparent rotation and define a crude hourglass characteristic of textural sector zoning. Although the porphyroblast in photomicrograph (B) is partially pseudomorphed by chlorite (gray), the distribution of inclusions in the remaining biotite is suggestive of a former hourglass. The photomicrographs in (C-D) show B2-section porphyroblasts from sample 1e that are completely pseudomorphed by chlorite (there is no biotite left in this sample; all biotite has been replaced by chlorite and carbonate minerals). Arrows point to locations of relict extension fractures in the precursor biotite. The morphology of the pseudomorphs and surrounding matrix in photomicrographs (C) and (D) suggest that the precursor biotite was rotated in sinistral and dextral senses, respectively. The photomicrograph in (E) shows a B2-section from sample 1f that is partially pseudomorphed by chlorite (gray to green). Crude quartz inclusions in the remaining biotite (brown) are suggestive of an hourglass that has been rotated in a sinistral sense.

(sample 1d)

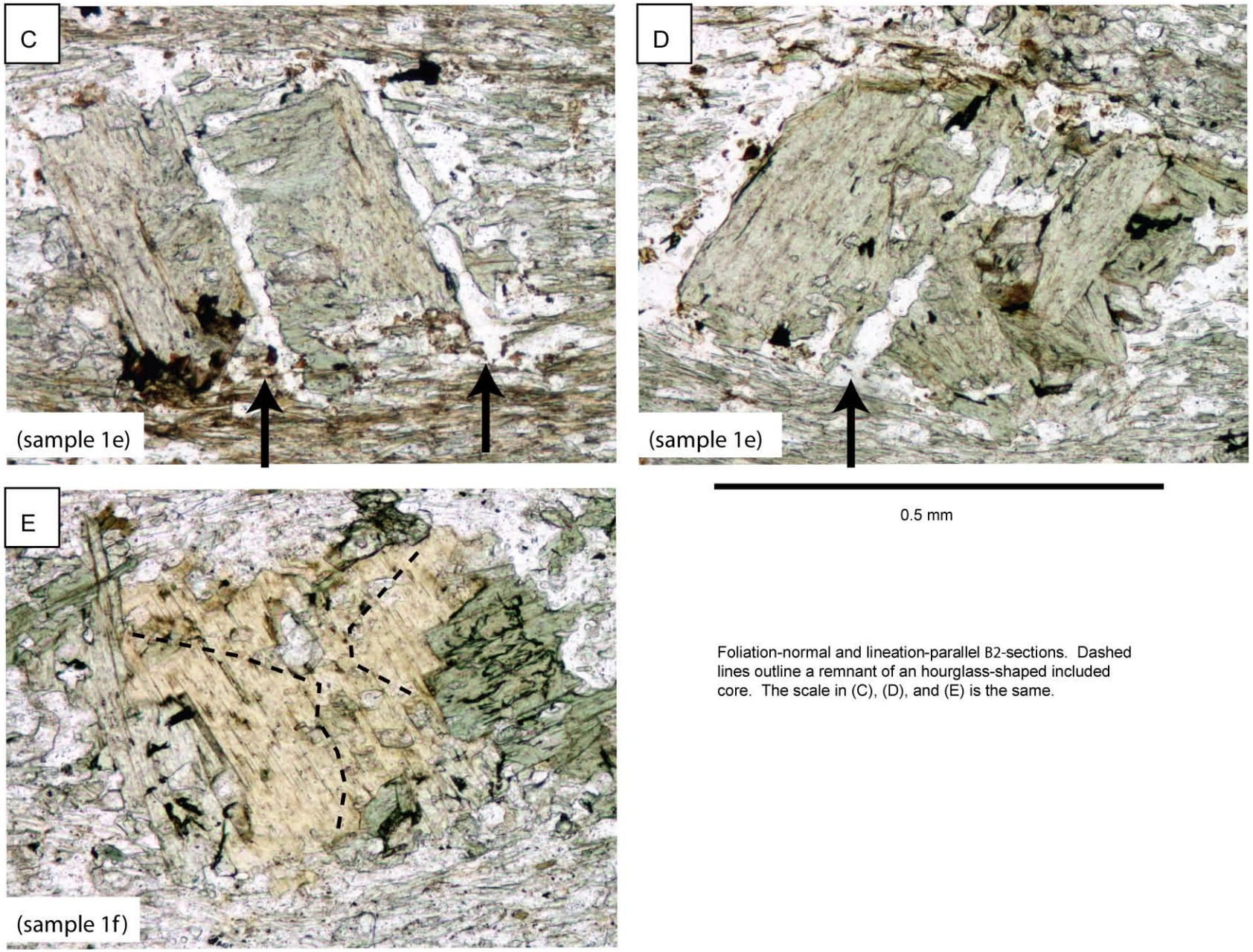


(sample 1d)



Foliation-normal and lineation-parallel B2-sections. Dashed lines outline hourglass-shaped included cores or remnants thereof.

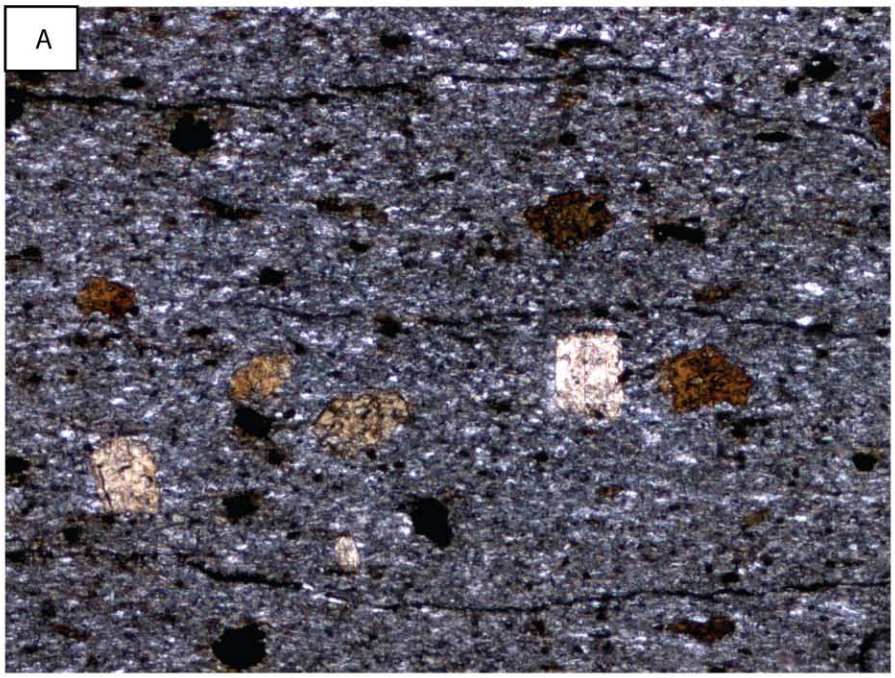
APPENDIX 6 CONTINUED
(samples 1d, 1e, and 1f)



Foliation-normal and lineation-parallel B2-sections. Dashed lines outline a remnant of an hourglass-shaped included core. The scale in (C), (D), and (E) is the same.

APPENDIX 7
(sample 2)

This sample is a phyllite with a foliation that is not as well developed as it is in other samples. The majority of porphyroblasts in this sample lack overt evidence of textural sector zoning (photomicrograph [A]). However, one grain shown in photomicrograph [B], on the basis of poorly resolved inclusions, has a subtle manifestation of zoning.



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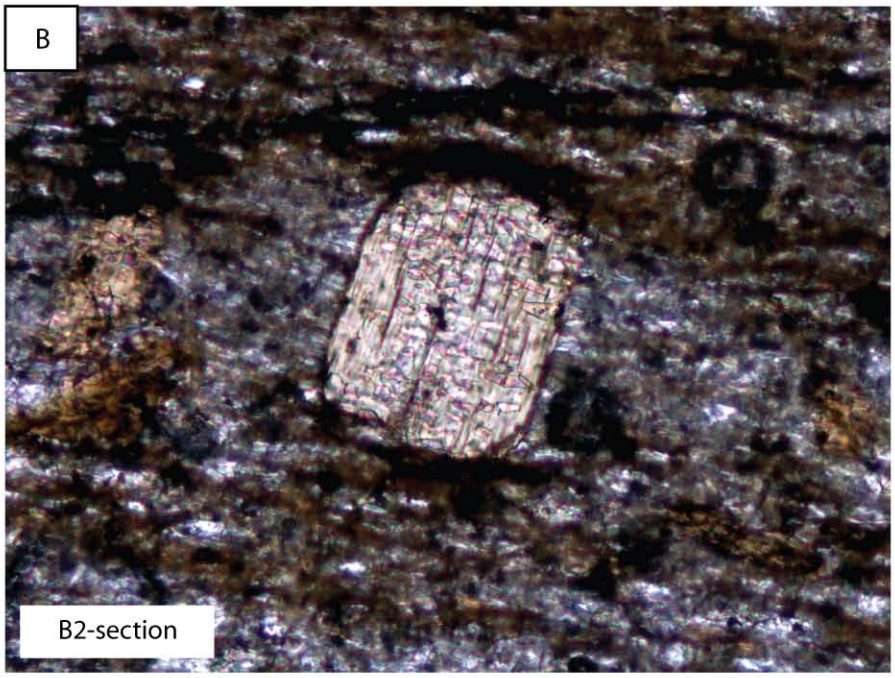
Foliation-normal, lineation-parallel sections



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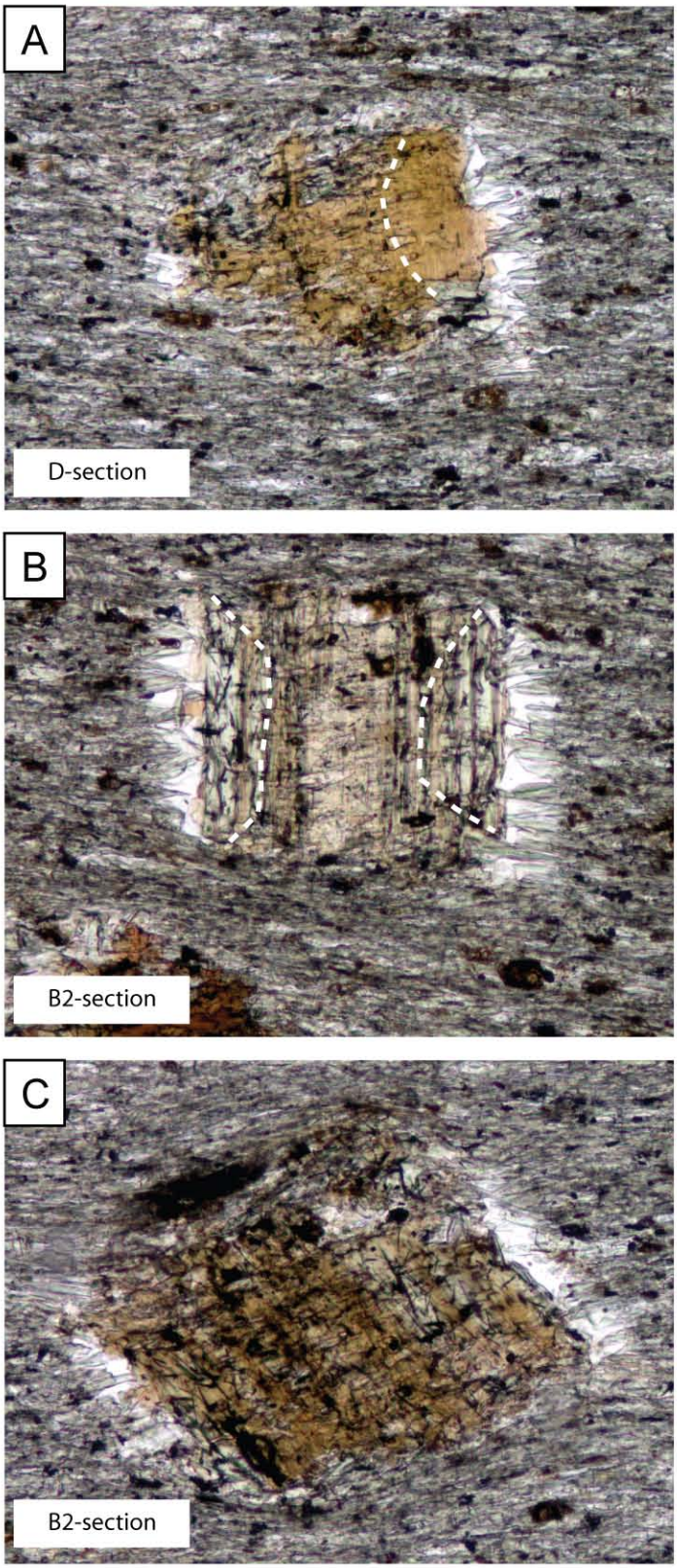
APPENDIX 8
(sample 3a)

