Controls on Growth of Quartz in Garnet Porphyroblasts.

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Introduction

We present results of a detailed SEM-based study of textural relations in and around garnet porphyroblasts from a thin graphitic schist horizon within the Furulund Group east of Jakobsbakken, in the Sulitjelma region of north Norway. The rock contains the assemblage Grt+Hbl+Bt+Qtz+Gr, with Ms locally preserved in garnet cores. Grt-Bt and Grt-Hbl thermometry indicates peak temperatures of about 500 °C, consistent with adjacent non-graphitic samples, and the position of this sample just above the regional garnet isograd.

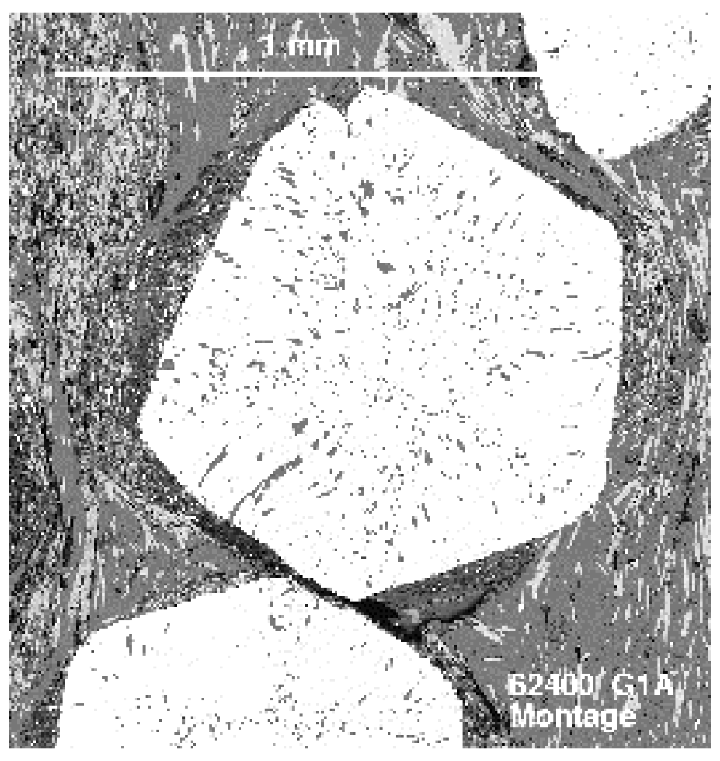


Fig. A1 BSE image of garnet porphyroblast showing well-developed type 1 'blobby' inclusions and type 2 'tubular' inclusions defining a sector-zoning habit. Note also the development of cleavage domes on {110} faces, and the curvature of some type 2 inclusions into the cleavage dome orientations.

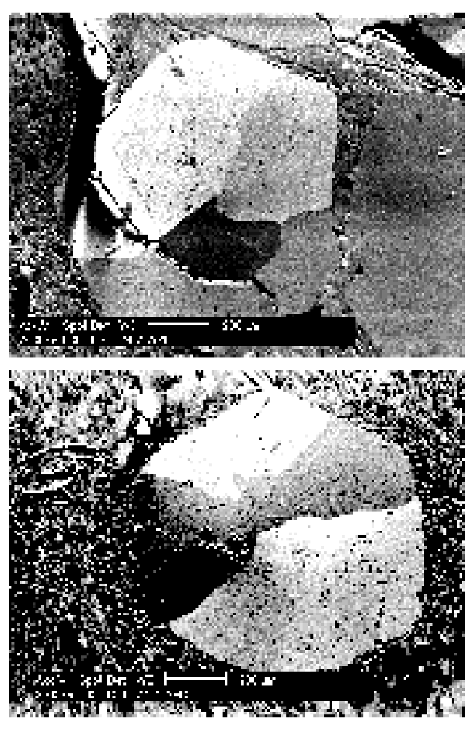


Fig. A2 FSE images of garnet porphyroblasts illustrating dislocation domains as different gray-tones. Note how the dislocation domains do not coincide with the textural sector-zone domains. Maximum misorientations across dislocation domains in these examples is 13°.

