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Native copper formation in mine-prop wood from Cyprus illustrates displacive growth by force of crystallization

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ABSTRACT

A long-standing issue in the study of metamorphic rocks concerns the question in how far replacement of the protolith assemblage during the growth of metamorphic porphyroblasts is accompanied by the additional operation of a displacive mechanism due to an alleged 'crystallization force' exerted by the growing porphyroblast. Whilst in few cases a component of displacive growth can be corroborated, unequivocal criteria to identify such displacements are lacking. It follows that the concept of a so-called 'crystallization force' is surrounded by uncertainties on the viability and operation of displacive growth in natural systems. We investigate the growth of Cu porphyroblasts in a sample of mine-prop wood from a Bronze Age copper mine in Cyprus. The pit prop became infiltrated with copper-saturated, polluted mine water during collapse of an ancient mine gallery. The microstructures associated with the copper porphyroblasts strongly indicate displacive growth, whilst the matrix wood has not been affected by any externally imposed deformation. We suggest that the displacement microstructures associated with the copper porphyroblasts substantiate the existence of 'crystallization forces'.

1. Introduction

Laboratory experiments show that chemical reactions involving an increase in solid volume in a confined space can under certain conditions generate mechanical stresses on the confining boundaries – a phenomenon known as the development of a 'force of crystallization' or 'crystallization pressure' (Becker and Day, 1905; Correns, 1949; Weyl, 1959; Schuiling and Wensink, 1962; Ostapenko, 1976; Wolterbeek et al., 2018). Recent studies have shown that certain mineral reactions are capable of generating stresses exceeding 150 MPa under laboratory conditions (Lambart et al., 2018; Skarbek et al., 2018; Wolterbeek et al., 2018; Zheng et al., 2018). This crystallization force is thought to be an important factor in a variety of geological processes, including mineral vein formation (Taber, 1916; Fletcher and Merino, 2001; Merino et al., 2006; Means and Li, 2001; Gratier et al., 2012), (pseudomorphic) mineral replacement (Maliva and Siever, 1988; Merino and Dewers, 1998; Fletcher and Merino, 2001; Putnis, 2009), spheroidal weathering (Røyne et al., 2008) and reaction-driven fracture (Jamtveit et al., 2008; Plumper et al., 2012; Putnis et al., 2009; Kelemen and Hirth, 2012; Van Noort et al., 2017). However, while envisioned to have a role in many geological processes, it is on the basis of the microstructures in natural examples by no means trivial to ascertain that displacive growth indeed occurred due to a force of crystallization.

The deflection of matrix schistosity around metamorphic porphyroblasts has classically been related to the question if growing crystals create space by concretionary growth, i.e. growth involving displacement of the surrounding matrix, or by volume-constant chemical replacement (Ramberg, 1952; Putnis, 2009). Distinction between these two mechanisms is important because in some cases they produce identical microstructures which, however, may reflect different structural-metamorphic histories (Zwart, 1962; Spry, 1969; Zwart and Calon, 1977). Displacement of the matrix by growing crystals has been ascribed to a crystallization force already by Lavalle (1853), Becke (1904) and Harker (1931). In an attempt to identify the effect of crystallization force during the growth of metamorphic porphyroblasts in a schistose matrix, Misch (1971) proposed and illustrated microstructural criteria. He recognized three types of relationships, labelled A, B and C, which are summarized in Fig. 1. Type A microstructures are characterized by the absence of any deflection of the matrix schistosity near the porphyroblasts, which truncate the undeformed schistosity. In type B microstructures, the porphyroblasts in part truncate foliation planes but the foliation also curves around the porphyroblasts. Type C

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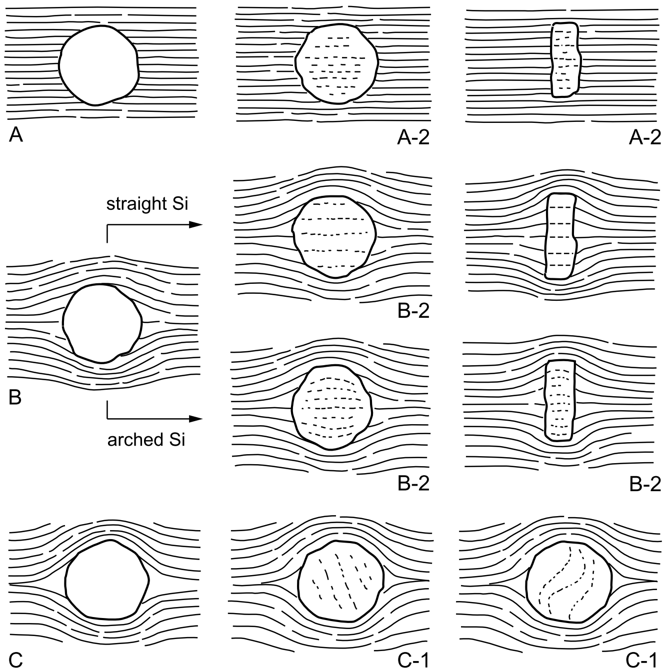

Fig. 1. Microstructures to identify replacive and/or displacive components of porphyroblast growth; terminology and sketches modified after Misch (1971). (a) Type A microstructures showing no deflection of the matrix schistosity near the porphyroblasts, which truncate the undeformed schistosity. Cases A-1a and A1b respectively show spherical and elongate porphyroblastst with straight inclusion patterns. (b) type B microstructures where the porphyroblasts in part truncate foliation planes but the foliation also curves around the porphyroblasts that may preserve either straight or arched inclusion patterns. B-1a and B-1b show spherical and elongate porphyroblasts with straight inclusion patterns, B-2a and 2b show the case of arched inclusion patterns. (c) type C microstructures in which all of the matrix schistosity bows around the porphyroblasts whilst there is no evidence of any truncation of the matrix foliation. Early formed inclusion trails shown in C-1a and C-1b suggest a stage of replacive growth prior to intense deformation of the matrix. For further explanation see text.

microstructures constitute an opposite end-member as all of the matrix schistosity bows around the porphyroblasts whilst there is no evidence of any truncation of the matrix foliation.

Type A microstructures (Fig. 1a) are conveniently explained by chemical replacement without any deformation of the matrix, i.e. replacement at constant volume. This is all the clearer when tiny particles not involved in the porphyroblast forming reaction have been enclosed as an internal fabric (Si) apparently continuous with the surrounding external matrix schistosity (Se), as shown in Fig. 1a, A-1a and A-1b. This microstructure has been extensively documented and the growth of the porphyroblasts is commonly referred to as post-kinematic (Zwart, 1962) or post-tectonic (Passchier and Trouw, 2005).