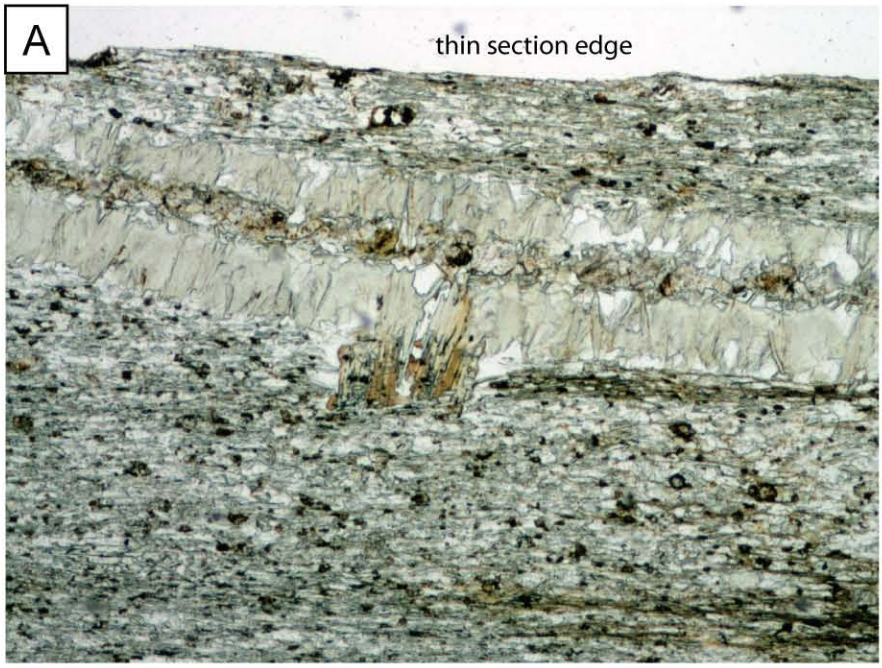


Foliation-normal, lineation-parallel sections

This sample contains texturally zoned porphyroblasts but zoning patterns tend to be subtle to completely obscured because of alternation of {001}-parallel domains of chlorite and biotite and the presence of exsolved (?) acicular, and opaque, minerals in chlorite domains. Dashed white lines denote crude clear zone boundaries. Inclusions are primarily defined by quartz but sparse graphite is also present. (A) Photomicrograph of a D-section with clear zone on the right and minor sinistral rotation. (B) Photomicrograph of a B2-section with alternating chlorite-biotite domains and no apparent rotation. Clear zones are obscured by minerals in chlorite. (C) Same description as in (B) except this porphyroblast has been rotated (sinistral sense) and either does not have clear zones or they are not resolvable because the porphyroblast has been cut very close to the edge of the crystal. Destructive phase microstructure in this sample includes weak post-zoning strain caps, strain shadows along {001} faces filled with quartz and chlorite (± sparse biotite), and rotated inclusion trails. The scale is the same in all photomicrographs.

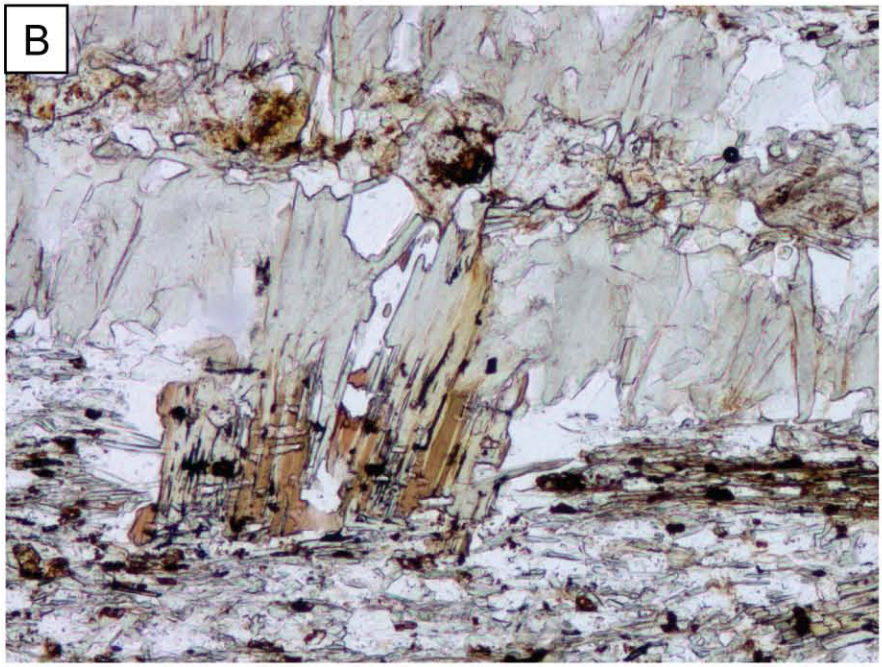
APPENDIX 9
(sample 3b)

This sample has a good example of a typical vein formed in the chlorite zone with subsequent growth of biotite in the biotite zone (see photomicrograph in [A]). The vein is an extension fracture filled with chlorite on the walls and carbonate minerals in the center. A poorly defined B2-section porphyroblast with alternating {001}-parallel domains of chlorite and biotite has overgrown the matrix and part of the vein. The photomicrograph in (B) shows an enlarged view of biotite-chlorite porphyroblast. Outside of the vein, this porphyroblast has quartz inclusions in the center with obscured clear zones on either side (similar to that shown in Appendix 8B). The porphyroblast also has an extension fracture in the center that separates the grain into two slightly misoriented halves as well as quartz-filled strain shadows on the {001} faces. These features formed in the destructive phase.



1 mm

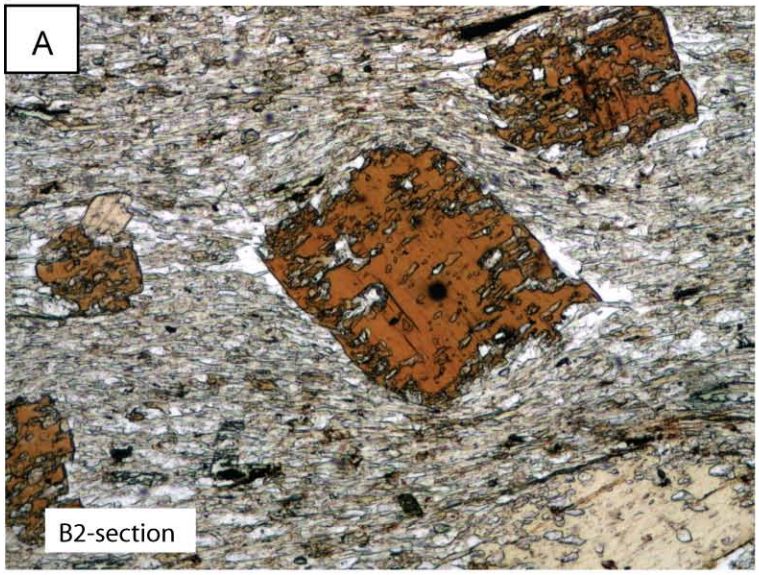
Foliation-normal, lineation-parallel sections

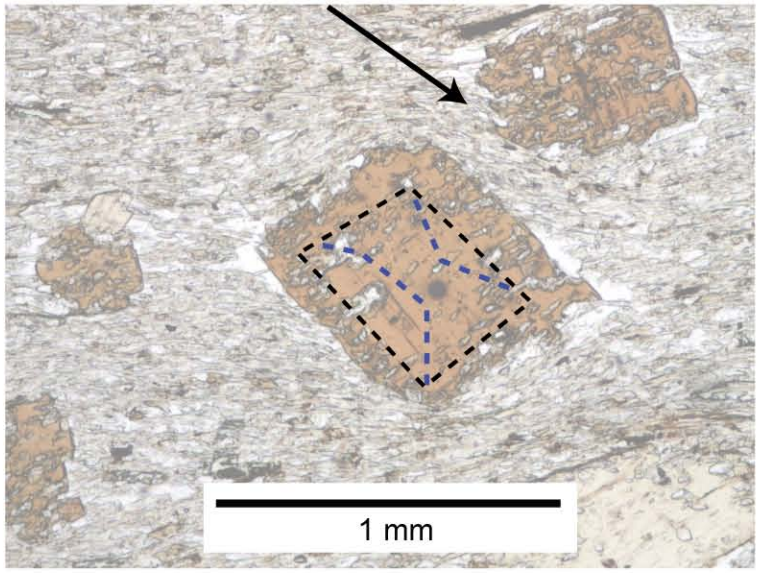


0.5 mm

APPENDIX 10
(sample 8a)

This is an example of a sample where most porphyroblasts do not exhibit overt evidence of zoning. The photomicrographs and associated line drawings in (A-C) show porphyroblasts that have poikiloblastic rims, subtle manifestations of zoning of quartz inclusions in the center, and various amounts of sinistral rotation. The porphyroblasts in (A) and (B) have small, sparse inclusions in the center that have a crude hourglass-shaped distribution, whereas the inclusions in the rim are much coarser. In addition, the porphyroblast in (B) contains two lines of quartz inclusions in the clear zones (indicated by purple lines) that are symmetric with respect to the crystal's center. These may reflect a brief cessation of TS growth due to an increase in growth rate or decrease in strain rate such that the porphyroblast overgrew foliation for a period of time before resuming TS growth. The arrow in the line drawing in (A) shows an area where a porphyroblast overgrew foliation during/following rotation (see inclusion trails and partial inclusions that curve into foliation along the grain margin).

