

Origin and mechanical significance of honeycomb garnet in high-pressure metasedimentary rocks from the Tauern Window, Eastern Alps

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ABSTRACT High-pressure schists (2–2.5 GPa) from the Eclogite Zone in the Tauern Window contain honeycomb garnet in which fine webs of garnet surround strain-free quartz $\pm$ carbonate grains. High-resolution X-ray computed tomography shows that the garnet webs form a cellular structure that coats all surfaces of the inclusions. Electron backscatter diffraction analysis shows that the garnet cells are crystallographically continuous with more massive garnet regions, and that the quartz $\pm$ carbonate inclusions have random orientations; in contrast, matrix quartz exhibits a prominent crystallographic preferred orientation (CPO). High-resolution transmission electron microscopy shows few dislocations in either the garnet or the inclusion quartz. Most honeycomb garnet is chemically homogeneous, but some displays asymmetric core–rim zoning. Taken together, these observations are most consistent with formation of the garnet sheets via precipitation from a wetting fluid along quartz–quartz grain boundaries, or possibly via wholesale precipitation of garnet + quartz $\pm$ carbonate from a fluid. In either case, a silicate-rich aqueous fluid must have been present. The likelihood that a fully wetting fluid existed at high pressure has important implications for rheology during subduction of metasedimentary rocks: strain may be accommodated by grain rotation and sliding in an aqueous silicate slurry, rather than via dislocation creep mechanisms at high pressures. The absence of a CPO in early quartz may thus point to involvement of a pervasive grain-boundary fluid rather than requiring low differential stresses during subduction.

Key words: fluid–rock interaction; garnet; high pressure; microstructure.

INTRODUCTION

Honeycomb garnet, in which garnet forms interconnected sheets a few microns thick around quartz $\pm$ dolomite grains, is abundant in 2.0–2.5 GPa metasedimentary rocks of the Eclogite Zone (EZ) in the Tauern Window, Eastern Alps. Garnet in compositionally similar, but lower pressure rocks, in adjacent tectonic units lacks the honeycomb morphology. This observation suggests that pressure may have been a key variable in controlling garnet growth mechanisms. Although few previous studies have looked at growth mechanisms of honeycomb porphyroblasts, the honeycomb morphology seems to be more common in high-pressure and ultrahigh-pressure rocks than it is in rocks that were buried to typical crustal depths (e.g. Spry, 1969; Stöckhert *et al.*, 1997; Beane & Sorensen, 2007).

In one of the few detailed studies of the honeycomb texture, Stöckhert *et al.* (1997) used the strain-free nature of quartz included within garnet to argue that very low differential stresses must prevail at the pres-

sure peak during subduction. This interpretation, however, depends upon the mechanism by which honeycomb garnet grows. In this study, several possible mechanisms for formation of honeycomb garnet are evaluated, focusing both on the role of pressure and on solid-state processes *v.* those that involve a fluid phase. We conclude that the honeycomb morphology requires the presence of a polymerized, silicate-rich aqueous fluid at high-pressure conditions, and examine the implications of this conclusion for interpretations of microstructures in high-*P* metasedimentary rocks.

Aqueous fluids play an important role in metamorphic reactions and in controlling rock rheology at crustal conditions. However, less is known about the compositional range and physical behaviour of fluids in equilibrium with natural rocks at high-pressure conditions, and hence it is not easy to extrapolate observations from moderate pressure regimes to regions affected by subduction. Several recent studies show that aqueous fluids and silicate melts become miscible at conditions above 1.5–2.0 GPa and temperatures as low as 600 °C (e.g. Shen & Keppler, 1997;

Bureau & Keppler, 1999; Manning, 2004; Mysen & Cody, 2004), and experimental data also show that silica and other species become more soluble in aqueous fluids at high pressures (Newton & Manning, 2000; Shmulovich *et al.*, 2001; Gerya *et al.*, 2005; Fockenberg *et al.*, 2006; Manning, 2006). Studies of fluid and solid inclusions in high-pressure and ultra-high-pressure rocks provide direct evidence for production of high-density, supercritical, silicate-rich aqueous fluids at great depths (Philippot & Selverstone, 1991; Scambelluri & Philippot, 2001; Ferrando *et al.*, 2005; Malaspina *et al.*, 2006). If such complex fluids are common, they may profoundly influence the processes whereby porphyroblasts grow and strain is accommodated at high pressure.

PREVIOUS STUDIES OF HONEYCOMB GARNET

One of the few descriptions of honeycomb garnet in the literature is that of Spry (1969, p. 271), who referred to the garnet as fishnets rather than honeycombs: 'Skeletal, fishnet garnets are large, web-like crystals containing so many quartz inclusions that the quartz predominates. The grain size and fabric of the quartz inclusions is similar to that in the matrix, and it appears that the garnet has crystallized along the intergranular boundaries of the quartz aggregate. This is a high surface energy form and would appear to be less stable than a single homogeneous idioblast of garnet. It is due to formation of garnet along grain boundaries, perhaps due to crystallization from an intergranular fluid'.

Voll (1960) also discussed what he referred to as 'the well-known fishnet garnet'. He implied that quartz–quartz–garnet dihedral angles were capable of switching between 0° and higher angles during growth of a single garnet porphyroblast in quartz-rich rocks. Vernon (1968) rejected Voll's (1960) argument that the fishnet morphology formed when quartz–quartz–garnet dihedral angles were 0° by noting that fishnet garnet from Broken Hill, Australia, had large dihedral angles.

Other authors have referred to similar garnet textures simply as 'skeletal' (Engvik *et al.*, 2000; Hosc hek, 2001) or 'poikiloblastic' (Stöckhert *et al.*, 1997). The only recent study that addresses the origin of the honeycomb microstructure is by Stöckhert *et al.* (1997). The garnet in that study (from the same eclogite facies region as samples described here) contains interlayered massive and honeycomb domains. Element distribution maps of the garnet show concentric zoning in all major elemental components. Thermobarometry indicates that the garnet began growing close to peak conditions of 2.5 GPa and 600 °C and continued to grow during the early stages of decompression. The quartz foam microstructure preserved inside the garnet was interpreted to predate garnet growth and to have been controlled by interfacial free energy rather than by dislocation creep

processes. This microstructural state can only be achieved at very low differential stress, which led Stöckhert *et al.* (1997) to infer that deformation was localized to zones of weakness while the rocks were at their maximum depths of burial or just beginning their ascent. The authors also stated that quartz–quartz–garnet dihedral angles are large, and hence that garnet did not wet the quartz grain boundaries. Rather, they argued that the garnet webs outline grain boundary diffusion pathways. They did not speculate on why honeycomb garnet is preferentially developed in eclogite facies rocks compared with the surrounding units.

GEOLOGICAL SETTING AND PREVIOUS WORK

The Tauern Window is located in the Eastern Alps, almost entirely within Austria. It is a tectonic window that exposes Penninic nappes of European affinity through the overlying Austroalpine nappes. The Penninic nappes are divided into three major units in the Tauern Window: the Zentralgneis (ZG), which largely consists of Hercynian granitoids; the Lower Schieferhülle (LSH) nappe stack, which includes Palaeozoic rocks into which the ZG intruded as well as younger Permo-Mesozoic continental metasedimentary rocks; and the Upper Schieferhülle (USH), which is a nappe stack of mafic and metasedimentary rocks of oceanic affinity that is locally subdivided into the Rote Wand-Modereck Nappe, Glockner Nappe imbricates, and a greenschist-dominated unit thought to be a retrogressed portion of the EZ (e.g. Frank *et al.*, 1987; Kurz *et al.*, 1998a). The EZ, the unit of interest in this study, is tectonically sandwiched between the LSH and USH series in the central part of the Window. The assorted eclogites and eclogite facies metaquartzites, marbles, mica schists, quartz–mica schists, graphitic schists and calc–mica schists of the EZ represent volcanoclastic and terrigenous sediments deposited on the passive margin of a spreading Penninic ocean basin, during the late Early Jurassic or possibly earlier (Kurz *et al.*, 1998b; Ratschbacher *et al.*, 2004).

Rocks of the EZ record several stages in their metamorphic history: Eoalpine blueschist facies metamorphism associated with rapid subduction; high-pressure eclogite facies metamorphism; a younger blueschist facies overprint; and finally overprinting by greenschist/amphibolite facies assemblages ('Tauern event') during exhumation (Hoinkes *et al.*, 1999; Kurz *et al.*, 1999). Kyanite eclogites in the EZ yield pressures of 1.7–2.3 GPa and 570–600 °C (Holland, 1979; Hosc hek, 2001; Dachs & Proyer, 2002) based on mineral assemblage and calculations in the NCFMASH system. Analyses of the associated metasedimentary rocks yield similar pressure and temperature conditions (Franz & Spear, 1983; Spear & Franz, 1986; Dachs, 1990; Hosc hek, 2001), but conditions as high as 2.5 GPa at 595 °C have also been reported (Stöckhert *et al.*, 1997). The age of the high-pressure event is still

unclear. $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of post- P_{max} amphibole and white mica yields dates of 42–39 Ma, leading Ratschbacher *et al.* (2004) to argue for eclogite metamorphism at *c.* 45 Ma. In contrast, Glodny *et al.* (2005) presented Rb–Sr mineral isochrons from high-pressure veins that yield dates of 31.5 ± 0.7 Ma. Exhumation of the EZ to intermediate levels after eclogitization has been estimated to be as rapid as 36 mm year^{-1} (Glodny *et al.*, 2005), a rate that is comparable to that of subduction.

