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Classification, Character, and Origin of Textural Zoning in Porphyroblasts: Significance and Relation to Strain

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Abstract—Texturally unzoned porphyroblasts have received considerable attention because their continuity of passive inclusions has utility in assessing strain history in an orogen. In contrast, texturally-zoned porphyroblasts, whose inclusions lack continuity, have received little attention and hence are poorly understood. In light of this, this study presents the first classification scheme for texturally-zoned porphyroblasts coupled with assessment of their origin and geometry, and finds that they form for myriad reasons, but are equally important for assessing growth and strain history in an orogen. Texturally-zoned porphyroblasts can be classified as texturally-sector- or non-sector zoned. Each type has subtypes wherein zoning may be strain induced, require the absence of strain, or develop irrespective of strain. Texturally sector-zoned porphyroblasts contain a crystallographically-controlled distribution of inclusions concentrated along growth sector boundaries (sector-boundary zoning) or in specific growth sectors (sector-hourglass zoning). Most sector-boundary zoned minerals such as chiastolite, garnet, and staurolite form in an environment that lacks strain. Sector-hourglass zoning occurs in chloritoid, biotite, and staurolite. Chloritoid develops sector-hour glass zoning irrespective of strain, but biotite requires strain. Non-sector zoning can occur in any mineral species and is characterized by inclusion-free or –poor zones that transect growth sector boundaries. Non-sector zoning includes concentric and replacement zoning that can develop with or without strain, as well as fracture-fill zoning, which requires strain to develop. Despite the lack of continuity of inclusions, the presence of textural zoning may be important because recognition of a particular zoning subtype may suggest the presence or absence of strain during porphyroblast growth.

Introduction

Large metamorphic minerals (e.g., porphyroblasts such as biotite, garnet, andalusite and staurolite) that contain passive inclusions are extraordinarily important because they are utilized in assessing the tectonic, metamorphic, and structural history of the mid- to deep-crustal levels of orogenic belts. In studies of exhumed metamorphic terrains, it is the nature and geometry of the inclusions in these porphyroblasts that allows assessment of whether or not the growth of the mineral was accompanied by strain (e.g., Passchier and Trouw, 2005, and references therein). This assessment, in turn, when coupled with thermobarometric and thermochronologic data, can be utilized to document the tectonic history of an orogen including inferring the timing and origin of metamorphism and structural features associated with tectonic burial and or exhumation of metamorphic terrains (e.g., Johnson, 1999, and references therein).

Much attention has focused on passive inclusions in porphyroblasts that are texturally unzoned; these porphyroblasts contain a relatively continuous distribution of passive inclusion trails (see diagram in Fig. 1a and photos in Fig. 2a, 2c, 2e and 2g for examples). The passive inclusion trails in these porphyroblasts represent matrix material that is not part of the porphyroblast forming reaction or that is an excess reactant. More importantly, however, the inclusions generally preserve a record of the matrix fabric and the presence or absence of strain during growth (Passchier and Trouw, 2005). Hence, texturally unzoned porphyroblasts have been the subject of much study because of their utility in assessing the strain and tectonic history of an orogen (Johnson, 1999; Passchier and Trouw, 2005, and references therein). In contrast, texturally zoned porphyroblasts, whose passive inclusions lack continuity (Figs. 1b, 2b, 2, 2f and 2h), are often overlooked because the lack of continuity of inclusion trails can hinder interpretation of the relation of growth to strain. Consequently, texturally zoned porphyroblasts have received limited study and are not well understood, but are probably equally important in deciphering protracted growth and strain histories (Rice and Mitchell, 1991; Rice et al., 2006). Currently there are many observations, and a few focused studies, of texturally zoned porphyroblasts, but they are distributed in diverse references and consequently there is no comprehensive assessment or synthesis of this phenomenon. In light of this, this paper brings together this information and synthesizes the patterns, origin, and strain significance of different types of textural zoning, as well as presents the first-ever classification scheme for texturally zoned porphyroblasts (Fig. 1b). This study also highlights areas where further research is needed to understand the origin of certain types of zoning.

Classification and character of texturally zoned porphyroblasts

A texturally zoned porphyroblast is herein defined as any porphyroblast that contains included and relatively clear, inclusion free (or poor) zones (Fig. 1b). Assessment of a diversity of texturally zoned porphyroblasts reveals that they can be broadly classified as either texturally sector zoned or

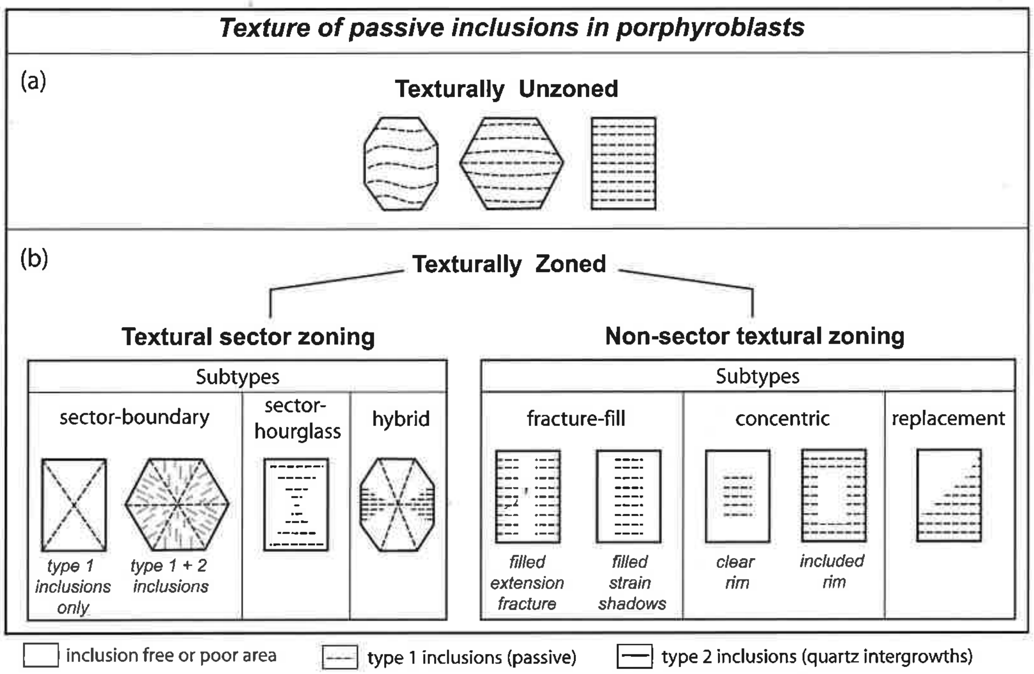

FIG. 1a-1b. Diagrams comparing two-dimensional cuts through texturally unzoned and zoned porphyroblasts. (a) Diagram showing texturally unzoned porphyroblasts whose inclusions are continuous. (b) Diagram showing texturally zoned porphyroblasts whose inclusions lack continuity. Sketch of sector-boundary zoned porphyroblast with type 1 and type 2 inclusions in lower-left corner is based on garnet from Burton (1986).