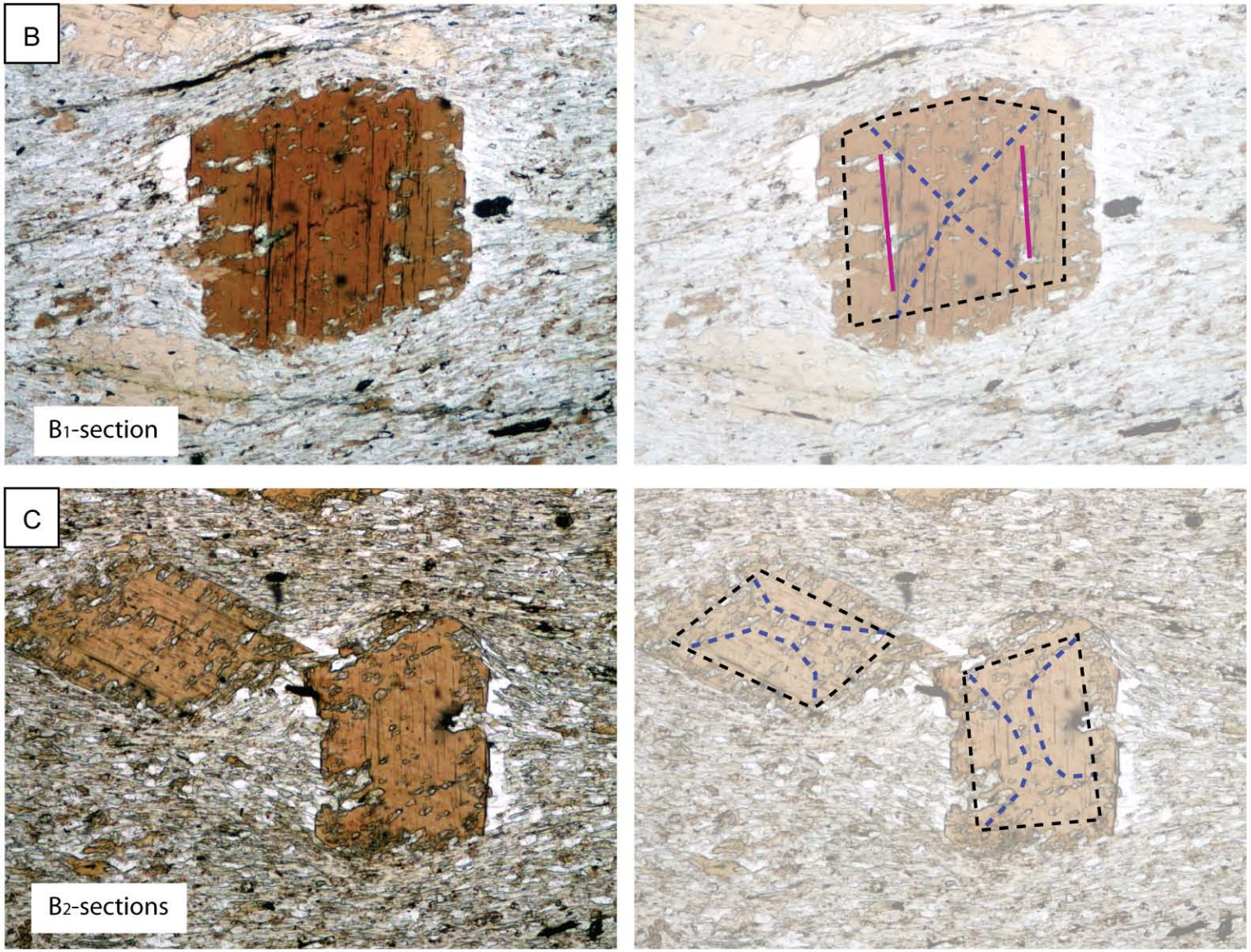




Foliation-normal and lineation-parallel section

Dashed black line outlines the zoned part of the crystal and the dashed blue line outlines a poorly defined hourglass-shaped included core.

APPENDIX 10 CONTINUED
(sample 8a)



1 mm

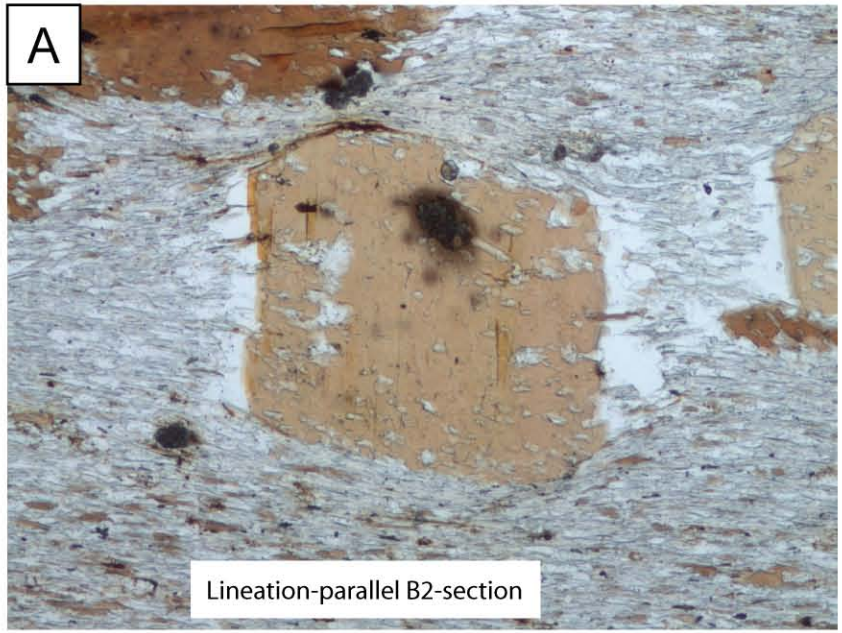
Foliation-normal and lineation-parallel sections

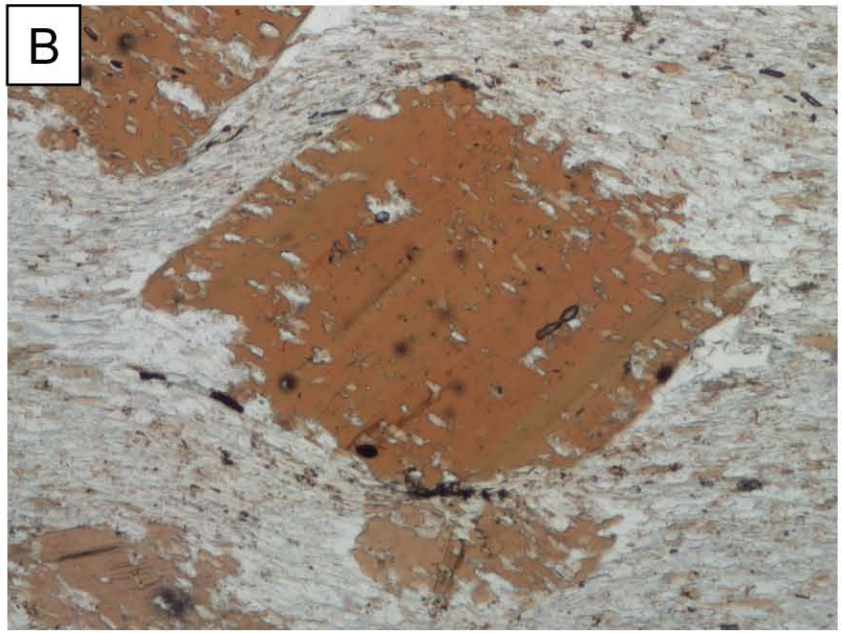
Dashed black line outlines the zoned part of the crystal and the dashed blue line outlines a poorly-defined hourglass-shaped included core. The scale in (B) is the same as in (C).

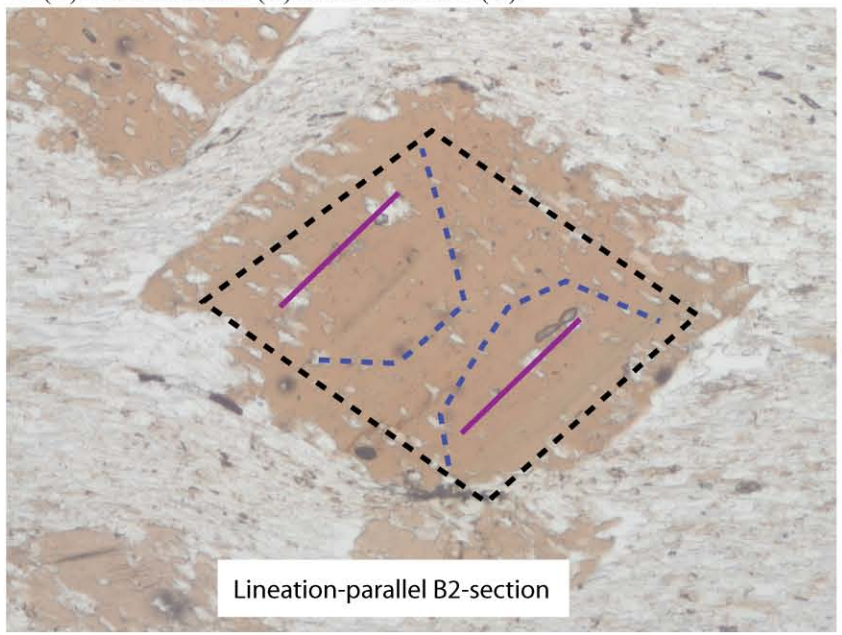
APPENDIX 11
(sample 8b)

Porphyroblasts in this sample do not appear to be zoned at first glance. What is most apparent about inclusions in these crystals is that their rims have a higher density of inclusions (i.e., poikiloblastic) in comparison to the central parts. However, the distribution of inclusions in the center of the crystals in photomicrographs (B-D) may reflect crude zoning. Overall, it is likely that this sample did not have the right composition and appropriate strain vs. growth rate to leave an overt zoning pattern.

The porphyroblast in (A) does not exhibit any definitive zoning patterns. Dark area in top of crystal is an allanite grain with a pleochroic halo. The line drawings of porphyroblasts in (B-C) illustrate possible zoning features inside the poikiloblastic rim. In addition, the porphyroblast in (B) contains two lines of quartz inclusions in the clear zones (indicated by purple lines) that are symmetric with respect to the crystal's center (i.e., similar to that described in Appendix 10 for sample 8a). These may reflect a brief cessation of TS growth due to an increase in growth rate or decrease in strain rate such that the porphyroblast overgrew foliation for a period of time before resuming TS growth. Porphyroblasts in (B-D) exhibit various amounts of dextral rotation. Dashed black lines outline the zoned parts of the crystals and dashed blue lines highlight zoning patterns. The scale (A) is the same as in (B) and the scale in (C) is the same as in (D).