The USH and LSH units between which the EZ was emplaced followed different metamorphic P – T paths. In the central Tauern Window, the LSH experienced maximum pressures of 0.9–1.2 GPa during early Alpine metamorphism (Brunsmann *et al.*, 2000). The USH locally contains slivers that record pressures as high as 1.2–1.7 GPa near the EZ (Holland, 1979; Dachs, 1990; Dachs & Proyer, 2001). The EZ was juxtaposed between the LSH and USH prior to amphibolite to greenschist facies overprinting associated with the Tauern thermal peak (Morteani, 1974). The mechanisms and conditions of emplacement of the EZ between the lower pressure LSH and USH series are still unclear (Kurz *et al.*, 1998a; Kurz, 2005).

Fluid inclusions in samples from the EZ record variable metamorphic fluid compositions. Luckscheiter & Morteani (1980a,b) determined that the texturally earliest inclusions are CO_2 -rich with little to no dissolved salt. These inclusions preserve isochoric pressures of only 0.7–0.8 GPa, and thus may have leaked or been otherwise modified following entrapment. Holland (1979) found fluid inclusions with low CO_2 contents, low salt contents and high water activity, and determined that they originated around 1.9 GPa, but such inclusions were not found in the Luckscheiter and Morteani study. Fluid inclusions studied by Thomas (1991) consisted of mixtures of H_2O , CO_2 , N_2 , and up to 60 wt% of various salts, as well as many daughter crystals. Selverstone *et al.* (1992) found that individual layers in finely banded mafic eclogites from the Frosnitz Tal equilibrated with fluids with different H_2O and CO_2 activities, indicating that fluid compositions were internally controlled. These studies show that water-rich, carbonic and saline fluids were all present in the EZ during high-pressure metamorphism and were heterogeneously distributed (Getty & Selverstone, 1994). No fluid inclusion data exist for the intercalated metasedimentary units.

SAMPLE DESCRIPTIONS

Samples of high-pressure metasedimentary rocks were collected from 15 localities in the Dorfer Tal and seven localities in the Frosnitz Tal (Fig. 1). Representative samples were also taken from the LSH immediately below the EZ and from the Rote Wand-Modereck nappe and greenschist-dominated unit of the USH above the EZ; these latter units both locally contain high-pressure relics (Dachs & Proyer, 2001;

Dachs *et al.*, 2005). Most samples were oriented in the field.

Honeycomb garnet occurs in all siliciclastic meta-sedimentary rock types in the EZ: quartz–mica schists, calc–mica schists, graphitic schists and quartzites. Honeycomb garnet is also locally present within the Venediger Nappe (LSH) and the Rote Wand-Modereck Nappe (USH) immediately adjacent to the EZ, but most LSH and USH samples contain subhedral garnet that lacks the honeycomb texture.

Twenty-five thin sections and polished sections were cut for petrographic analysis and for microprobe, scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD) analyses. Thin sections were cut parallel to lineation and perpendicular to foliation where orientations were available. Some sections were also cut perpendicular to both lineation and foliation.

Structural data are in agreement with the measurements of Kurz *et al.* (1998a). The dominant foliation strikes NE–ENE and dips moderately to steeply to the SE–ESE. Many of the schist horizons lack a prominent lineation, but intercalated mafic eclogites generally display a shallowly S–SW plunging lineation defined by aligned omphacite and zoisite. Local rodding in the schists shows the same orientation. S–C fabrics are locally well developed in the schists and generally indicate dextral shear with a component of top–SW normal motion.

Mineral assemblages are listed in Table 1 and are similar to those reported by Hoschek (2001). Mica schists are characterized by millimetre-scale layering of quartz-rich and mica-rich horizons. Accessory minerals, predominantly tourmaline, rutile and opaques, are abundant in the more pelitic layers. Most samples contain garnet with the honeycomb morphology. Many samples contain zoisite or clinozoisite, and graphite is locally present in most samples. Chloritoid is present in the matrix and/or as inclusions in garnet in a few samples.

Calc–mica schists are dominated by white mica and carbonate (dolomite $\pm$ calcite) that define the foliation. Quartz-rich layers are less abundant than in the mica-schists. Garnet and zoisite/clinozoisite occur in most samples. Tourmaline, rare chlorite and biotite, rutile and opaques are locally present. Some samples are nearly black due to the high abundance of graphite. The single quartzite sample contains quartz, kyanite, chloritoid, clinozoisite and white mica, and one poorly developed honeycomb garnet.

Honeycomb garnet is most abundant in the mica schists and calc–mica schists (e.g. Fig. 2a), with some samples containing up to 10 garnet per thin section, although two to five garnet per section is more typical. Garnet ranges from 1 to 2 mm to as much as 2 cm in diameter (e.g. Fig. 2a *v.* 2b). The morphology of honeycomb garnet is highly variable and does not appear to follow a spatial or lithological pattern (Figs 2 & 3). Some garnet is entirely skeletal, con-

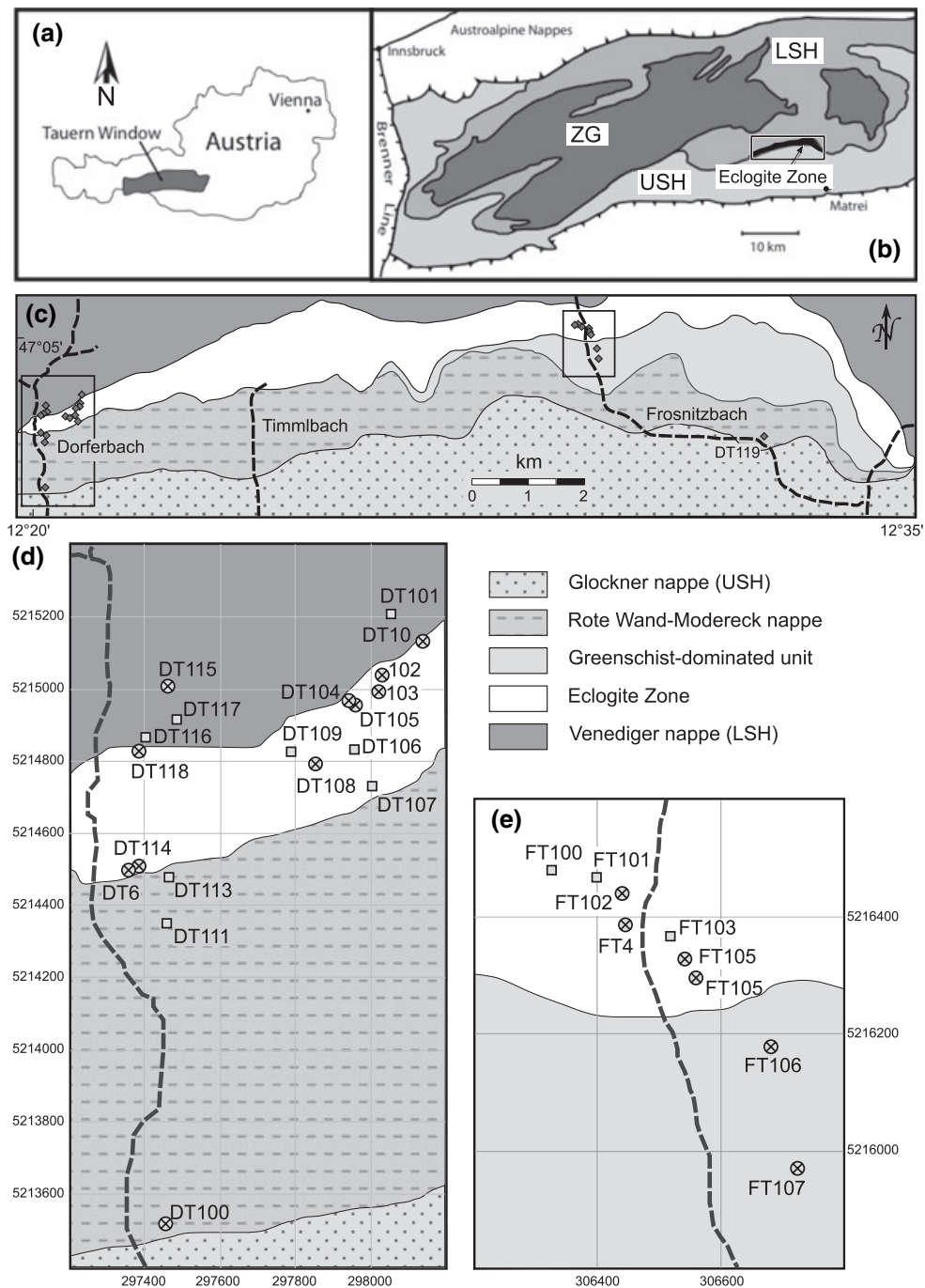


Fig. 1. Maps showing location of Eclogite Zone within the Tauern Window (a, b), the location of sample transects in the Dorfer and Frosnitz valleys (c), and metasedimentary sample localities within these valleys (e, f). Samples that contain honeycomb garnet are indicated by circles with crosses; garnet-bearing sample localities that lack honeycomb morphology are shown in squares. Austrian UTM grid shown in (d) and (e).