Misch (1971) suggests that type B microstructures (Fig. 1b) may reflect a replacement pattern combined with variable increments of volume increase in the space occupied by the growing porphyroblasts, and as the co-existing replacement relationship shows that the porphyroblast postdates the matrix foliation which it truncates, he considers this type of microstructures unequivocal evidence for pushing-out of a pre-existing matrix foliation. This argument was strongly challenged by Spry (1972), who emphasized that the difficulty of interpretation arises because the geometry of a crystal pushing outward against foliation is indistinguishable from that of the foliation being pushed inward. Likewise, Ferguson and Harvey (1972) questioned the interpretation of type B microstructures by Misch (1971), and noted that there are in fact three cases at stake, namely (1) replacive growth, followed by flattening about the porphyroblast perpendicular to the foliation (shown in Fig. 1b as type B1), (2) synkinematic replacive growth during flattening, leading to geometries with progressively arched inclusion patterns as described by Zwart (1962), and (3) both replacement and displacement of a pre-existing matrix as envisaged by Misch (1971), that would lead to the same Si pattern as case (2) shown in Fig. 1b as type B2. with inclusion patterns shown in B-2a and B-2b. Ferguson and Harvey (1972) emphasize that in the absence of inclusion trails these three cases are indistinguishable, such that, as opposed to what is suggested by Misch (1971), the type B microstructures without Si patterns are not an unequivocal criterion for a component of displacive growth.

In type C microstructures (Fig. 1c) the matrix schistosity bows completely around the porphyroblasts. Misch (1971) emphasizes that in the absence of evidence for replacement, i.e. if the porphyroblasts have no internal fabric, interpretation of this microstructure may be difficult. There are two options in this case: (1) concretionary growth of the porphyroblast such that during growth the matrix and its pre-existing structure was pushed aside suggesting crystallization force, and (2) the matrix structure represents later flow around a pre-existing porphyroblast. As we may expect that metamorphic porphyroblasts grow mainly at the expense of the matrix, hence by replacement, genuinely displacive growth seems unlikely unless in the exceptional case that the mineral chemistry of the porphyroblasts is not indigenous to the matrix such as in the case of sulfide porphyroblasts (Misch, 1971). However, the common presence in such cases of early formed inclusion trails points to a stage of replacive growth prior to intense deformation of the matrix (e.g., Fig. 1c, C-1a and C-1b).

2. Can displacive growth be identified, and is it viable?

2.1. Displacive growth in natural rocks

In their discussion, Ferguson and Harvey (1972) emphasize that two issues need to be distinguished, i.e. (1) the question if a mineral, by virtue of its growth under metamorphic conditions, can displace its matrix, and (2) in case this does occur, if there are unequivocal criteria to recognize such displacement. Spry (1972) suggested that one would presumably look for proof in undeformed types, such as simple thermal metamorphic rocks. This led Saggerson (1974) to investigate a sequence of shale converted into porphyroblastic hornfels adjacent to the Bushveld Igneous complex. There is no evidence whatsoever for any post-metamorphic deformation of this sequence on the large scale nor on the outcrop- or hand specimen-scale, whilst helicitic porphyroblasts of cordierite and staurolite occasionally show discontinuous Si–Se relationships and bowed Se adjacent to staurolite coigns, somewhat reminiscent of Misch, (1971) type B structures. The microstructures indeed suggest operation of a displacive mechanism in addition to largely replacive growth. In view of the mineralogy of the Bushveld aureole rocks these processes may have operated at $\sim$ 3–4 kbar overburden pressure (e.g. Pattison et al., 1999). However, whilst in few cases like the Bushveld hornfelses and the Dalradian chloritoid-bearing schists a component of displacive growth can be corroborated, unequivocal criteria to identify such displacements are generally lacking.

Quite remarkably, Ferguson and Harvey (1972) mention a type B chloritoid with an arched inclusion pattern from a Dalradian chlorite-muscovite-chloritoid-ilmenite-garnet schist that may indeed reflect displacement rather than growth during flattening, because other chloritoids in the same sample show posttectonic type A microstructures. On the other hand, a detailed study by Zwart and Calon (1977) of a Liassic chloritoid-bearing micaschist from the Urseren Garvera syncline near the village of Curaglia reveals type B microstructures with arched inclusion patterns in chloritoids oriented at a high angle to the schistosity, but also strong evidence in the same sample for rotation of chloritoids during synmetamorphic flattening. These two different results show that the microstructure of an arched Si is an ambiguous criterion which at best suggests that it may either reflect displacive growth or synmetamorphic flattening.

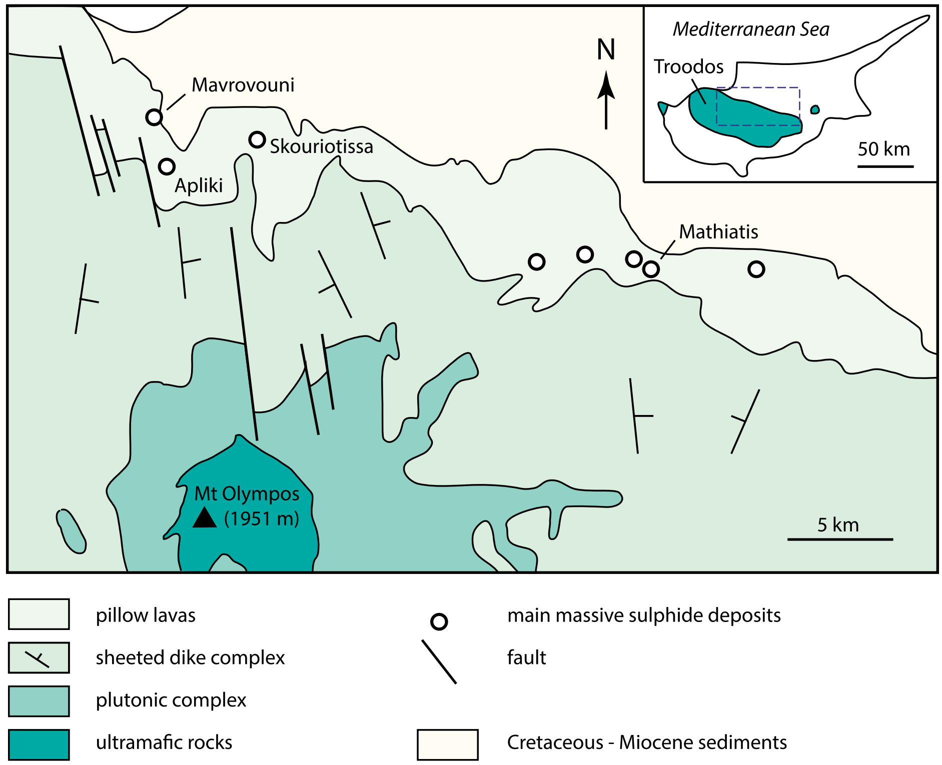

Fig. 2. Geological sketch map of the northern Troodos massif, slightly modified after Bickle and Teagle (1992), indicating the main massive sulfide deposits mined since the Bronze Age.