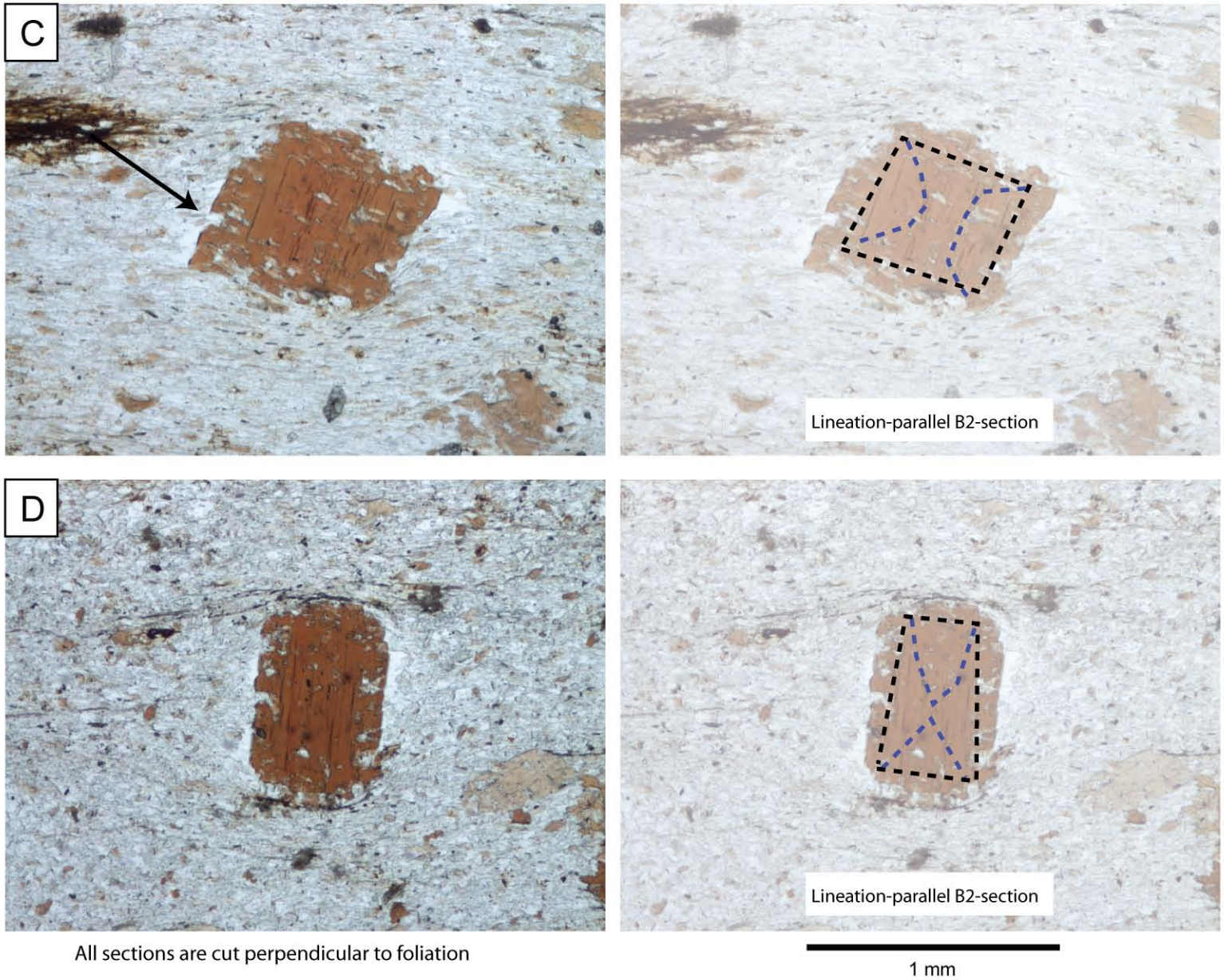




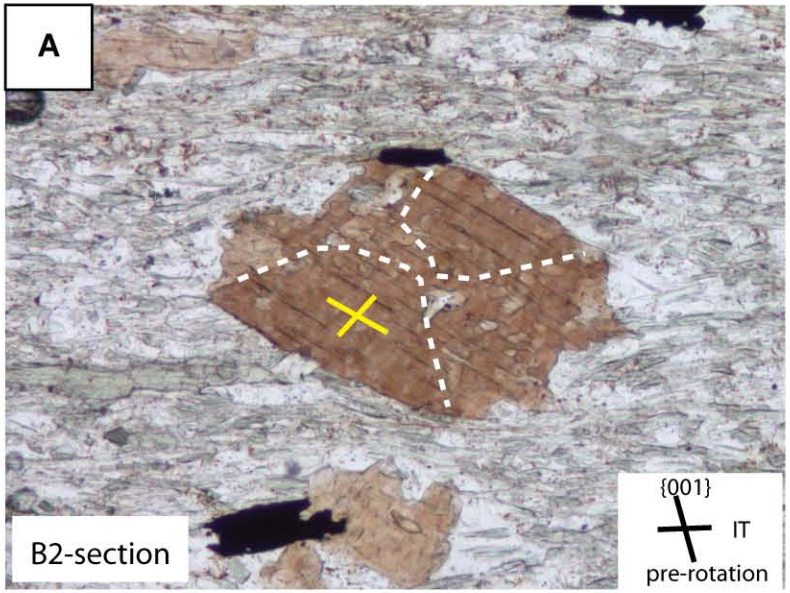
1 mm

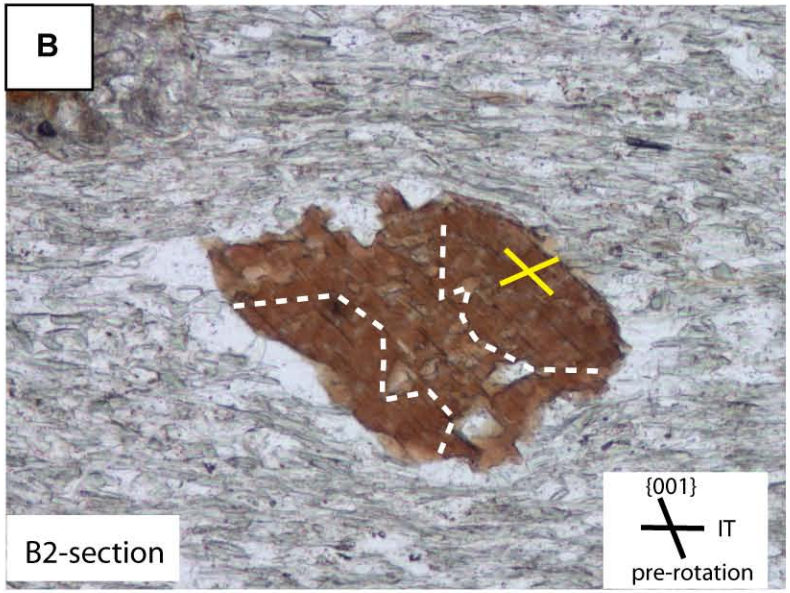
All sections are cut perpendicular to foliation

APPENDIX 11 CONTINUED
(sample 8b)

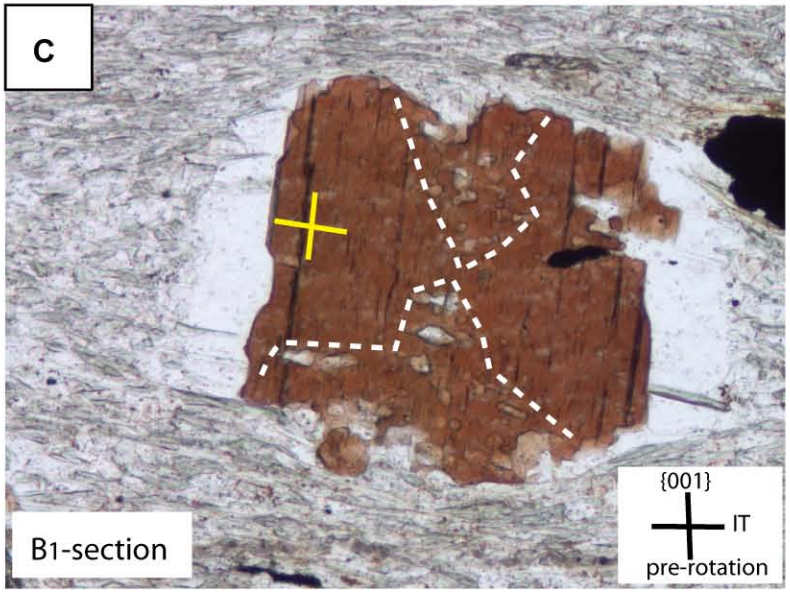


APPENDIX 12
(sample 10)





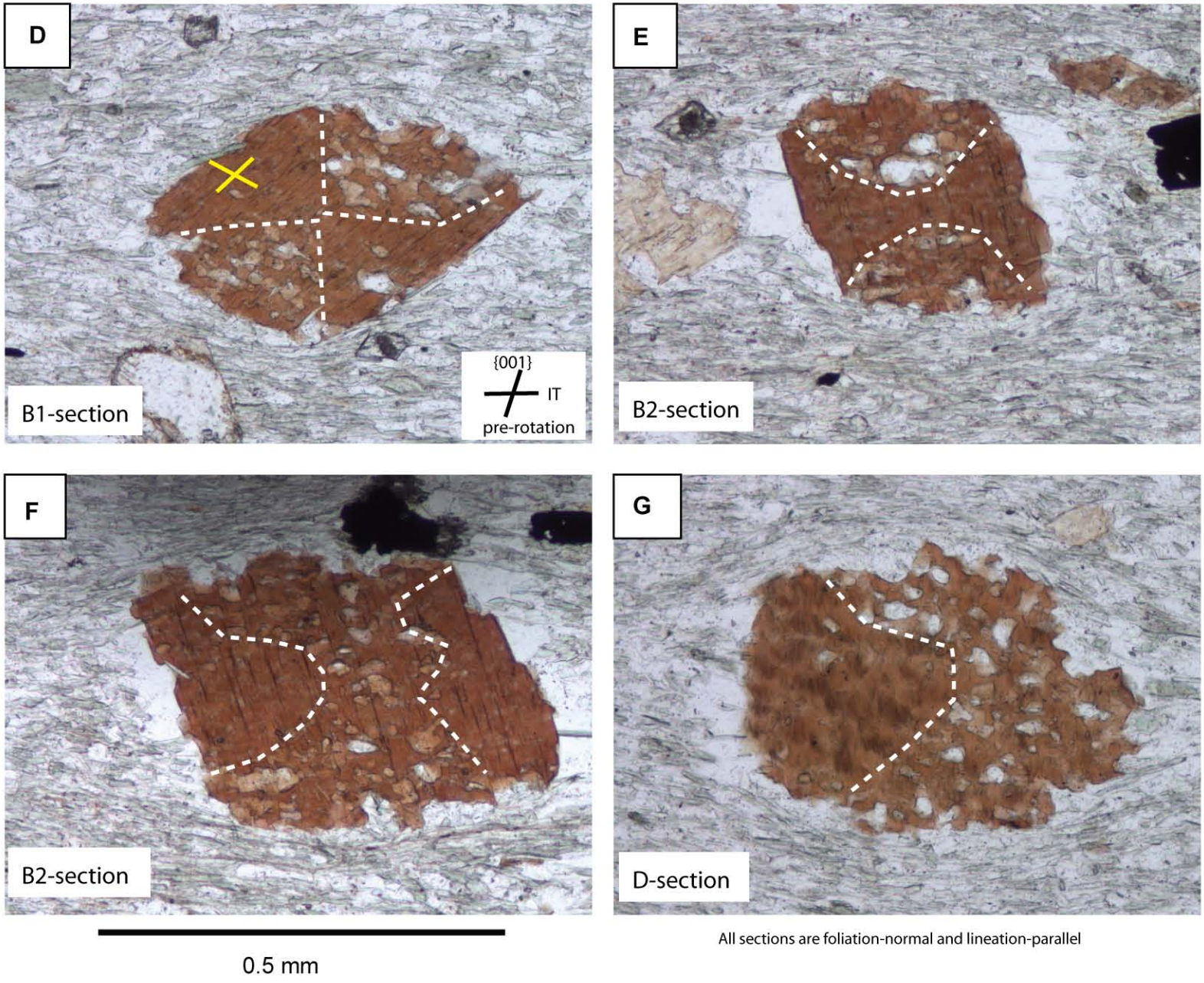
0.5 mm



All sections are foliation-normal and lineation-parallel

This sample contains porphyroblasts that exhibit subtle zoning and lack a poikiloblastic rim. Zoning is defined by sparse quartz inclusions. All photomicrographs are foliation-normal and parallel to a faint lineation. Porphyroblasts in (A) and (B) have a sinistral sense of rotation; (C) and (D) a dextral sense; (E) and (G) no apparent rotation. Dashed white lines highlight zoning patterns. Yellow lines in the clear zones in (A-D) represent the traces of {001} and inclusion trails in the hourglass. These traces are also shown in the lower right corner in their pre-rotation positions where IT = inclusion trails. The scale is the same for all photomicrographs.