taining high percentages of quartz $\pm$ dolomite inclusions surrounded by the honeycomb garnet structure (Fig. 3a,e). Other garnet displays alternating elongate bands of massive and honeycomb regions (Figs 2a & 3e), but with no consistent orientation of the bands relative to the matrix fabric. Still other garnet is nearly

euhedral but has linear honeycomb regions that crosscut the grain. Honeycomb regions also occur both within cores of otherwise massive grains and as overgrowths around massive cores (Fig. 3c), and they locally follow rational crystallographic faces of the garnet. These textural relationships suggest that honeycomb

Table 1. Mineral assemblages.

	grt	wm	Cal.dol	zo	czo/ep	ky	cld	gr	rt	tur	chl	bt	pl
<i>Eclogite Zone</i>													
DT6	H	x	x	x				x					
DT10	H	x	x		x					x	x		
DT102A	H	x	2x	x				x	x		r		
DT103A	H	x	x							x			
DT104B	H	x	x	x				x		x	x	r	
DT105	H	x	2x	x				x		x	± r		
DT107C	H	x	x	x							x		
DT108	H	x	x	x				x	x	x			
DT114B	H	x	x		x					x	r	r	r
DT114C	H	x	x	x				x	x	x	x		
DT114D	H	x	x	x			x	x	x	x	r		
DT118A	H	x				x	x						
DT119BP	H	x	2x	x				x	x	x	r		
HT4C	H	x						x					
HT102	H	x	x					x	x	x	r		r
HT104	H	x	2x	x				x	x				
<i>Lower and Upper Schieferhülle ± retrogressed Eclogite Zone</i>													
DT100	± H	x					inc			x	r		
DT101B	NH	x	x								x	x	x
DT115	NH	x							x		r	x	x
DT116	NH	x							x		r		x
DT117	NH	x							x		r	r	x
HT106A	PH	x	2x		x						r		x
HT106B	H	x	x		x						r	x	
HT107A	± H	x	x				inc		x	x			
HT108	± H	x	x					x		x	± r		

H: garnet has honeycomb morphology; NH: no honeycomb garnet observed; ± H: most garnet lacks honeycomb morphology, but one to two garnets per thin section show some honeycomb structure; PH: chlorite + mica pseudomorphs after garnet preserve honeycomb structure; 2x: sample contains two coexisting carbonates; r: mineral is retrograde; inc: mineral only present as inclusions in garnet.

garnet growth both preceded and followed growth of more typical garnet shapes. Regardless of morphology, all of the honeycomb garnet is characterized by $\leq 20 \mu\text{m}$ thick webs of garnet surrounding rounded inclusions of quartz $\pm$ carbonate (e.g. Fig. 4a). Quartz inclusions are ubiquitous within the honeycomb regions and range from ≤ 10 to 200–300 μm even within a single garnet. The quartz inclusions themselves contain ubiquitous, randomly oriented micro-inclusions of clinozoisite + rutile $\pm$ paragonite $\pm$ dolomite $\pm$ apatite $\pm$ epidote (Fig. 4b). No such inclusions are present in matrix quartz. Dolomite inclusions are present only in some honeycomb garnet from calc–mica schists, but where present are similar in size to quartz inclusions and also appear strain free.

Massive regions of some garnet display abundant fractures that are filled with chlorite and/or white mica. The fractures are parallel to one another and usually perpendicular to the long axis of elongate portions of the garnet (Fig. 3e), but there is no systematic orientation of either the garnet or the fractures with respect to the regional foliation and lineation. The fractures in the massive portions of the garnet do not extend into honeycomb regions.

The quartz inclusions that are enclosed within the garnet webs show no undulose extinction and no development of subgrains. When viewed with a gypsum plate, each inclusion shows a different colour (Fig. 3), indicating that the grains are in different crystallographic orientations. This is in striking contrast to quartz in the matrix, which shows sutured and

bulging grain boundaries, undulose extinction, and a prominent crystallographic preferred orientation (CPO) (Fig. 3). The matrix quartz primarily records strain accommodation by subgrain rotation recrystallization (Hirth & Tullis, 1992; Heilbronner & Tullis, 2002), insofar as few samples exhibit the larger grains and smoother grain boundaries of Regime 3 dislocation creep. The large difference in quartz microstructures observed between inclusions and the matrix contrasts with Spry's (1969) description of similar grain sizes and fabrics recorded by quartz within garnet v. matrix quartz, but is similar to observations made by Stöckhert *et al.* (1997) and Stöckhert (2002).

The timing of quartz $\pm$ dolomite inclusion growth relative to garnet web growth has been difficult to tease out of the available data. Most of the inclusions are rounded rather than euhedral, an observation that is consistent with several possible interpretations: (i) quartz predates garnet and was partially consumed in the garnet-forming reaction; (ii) quartz predates garnet, and the grain shapes reflect interfacial energy minimization and grain boundary adjustment during growth of the surrounding garnet (e.g. Vernon, 1968); or (iii) garnet and quartz nucleated and grew simultaneously. Regardless of the relative age of the quartz, variations in apparent quartz–quartz–garnet dihedral angles (e.g. Fig. 4b) suggest that grain boundary readjustment was incomplete and that remnants of the original garnet–quartz fabric were quenched in place.

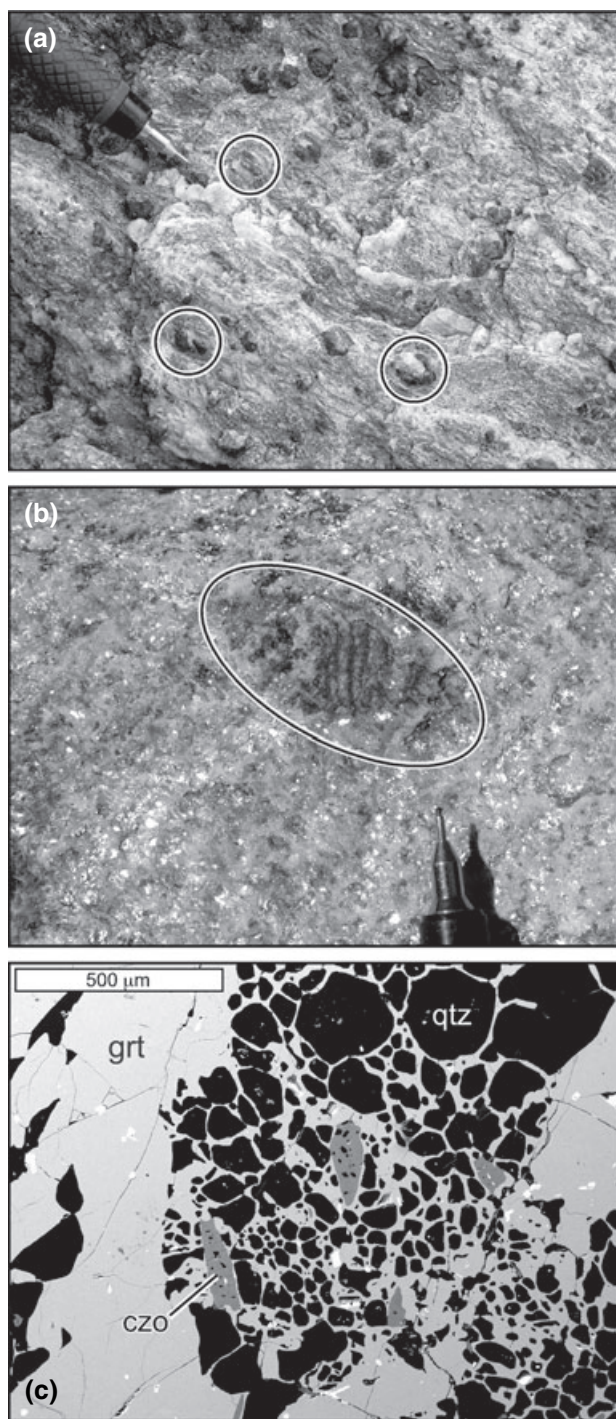


Fig. 2. Photos showing field appearance of honeycomb garnet in (a) graphitic schist, and (b) quartz-rich mica schist. (c) Back-scattered electron image showing massive garnet and webs of honeycomb garnet around quartz inclusions.

ANALYTICAL TECHNIQUES

The major element composition of nine metasedimentary samples from the USH, LSH and EZ was determined with a Rigaku RIX 2100 wavelength dispersive

X-ray fluorescence spectrometer in the Analytical Geochemistry Laboratory at the University of New Mexico, USA. Samples were prepared by first crushing hand samples to gravel size in a Bico jaw crusher before further processing by hand with a mortar and pestle. A Spex shatter box was used to reduce the samples to a fine powder. The sample powder was passed through a 100 µm mesh sieve. Approximately 0.50 g of sample were taken for loss on ignition determination, and 1.0 g of each sample was mixed with nine parts by weight of a lithium tetraborate flux and fused into a disc for analysis.