Fig. 3. Slice of pit prop sample studied. Note fine light-colored grains of native copper. Approximate size of sample 7.5 cm long, 1 cm wide, and about 2 cm high.

2.2. *Is displacive growth viable?*

Both Rast (1965) and Spry (1969) have argued that a growing porphyroblast must overcome the load pressure to displace the surrounding matrix. This notion, however, was challenged by Yardley (1974) who argued that, in metamorphic rocks, all grains are in contact with a random pore phase analogous to a fluid. Yardley (1974) notes, that when a porphyroblast grows at a boundary with a mineral, not all of whose molecules will be incorporated in the porphyroblast, then surplus molecules of that mineral will be removed in the fluid. If the matrix mineral is rather insoluble, and other more soluble matrix minerals are present nearby, then the growing porphyroblast may push the insoluble mineral ahead of it into space created by the solution of soluble ones. Yardley (1974) suggests that in this way it is possible that displacement of matrix fabrics may occur and produce textures similar to some of those described by Misch (1971). Yardley (1974) continues to argue, that in case a porphyroblast, growing in response to a metamorphic reaction, partially makes room for itself by displacing the matrix, it only needs exert sufficient stress to overcome any yield strength of the matrix, and then to strain the matrix at a rate dictated by the porphyroblast's rate of growth. Assuming a simple viscous model for the behavior of the matrix, the stress σ that the crystal need exert is given by $\sigma = \mu\ de/dt$,

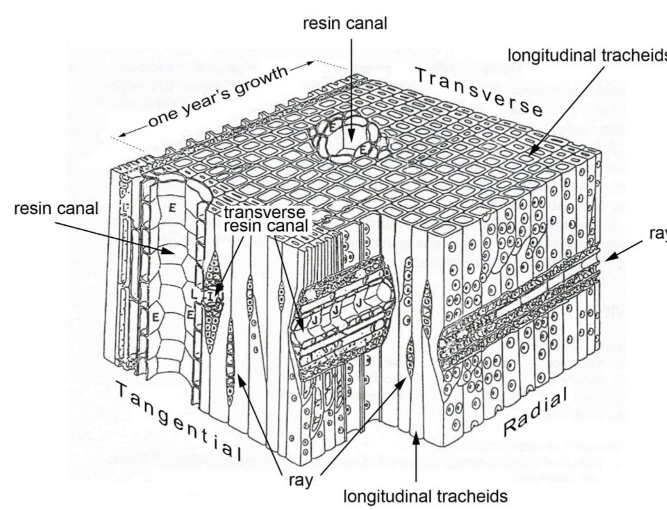

Fig. 4. Microstructure of pine wood modified after Bowyer et al. (2003), shown as a block diagram with transverse, tangential and radial faces. Note dominantly longitudinal structure made up by the elongate tracheid cells, and the occurrence of resin canals parallel to the tracheid cells, mantled by flat epithelial cells (E). There are also radially oriented transverse resin canals (I) equally mantled by epithelial cells (labelled J) and well visible in tangential section. Note that both sets of resin canals are locally connected (L).

where de/dt is the rate of strain of the matrix, and μ is its coefficient of viscosity. As the rate of growth of the crystal, itself dictated by the reaction rate, becomes vanishingly slow, the stress the crystal need exert to displace the matrix likewise becomes vanishingly small.

From the foregoing it may be concluded that the existence of a 'crystallization force' in natural rocks is surrounded by uncertainties on possible criteria to identify displacive growth, as well as on the viability of such processes. This suggests that insight in the issue of displacive

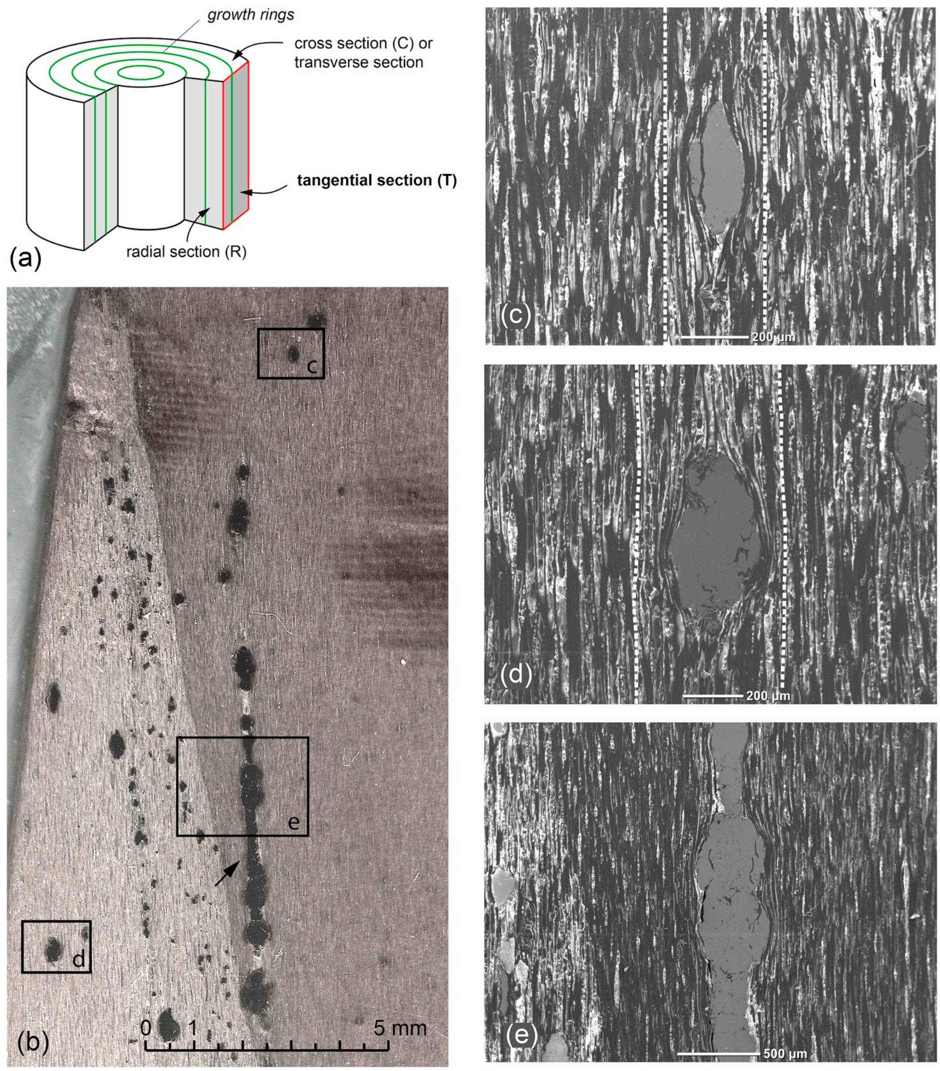

Fig. 5. Microstructures of copper porphyroblasts observed in tangential sections. (a) Diagram illustrating principal wood sections, tangential section (T) accentuated in red. (b) Polished surface of tangential slice, with dark grains representing native copper grains. Note string of copper grains (arrow). Rectangles indicate detailed micrographs shown in c, d and e. The two different shades result from a slightly oblique sectioning of year ring. (c) and (d) SEM micrographs of wood structure and copper porphyroblasts. Note deflection of tracheid structure adjacent to copper crystals; dashed lines delineate boundaries between domains of deflected tracheids and domains of virtually undeformed tracheids. (e) SEM micrograph showing detail of string of copper crystals, suggesting amalgamation of copper grains presumably grown in pre-existing resin canals. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