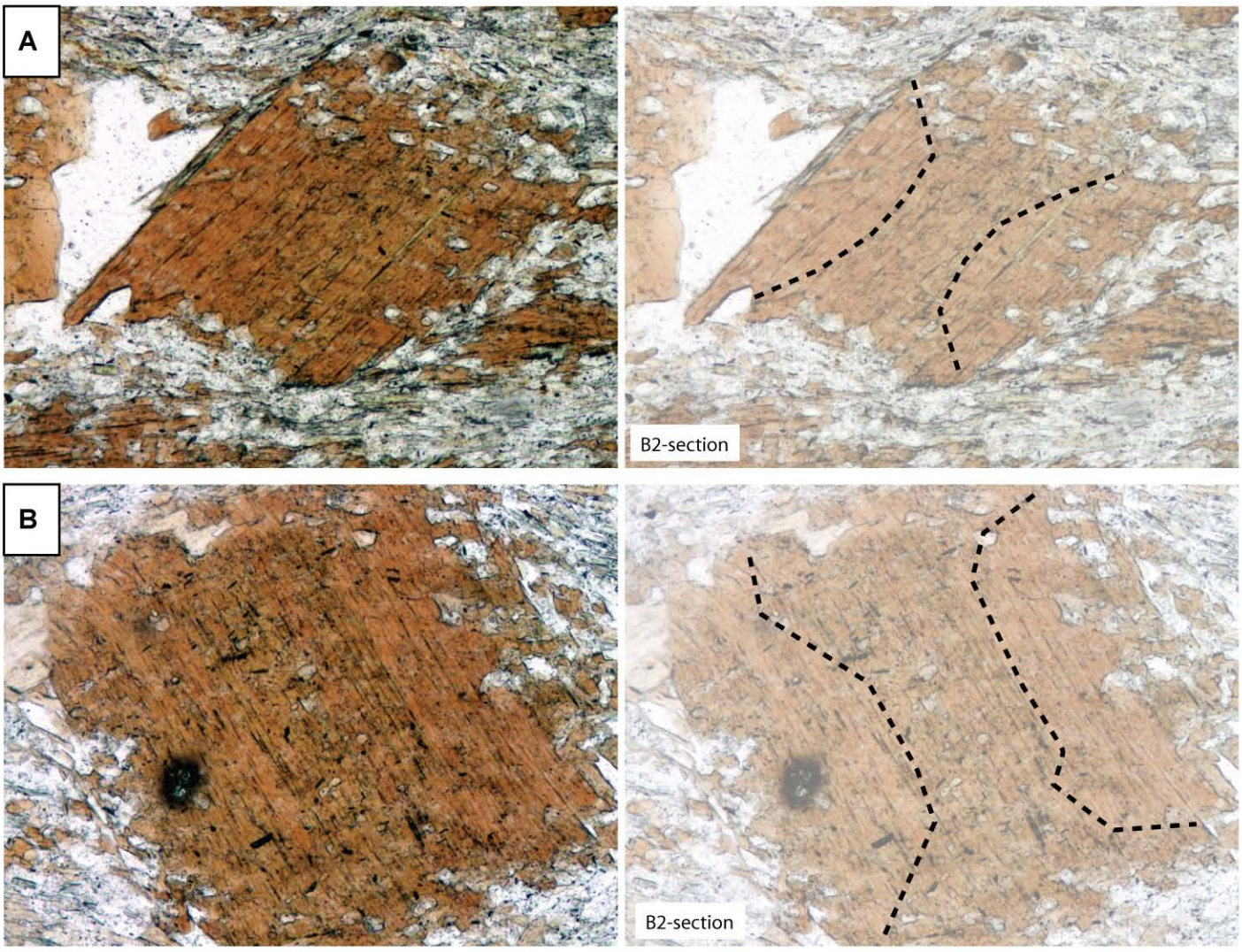
APPENDIX 12 CONTINUED
(sample 10)



All sections are foliation-normal and lineation-parallel

APPENDIX 13
(sample 11a)

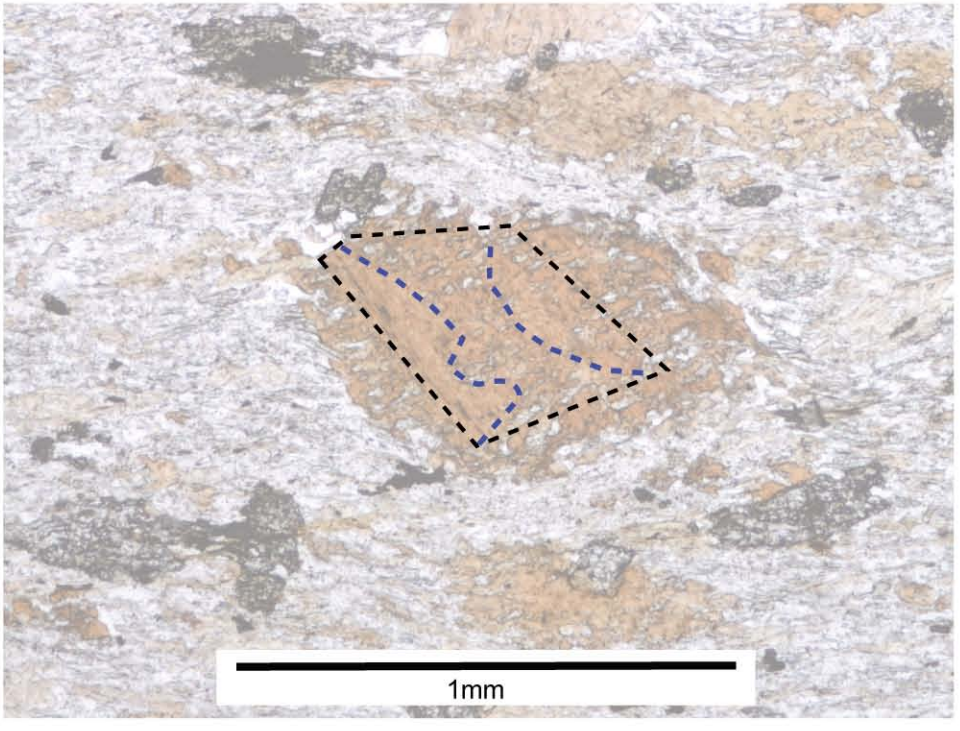
The porphyroblasts in this sample exhibit very crude zoning defined by sparse inclusions that include quartz and graphite. Although inclusion trails are poorly defined, it is the greater density and distribution of inclusions that define the hourglass shape in the central part of the crystal. The porphyroblasts in (A) and (B) exhibit dextral and sinistral senses of rotation, respecitvely. Some of the rotation occurred during textural sector growth as indicated by the curvature of inclusion trails in the clear zones. Dashed black lines in the line drawings denote the shape of included hourglass. The scale in (A) and (B) is the same.



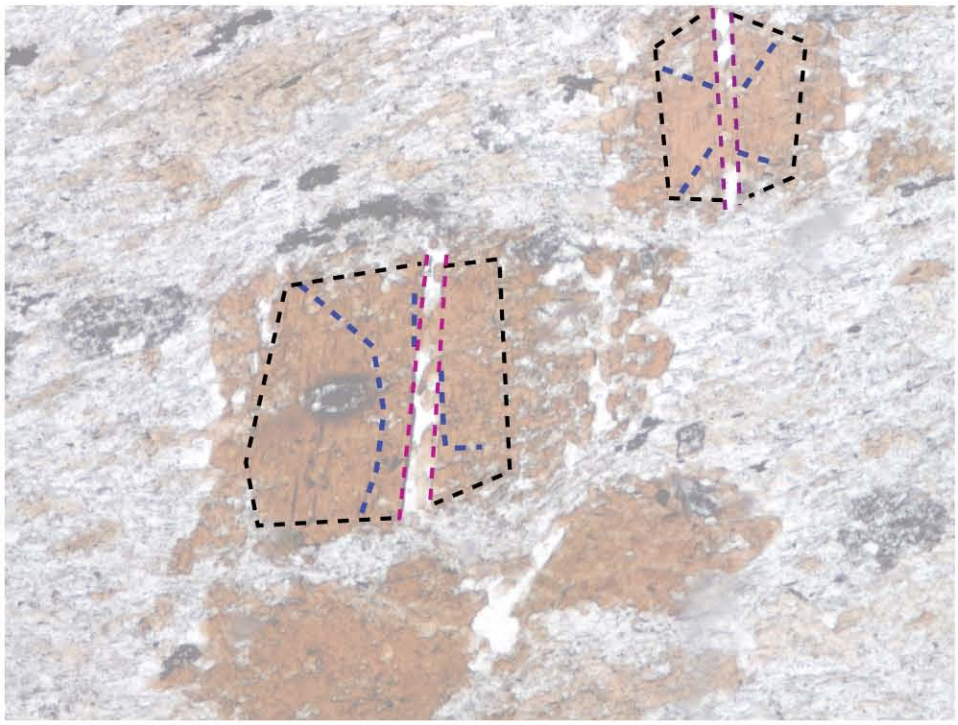
Foliation-normal, lineation-parallel sections

APPENDIX 14
(sample 11b)

Porphyroblasts in this sample have poorly defined zoning patterns and wide poikiloblastic rims. Dashed black lines in the line drawings outline the zoned parts of crystals and dashed blue lines outline the included hourglass. Both porphyroblasts highlighted in (B) have an extension fracture in the center filled with biotite and quartz, which almost completely obscures the zoning patterns. The extension fractures are outlined by dashed purple lines. The large porphyroblast in (B) has an allanite grain rimmed by zoisite on the left (it looks like an eye). These epidote minerals are also present in the matrix in (A) and (B).