non-sector zoned depending on the relationship of passive inclusions to the crystallography of the mineral (Fig. 1b). The distribution of inclusions in texturally sector zoned porphyroblasts is controlled by the crystallography of the porphyroblast (Rice and Mitchell, 1991). In contrast, the distribution of inclusions in non-sector zoned porphyroblasts is not controlled by crystallography (Fig. 1b). Moreover, both types of zoning can be further classified into three distinct subtypes that are characterized by different origins and geometric distributions of inclusions (Fig. 1b). This paper defines and names the various zoning subtypes and shows that some subtypes appear to require the presence or absence of strain to develop whereas others develop irrespective of strain.

Textural sector zoning

Texturally sector-zoned porphyroblasts form when passive inclusions are preferentially incorporated along specific crystal faces (growth sectors) and or corners between faces during growth (Fig. 3a). This crystallographically controlled incorporation of inclusions produces three zoning subtypes: sector-boundary zoning, sector-hourglass zoning, and hybrid (Figs. 1b, 3b–d). Sector-boundary zoning involves incorporation of inclusions along the corners of grains during growth, which in three dimensions ultimately yields planes of inclusions that define growth sector boundaries (Fig. 3a). Sector-hourglass zoning involves preferential incorporation of inclusions along a particular set of crystal faces during growth (Fig. 3a). In three-dimensions this type of zoning ultimately results in one or more pyramid-shaped distributions of inclusions. The apexes of these pyramids are joined at the center of the crystal and each pyramid defines a growth sector for a face that incorporates inclusions (Fig. 3a). Hybrid sector zoning is a combination of sector-hourglass and sector-boundary zoning.

Inclusion free (or poor) areas in texturally sector-zoned porphyroblasts commonly form when porphyroblast growth is accommodated by dissolution and diffusion of material not needed during growth and or by displacement of insoluble matrix material (Passchier and Trouw, 2005; Ferguson et al., 1981). Development of included areas is generally ascribed to either fast growth with insufficient time for dissolution and diffusion of unneeded material, or to preferential adsorption of impurities along certain crystallographic directions (Frondel, 1934; Barker, 1998; Spry, 1969; Shelly, 1993; Vernon, 2004; Passchier and Trouw, 2005).

Sector-boundary zoning—Sector-boundary zoning occurs in chiastolite (andalusite; Fig. 2b), garnet (Fig. 2d), and staurolite (Fig. 3b; Pennifield and Pratt, 1894; Harker, 1939; Rast 1965; Hollister and Bence, 1967; Spry 1969; Rice and Mitchell, 1991). Porphyroblasts with sector-boundary zoning commonly contain two different types of inclusions designated type 1 and type 2 (Figs. 1b, 3b-d). Type 1 are passive inclusions and type 2 are cylindrical quartz intergrowths that are coprecipitated with the porphyroblast (Fig. 3b; Anderson, 1984; Burton, 1986; Rice and Mitchell, 1991; Mason et al., 2010). The passive inclusions (type 1) in these porphyroblasts are generally only concentrated along sector boundaries whereas type 2 inclusions occur in the growth sectors where they are typically oriented normal to crystal faces (Figs. 2d, 3b).

The origin of sector-boundary zoning is not well understood, but Wilbur and Ague (2006) suggest that, for at least garnet, this type of zoning is associated with chemical disequilibrium and requires significant overstepping of the garnet producing reaction. Beyond this observation, the mechanisms by which inclusions are preferentially preserved