Detailed light microscopic and SEM observation of the sample reveals:

1. growth sector zoning of garnets defined by type 1 and type 2 quartz inclusions (see Figure A1);
2. sector dislocation domains in garnets revealed by fore-scatter electron (FSE) imaging (see Fig. A2), and confirmed by electron back-scatter pattern (EBSP) interpretation as up to 12° relative rotations. There are as yet insufficient data to know whether the rotation axes are systematic. Quartz inclusions are apparently not dislocated;
3. non-symmetrical matrix wrapping of the garnets;
4. cleavage domes defined by domal accumulations of graphite and biotite with minor quartz on garnet {110} crystal faces;
5. cleavage domes locally truncate the matrix wrapping structures;
6. type 2 inclusions occur as single crystal tubes entirely within garnets, but also as crystallographically continuous “nail”-like structures with the nail shaft inside the host garnet and nail head outside the host garnet and often cross-cutting cleavage domes;
7. type 2 tubular inclusions are typically parallel to {110} directions in garnet, but often curve into exterior mica domes;
8. matrix quartz preserves a complex c-axis pattern dominated by a girdle (Fig. A3a);
9. type 1 inclusions preserve a similar c-axis girdle to that in the matrix (Fig. A3b), but with some unusual orientations in the top right quadrant (which probably represent type 2 inclusions misidentified as type 1, see 10 below);
10. type 2 quartz c-axes measured from six sectors in one single garnet preserve a clustered c-axis distribution in the top-right quadrant (Fig. A4), not present in the matrix pattern. So, whereas type 2 inclusions have very different shape orientations in different sectors, they have similar c-axis orientations, which in turn are independent of garnet host crystallographic directions.

Cleavage domes and growth sector zoning have been interpreted as the result of growth in local stress fields developed under bulk hydrostatic conditions (Ferguson et al. 1980, Contrib. Min. Pet., Rice & Matthews 1991, Min. Mag.). However, textural observations made here, coupled with the style of deformation in adjacent rocks, suggest that these garnets grew under active deformation (wraps and dislocations) rather than hydrostatic conditions. The patterns of mica dome and locally curved type 2 inclusions observed in this study are consistent with development under bulk pure-shear conditions as modeled by Masuda and Mizuno (1995, J. Struct. Geol.), who predict significant differential stress distributions near rigid bodies in a pure-shear deformation system. The curved type 2 inclusions change their shape but not their crystallographic orientation. This raises the possibility that while tube orientation may be controlled by garnet growth mechanisms when the tubes are normal to pyramid faces (c.f. Rice & Mitchell 1991), curvature may reflect an increasing effect of a local stress system at or near the garnet growth surface, particularly as the garnet enlarges by growth. Quartz “nail” generation must involve precipitation of quartz outside the garnet (to cross-cut the already developed mica dome) in crystallographic continuity with the tube. If this takes place during garnet growth then the nail head has to be “cored” by the garnet during further garnet growth. The similarity of type 2 c-axis orientation in different textural sector zones of the same garnet suggests they “know about each other”, and this may be controlled by the external stress field during growth.