porphyroblast growth may be better obtained via experiments that are not hampered with the uncertainties posed by naturally deformed and metamorphosed rocks. In this study, we address an uncommon case of porphyroblast growth, probably best described as an unintentional long-term analog experiment. It concerns the growth of porphyroblasts of native copper in a piece of mine wood contaminated with acid mine water from a Bronze Age copper mine in Cyprus.

3. Pit props from the Troodos Cu mines

3.1. Geological background

The Troodos massif on Cyprus (Fig. 2) is generally considered to be a fragment of Mesozoic ocean floor (Gass, 1968; Moores and Vine, 1971), emplaced during the collision between Eurasia and Africa. It is often cited as a type example of an oceanic crustal section and is one of the few ophiolites with an undisrupted stratigraphy. The Pillow Lava Series of the Troodos ophiolite hosts numerous small massive sulfide mines (Bickle and Teagle, 1992; Antivachis, 2015) dominated by pyrite (Fe) and chalcopyrite (Cu) that were already exploited in historical times. Copper mining in Cyprus dates back to the Early Bronze Age and continued in Phoenician and Roman times (Knapp et al., 1998). With the collapse of the Roman empire, mining in Cyprus declined and eventually ceased sometime around the fourth century. Around the beginning of the twentieth century several ore companies explored the area which led to larger-scale mining activities, mostly since the second world war till about the nineteen-eighties. The remnants of these activities are characterized by large piles of mine spoil, acidic pit waters and metal-rich sediments such as around the abandoned Mathiatis mine (Fig. 2; Hudson-Edwards and Edwards, 2005; Stylianou et al., 2014).

Evidence uncovered by the twentieth-century mining operations shows that the Romans worked the ores by opencast methods as well as by underground mining. The latter required timber as pit props in the mining galleries, for which local pine trees were used (Constantinou, 1992; Knapp et al., 1998). As the Romans were only interested in high-grade copper ore, the lower grade ore served as back fill, and albeit at a much smaller scale than due to recent mining, this must have led to strongly polluted waters in the abandoned mines, as evidenced in studies of about two millennia old spoil tips (Pyatt, 2001). Pit props in deteriorating abandoned mine galleries occasionally became infiltrated with these polluted waters, leading to growth of porhyroblasts of native copper within the wood. Here we investigate a sample of such copper-bearing mine wood (Fig. 3). The precise location of the sample is unfortunately not documented, but copper-bearing wood props are occasionally reported on the internet (e.g. Crystal Classics website) from the ancient Mavrovouni mine in the Skouriotissa area (Fig. 2).

3.2. Microstructures of Cu-bearing pine wood

With reference to Constantinou (1992), Knapp et al. (1998) mention

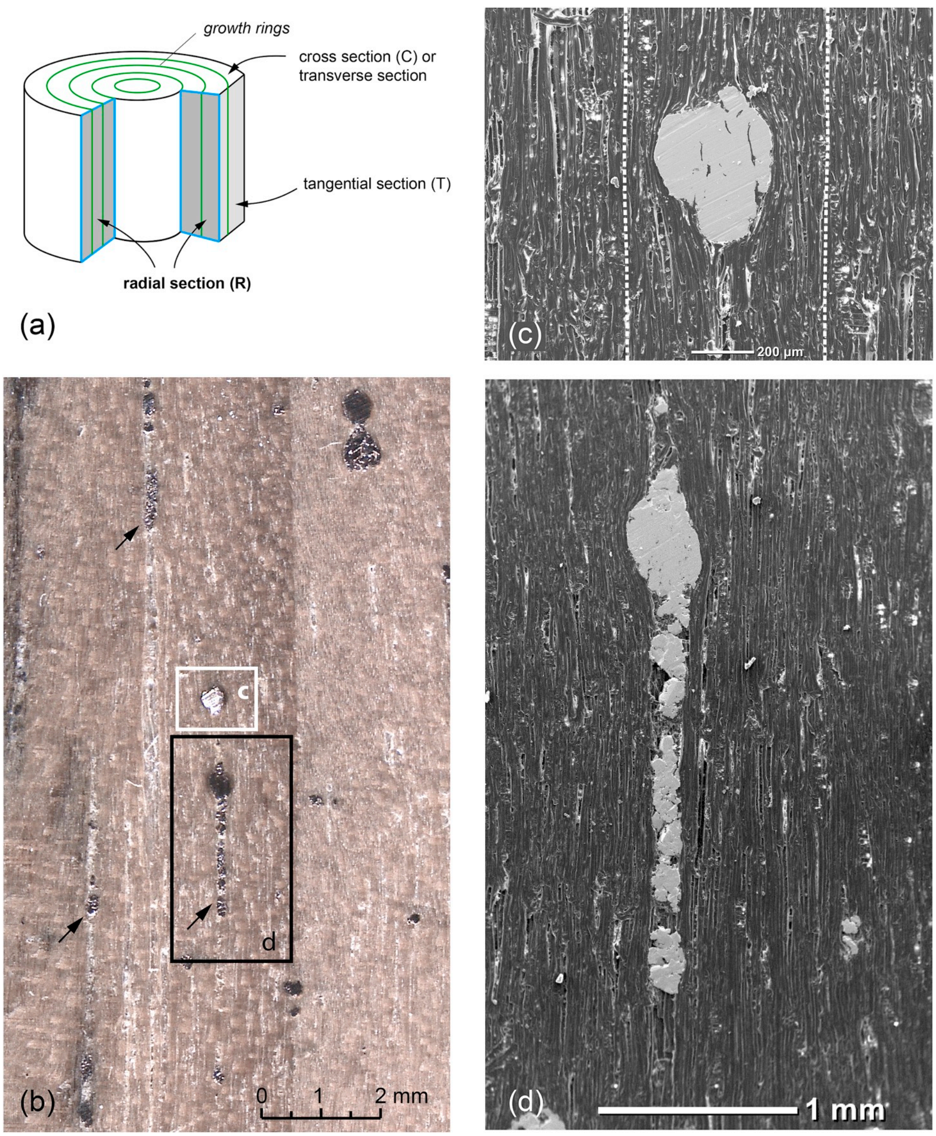

Fig. 6. Microstructures of copper porphyroblasts in radial sections. (a) Diagram illustrating principal wood sections, radial sections (R) accentuated in blue. (b) Polished surface of radial slice, with mostly dark and occasionally light grains of native copper. Note strings of small copper grains (arrows) possibly formed in resin canal. Details shown in c and d as indicated. (c) SEM micrograph of copper porphyroblast. Note flattening and deflection of tracheid cells adjacent to the copper porphyroblast; dashed white lines accentuate boundaries with domains of virtually undeformed tracheids. (d) SEM micrograph showing string of copper porphyroblasts presumably grown in resin canal. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