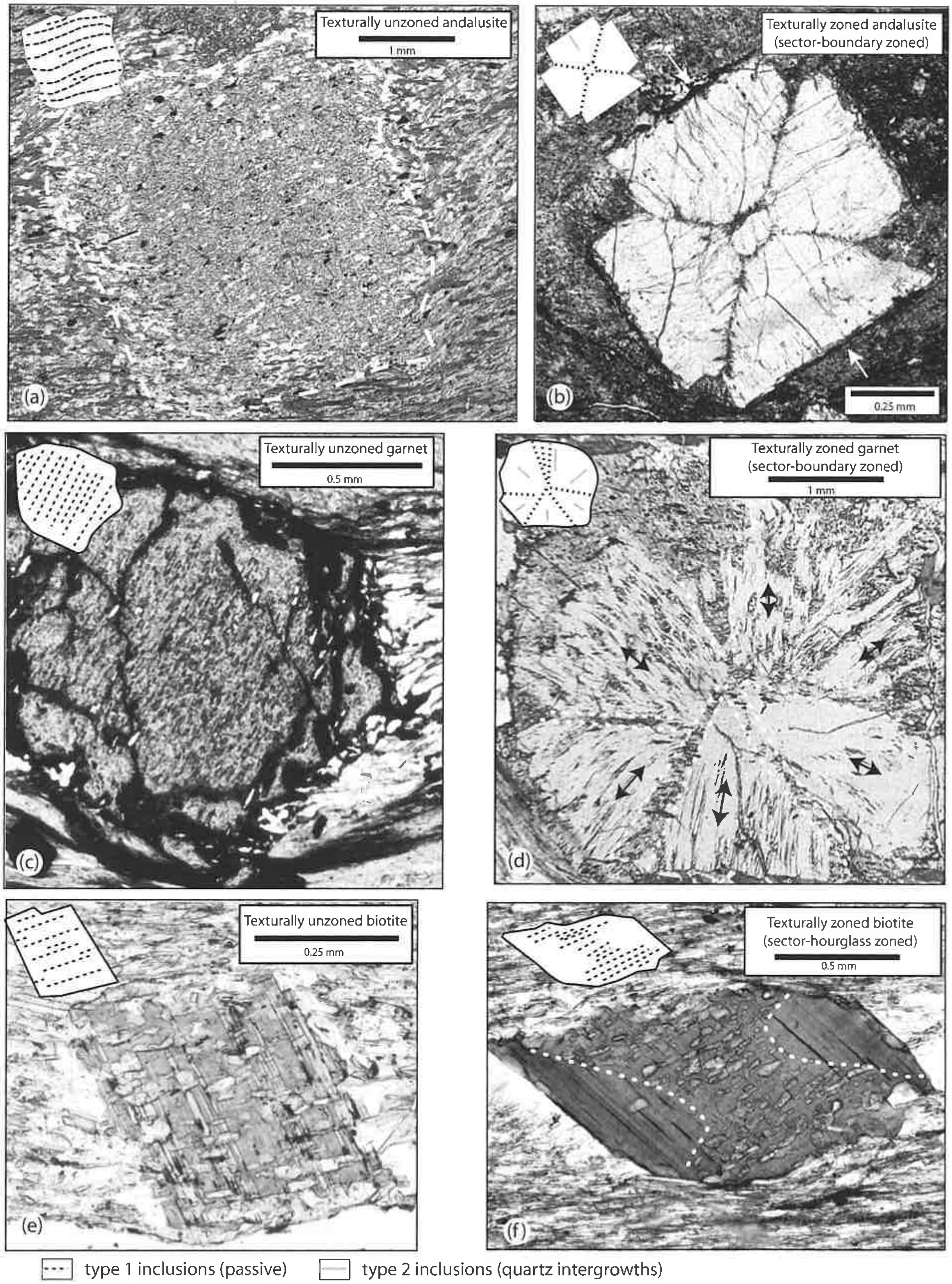

FIG. 2a–2f. Photomicrographs comparing texturally unzoned and zoned porphyroblasts of the same mineral species. Photos are in plane-polarized light. Line drawings schematically show the geometry of inclusions in each porphyroblast. (a) Schist with texturally unzoned andalusite from the Banff coast, Aberdeenshire, Scotland. White dashed line denotes margin of andalusite. (b) Texturally-sector zoned andalusite (chiastolite) displaying sector-boundary zoning and reentrant zones. White arrows point to dark cleavage domes (?) on crystal faces. From hornfels in the contact aureole of the Skiddaw granite in Cumbria U.K. Photos in (a) and (b),

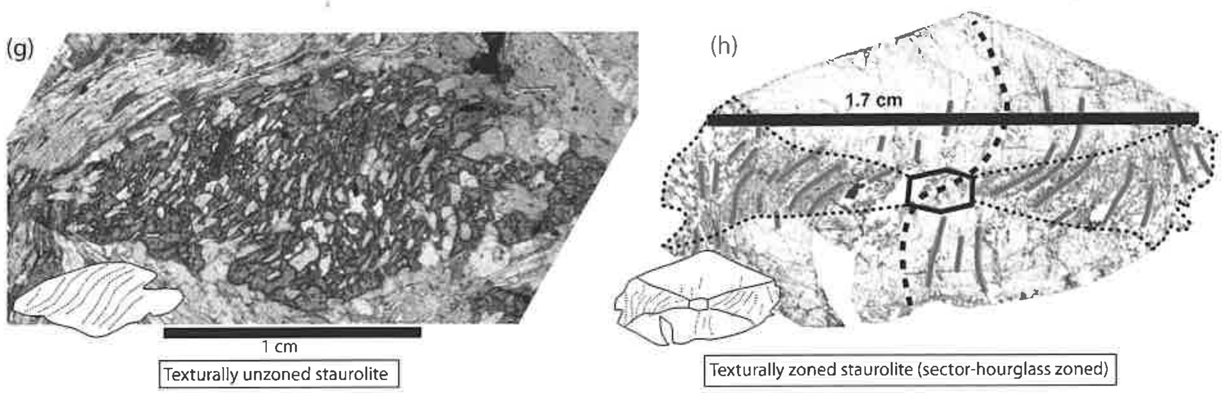

FIG. 2. Continued.
which were annotated in this study, are from http://www.virtualmicroscope.org/content/s339-25-andalusite-staurolite-schist and http://www.virtualmicroscope.org/content/andalusite-cordierite-hornfels, respectively, and both are courtesy of The Open University by https://creativecommons.org/licenses/by-nc-sa/2.0/uk/. (c) Texturally unzoned garnet from Murphy North Carolina. Dark material around the edge of the garnet is iron oxide produced by weathering. (d) Texturally zoned garnet displaying sector-boundary zoning of inherited (Type 1) inclusions, which are outlined by the white dotted lines. Garnet contains numerous type 2 quartz inclusions normal to crystal faces. Double-headed arrows show orientation of type 2 inclusions. Photo is modified from Wilbur and Ague (2006) and shows the Wepawaug schist from Connecticut. (e and f) Texturally unzoned (e) and texturally sector zoned (f) biotite porphyroblasts from the Pequop Mountains, Nevada. In biotite in (e), the lighter colored areas that are normal to inclusion trails are areas of chlorite. White dotted line in (f) outlines the hourglass-shaped distribution of inclusions in biotite. (g) Texturally unzoned staurolite with sigmoidal inclusion trails from the Wood Hills, Nevada. (h) Texturally sector-zoned staurolite displaying sector-hourglass zoning. Solid gray lines denote the trace of inclusion trails and thick, dashed black line in the center schematically shows the overall sigmoidal geometry of the inclusion trails. Black line defining polygon in the center of the photo shows growth sector boundaries in the center of the crystal, and the connecting dotted lines outline the heavily included sectors. This photomicrograph (and annotation) is courtesy of Mark Busa and represents a photo of Busa and Gray's (1992) texturally sector zoned staurolite in sample SS4 (cut C) that is sketched in their Figure 3. Sample is from Bolton, Connecticut.