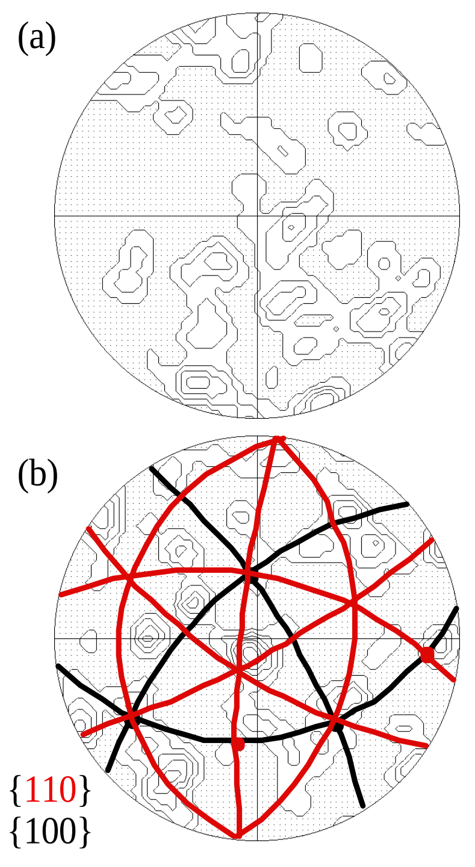


Fig. A3 c-axis orientations on equal angle stereonet plots for 150 matrix quartz grains (a) and 150 Type 1 quartz grains (b), which also summarises the crystallographic orientation of the host garnet. Note that the c-axis girdle defined by matrix quartz grains in (a) is also present in the type 1 inclusion pattern in (b). It is probable that the top-right quadrant orientations in (b) are misidentified type 2 tubular inclusions (i.e. tubes with a small aspect ratio due to cut-effect in the analysed surface.