that examination of timber preserved in mining galleries at Skouriotissa has shown that *Pinus brutia*, a species that grows particularly well on Cyprus's pillow lavas, was most commonly used as pit props. This is corroborated by the main characteristics of our wood sample under the scanning electron microscope (SEM). For present purposes it is important to note that the wood microstructure is dominated by elongate cells called tracheids, lending a fibrous, linear structure to the material as opposed to the commonly planar foliated structure in natural rocks. As a result, wood is an orthotropic material, i.e. it has material properties that differ along three mutually orthogonal twofold axes of rotational symmetry, and as a consequence, physical properties such as shrinking upon drying do strongly differ in the three main section directions illustrated in Figs. 4, 5a and 6a. The elongate tracheid structure of *Pinus brutia* moreover includes conspicuous irregularities in the form of resin ducts (Fig. 4), forming canals rimmed by flat epithelial cells and embedded in a virtually straight longitudinal tracheid structure (Crivellaro and Schweingruber, 2013). We note that resin canals also occur as transverse canals parallel to the radial direction (Hoadley, 1990) and that the longitudinal and transverse resin canals are locally connected (Bowyer et al., 2003).

At the microscale, grains of native copper up to a few 100 µm in size form porphyroblasts wrapped by the tracheid cell structure. This is particularly clear in tangential sections such as shown in Fig. 5b, c and d. The tracheid structure mostly bows around the porhyroblasts reminiscent of the type C microstructures distinguished by Misch (1971). The microstructure in radial sections (e.g. Fig. 6b, c and d) is very similar to that seen in tangential sections. In both sections there are aligned and amalgamated porphyroblasts of native copper, possibly grown in tube-like resin canals. In transverse cross sections, the tracheids are nearly equant as illustrated in Fig. 7, but adjacent to the copper porphyroblasts they are clearly flattened, with the long axes of the flattened tracheids trending parallel to the porphyroblast margin. This suggests some form of constriction, consistent with the microstructures in tangential and radial sections.

With the aim to quantify the deformation associated with porphyroblast growth we first note that this deformation is commonly confined to a relatively narrow band, outside of which the tracheid microstructure is apparently undisturbed as seen, e.g., in Fig. 5c, d and 6c. We may quantify such deformed bands and the associated strain by comparing the size d of the porphyroblast with the width w of the deformed band. Because the tracheids within the band of width w are flattened to a width $w - d$ (Fig. 8a), the magnitude of the associated flattening (shortening) strain should be $e = d/w$. As shown in Fig. 8b, measurement of 12 porphyroblasts and their enveloping deformed bands in tangential section and of 16 porphyroblasts and their deformed bands in radial section yield shortening strains e between 40% and 70%, with a slight tendency

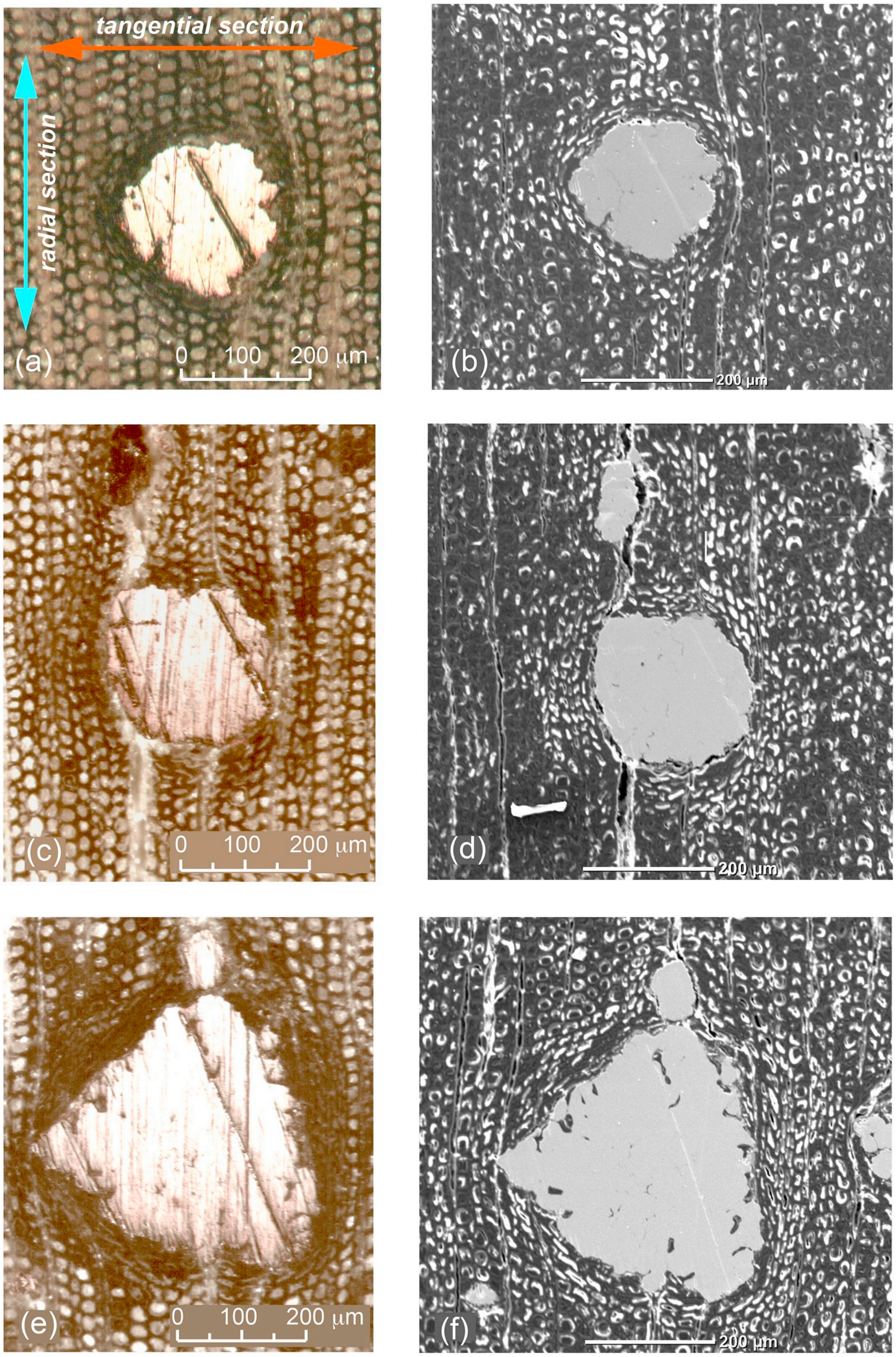

Fig. 7. Transverse cross section of the mine wood sample, viewed parallel to the tracheid long axes. (a, c and e) Reflected light micrographs of copper porphyroblast in wood matrix showing an equant tracheid cell geometry away from the copper grains. Red and blue lines in (a) indicate orientations of respectively tangential and radial sections. (b, d and f)) SEM micrographs of same copper porphyroblasts. Note intense flattening of the tracheid cells close to the copper grains, with the long axes of flattening oriented parallel to the porphyroblast margins. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