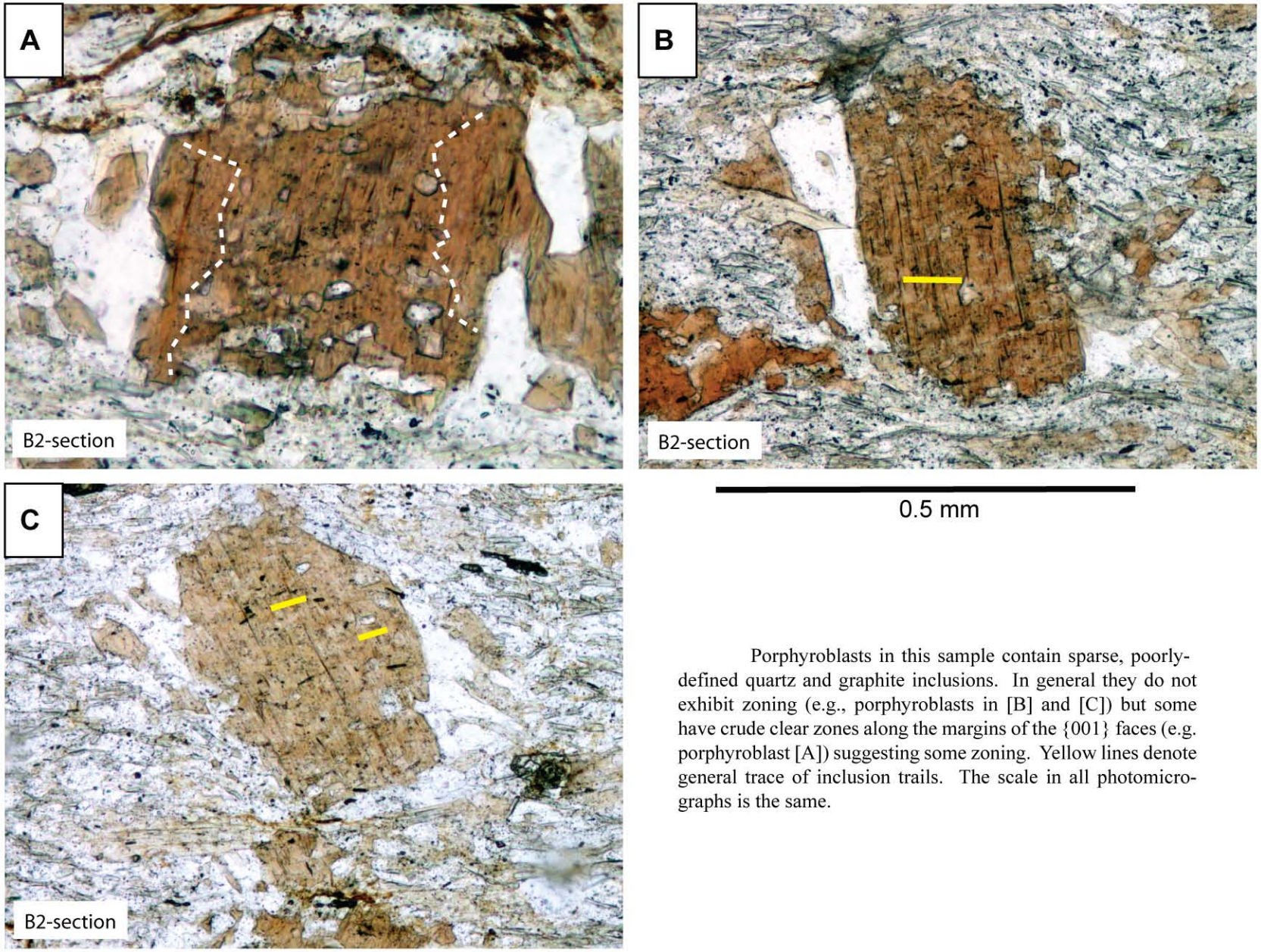


APPENDIX 14 CONTINUED
(sample 11b)



1mm

APPENDIX 15
(sample 12a)

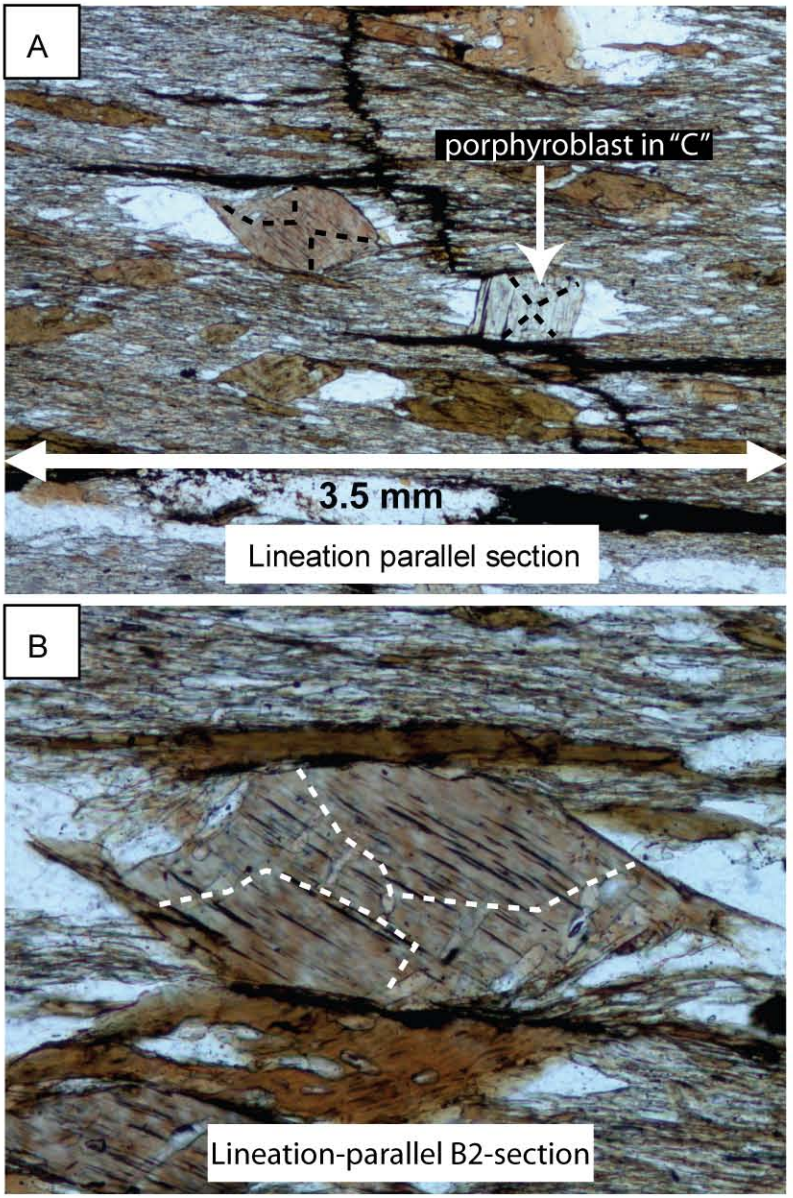


Foliation-normal, lineation-parallel sections

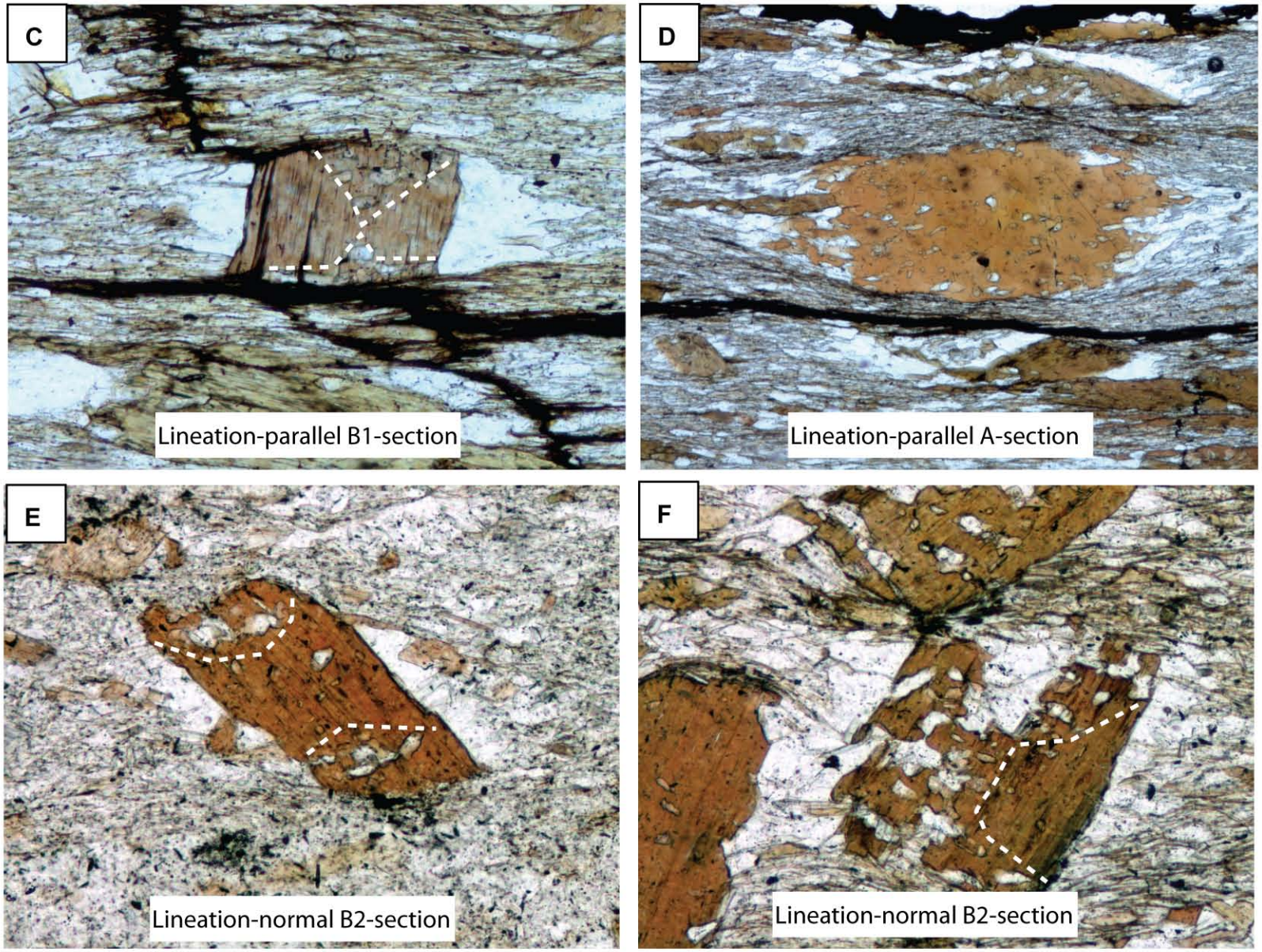
Porphyroblasts in this sample contain sparse, poorly-defined quartz and graphite inclusions. In general they do not exhibit zoning (e.g., porphyroblasts in [B] and [C]) but some have crude clear zones along the margins of the {001} faces (e.g. porphyroblast [A]) suggesting some zoning. Yellow lines denote general trace of inclusion trails. The scale in all photomicrographs is the same.