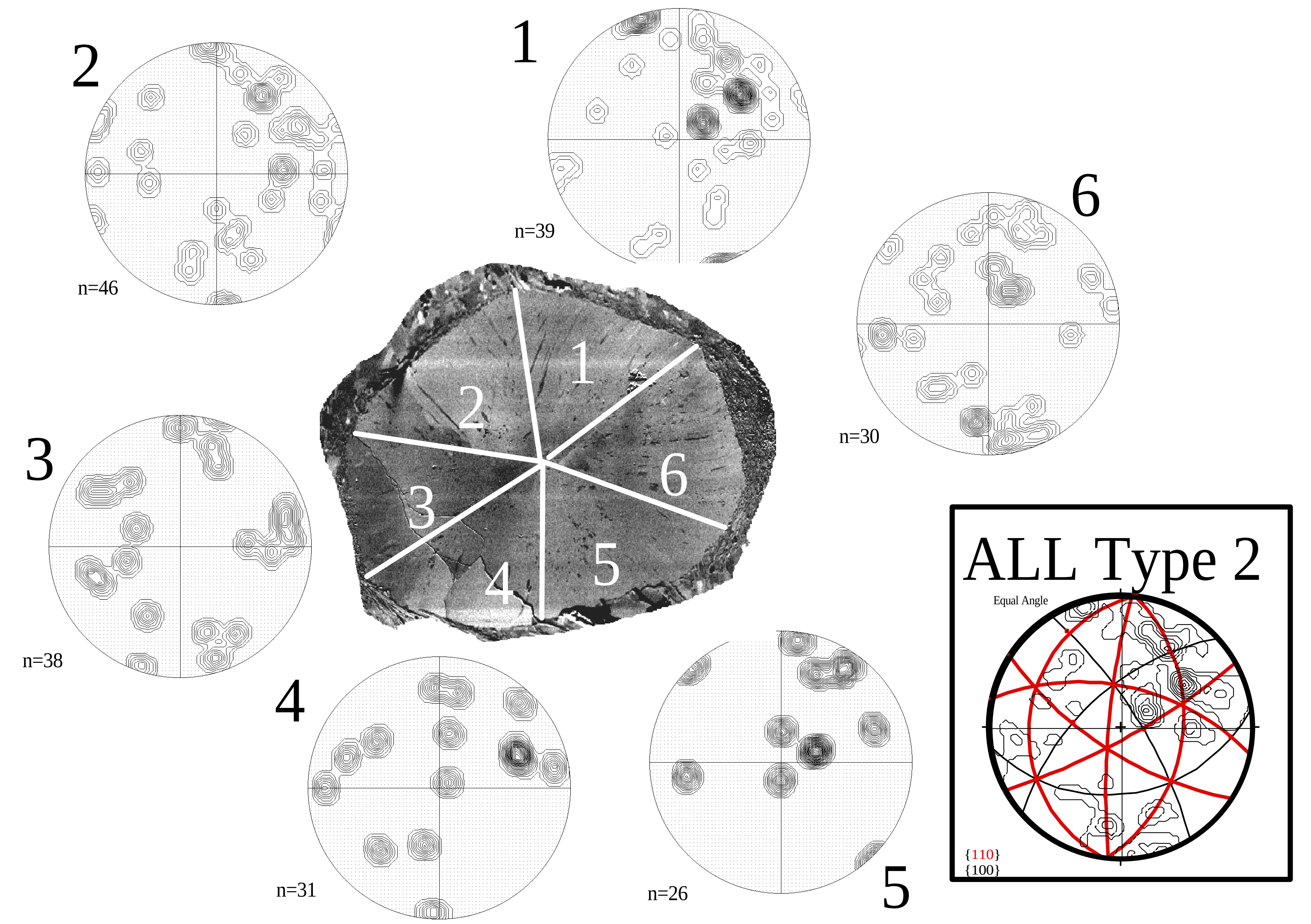


Fig. A4 Summary of Type 2 qtz inclusion c-axis orientations in 6 sectors of same garnet. Note how c-axis orientations in the top right quadrant