towards higher strains at larger porphyroblast sizes. Since it is possible that the native copper porphyroblasts formed preferentially inside resin canals, we must consider the effect of preexisting wood microstructure (Fig. 8c). Analogous to the above, the flattening strain would then be given by $e = (d - r)/(w - r)$, where r is the width of the original resin canal. For species from section *Pinus*, like *Pinus brutia* (subsection *Pinaster*), axial resin canals generally range 40–170 μm in size when measured in cross-sections (Richter et al., 2004). Taking $r = 170$ μm, Fig. 8d shows the corresponding shortening strains for the 28 measured porphyroblasts.

4. Discussion and interpretation

The microstructures associated with porphyroblastic growth of native copper grains in the studied mine wood sample are similar to the type C microstructures distinguished by Misch (1971), albeit that the linear structure of the tracheid cells clearly differs from the commonly planar schistose structure in most metamorphic rocks. The tracheid microstructure bends around and is flattened adjacent to the porphyroblasts both in tangential and radial sections (Figs. 5 and 6), whilst in transverse cross section the elsewhere equant tracheid cells are stretched and flattened adjacent to the copper crystals with the stretched dimensions parallel to the copper grain margins (Fig. 7). This is consistent

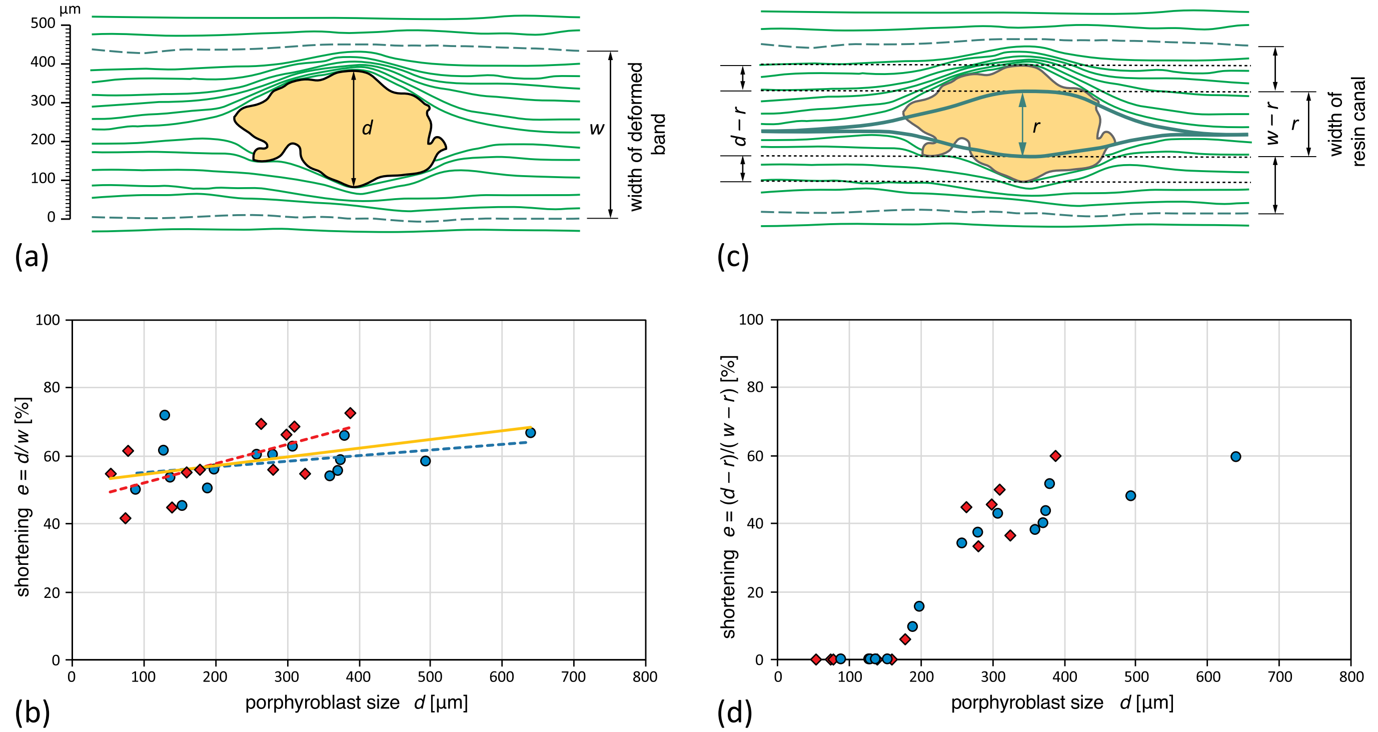

Fig. 8. Estimates of shortening around copper porphyroblasts in tangential and radial sections. (a) Sketch showing porphyroblast of size d (measured perpendicular to tracheid fabric), surrounded by band of width w of deformed matrix material. (b) Shortening ($e = d/w$) versus porphyroblast size, with red and blue dashed lines indicating least squares best fits to shortening values for respectively tangential (red diamonds) and radial sections (blue dots), and green line for all measurements. (c) Sketch showing porphyroblast of size d, grown in a pre-existing resin canal of size r (measured perpendicular to tracheid fabric), surrounded by band of width $w - r$ of deformed matrix material. (d) Shortening ($e = (d - r)/(w - r)$) versus porphyroblast size assuming growth occurred inside an initially 170 µm-wide resin canal. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

with flattening of the matrix adjacent to the copper grains in two mutually perpendicular directions. Note in addition that there is hardly evidence for truncation of the linear tracheid structure, nor is there clear evidence for shortening in the direction of the tracheid linear fabric.

Aside isolated copper porphyroblasts seen in the different wood sections, both the tangential and radial slices contain trails of copper that seem to have grown as amalgamating porphyroblasts in channel-like features probably representing preexisting resin canals. This may indicate that the resin canals acted as pathways for copper-saturated polluted mine waters to penetrate pit props such as the one studied here. The local coupling between longitudinal and radially oriented resin canals (Bowyer et al., 2003) shown in Fig. 4 may have facilitated this process.