Mineral compositions, backscatter electron (BSE) images and chemical zoning maps were obtained using the JEOL 8200 microprobe at the University of New Mexico. Quantitative analysis and X-ray maps were obtained at an accelerating voltage of 15 kV and a beam current of 20–30 nA. Natural samples of known composition were used as standards. BSE and cathodoluminescence (CL) images were collected on a JEOL 5800LV SEM at the University of New Mexico. BSE images were taken with an accelerating voltage of 15 kV and CL images at 10 kV.

Information on garnet distribution in the third dimension was obtained with high-resolution X-ray computed tomography (HRXCT) scans of two honeycomb samples at the University of Texas at Austin (UTCT). Samples were scanned with unfiltered X-rays at 180 kV and 0.133 mA, calibrated using an air wedge. Images were reconstructed from 2400 views, with 0.2 s acquisition time per view. Data pixel and slice spacing for sample FT105A were 11.52 and 12.62 µm, respectively, and 8.79 and 9.55 µm for DT102A.

Electron backscatter diffraction analysis was conducted at Bowdoin College on a LEO 1450VP SEM fitted with an HKL Nordlys II detector and Channel 5 software. Samples were prepared by taking standard polished thin sections weighted with halved brass rods and polishing for an additional 6 h in a non-crystallizing colloidal silica suspension on a Buehler Vibromet2 vibratory polisher (SYTON method of Fynn & Powell, 1979). Thin sections were not carbon coated; charging was minimized by using a chamber pressure of 10 Pa, combined with the 70° tilt. Operating parameters for collecting EBSD patterns were an accelerating voltage of 20 kV, working distance of 25 mm, probe current of 2.2 nA and 4–5 µm step size. Honeycomb garnet and quartz inclusions in sample DT6 were mapped for orientation information. Mean angular deviations between the detected Kikuchi bands and the simulations were less than 1.3°. Data were post-processed by removing wild spikes, and by extrapolating zero solutions based on four neighbours. (Wild spikes are isolated measurement points that differ significantly from adjacent measurements, usually as a result of sample damage that causes poor pattern generation.)

For transmission electron microscopic (TEM) analyses, doubly polished, demountable petrographic thin

sections mounted using Superglue were prepared from selected honeycomb garnet-bearing samples. Slotted 3-mm diameter Cu grids were glued over representative garnet using an acetone-insoluble epoxy and the garnet was then removed from the glass mounting slide by immersion in acetone. These samples were prepared for TEM studies by conventional ion milling techniques (Ar^+ ions) using a GATAN Duobeam ion mill. An additional sample of the interface between garnet and quartz was also prepared using the FIB (focused ion beam) preparation technique at the Kelvin Nanocharacterization Facility, Department of Physics and Astronomy, University of Glasgow, Scotland. TEM was carried out using both the JEOL 2010 high-resolution TEM (HRTEM) and the JEOL 2010F FASTEM field emission gun scanning TEM (STEM) at the TEM Laboratory at the University of New Mexico. Average accelerating velocity was 200 kV for the JEOL 2010 and 197 kV for the JEOL 2010F. The samples were studied using bright and dark field TEM, high angle annular dark field STEM imaging, as well as high-resolution TEM and electron diffraction techniques.

DISCUSSION OF RESULTS

Bulk composition v. P - T conditions

Bulk rock geochemical analyses of samples from the USH, LSH and EZ units show a range of compositions (Fig. 5), with SiO_2 concentrations between 56 and 71 wt% (Table 2). Honeycomb garnet was found in all analysed samples from the EZ, and in one sample of uncertain P - T history from the USH. Two samples each from the LSH and USH lack honeycomb garnet. All samples that contain honeycomb garnet have SiO_2 concentrations of <67 wt%, but there are no other systematic chemical variations between samples with and without the honeycomb morphology (e.g. Fig. 5). Honeycomb garnet has not been documented in demonstrably lower pressure rocks elsewhere in the Tauern Window; therefore, the metamorphic and structural history of the rocks is more likely to be the controlling factor than bulk rock chemistry.

Garnet composition and zoning

Honeycomb garnet in samples DT10, DT103A and DT114C from the EZ and sample DT100 from the USH has remarkably similar compositions that average $\text{Pyr}_{90}\text{Alm}_{69}\text{Sps}_{20}\text{Grs}_{20}$ and show less than 5 mol.% variation among the end-members (Table 3). X-ray maps of the EZ samples indicate that the limited zoning is patchy and discontinuous (Fig. 6). Mn shows the most pronounced zoning, but with no systematic difference between massive and honeycomb regions of individual garnet. In most cases, Mn zoning parallels the main foliation trace within a sample, but this is not universally true. Figure 7 shows quantitative analyses along the garnet webs and across the massive portion

of a honeycomb garnet in sample DT100 from the USH. Again, there is no significant difference between massive and honeycomb portions of the garnet, and the average composition is nearly identical to garnet from the EZ.

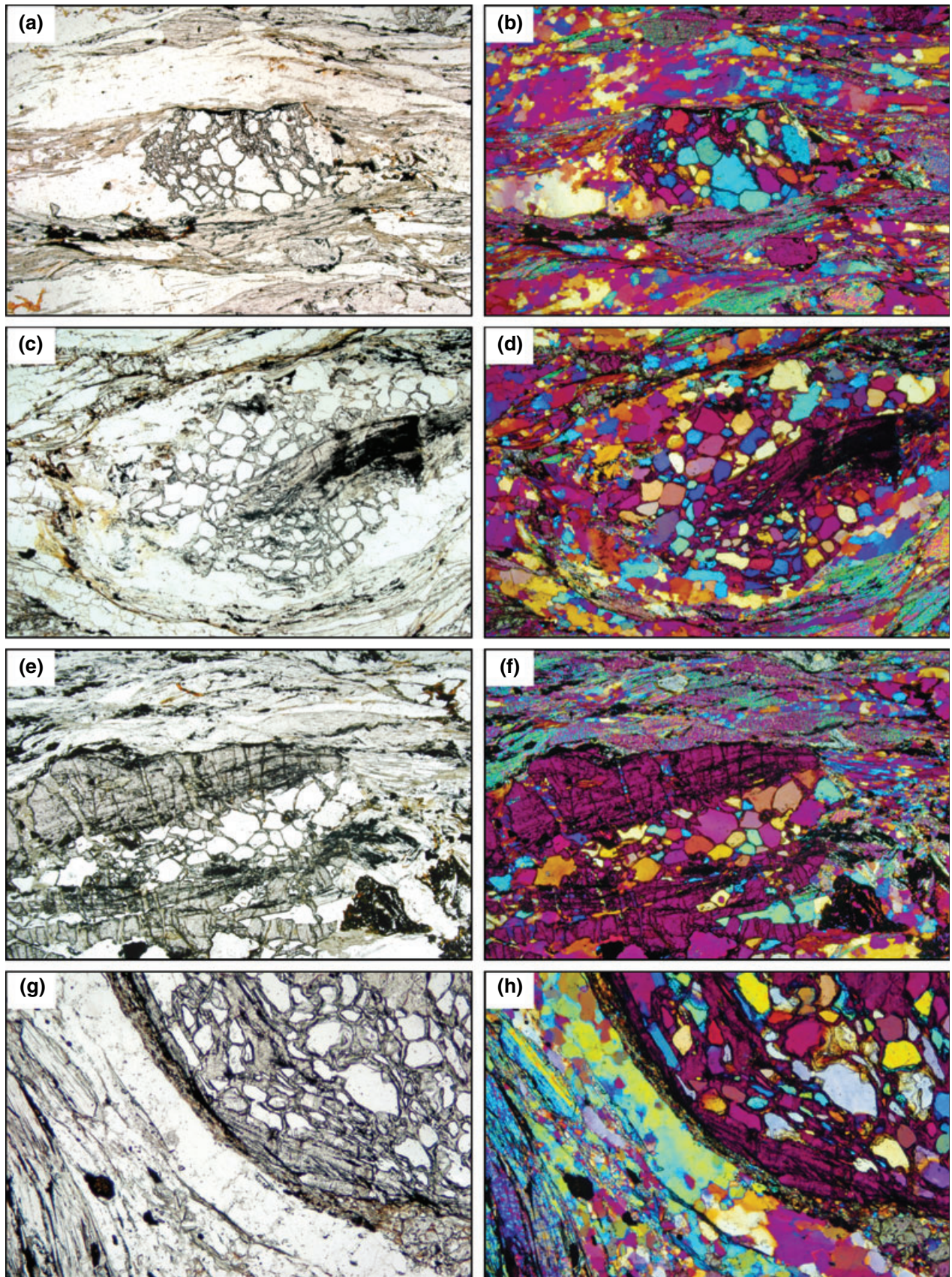
The patchy zoning in honeycomb garnet of this study differs from the concentric zoning reported by Stöckhert *et al.* (1997), but appears to be a widespread feature within the sample set. Irregular and/or truncated zoning patterns observed in other metamorphic settings have been interpreted to reflect garnet growth from chemically heterogeneous precursor phases coupled with slow diffusion rates (Spear & Daniel, 2001; Hirsch *et al.*, 2003), or garnet modification via dissolution-precipitation creep (Wintsch & Yi, 2002). Either of these mechanisms could account for the patchy zoning in honeycomb garnet, but the absence of clear truncations in zoning is more consistent with the former case. The limited compositional range of each garnet, coupled with the lack of concentric zoning, suggest that garnet grew at conditions where intergranular diffusion rates of Fe, Mg and Ca were rapid, but Mn diffusion rates may have been more sluggish (e.g. Carlson, 2002).