along sector boundaries is debated. Harker (1939) originally suggested that the reason passive inclusions are concentrated along sector boundaries is because they are swept laterally away from growing crystal faces into grain corners. This idea has not been well accepted because of a lack of evidence, or a viable mechanism, for such a process (Spry, 1969; Rice and Mitchell, 1991; Mason et al., 2010, and references therein). More recently, the development of sector-boundary zoning has been ascribed to directional variations in growth rate or ability to adsorb impurities at sector boundaries. Rast (1965) and Kerrick (1990) suggest that zoning is produced by relatively fast dendritic growth and trapping of inclusions along sector boundaries. This fast growth initially produces a dendritic skeleton of the crystal, which is then followed by slower infilling of the growth sectors. A similar mechanism has been proposed for sector-boundary-zoned ruby (corundum) in contact-metamorphic carbonate rocks by Sunagawa et al. (1999) and Sunagawa (2005). In contrast, two growth scenarios have been proposed that ultimately involve slow, rather than fast, growth at sector boundaries. These scenarios are commonly cited as viable explanations of the common presence of reentrants along sector boundaries (e.g., Figs, 2b, 3b), especially in chiastolite (e.g., Spry, 1969; Shelly, 1993). In one scenario, zoning is attributed to preferential adsorption of impurities at crystal edges that in turn causes slow edge growth (Spry, 1969; Shelly, 1993). In the other scenario, Rice and Mitchell (1991) suggest that growth rate is directionally variable with growth in a direction normal to crystal faces being relatively fast and accompanied by displacement of matrix insolubles, and lateral growth in directions parallel to crystal faces being relatively slower resulting in entrapment of the insolubles as passive inclusions along sector boundaries.

Although there may not be a consensus or explicit understanding of the origin of sector-boundary zoning, Rice and Mitchell (1991) suggested that this type of zoning may be indicative of growth in a lithostatic (or hydrostatic) state of stress, i.e., the porphyroblasts grow in a pretectonic, intertectonic, or posttectonic environment. The basis for this inference is that the crystal faces of sector-boundary zoned porphyroblasts that grow in graphitic rocks are commonly mantled by domes of graphite or other insoluble matrix material that was displaced by the growing porphyroblast. Such graphite or cleavage domes are thought to only develop in a strain free environment in a state of hydrostatic stress, i.e., no differential stress (Rice and Mitchell, 1991; Ferguson et. al. 1981). However, Mason et al. (2010) recently interpreted sector-boundary zoned chiastolite as syntectonic on the basis of the presence of curved type 2 quartz inclusions (intergrowths). They interpret the curved quartz intergrowths to be a product of rotation of the crystal during growth. Although Mason et al. (2010) do not discuss the fabric of the passive (type 1) inclusions associated with the curved type 2 inclusions, they show the passive inclusions as being randomly oriented (their Fig. 7), which would suggest growth in a strain free environment. Consequently, it is unknown if the passive inclusions can corroborate the sense of syntectonic rotation inferred by the curved quartz intergrowths. Similar curved type 2 quartz inclusions have been recognized in garnet (Burton, 1986; Fig. 3 of Andersen, 1984). Burton (1986) suggested that because the quartz intergrowths in garnet grow in a direction that is normal to the growth front, any curvature is likely caused by the change in direction of the growth front of a particular crystallographic face rather than syntectonic rotation. In light of this, further study is needed to assess whether curved quartz intergrowths reflect rotation, and hence syntectonic growth of some sector-boundary zoned porphyroblasts.

Sector-hourglass zoning—Sector-hourglass zoning typically occurs in chloritoid, and less commonly in biotite and staurolite (Fig. 3c). Porphyroblasts that display only sector-hourglass zoning generally lack type 2 inclusions and, with few exceptions, cleavage or graphite domes along their margins. The origin of hourglass zoning varies depending on mineral species and in some cases it is poorly understood.

Biotite and chloritoid. Biotite and chloritoid have similar crystal forms and zoning patterns (Fig. 3c). In these minerals the {001} growth sectors lack abundant inclusions and the non-{001} sectors, which represent the fast growth directions, are heavily included. Zoning in both minerals is characterized by an hourglass-shaped distribution of inclusions in sections cut parallel or sub-parallel to the crystallographic c-axis (Figs. 2f, 3c, 4a–b; Halferdahl, 1961; Camilleri, 2009). Despite all similarities, the conditions required to develop zoning in biotite and chloritoid appear to be different.

Development of sector-hourglass zoning in biotite (Figs. 2f, 4a) requires a strain field characterized by protracted shortening perpendicular to foliation and extension parallel to foliation as well as an appropriate growth versus strain rate. In this environment, biotite that is growing with {001} orthogonal or at a high-angle to foliation will develop zoning (Camilleri, 2009). Zoning is produced because growth along the porphyroblast margins that parallel foliation proceeds by matrix replacement and incorporation of inclusions whereas growth in the {001} sectors that are at a high angle to foliation involves syntaxial precipitation of biotite in dilating strain shadows, which generally precludes development of inclusions (Fig. 4c; Camilleri, 2009). This growth mechanism is sensitive to the strain versus growth rate because growth rate of the {001} faces overall must not exceed rate of recession of matrix in the dilating strain shadows otherwise growth would occur by matrix replacement and inclusions would develop. Hourglass-zoned biotite is not widely recognized, but has been reported in metamorphic terrains in Ontario, Canada (McCarron et al., 2014), in Nevada (Camilleri, 2009) and New Mexico (Grambling, 1986), and is likely present in the Pyrenees (Lister et al., 1986, their Fig. 7a).

Sector-hourglass zoning in chloritoid (Fig. 4b) is unlike biotite in that its development does not appear to require strain. This inference is based on the observation that hourglass-zoned chloritoid is reported to have formed syntectonically (e.g., Zwart and Calon, 1977; Manby, 1983; Prior, 1987; Molli et al., 2000; Passchier and Trouw, 2005 [their Fig. 7.17]) as well as without strain either pre-, inter- or post-tectonically (e.g., Card, 1964; Fox, 1971; Manby, 1983; Likhanov et al., 2001). Another fundamental difference between chloritoid and biotite is that zoning in chloritoid appears to develop in crystals with {001} in a diversity of orientations with respect to fabric elements whereas in biotite it develops in crystals that grew with {001} at a high angle to the actively forming foliation (e.g., Figs. 4a, 4b). Spry (1969) suggested that zoning in chloritoid is a result of preferential adsorption of impurities along the non-{001} faces. More recently, Vernon (2004) ascribed zoning to fast growth along non-{001} faces resulting in incorporation of inclusions.