We have noted that there are two options to explain type C structures in natural rocks, i.e., (1) concretionary, displacive growth of the porphyroblast such that the matrix is pushed aside, suggesting the existence of a crystallization force, and (2) that the matrix might result from later flow around the porphyroblast. For the case of the mine wood sample, this latter option must be rejected because, albeit deformed, the microstructure clearly predates the growth of the copper grains. The question remains if the wood microstructure deformed due to any externally applied force comparable to tectonic forces acting on natural metamorphic rocks, or if the observed flattening is indeed due to concretionary expansion of the growing copper porphyroblasts. At this stage, we note that there is one factor that might affect the developing microstructures, i.e., shrinking upon drying of the wood. The magnitude of such shrinking, however, differs in different directions, being largest in tangential sections with values up to about 8% for most pine woods, equal or smaller in radial directions (down to ~ 4%), and almost negligible in the (longitudinal) tracheid fibre direction (~0.5–1%, e.g., Ozkaya, 2013). Careful inspection of the porphyroblast microstructures clearly shows that the flattening deformation adjacent to the porphyroblasts is confined to relatively small domains, indicated in Figs. 5, 6 and 8, as deformed bands in which the magnitude of the flattening is much larger, i.e. of the order of 40–70% as shown in Fig. 8b. Even after correction for a pre-existing resin canal microstructure (Fig. 8c and d), these flattening strain values can clearly not be explained by shrinking upon drying of the wood. As there is no evidence for large strains resulting from externally applied forces, and because in the case of a mine-prop remnant such externally induced strains are unlikely, we conclude that the observed flattening of the wood microstructure adjacent to the copper porphyroblasts indeed reflects concretionary displacive growth and associated pushing aside of the surrounding matrix. The microstructures associated with the copper porphyroblasts seem therefore genuine proof to demonstrate the existence of a crystallization force. Note that porphyroblastesis in this case concerns the growth of a mineral that is obviously not indigenous to the wood matrix, comparable to the case of the growth of sulfide porphyroblasts in metamorphic rocks such as mentioned by Misch (1971).