Quartz microstructures

Quartz inclusions within garnet of this study and that of Stöckhert *et al.* (1997) show no CPO (Fig. 8), despite tectonic transport to depths in excess of 70 km and return to the surface. In general, dynamic recrystallization involving dislocation creep processes will generate a prominent CPO (e.g. Gleason *et al.*, 1993; Kurz *et al.*, 2004). Both experimental and natural studies show that it is very difficult to erase a previously formed quartz CPO, even by extensive annealing at elevated temperatures (e.g. Heilbronner & Tullis, 2002; Otani & Wallis, 2006). The absence of a CPO in the quartz inclusions in honeycomb garnet thus rules out growth of garnet around quartz grains during or following strain accommodation via dislocation creep of dry quartz.

Cathodoluminescence images show that the quartz inclusions have characteristics similar to typical metamorphic quartz (Fig. 9a), with lines exhibiting bright CL, indistinct mottling and regions of uniform CL (terminology from Seyedolali *et al.*, 1997). The bright lines do not continue across garnet webs into adjacent quartz grains in any obvious way. The intensity of uniform CL varies from grain to grain. One trail of quartz with brighter CL was observed, but in BSE this was seen as secondary quartz growth that crosscuts both quartz inclusions and garnet. HRTEM analysis shows that quartz inclusions in garnet contain very few point defects or dislocations (e.g. Fig. 9b). Only rare subgrain boundaries can be seen in the quartz, consistent with EBSD analysis.

In contrast to the inclusion quartz, matrix quartz displays a prominent CPO (e.g. Fig. 3) and retains



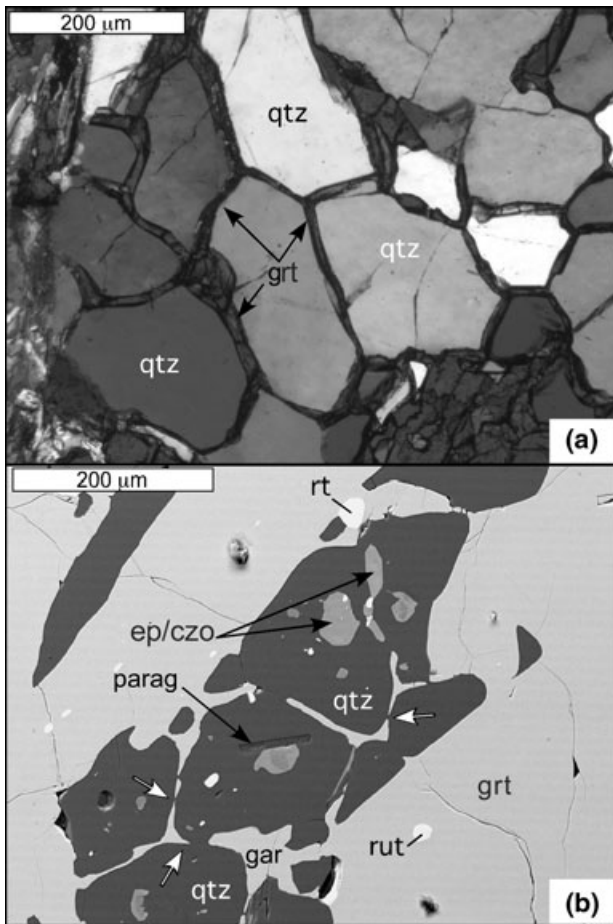


Fig. 4. (a) Photomicrograph showing continuous garnet webs outlining garnet grains in DT114C. This 2-D topology requires that garnet completely coat all quartz faces in 3-D. (b) Back-scattered electron image of honeycomb garnet webs surrounding quartz inclusions, and inclusions of clinozoisite, paragonite, and rutile within the quartz inclusions. Note local preservation of regions of apparently low quartz–quartz–garnet dihedral angle (white arrows), and regions where the dihedral angle evolved towards 120°.

evidence of crystal plastic deformation. This indicates that the garnet webs protected the quartz inclusions from subsequent deformation, despite the fact that most of the webs are $\leq 20 \mu\text{m}$ in thickness. Cellular metals and ceramics are synthesized deliberately in the materials industry because of their high strength (Markaki & Clyne, 2000), and the textural evidence presented here suggests that honeycomb garnet is similarly strong.

Several possibilities could explain the lack of a CPO in the quartz inclusions. (i) The quartz grew under

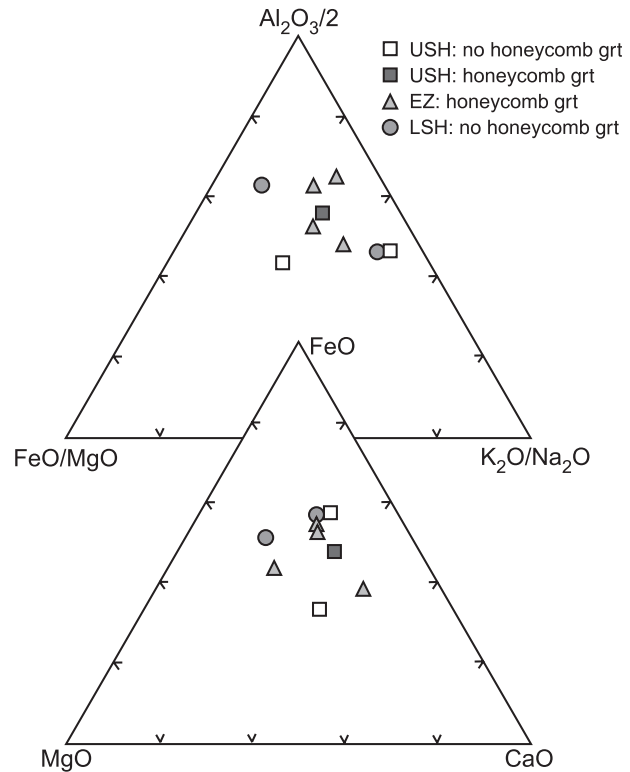


Fig. 5. Plots of $\text{Al}_2\text{O}_3/2$ – FeO/MgO – $\text{K}_2\text{O}/\text{Na}_2\text{O}$ and FeO – MgO – CaO showing that there is no systematic difference in bulk composition between samples containing honeycomb garnet and those that lack honeycomb morphology. Data given in Table 2.

conditions of low differential stress, resulting in a foam texture controlled solely by interfacial free energies (Stöckhert *et al.*, 1997; Stöckhert, 2002). If the samples were dry, the foam texture requires this interpretation. (ii) Quartz that was present prior to garnet growth accommodated strain via grain-boundary sliding and diffusive mass transfer (Law, 1990). This process would be favoured by the presence of a pervasive grain-boundary fluid phase during deformation. (iii) Quartz precipitated from the same silicate-bearing fluid phase that produced the enclosing garnet webs. Co-nucleation of garnet and quartz resulted in growth of garnet around quartz inclusions. The incorporation of clinozoisite, rutile, and other microinclusions into the quartz grains is consistent with synchronous precipitation of all of these phases from a fluid.

Garnet microstructure and distribution in third dimension

Electron backscatter diffraction analysis demonstrates that individual honeycomb garnet forms continuous

Fig. 3. Photomicrographs showing honeycomb garnet morphologies and quartz fabrics in plane light and with gypsum plate inserted. Quartz within honeycomb garnet is coarse-grained, strain free, and shows random orientations, in contrast to ribbon quartz with prominent crystallographic preferred orientation (CPO) in matrix. (a, b) Garnet composed entirely of honeycomb material in DT114D. (c, d) Honeycomb overgrowth on massive garnet core, sample DT102A. (e, f) Slabs of massive garnet separated by honeycomb region, DT114D. (g, h) Detail showing randomly oriented quartz inclusions in honeycomb garnet, compared with quartz ribbons with well-developed CPO in matrix surrounding garnet, DT114C. FOV = 5 mm in (a)–(f), = 3 mm in (g) and (h).

Table 2. Representative whole-rock compositions of schists from different tectonic units.

Sample ID unit	DT101B LSH	DT115 LSH	DT114C *EZ	FT105B *EZ	DT102A *EZ	FT104 *EZ	DT112 USH	DT119A USH	FT108 *USH
SiO ₂	67.98	71.19	66.32	61.08	63.81	56.07	69.70	70.04	56.64
TiO ₂	0.60	0.39	0.64	0.88	0.57	0.97	0.46	0.54	0.73
Al ₂ O ₃	14.80	14.38	13.57	16.49	12.21	20.76	13.65	10.25	16.25
FeO	3.91	2.53	5.44	4.18	4.08	4.37	2.39	4.25	3.79
MnO	0.06	0.02	0.38	0.04	0.15	0.07	0.06	0.28	0.23
MgO	1.22	1.56	1.98	3.30	1.87	1.65	2.17	1.11	1.50
CaO	1.80	0.90	2.85	2.31	4.88	2.40	2.83	2.16	2.76
Na ₂ O	2.66	0.60	0.67	1.45	0.52	1.21	0.64	0.61	0.94
K ₂ O	3.45	4.21	2.42	4.91	2.46	4.52	4.45	1.78	3.78
H ₂ O + CO ₂	1.72	2.53	4.32	3.05	6.68	5.38	4.12	3.52	4.94
P ₂ O ₅	0.21	0.18	0.11	0.12	0.08	0.13	0.10	0.11	0.06
Total	98.84	98.86	99.38	98.34	101.66	98.09	100.83	95.13	92.06

*Sample contains honeycomb garnet.