Staurolite. Sector-hourglass zoning in staurolite is similar to biotite and chloritoid in that the {001} sectors are unincluded but it is different because only one of the various non-{001} sectors is typically included (Figs. 2h and 3c) and that sector is reportedly different in various metamorphic terrains. For example, Ward (1984) reports that {010} sectors are included, Busa and Gray (1992) the {110} sectors, and Grambling (1986) the {101} sectors. Consequently, unlike biotite and chloritoid where all two-dimensional cuts parallel to the c-axis yield an hourglass-shaped included core, in staurolite this occurs only in cuts that transect the particular included sectors (Fig. 3c).

Sector-hourglass zoning in staurolite has not been studied in detail and hence its origin and the reason(s) why a particular non-{001} sector becomes included are unclear. However, fast growth does not appear to be a primary controlling factor in development of included sectors in staurolite as it may be in chloritoid. This is because in staurolite the slower growing sectors (e.g., {110} and {010}), rather than fast, become included (Fig. 3c). Although some reports of hourglass-zoned staurolite do not indicate the relationship of growth relative to strain (e.g., Ward, 1984; Grambling, 1986), work by others suggest that hourglass zoning can develop syntectonically. For example, Busa and Gray (1992) show porphyroblasts with included {110} sectors that grew syntectonically as the porphyroblast rotated, and Passchier and Trouw (2005, their

FIG. 3a-3e. Diagrams showing how different types of textural sector zoning develop and their resultant zoning patterns in various mineral species. (a) Diagram showing the progressive development of sector-boundary and sector-hourglass zoning in a two dimensional cut through the center of a hypothetical cubic crystal. Shading and gray lines highlight the pyramid shape of growth sectors. (b), (c), and (d) Diagrams illustrating the general three-dimensional crystal forms, growth sectors, and select two-dimensional textural-sector zoning patterns of various porphyroblast species. Growth sectors are denoted by gray lines in the crystal forms. Zoning patterns labeled "a" and "b" represent cuts that are perpendicular to the crystallographic c-axis with "a" representing a cut through the center of the crystal and "b" representing a cut closer to the margin of the crystal. The zoning pattern shown in "c" represents a cut that includes, and is parallel to, the crystallographic c-axis. The sketches of garnet are after Rice et al. (2006) whereby the sketch on the left shows growth sectors and the sketch in the middle shows a shaded plane that represents the two-dimensional cut and associated zoning shown in the sketch of garnet on the right. The generalized zoning patterns depicted in the other minerals are synthesized from zoning patterns shown in sketches and photomicrographs of porphyroblasts in references cited in the text. Note that the zoning patterns shown in this figure represent just a few of the myriad zoning patterns for an individual mineral, which can vary considerably with cut orientation. For examples of the diversity of zoning patterns see figure 1 of Hollister and Bence (1967) for staurolite; Rice et al. (2006) for garnet; figure 4 of Camilleri (2009) for biotite. (e) Photomicrograph

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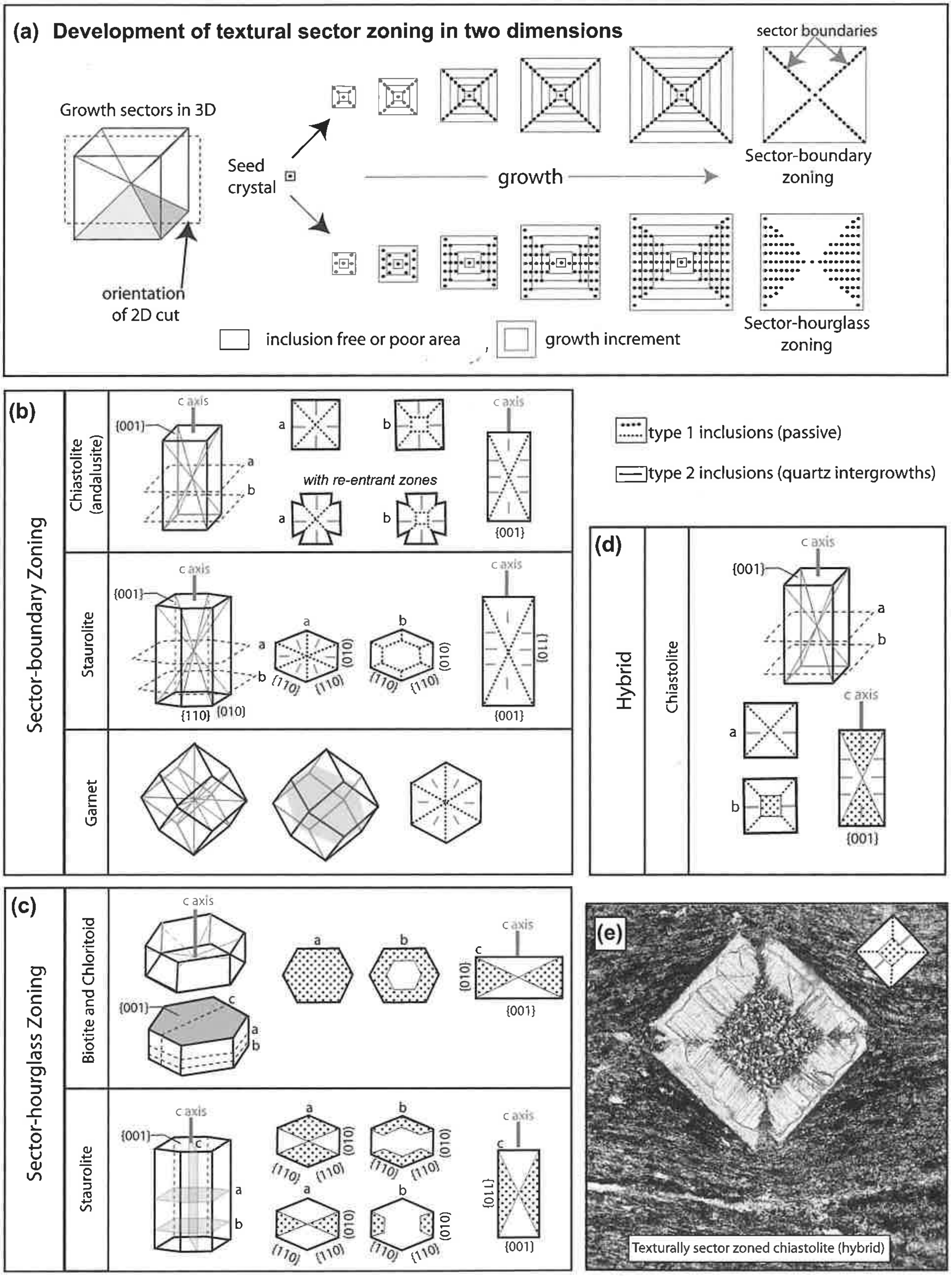

of chiastolite in plane-polarized light displaying hybrid textural sector zoning. This is an example of the "b" zoning pattern shown in (d), but it is rotated 45°. The lack of evidence of foliation in the included center of, and the wrapping of foliation around, the chiastolite suggests the that it is pretectonic. Photo is courtesy of Omar Corrales and is from the collection of the University of Barcelona.