APPENDIX 16
(sample 12b)

This sample contains porphyroblasts with crude zoning patterns defined by sparse quartz inclusions. All photomicrographs shown are from foliation-normal thin sections. This sample appears to have sustained more strain than most samples during the destructive phase, which resulted in rotation and production of well-developed strain caps that likely involved dissolution of biotite on grain margins parallel to foliation and re-precipitation in strain shadows (e.g., see well-developed strain caps and growth prongs paralleling foliation in the strain shadows in the porphyroblast shown in [D]). In a lineation-parallel thin section, the B-sections exhibit 0 (photomicrograph [C]) to as much as 45 degrees of apparent rotation (photomicrograph [B]) whereas A-sections commonly exhibit little or no rotation (photomicrograph [D]). However, the A-sections viewed in the lineation-parallel thin section appear as B-sections in a lineation-normal thin section, which do actually exhibit rotation (see photomicrographs [E] and [F]). The reason that the corresponding A-sections in the lineation-parallel thin section do not exhibit much rotation is because the apparent dip of rotated inclusion trails in these grains is zero parallel to lineation, i.e., these biotite grains experience rotation in and out of the plane of the lineation-parallel thin section. This implies that although there is little or no apparent rotation of A-sections parallel to lineation there may have been rotation in and out of the plane of the thin section. The lineation-normal B-sections in (E) and (F) show sinistral and dextral senses of rotation, respectively. Dashed lines outline included hourglasses. The photomicrographs in (B-F) are the same scale.



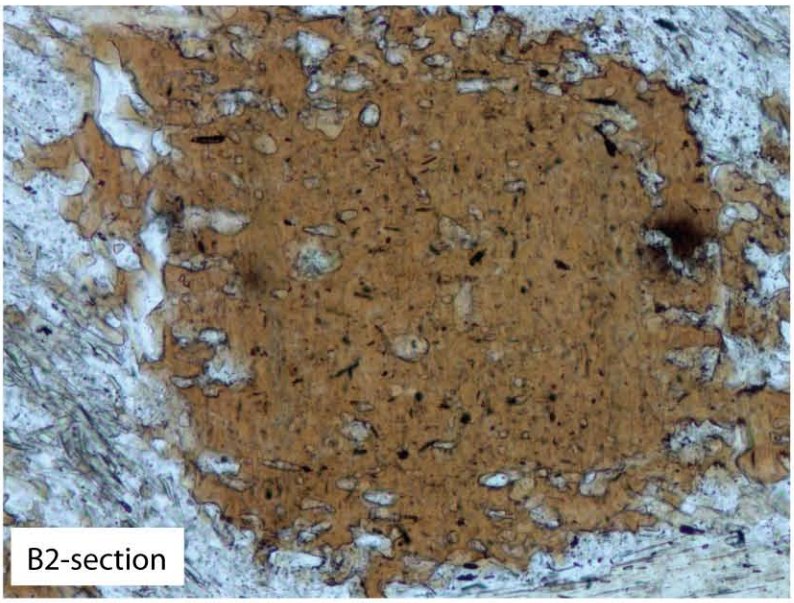
APPENDIX 16 CONTINUED
(sample 12b)



0.5 mm

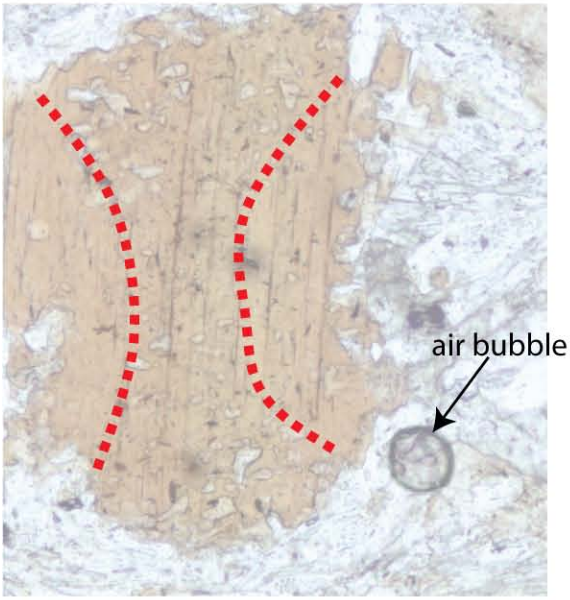
APPENDIX 17
(sample 12c)

no overt zoning



This sample has porphyroblasts that exhibit no zoning or very crude zoning of quartz inclusions in the central part of the crystal. Dashed red lines denote shape of included hourglass. The scale in all photomicrographs is the same.

subtle zoning

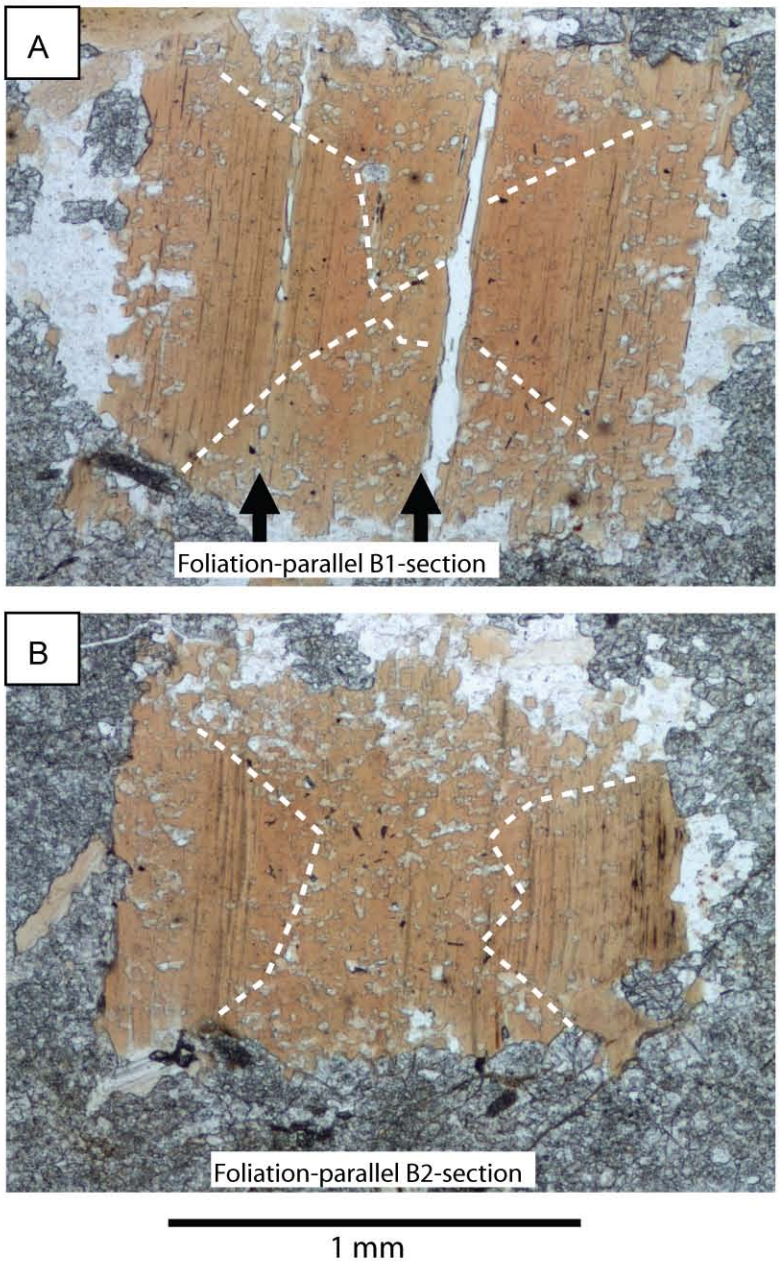


0.5 mm

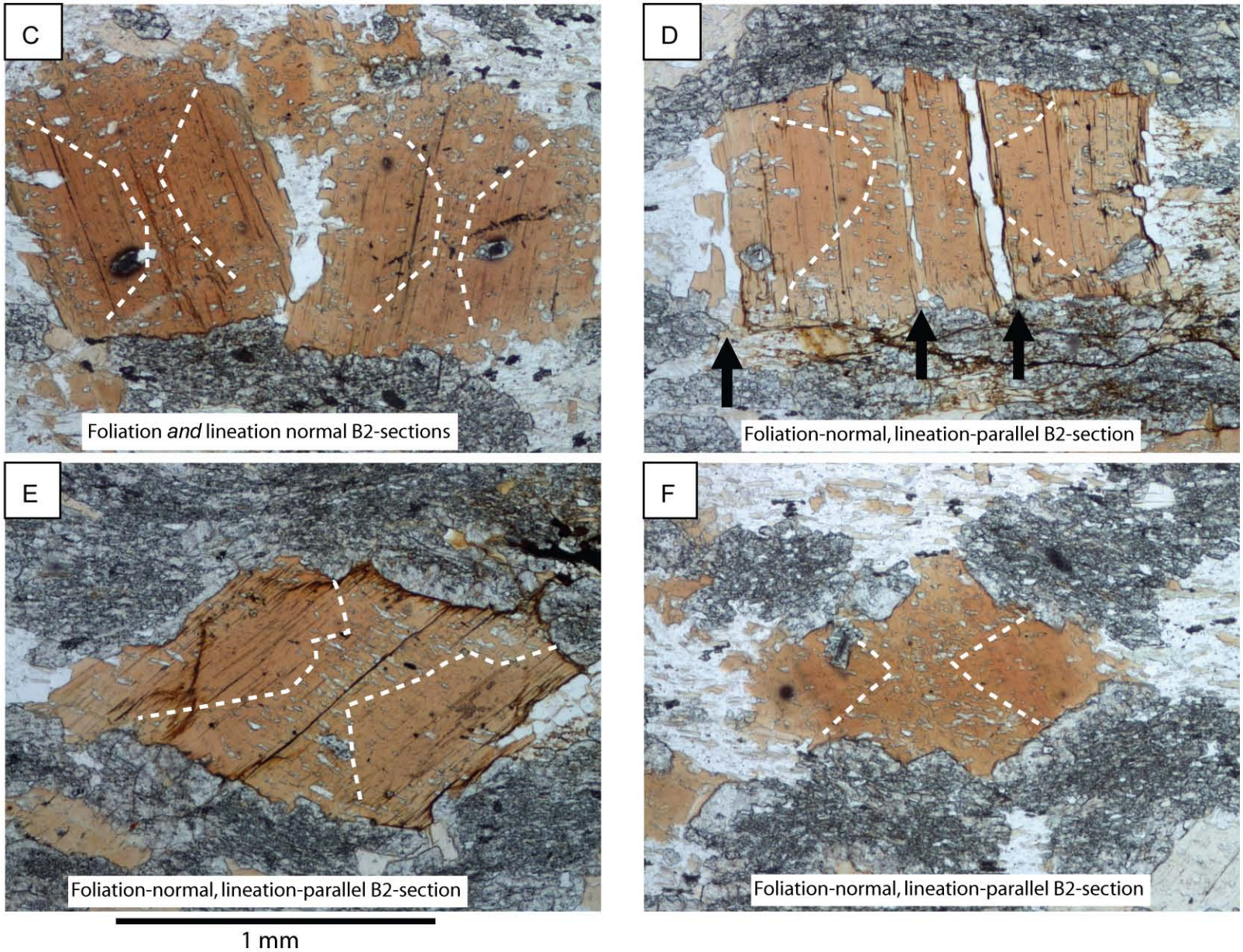
Foliation-normal, lineation-parallel sections

APPENDIX 18
(sample 13a)

This sample is unusual in that biotite is variably replaced by epidote (dark gray mineral surrounding biotite). Replacement post-dates the biotite constructive and destructive phases and has produced scalloped margins on biotite as well as sparse growth of epidote inside biotite (see photomicrographs in [C-F]). Some of the epidote in biotite has an allanitic core (= dark area ± a pleochroic halo). Despite the epidote, porphyroblasts in this sample display overt zoning in all thin section orientations (see photomicrographs in [A-F]). In addition, many porphyroblasts have vestiges of a poikiloblastic rim. Zoning is more subtle in the foliation-parallel (A-B) and foliation-and-lineation-normal (C) sections than in the foliation-normal, lineation-parallel sections (D-F). The lineation-normal photomicrograph in (C) shows two separate B2-sections that have been rotated in opposing directions. The photomicrograph in (F) shows that despite replacement of a significant portion of the porphyroblast with epidote, a crude hourglass is evident in center of the biotite grain. Arrows indicate extension fractures filled with biotite and quartz. Dashed white lines outline the included hourglass in each porphyroblast. The scale in all photomicrographs is the same.