Table 3. Representative garnet analyses.

Sample Type	DT-10 net	-10 net	-10 net	-100 M-rim	-100 M-int	-100 net	-100 net	-103A M-rim	-103A M-core	-114C M-rim	-114C M-int
SiO ₂	37.87	37.89	37.73	38.06	37.71	37.95	37.97	38.35	37.58	38.52	37.91
TiO ₂	0.03	0.12	0.16	0.06	0.08	0.02	0.09	0.02	0.16	0.07	0.07
Al ₂ O ₃	21.51	21.28	21.31	21.67	21.32	21.40	21.46	21.71	20.93	21.91	21.76
Cr ₂ O ₃	0.10	0.13	0.14	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02
MgO	2.25	2.11	2.01	2.29	2.03	2.15	2.03	4.79	2.24	3.72	3.15
FeO	30.97	29.62	30.20	31.70	32.91	32.79	31.70	28.21	30.36	28.50	28.66
MnO	0.96	0.91	0.91	0.19	0.28	0.21	0.20	0.24	2.07	1.27	2.18
CaO	6.84	8.15	8.03	7.25	6.52	6.36	7.42	7.34	7.32	7.38	7.03
Total	100.53	100.21	100.48	101.22	100.84	100.87	100.87	100.66	100.65	101.37	100.79
Si	3.00	3.01	2.99	3.00	3.00	3.01	3.00	2.99	2.99	3.00	2.98
Ti	0.00	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00
Al	2.01	1.99	1.99	2.01	2.00	2.00	2.00	2.00	1.96	2.01	2.02
Cr	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.27	0.25	0.24	0.27	0.24	0.25	0.24	0.56	0.27	0.43	0.37
Fe	2.05	1.97	2.01	2.09	2.19	2.17	2.10	1.84	2.02	1.85	1.89
Mn	0.06	0.06	0.06	0.01	0.02	0.01	0.01	0.02	0.14	0.08	0.15
Ca	0.58	0.69	0.68	0.61	0.56	0.54	0.63	0.61	0.62	0.61	0.59
Total	7.99	7.99	7.99	7.99	8.00	7.99	7.99	8.01	8.02	7.99	8.00
alm	0.69	0.66	0.67	0.70	0.73	0.73	0.70	0.61	0.66	0.62	0.63
pyr	0.09	0.08	0.08	0.09	0.08	0.09	0.08	0.18	0.09	0.14	0.12
spes	0.02	0.02	0.02	0.00	0.01	0.00	0.00	0.01	0.05	0.03	0.05
gros	0.20	0.23	0.23	0.21	0.18	0.18	0.21	0.20	0.20	0.21	0.20

Net: narrow garnet band in honeycomb region; M: massive garnet; int: interior of grain.

crystals of a single orientation. In sample DT6 the webs and the more massive parts show no misorientations or subgrain boundaries. The uniform colour of the honeycomb garnet in Fig. 8 indicates that all analysed points have the same crystallographic orientation, as confirmed in the pole figure. Subgrain boundaries are visible in a few of the larger quartz inclusions, but most inclusions are single crystals with a single crystallographic orientation.

High-resolution X-ray computed tomographic scans of honeycomb garnet from samples DT102A and FT105A show that the garnet webs define a three-dimensional sheet-like structure (Movies S1 & S2). In other words, garnet occurs as continuous sheets (closed-cell foam) that fully encase the quartz and carbonate inclusions rather than along tubules at grain triple junctions. The three-dimensional observations are in agreement with the two-dimensional garnet distribution shown in Fig. 4(a).

Transmission electron microscopic analysis of regions of the honeycomb structure also shows that

garnet lacks major dislocation features or any kind of inclusion phase (Fig. 9b). Owing to the differential milling properties of the minerals, it proved difficult to ion mill the interface between garnet and quartz to electron transparency. Quartz typically milled completely away before the adjacent garnet was thin enough to image using 200 kV electrons. To overcome this problem we studied one sample of the interface between garnet and quartz that had been prepared by the FIB technique. A section of the interface 5 µm in length was present in the FIB section and showed that the interface is a typical incoherent grain boundary with no unusual characteristics. No fine-grained phases are present along the boundary, and voids and other direct evidence for the presence of a fluid phase are lacking.

Based on the evidence that the rocks did not reach temperatures much above 600 °C (Holland, 1979; Hoschek, 2001), it seems unlikely that the lack of dislocations or the scarcity of subgrain boundaries is due to dislocation creep and recovery. It is more likely

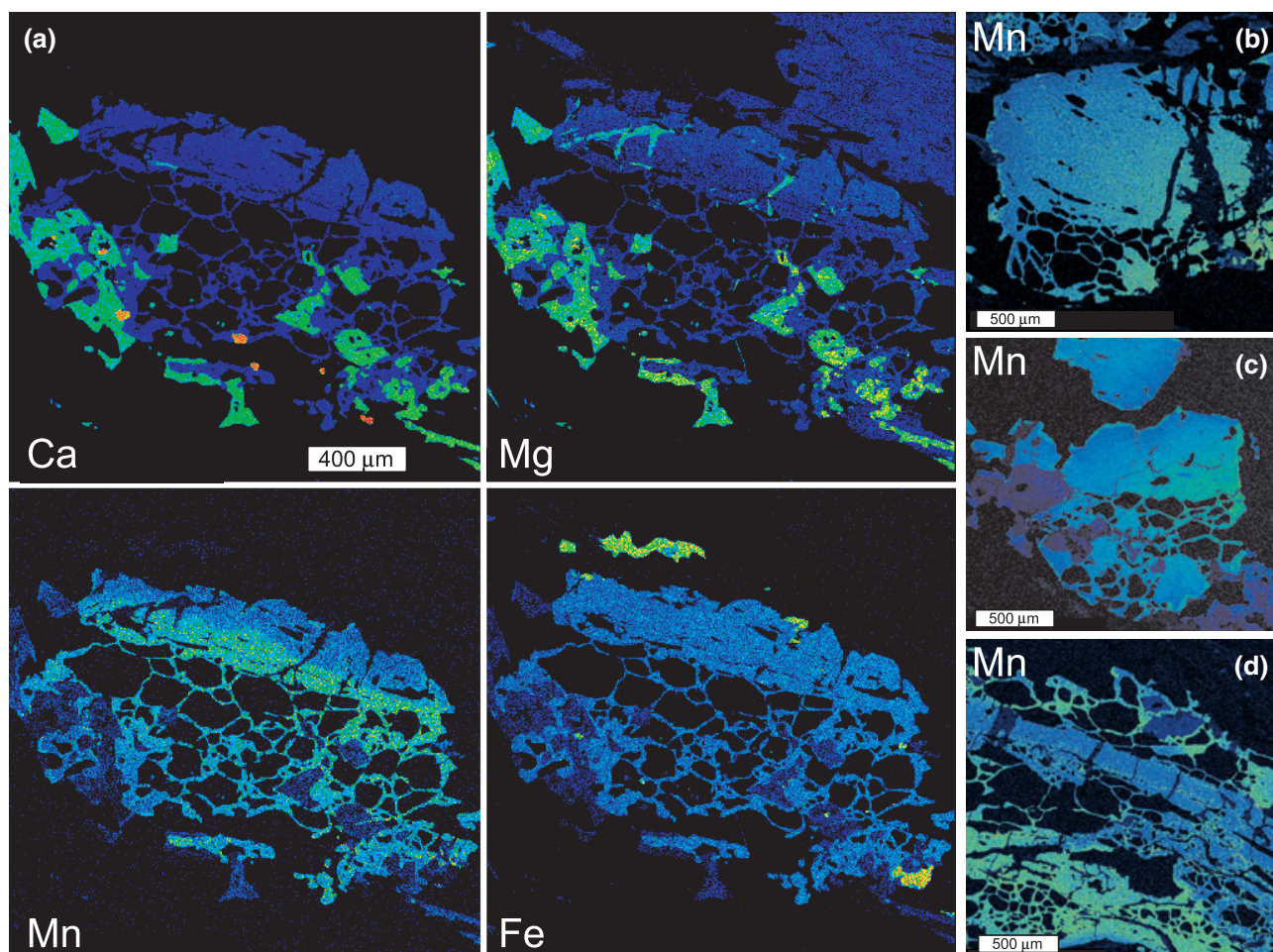


Fig. 6. (a) X-ray maps showing distribution of Ca, Mg, Mn and Fe in honeycomb garnet from sample DT6; note lack of concentric zoning. Bright grains in Ca and Mg maps are dolomite inclusions. (b)–(d) Maps showing patchy Mn zoning in additional garnet in sample DT6; maps from other samples are similar.