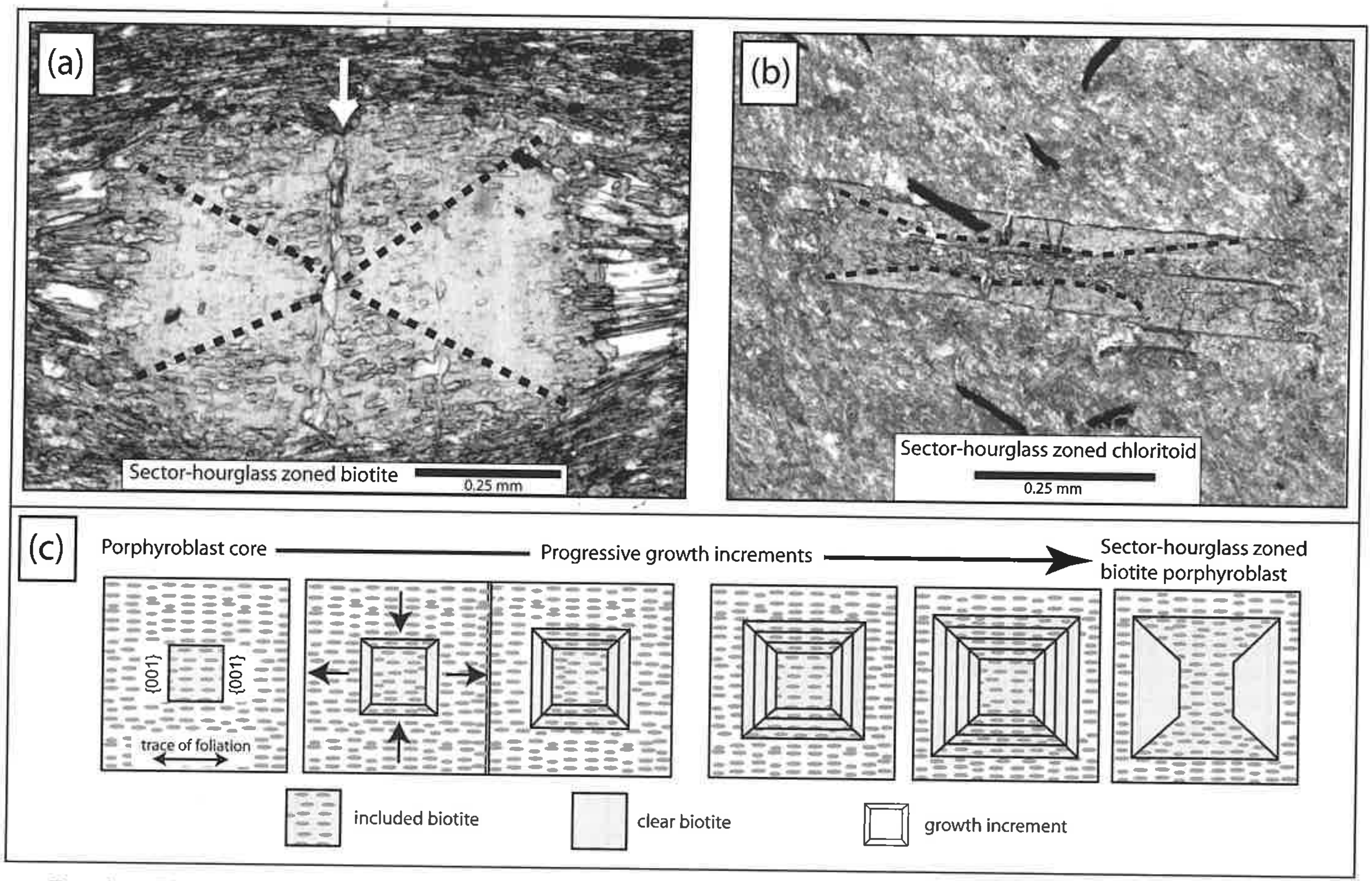

FIG. 4a-c. Photomicrographs and sketches of porphyroblasts with sector-hourglass zoning. (a) Photomicrograph of biotite with sector-hourglass zoning defined by quartz inclusions. Black dashed line highlights the included hourglass shape. This porphyroblast has a thin included rim. Arrow points to {001}-parallel extension fracture filled with biotite and quartz in the center of the porphyroblast. Sample is from the Pequop Mountains, Nevada U.S.A. (b) Photomicrograph of chloritoid with sector-hourglass zoning defined primarily by quartz inclusions. Black dashed line highlights the included hourglass shape. Sample is from the Agnew Lake area, Ontario, Canada. (c) Diagram illustrating how sector-hourglass zoning develops in biotite with {001} at a high-angle to foliation (modified from Camilleri, 2009). Protracted shortening at a high angle to foliation during growth of biotite results in progressive dilation and precipitation of biotite in strain shadows. This process produces an hourglass-shaped distribution of passive inclusions. Photomicrographs in (a) and (b) are in plane-polarized light.

Fig. 7.46) show a staurolite porphyroblast with included {010?} sectors that they interpret to reflect syntectonic growth. The aforementioned observations suggest that hourglass zoning in staurolite can develop during deformation but it is unknown whether strain is a requirement for zoning to develop and what factors control which particular sector(s) will become included.