5. Conclusions

There is general agreement that the growth of metamorphic porphyroblasts involves replacement of the protolith assemblage, but it is less clear if this process is accompanied by the additional operation of a displacive mechanism. Whilst in few cases such as the Bushveld hornfelses and the Dalradian chloritoid-bearing schists a component of displacive growth can be corroborated, unequivocal criteria to identify displacive growth are lacking. It follows that for natural metamorphic rocks the concept of a 'crystallization force' is surrounded by uncertainties on criteria to conclusively identify growth-related displacement as well as on the viability of displacive growth. In other words, based on microstructures in metamorphic rocks it is impossible to unequivocally demonstrate the existence of a crystallization force. In this study we have investigated wood microstructures in a pit prop from a Bronze Age copper mine in Cyprus containing Cu porphyroblasts. The pit prop became infiltrated with copper-saturated, polluted mine water during collapse of an ancient mine gallery. The microstructures associated with the copper porphyroblasts strongly indicate displacive growth whilst the matrix wood has not been affected by any externally imposed deformation, suggesting that the displacement microstructures associated with the copper porphyroblasts indeed reflect the existence of a 'force of crystallization'.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Hoadley, R.B., 1990. Identifying Wood: Accurate Results with Simple Tools. The Taunton Press, Inc, Newtown, Connecticut, USA, 224p.
Antivachis, D.N., 2015. The geology of the northern part of the Apliki Cyprus-type ore deposit. Bull. Geol. Soc. Greece 4–28. XLIX.
Becke, F., 1904. Über Mineralbestand und Struktur der kristallinischen Schiefer: Int. Geol. Congr., Rept. 4, reprinted in Akad. Wiss. Wien Denkschr, vol. 75, pp. 1–53, 1913.
Becker, G.F., Day, A.L., 1905. The linear force of growing crystals. Proc. Washingt. Acad. Sci. 8, 238–288.
Bickle, M.J., Teagle, D.A.H., 1992. Strontium alteration in the Troodos ophiolite: implications for fluid fluxes and geochemical transport in mid– ocean ridge hydrothermal systems. Earth Planet. Sci. Lett. 113, 219–237.
Bowyer, J.L., Shmulsky, R., Haygreen, J.G., 2003. Forest Products and Wood Science: an Introduction, fourth ed. Blackwell Publishing, Ames, Iowa, USA, p. 554p.
Constantinou, G., 1992. Ancient copper mining in Cyprus. In: Marangou, A., Psillides, K. (Eds.), Cyprus, Copper and the Sea, 43-74. Nicosia, Republic of Cyprus.
Correns, C.W., 1949. Growth and dissolution of crystals under linear pressure. Discuss. Faraday Soc. 5, 267–271.
Crivellaro, A., Schweingruber, F.H., 2013. Atlas of Wood, Bark and Pith Anatomy of Eastern Mediterranean Trees and Shrubs with a Special Focus on Cyprus. Springer, Heidelberg New York Dordrecht London, p. 583.
Crystal Classics website: https://www.crystalclassics.co.uk/product/native-copper-replacing-wood (accessed 25 March 2019).
Ferguson, C.C., Harvey, P.K., 1972. Porphyroblasts and "crystallization force": some textural criteria: Discussion. Bull. Geol. Soc. Am. 83, 3839–3840.
Fletcher, R.C., Merino, E., 2001. Mineral growth in rocks: kinetic-rheological models of replacement, vein formation, and syntectonic crystallization. Geochem. Cosmochim. Acta 65, 3733–3748. https://doi.org/10.1016/S0016-7037(01)00726-8.
Gass, I.G., 1968. Is the Troodos massif of Cyprus a fragment of Mesozoic ocean floor? Nature 220, 39–42.
Gratier, J.-P., Frery, E., Deschamps, P., Røyne, A., Renard, F., Dysthe, D., Ellouz-Zimmerman, N., Hamelin, B., 2012. How travertine veins grow from top to bottom and lift the rocks above them: the effect of crystallization force. Geology 40, 1015–1018.
Harker, A., 1931. Metamorphism, 2d Ed. Methuen & Co., London, p. 362.
Hudson-Edwards, K.A., Edwards, S.J., 2005. Mineralogical controls on storage of As, Cu, Pb and Zn at the abandoned Mathiatis massive sulphide mine, Cyprus. Mineral. Mag. 69 (5), 695–706.
Jamtveit, B., Putnis, C.V., Malthe-Sørenssen, A., 2008. Reaction induced fracturing during replacement processes. Contrib. Mineral. Petrol. 157, 127–133. https://doi.org/10.1007/s00410-008-0324-y.
Kelemen, P.B., Hirth, G., 2012. Reaction-driven cracking during retrograde metamorphism: olivine hydration and carbonation. Earth Planet. Sci. Lett. 345, 81–89.
Knapp, A.B., Pigott, V.C., Herbert, E.W., 1998. Social Approaches to an Industrial Past: the Archeology and Antropology of Mining. Routledge, London, p. 306.
Lambart, S., Savage, H.M., Robinson, B.G., Kelemen, P.B., 2018. Experimental investigation of the pressure of crystallization of Ca(OH)2: implications for the reactive cracking process. Geochem. Geophys. Geosyst. 19 (9), 3448–3458.
Lavalle, J., 1853. Recherches sur la formation lente des cristeaux à la température ordinaire. Acc. Sess. Acad. Sci. 36, 493–495.
Maliva, R.G., Siever, R., 1988. Diagenetic replacement controlled by force of crystallization. Geology 16 (8), 688–691.
Means, W.D., Li, T., 2001. A laboratory simulation of fibrous veins: some first observations. J. Struct. Geol. 23, 857–863.
Merino, E., Dewers, T., 1998. Implications of replacement for reaction–transport modeling. J. Hydrol 209, 137–146. https://doi.org/10.1016/S0022-1694(98)00150-4.
Merino, E., Canals, A., Fletcher, R.C., 2006. Genesis of self-organized zebra textures in burial dolomites: displacive veins, induced stress, and dolomitization. Geol. Acta 4 (3), 383–393.
Misch, P., 1971. Porphyroblasts and 'crystallization force': some textural criteria. Geol. Soc. Am. Bull. 82, 245–252.
Moores, E.M., Vine, F.J., 1971. The Troodos Massif, Cyprus and other ophiolites as oceanic crust: evaluation and implications. Philos. Trans. R. Soc. London, Ser. A 268, 443–466.
Ostapenko, G.T., 1976. Excess Pressure on the Solid Phases Generated by Hydration (According to Experimental Data on the Hydration of Periclase), 6, pp. 824–844. Translated from Geokhimikiya.
Ozkaya, K., 2013. Determination of some physical and mechanical properties of Calabrian pine (Pinus brutia Ten.) trees grown in the Denizli area of Turkey. Int. J. Phys. Sci. 8, 2063–2068. https://doi.org/10.5897/IJPS2013.3877.
Passchier, C.W., Trouw, R.A.J., 2005. Microtectonics. Springer Berlin Heidelberg, New York, p. 371.
Pattison, D.R.M., Spear, F.S., Cheney, J.T., 1999. Polymetamorphic origin of muscovite+cordierite+staurolite+biotite assemblages: implications for the metapelitic petrogenetic grid and for P–T paths. J. metamorphic Geol. 17, 685–703.
Plumper, O., Royne, A., Magraso, A., Jamtveit, B., 2012. The interface-scale mechanism of reaction-induced fracturing during serpentinization. Geology 40, 1103–1106. https://doi.org/10.1130/G33390.1.
Putnis, A., 2009. Mineral replacement reactions. Rev. Mineral. Geochem. 70 (1), 87–124.
Putnis, A., Janssen, A., Jamtveit, B., Putnis, C.V., 2009. Reaction-induced fracturing during replacement reactions. Geochem. Cosmochim. Acta Suppl. 73.
Pyatt, F.B., 2001. Copper and lead bioaccumulation by Acacia retinoides and Eucalyptus torquata in sites contaminated as a consequence of extensive ancient mining activities in Cyprus. Ecotoxicol. Environ. Saf. 50, 60–64. https://doi.org/10.1006/eesa.2001.2087.
Ramberg, H., 1952. The Origin of Metamorphic and Metasomatic Rocks. University of Chicago Press, Chicago, p. 317.
Rast, N., 1965. Nucleation and growth of metamorphic minerals. In: Pitcher, W.S., Flinn, G.W. (Eds.), Controls of Metamorphism. Oliver and Boyd, Edinburgh, pp. 73–102.
IAWA list of microscopic features for softwood identification. In: Richter, H.G., Grosser, D., Heinz, I., Gasson, P.E. (Eds.), IAWA J. 25 (1), 1–70.
Røyne, A., Jamtveit, B., Mathiesen, J., Malthe-Sørensen, A., 2008. Controls on rock weathering rates by reaction-induced hierarchical fracturing. Earth Planet. Sci. Lett. 275, 364–369.
Saggerson, E.P., 1974. Porphyroblasts and displacement: some new textural criteria from pelitic hornfels. Mineral. Mag. 39, 793–797.
Schuiling, R.D., Wensink, H., 1962. Porphyroblastic and poikiloblastic textures: the growth of large crystals in a solid medium. Neues Jahrb. Mineral. Monatshefte 11/12, 247–254.
Skarbek, R.M., Savage, H.M., Kelemen, P.B., Yancopoulos, D., 2018. Competition between crystallization-induced expansion and creep compaction during gypsum formation, and implications for serpentinization. J. Geophys. Res.: Solid Earth 123 (7), 5372–5393.
Spry, A., 1969. Metamorphic Textures. Pergamon Press, Oxford, p. 350.
Spry, A., 1972. Porphyroblasts and 'crystallization force': some textural criteria: Discussion. Geol. Soc. Am. Bull. 83, 1201–1202.
Stylianou, M., Tsiftes, K., Gavriel, I., Kostarelos, K., Demetriou, C., Papaioannou, A., 2014. Environmental impacts of abandoned sulphide mines—the example of Mathiatis Mine in Cyprus. In: Proceedings of the SYMBIOSIS International Conference, Athens, pp. 19–21. June 2014.
Taber, S., 1916. The growth of crystals under external pressure. Am. J. Sci. Series 4 (41), 532–556.
Van Noort, R., Wolterbeek, T., Drury, M., Kandianis, M., Spiers, C., 2017. The force of crystallization and fracture propagation during in-situ carbonation of peridotite. Minerals 7 (10), 190.
Weyl, P.K., 1959. Pressure solution and the force of crystallization – a phenomenological theory. J. Geophys. Res. 64, 2001–2025.
Wolterbeek, T.K., van Noort, R., Spiers, C.J., 2018. Reaction-driven casing expansion: potential for wellbore leakage mitigation. Acta Geotechnica 13, 341–366.
Yardley, B.W.D., 1974. Porphyroblasts and 'crystallization force': discussion of some theoretical constraints. Geol. Soc. Am. Bull. 85, 61–62.
Zheng, X., Cordonnier, B., Zhu, W., Renard, F., Jamtveit, B., 2018. Effects of confinement on reaction-induced fracturing during hydration of periclase. Geochem. Geophys. Geosyst. 19 (8), 2661–2672.
Zwart, H.J., 1962. On the determination of polymetamorphic mineral associations, and its application to the Bosost area (Central Pyrenees). Geol. Rundsch. 52, 38–65.
Zwart, H.J., Calon, T., 1977. Chloritoid crystals from Curaglia: growth during flattening or pushing aside. Tectonophysics 39, 477–486.