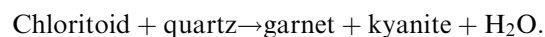
that the garnet never developed these deformation microstructures (Voegélé *et al.*, 1998). The continuity of the crystal structures also suggests that the honeycomb morphology is a primary growth structure rather than a result of post-growth recrystallization.

MECHANISMS OF HONEYCOMB GARNET FORMATION

The challenge of this study is incorporating the numerous enigmatic observations and speculations into coherent hypotheses of honeycomb garnet formation. Below, we evaluate three hypotheses for development of the honeycomb microstructure (Fig. 10); the mechanisms outlined in these hypotheses are not mutually exclusive, and may have operated to different degrees in the development of the cellular garnet structure. The apparently rare preservation of such a high surface energy crystal form testifies to a process that is either uncommon or exceedingly brief in the metamorphic cycle.

Hypothesis 1: Solid-state reaction

Development of the honeycomb texture via solid-state reaction could result either from garnet growth around preexisting quartz or from simultaneous production of garnet + quartz. Most pelitic reactions that produce garnet also consume quartz (e.g. chloritoid + quartz = garnet + H_2O), but could potentially result in growth of garnet around rounded, partially reacted quartz grains. Stöckhert *et al.* (1997) argued for poikiloblastic garnet growth via the reaction:



This reaction cannot account for garnet growth in the samples that we examined, however, because kyanite is absent from all but one (DT118) of the samples containing honeycomb garnet. Furthermore, reactions in a purely pelitic system cannot explain the Ca content of honeycomb garnet or the presence of microscopic clinozoisite inclusions in quartz within the honeycomb garnet.

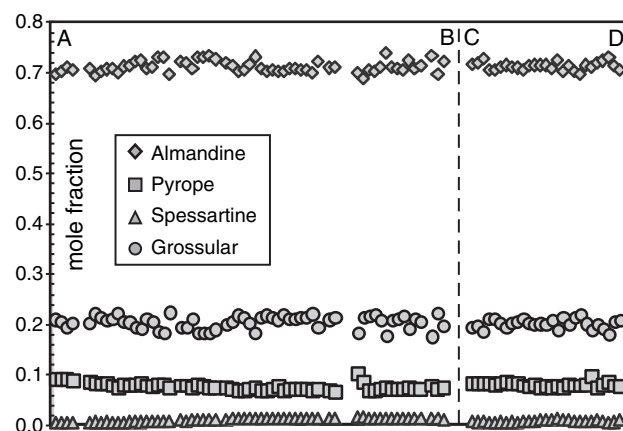
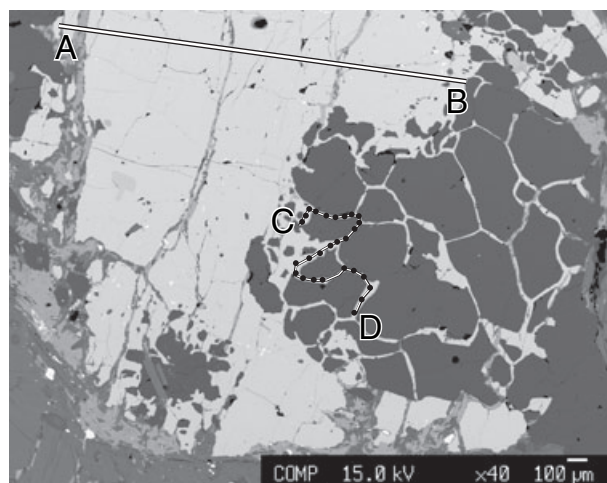
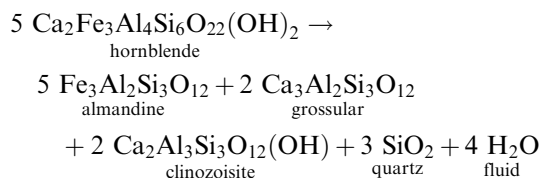


Fig. 7. Backscattered electron image and representative microprobe data showing that there is no systematic difference in composition between massive and honeycomb regions of individual garnet.

If honeycomb garnet resulted from simultaneous production of garnet and 50–75 vol.% quartz inclusions, a single precursor mineral would have to contain 30–36 atomic wt% Si (64–77 wt% SiO_2). The mineral would also have to be stable in a pelitic to marly bulk composition along a blueschist facies P – T – t trajectory leading to eclogite equilibration. It is difficult to identify a single metamorphic mineral with a sufficiently high Si content that also contains significant amounts of Fe, Ca and Al. Aluminous amphibole (glaucophane: 28 wt% Si; barroisite: 24 wt% Si; hornblende from the LSH: 20 wt% Si) is a possible candidate, as illustrated by the generalized reaction:



Clinozoisite inclusions inside both the quartz inclusions and the honeycomb garnet could represent the products of such a reaction. This reaction produces 50 times as much garnet as quartz (volumetric basis), and hence cannot explain the abundance of quartz that is present within honeycomb garnet. Such a reaction could produce garnet around largely preexisting quartz, but in this case we might expect to see evidence from CL imaging (e.g. Fig. 9) for overgrowths of new quartz on preexisting quartz within the inclusions. Such evidence is lacking.

Lower Schieferhülle and USH rocks of similar bulk composition also contain garnet, but it typically lacks the honeycomb morphology. Honeycomb garnet growth occurred both before and after growth of more typical garnet forms in the EZ. It is thus likely that the honeycomb garnet grains grew by different processes, rather than from decomposition of an unusual precursor phase, and that these processes were ephemeral. Furthermore, the compositional similarity between massive and honeycomb garnet suggests that both garnet morphologies grew at similar P – T conditions. It is difficult to imagine that two different solid-state reactions could produce two morphologically different types of garnet at the same conditions. For these reasons, we reject hypothesis 1.

Hypothesis 2: Deformation-controlled growth of honeycomb regions

Another possibility is that deformation of preexisting garnet played a major role in development of regions of honeycomb morphology. Shape change of garnet porphyroblasts can be accomplished by a variety of different mechanisms (e.g. Prior, 1993; Austrheim *et al.*, 1996; Voegelé *et al.*, 1998; Wang & Ji, 1999; Prior *et al.*, 2000, 2002; Kleinschrodt & Duyster, 2002; Trepman & Stöckhert, 2002; Storey & Prior, 2005). At low temperatures and/or high differential stresses, fracture and cataclasis dominate. Higher temperatures shift deformation into the field of dislocation creep, which is accommodated through dislocation glide or climb and recovery. These mechanisms produce dislocation bands or loops and subgrain boundaries. At low temperatures and over a range of differential stress conditions, shape change can be achieved through dissolution–precipitation creep, or pressure solution. Higher temperatures change the mechanism to grain-boundary diffusion creep (Coble creep) and finally volume diffusion creep (Nabarro–Herring creep). Diffusion of material may produce a shape-preferred orientation, a change of composition, or both. These mechanisms often work together in varying degrees to accommodate strain. If the honeycomb garnet morphology is achieved through the deformation of a previously euhedral or subhedral garnet, evidence of the deformation mechanism is likely to remain.

The presence of alternating massive and honeycomb layers within single garnet in some samples suggests