Hybrid sector zoning—Hybrid sector zoning, which is combined hourglass- and sector-boundary zoning, occurs in

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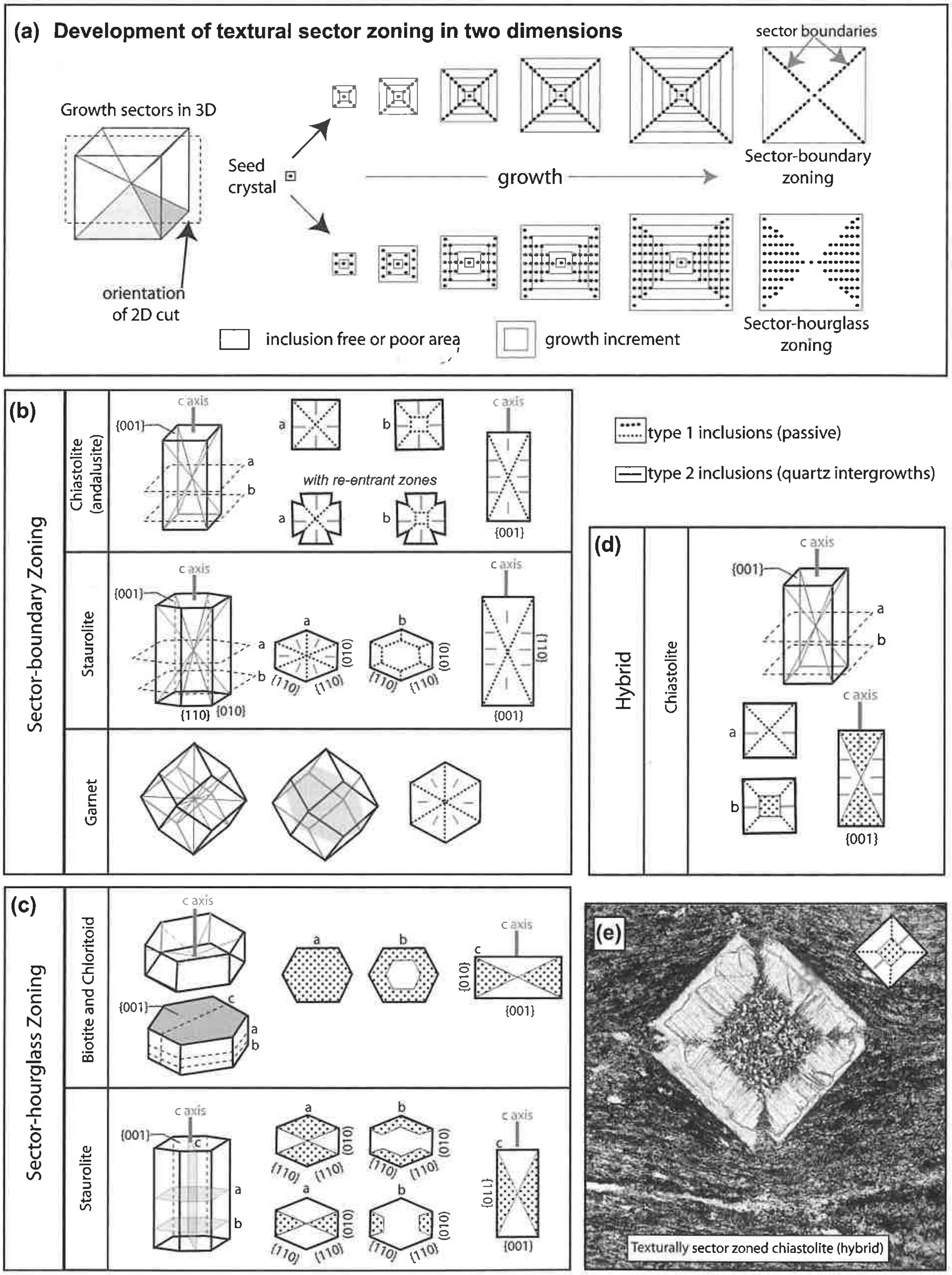
FIG. 5a-5e. Photomicrographs of porphyroblasts with non-sector zoning. (a) and (b) show photomicrographs of biotite porphyroblasts with concentric zoning defined by an included rim that surrounds a sector-hourglass zoned core. Inclusions are predominantly graphite. The porphyroblast in (a) contains fracture-fill zoning, which is manifest as an extension fracture filled with biotite and minor quartz (areas outlined in gray and labeled q). The biotite-filled fracture transects the sector- and concentrically-zoned parts of the porphyroblast. Fracture margin is denoted by black dotted line. White line denotes the margin of the porphyroblast; thick dashed black line separates the included rim from the sector zoned core; thin dashed black line highlights the included hourglass shape. Arrow points to {001}-parallel extension fracture filled with biotite and quartz in (b). (c) Photomicrograph of a garnet porphyroblast showing concentric zoning defined by a clear rim that surrounds an included core. Inclusions are predominantly quartz. White dashed line separates the clear rim from the core. (d) Photomicrograph of garnet porphyroblast with replacement zoning. Garnet has partially replaced biotite (left) with sparse quartz inclusions. White dashed line separates garnet with a high density of passive inclusions above from poorly included garnet below. Inclusions in garnet are predominantly quartz. Small photos show the biotite porphyroblast (outlined by black dashed line) that has been partially replaced by garnet. (e) Photomicrograph of a biotite porphyroblast that has replaced matrix and part of a chlorite-filled extension



vein with sparse quartz. A black dashed line outlines the extension vein. The part of the biotite porphyroblast that has replaced the vein contains sparse quartz inclusions that appear to be inherited from the vein. The part of the porphyroblast that has replaced matrix contains numerous passive inclusions of quartz. Samples shown in (a), (b), and (e) are from the Pequop Mountains, Nevada U.S.A. and samples in (c) and (d) are from the Wood Hills, Nevada. Photomicrographs are in plane-polarized light.

chiastolite wherein the {001} growth sectors are included (Fig. 3d; Nokolds et al., 1978; Kerrick, 1990). Chiastolite with hybrid zoning yields an hourglass-shaped distribution of inclusions in sections cut through and parallel to the c-axis, or a central square-shaped distribution of inclusions in most cuts at a high angle to the c-axis (Figs. 3d-e). Nokolds et al. (1978) attributes the development of included {001} sectors as a result of fast growth in a direction parallel to the crystallographic c axis, which typically is chiastolite's longest dimension and hence fast growth direction.

Non-sector textural zoning

Non-sector zoning may develop in any porphyroblast species and is generally characterized by clear zones that transect growth sector boundaries or appear to have no specific relation to them (Fig. 1b). There are three general subtypes of non-sector zoning: fracture-fill, concentric, and replacement zoning. Fracture-fill and concentric zoning typically form in the latter stages of porphyroblast growth and may be superimposed on a texturally sector-zoned core (e.g., Fig. 5a, 5b) whereas replacement zoning develops throughout growth.