are common in all six sectors despite very different inclusion shape orientations in each sector.

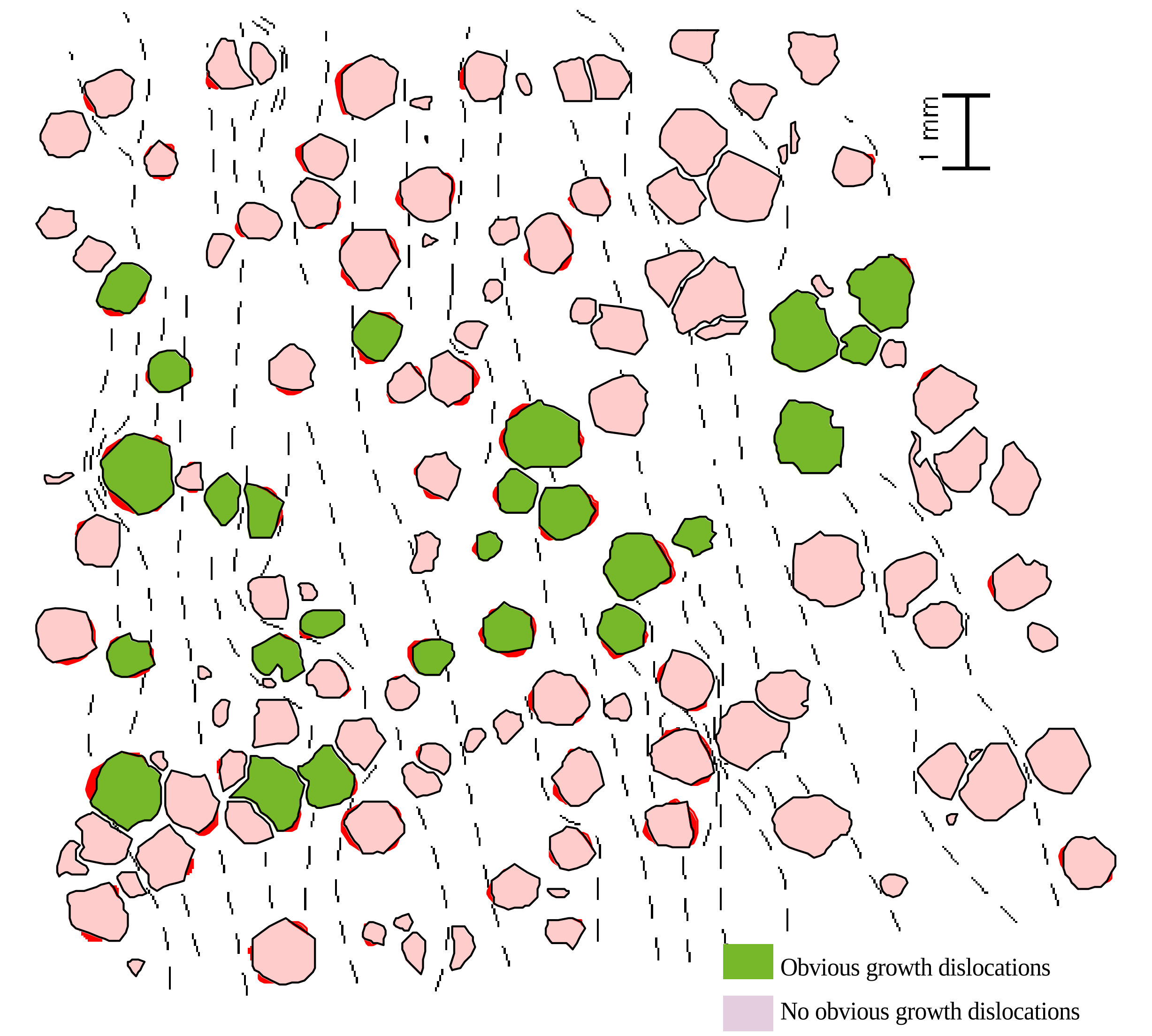
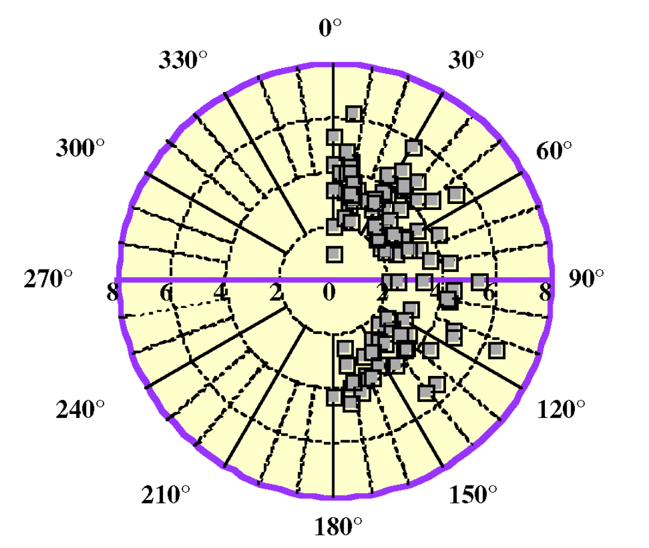