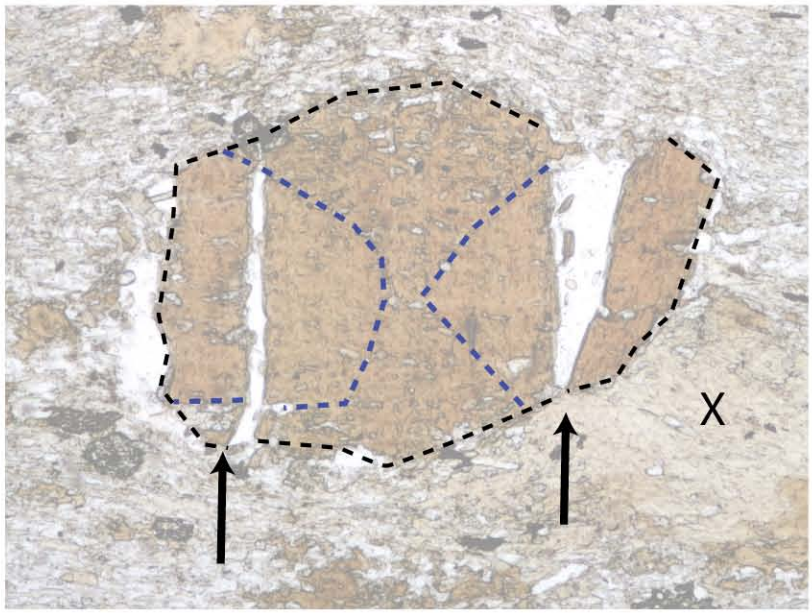


APPENDIX 18 CONTINUED
(sample 13a)



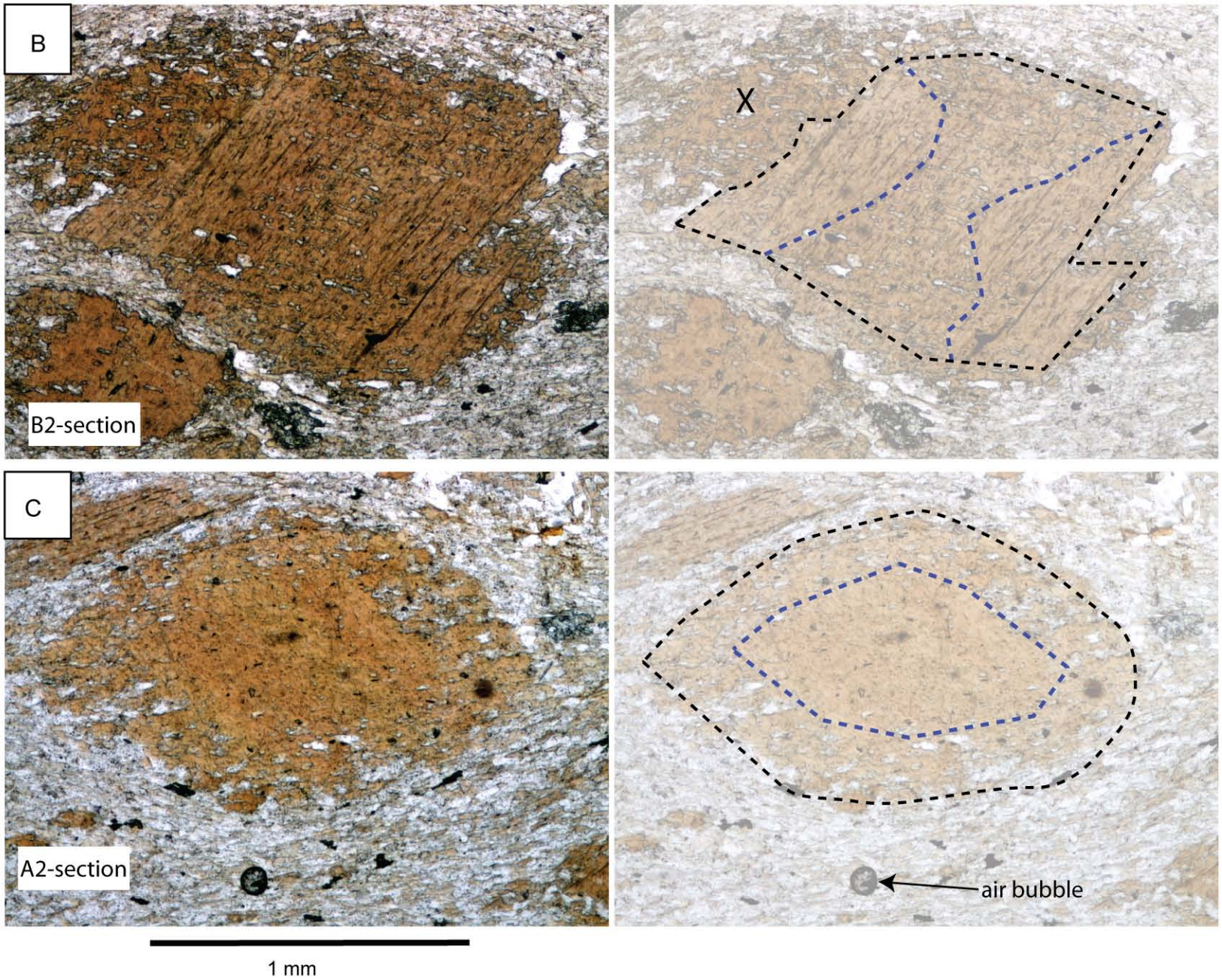
APPENDIX 19
(sample 15b)

Porphyroblasts in this sample have quartz inclusions and they exhibit overt textural sector zoning. Dashed black lines outline the zoned parts of the crystals and dashed blue lines highlight zoning patterns. The "X's" in the photomicrographs in (A) and (B) lie on top of biotite porphyroblasts that share a grain boundary with the outlined porphyroblasts. Arrows indicate locations of extension fractures. The scale is the same in all photomicrographs.



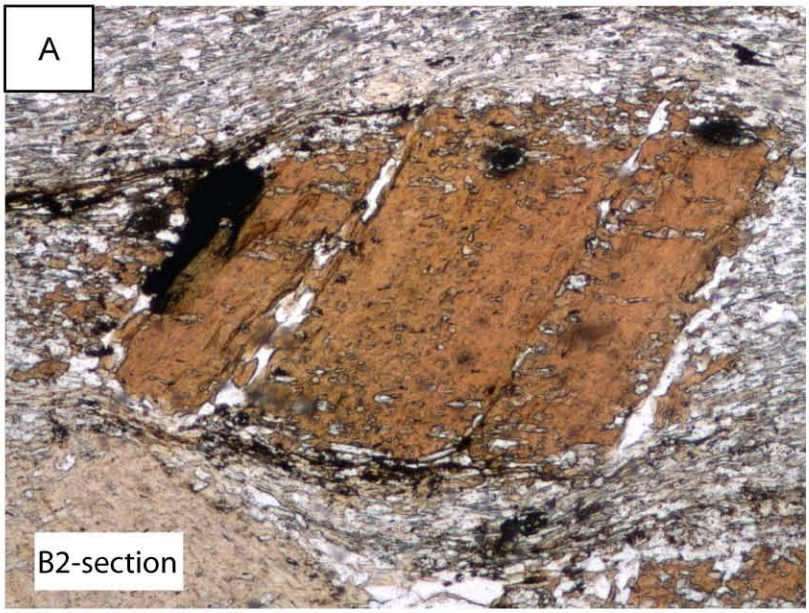
1 mm

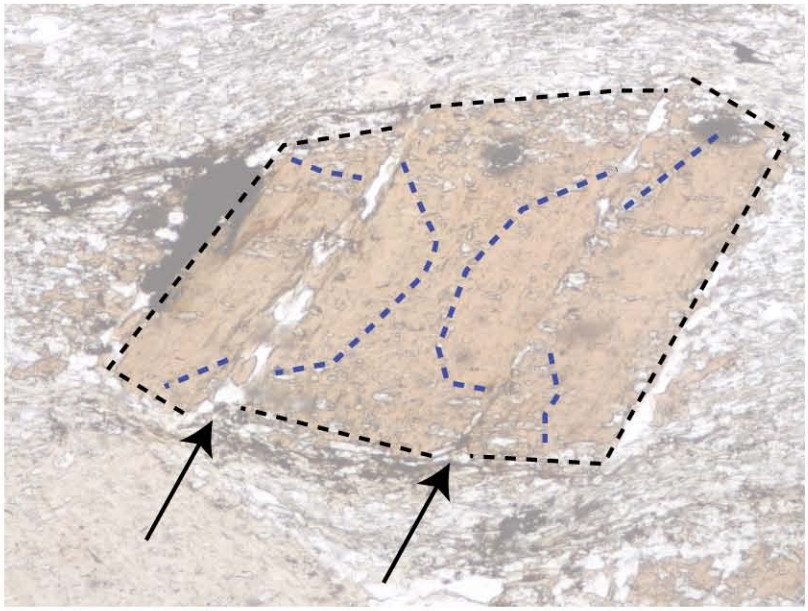
APPENDIX 19 CONTINUED
(sample 15b)



APPENDIX 20
(sample 16b)

Porphyroblasts in this sample have quartz inclusions and they exhibit overt textural sector zoning. The porphyroblasts in (A) and (B) have extension fractures that appear to have been localized along an area in the clear zones that has abundant quartz inclusions. Prior to fracturing these porphyroblasts may have looked like those in photomicrograph "B" of Appendices 10 and 11 wherein the purple lines in these photomicrographs denote the location of a concentration of quartz inclusions in the clear zones that are symmetric with respect to the crystal's center, which may reflect a brief cessation of TS growth due to an increase in growth rate or decrease in strain rate such that the porphyroblast overgrew foliation for a period of time before resuming textural sector growth. Nonetheless, these types of zones are a structural anisotropy that may have localized tensile stress in the porphyroblasts shown in (A) and (B) during the destructive phase, which ultimately resulted in development of an extension fracture. Dashed black lines outline the zoned parts of the crystals and dashed blue lines highlight zoning patterns. The scale in all photomicrographs is the same.





1 mm

Foliation-normal, lineation-parallel sections

APPENDIX 20 CONTINUED
(sample 16b)