Fracture-fill zoning—Fracture-fill zoning is characterized by clear zones that are generally oriented at a high-angle to foliation. The clear zones may be located in the middle of the grain and or at the ends of the grain (Figs. 1b and 5a). This type of zoning is produced syntectonically during the latter stages of growth in generally low grade metamorphic conditions where pressure solution is an important deformation mechanism and growth in a direction perpendicular to foliation is restricted. The clear zones form as a consequence of growth of the porphyroblast into voids created by separation of matrix from the porphyroblast in strain shadows and by the development of extension fractures in the middle of a grain, which yields clear zones at the ends and middle of the grain respectively. This phenomenon is thought to, in part, require high fluid pressures (e.g., Lister et al., 1986) and has been referred to as crack-fill porphyroblastesis (Barker, 2002). Fracture-fill zoning is common in biotite and chlorite porphyroblasts with {001} oriented at a high angle to the shortening direction (e.g., Vernon and Flood, 1979; Lister et al., 1986; Miyake, 1993; Barker, 2002; Little et al., 2002; Kim and Cho, 2008; Camilleri, 2009). Fracturing preferentially occurs in these minerals along the {001} cleavage within the grain and along the interface between the {001} crystal faces and the matrix. Fracture-fill zoning has also been recognized in garnet (Barker, 2002) and staurolite (Busa and Gray, 2005).

Concentric zoning—Concentric zoning is characterized by a clear or included rim that surrounds the core of a porphyroblast. This type of zoning involves growth in all directions away from the core and can form with or without strain. Development of a clear rim (Fig. 5c) is the most common type of concentric zonation and it may develop when growth rate slows or diffusion rate increases allowing sufficient time for diffusion of material not needed in the porphyroblast-forming reaction (Philpotts and Ague, 2009). Philpotts and Ague (2009) note that with increasing temperature, the diffusion rate should increase even if growth rate stays the same. Hence the development of clear rims could be, for some minerals, a natural consequence of prograde metamorphism. Alternatively, development of a clear rim may be the result of initiation of a porphyroblast forming reaction that consumes the mineral that is being included (Passchier and Trouw, 2005; Philpotts and Ague, 2009; Farber et al., 2014; Kelly et al., 2015). Development of an included rim (Fig. 5b) may reflect an increase in growth rate or decrease in diffusion rate perhaps accompanied by dendritic growth.

Concentrically zoned minerals commonly only contain a single included or clear rim, but in rare instances a mineral may develop alternating concentric inclusion-rich and inclusion-poor zones. Passchier and Trouw (2005, their Fig. 7.49) show an example of this in an hourglass-sector-zoned chloritoid porphyroblast with superimposed concentric inclusion-rich and inclusion-poor zones. The repetition of these zones could reflect rhythmic alternation of growth and or diffusion rates.

Replacement zoning—Porphyroblasts that grow by partial or complete replacement of another porphyroblast, or by replacement of matrix with layers of varying composition, may develop replacement zoning (see examples in Fig. 5d and 5e, and also in Rubenach and Bell, 1988; Barker, 2002; Passchier and Trouw, 2005; Kim and Cho, 2008). Clear zones in minerals that display replacement zoning can form as a consequence of replacing a domain where there are little or no insoluble matrix minerals and or excess reactant. Hence, this type of zoning can form with or without strain.

Discussion and conclusions

Textural zoning in porphyroblasts is manifest as inclusion-free or -poor zones adjacent to more heavily included areas and may be crystallographically controlled reflecting geometry of growth sectors (textural sector zoning) or can transect sector boundaries (non-sector zoning). Inclusion-free or -poor zones may form in two general ways: 1) if growth is accompanied by dissolution and diffusion of unneeded material and or displacement of matrix insolubles, if present, and 2) by porphyroblast growth into fractures or openings at the interface between the porphyroblast and strain shadow.

The origin and type of textural-sector zoning that develops is in part dependent on mineral species (Fig. 3), but the various types of non-sector zoning may form in any mineral species. The important points about the various types of textural zoning, their significance and remaining uncertainties regarding their origin are:

1) Most sector-boundary-zoned minerals likely develop in an environment that lacks strain with concentration of passive inclusions along sector boundaries developing as a consequence of preferential adsorption or directional variations in growth rate. However, it is possible that the presence of curved quartz intergrowths (type 2 inclusions) may indicate some syntectonic development of sector-boundary zoning, but this inference needs to be reconciled with a microstructural assessment of passive (type 1) inclusions to determine if they reflect the same sense of tectonic rotation as the type 2 inclusions. More research is needed to determine the significance of curved type 2 inclusions.
2) Sector-hourglass zoning may have a number of origins that are unique to specific mineral species. Chloritoid and biotite have crystallographically similar zoning patterns wherein the non-{001} sectors are heavily included and {001} sectors are clear or poorly included, but zoning in chloritoid can develop in the absence or presence of strain whereas zoning in biotite requires a strain field characterized by shortening at a high angle to foliation and growth of a crystal with {001} oriented at a high angle to foliation. Development of clear {001} sectors in biotite

reflects progressive growth by syntaxial precipitation in dilating strain shadows whereas clear sectors in chloritoid are likely produced by slower growth with sufficient time for dissolution and diffusion of unneeded material. Development of sector-hourglass zoning in staurolite is enigmatic in that the slower growing sectors are typically included rather than clear as they are in chloritoid. Furthermore, limited information suggests that zoning in staurolite can develop during strain, although it is unknown if it can form in the absence of strain.

3) Non-sector zoning develops in the latter stages of growth (fracture-fill and concentric zoning) or progressively during growth (replacement zoning). Fracture-fill zoning develops syntectonically when growth in a direction perpendicular to foliation is restricted and porphyroblast growth occurs in fractures. Concentric zoning requires unrestricted growth in all directions, may form with or without strain, and develops mostly in response to changes in growth or diffusion rates. Replacement zoning may take place in the presence or absence of strain and is a product of growth over compositionally or texturally zoned matrix layers, or by partial or complete replacement of other porphyroblast species.

In summary, there is much to be learned about the growth processes that yield textural zoning in many porphyroblast species as well as the role that strain, or the lack of it, plays in controlling the presence or absence of textural zoning. Nonetheless, texturally zoned porphyroblasts should not be overlooked because recognition of certain types of zoning could be significant in that they may suggest the presence or absence of strain during growth.

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