Fig. A5 Distribution of cleavage domes (in red) and trace of matrix schistosity around outlines of garnet porphyroblasts. Note that garnets with well developed dislocation textures as in Figure A2 occur in a band running across the major foliation developed in the rock.



Length of domal arc v. orientation of length

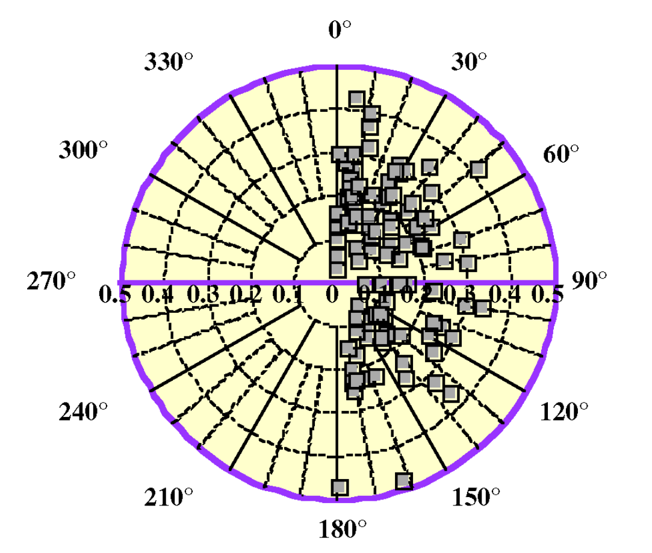


Fig. A6 Summary of cleavage dome lengths and aspect ratios against orientation. Note that domes are evenly distributed about the garnet surfaces reflecting the general control of the {110} face orientation on dome development.

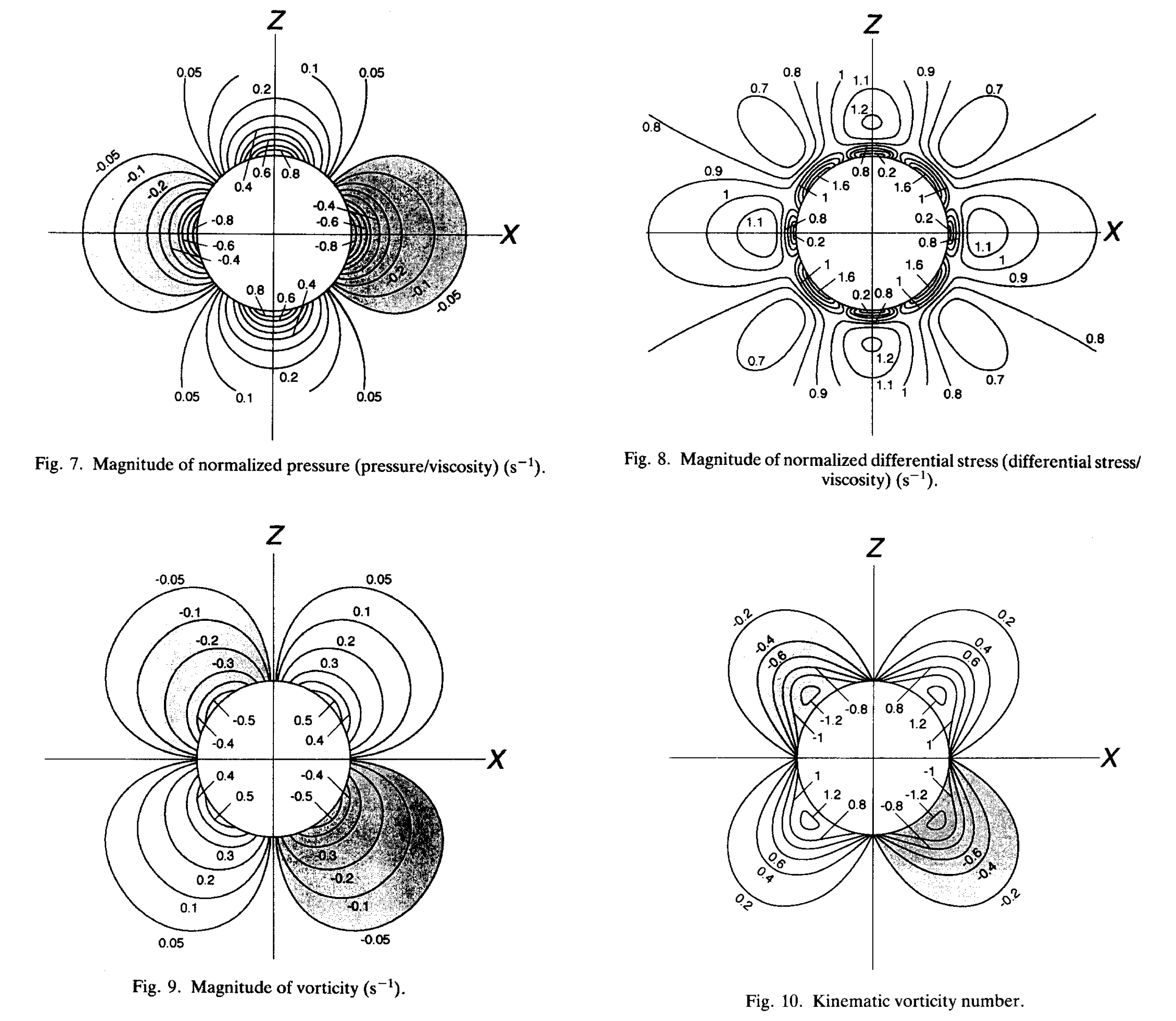


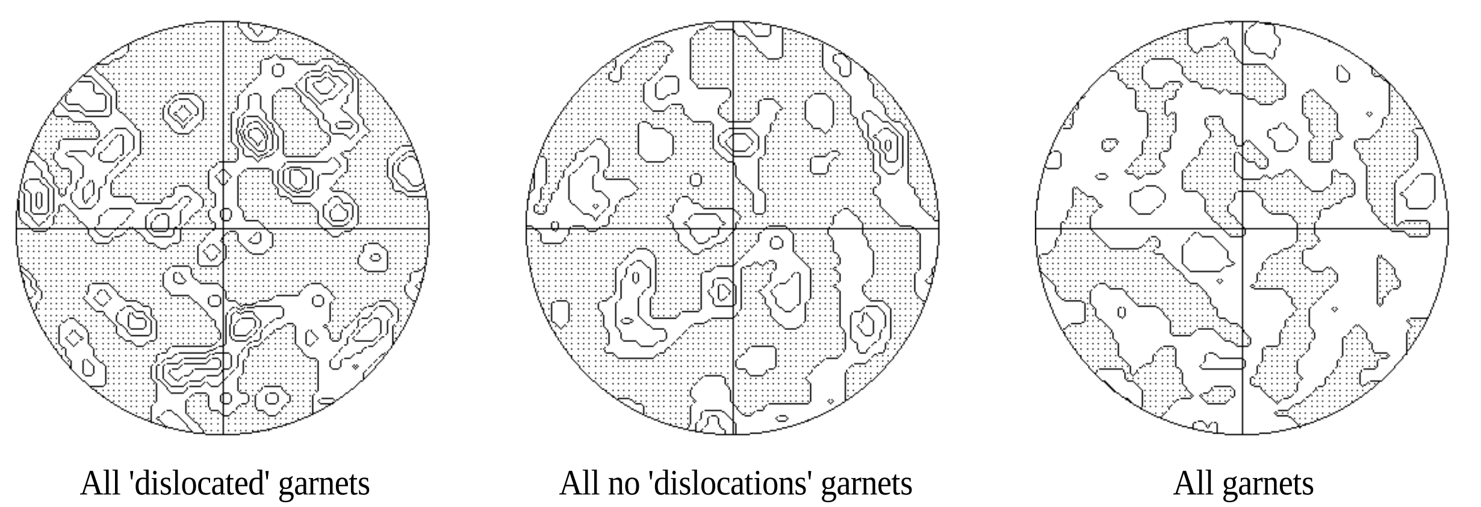
Fig. 7. Magnitude of normalized pressure (pressure/viscosity) (s^{-1}).

Fig. 8. Magnitude of normalized differential stress (differential stress/viscosity) (s^{-1}).

Fig. 9. Magnitude of vorticity (s^{-1}).

Fig. 10. Kinematic vorticity number.

Fig. A7 Theoretical stress distributions around a rigid body during pure shear deformation (from Masuda and Mizuno (1995, J. Struct. Geol.). Note the similarity of cleavage dome distributions and dimensions (in Figs. A5 & A6) with differential stress distributions in the top right figure.



All 'dislocated' garnets
n = 25

All no 'dislocations' garnets
n=95

All garnets
n=120

Fig. A8 Summary equal angle stereonets for {100} orientations in garnet porphyroblasts illustrated in Fig. A5. Data separated into garnets with growth dislocations, garnets without, and all garnets.

Garnet crystallographic orientations:

Fig. A8 summarises the crystallographic orientations (CO) of 120 garnet porphyroblasts from Fig. A5 as equal-angle stereographic projections of {100} orientations. Garnets with dislocations tend to have different CO to those without. For example, there is a cluster of {100} orientations in the top-right quadrant for dislocated garnets absent from non-dislocated garnets. This implies that there may be a relationship between CO and the development of growth dislocations, and that this may have been developed at the time of nucleation. It therefore seems possible that local microstructural controls have governed CO and the development of growth dislocations. However, the fact that garnets so affected have no simple relationship to observable microstructural domains (see Fig, A5) means that we do not as yet have a proper explanation.

Results indicate that:

- these garnets and their associated textures developed during growth under non-hydrostatic stress conditions;
- while type 2 tube inclusion shapes may be primarily controlled by garnet crystallography and growth {110}, when garnet reaches a critical size local stress fields develop at the garnet face to produce cleavage domes and it seems that quartz shape orientation then also reflects this change;
- while type 2 inclusions have very different shape orientations in different sectors of the host garnet they have similar CPOs, suggesting some external control on CO at the time of quartz nucleation, and we provisionally suggest that this control is the external stress field;
- there appears to be a possible relationship between garnet CO and the development of growth dislocation textures, suggesting there may be some local microstructural control at nucleation affecting both CO and development of dislocations;
- we need to do a lot more work taking apart more garnets and their immediate matrix !