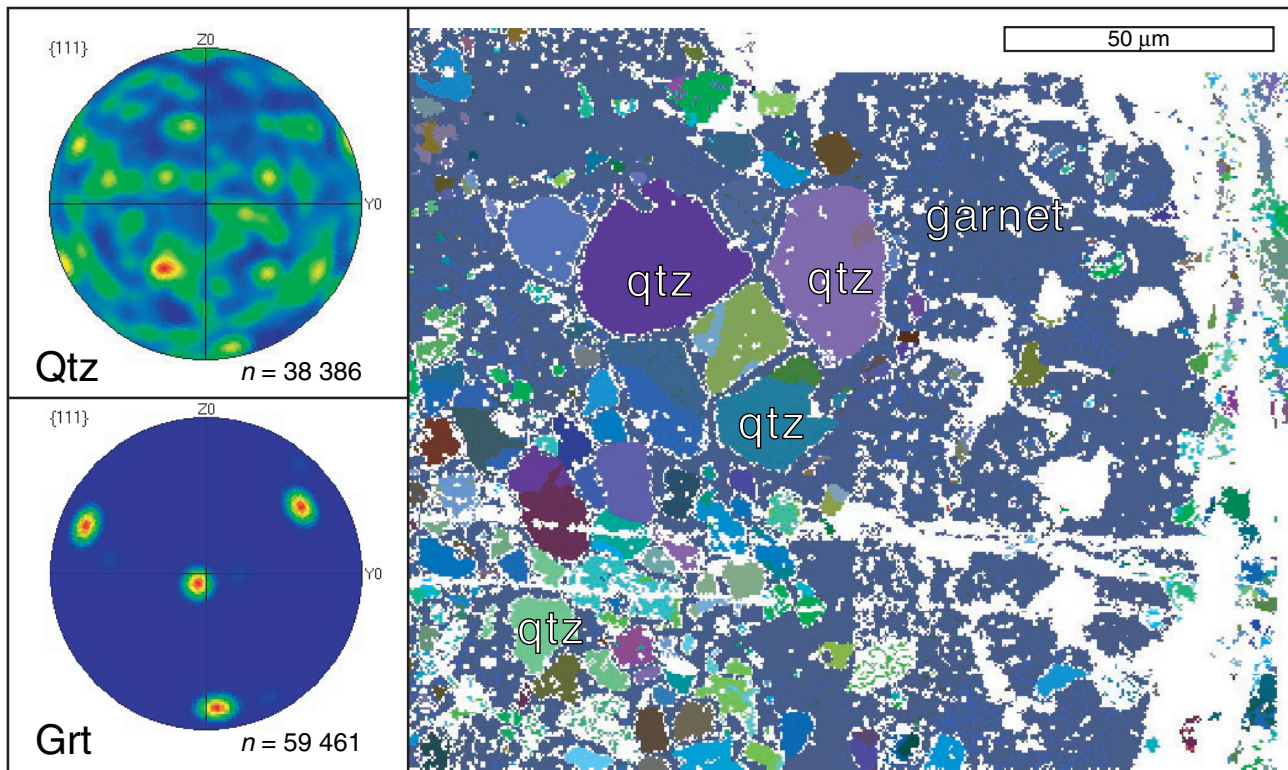


Fig. 8. EBSD orientation map and pole figures for a portion of a honeycomb garnet in DT6. Uniform colour of garnet indicates that all points show the same crystallographic orientation, as confirmed in the pole figure. In contrast, quartz inclusions show no crystallographic preferred orientation. Subgrain boundaries are visible within a few of the larger quartz inclusions, but most inclusions show only a single orientation.

that the honeycomb regions may have developed in response to fracture and pull-apart of preexisting garnet. A local stress drop following a fracturing event could force precipitation of garnet $\pm$ quartz that was removed from high-stress flanks of garnet via pressure solution (Fig. 10b). For this model to be correct, the honeycomb regions need to be favourably oriented to reflect fractures in preexisting garnet, and the massive garnet should show microstructural and compositional evidence consistent with initial strain accommodation via dissolution–precipitation creep.

Microstructural analysis of garnet reveals few dislocations and no subgrain boundaries within the garnet. Thus, dislocations were either removed via recovery processes, or few dislocations were ever generated. Given the relatively low temperatures attained by the EZ ($625 \pm 25^\circ\text{C}$), the latter possibility is more likely, and is consistent with strain accommodation via dissolution–precipitation creep prior to fracturing. The compositional similarity between massive and honeycomb portions of the same garnet is also consistent with local dissolution and reprecipitation of garnet. These observations and interpretations lend support to the hypothesis that *some* of the honeycomb garnet formed by fracturing of preexisting garnet and precipitation of new garnet + quartz within the fractures. In this case, the lack of a CPO within the quartz

inclusions implies nothing about the overall state of stress at high pressures (in contrast to the interpretation of Stöckhert, 2002), as the quartz would have locally precipitated from a fluid phase following a stress drop.

Although this hypothesis may explain formation of some of the honeycomb garnet, it does not easily account for all of them. Even within single samples, the orientation of the alternating massive and honeycomb garnet layers is random with respect to the matrix fabric, which does not support fracturing in response to high differential stress unless each garnet rotated a different amount following fracture. Furthermore, this model does not explain the occurrence of garnet poikiloblasts that are composed entirely of honeycomb material (confirmed by HRXCT analysis). We thus reject the hypothesis that *all* honeycomb regions developed following cataclastic deformation of preexisting garnet, although this process may have operated locally.

Hypothesis 3: Fluid-mediated garnet growth

The thin webs of garnet surrounding quartz grains are strikingly similar in appearance to a fully wetting fluid (dihedral angle near 0°) coating all grain surfaces, and may provide microstructural evidence for the opera-

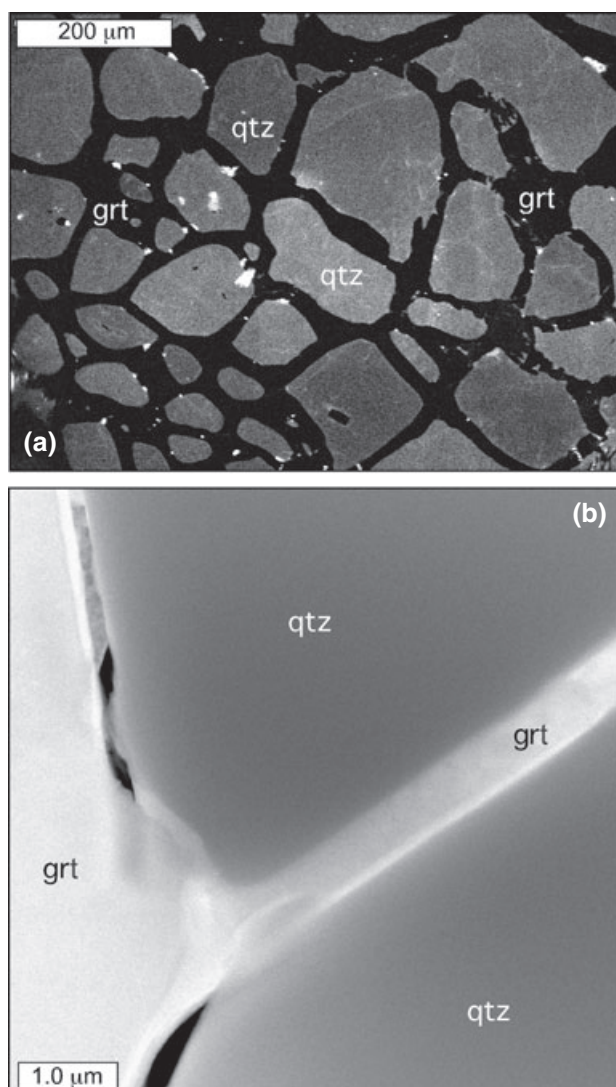


Fig. 9. (a) Cathodoluminescence image of quartz inclusions in honeycomb garnet in DT102A. Quartz grains show indistinct mottling, but no obvious fractures or overgrowths. (b) Representative dark-field STEM image of honeycomb garnet web and included quartz grains. No dislocations were observed in garnet or in quartz inclusions within honeycomb garnet regions.

tion of liquid phase sintering processes during high-pressure metamorphism. Indeed, Stöckhert & Renner (1998) argued that processes similar to liquid phase sintering could be important in ultrahigh-pressure rocks and that microstructural evidence for such processes should be sought. Here, we evaluate the possibility that either the garnet alone or the quartz–garnet intergrowths precipitated directly from a supercritical, silicate-rich aqueous fluid phase around 2 GPa.

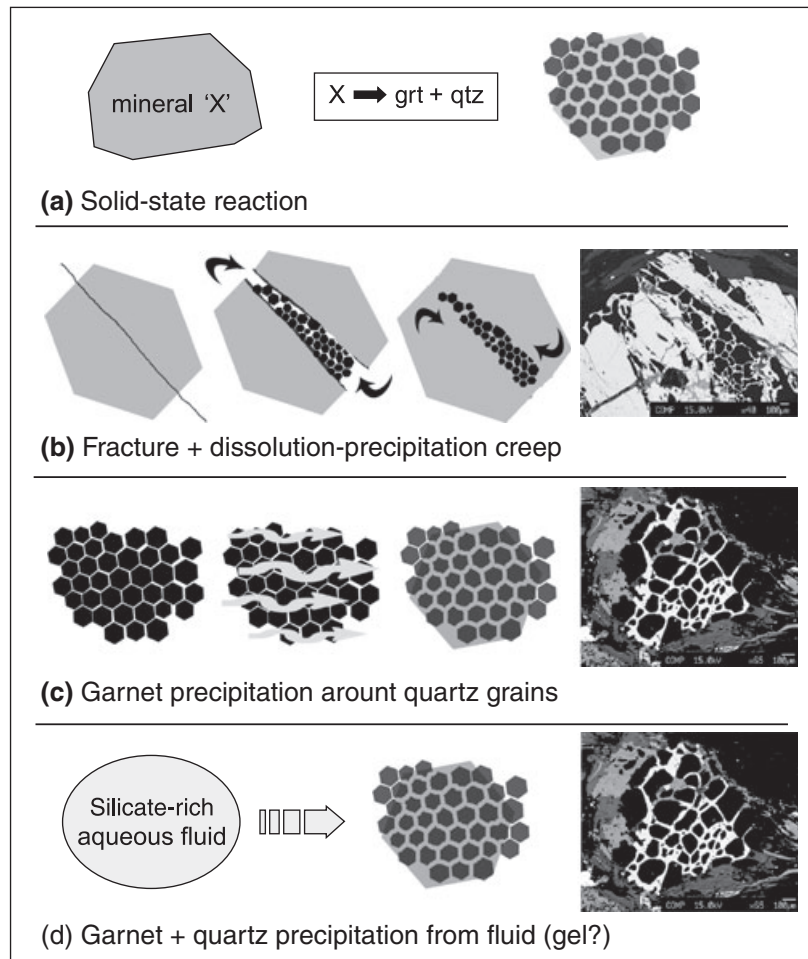
Several experimental studies show that mixed aqueous-silicate fluids with high concentrations of solute and high degrees of polymerization can exist at high pressure (Shen & Keppler, 1997; Mysen, 1998; Bureau & Keppler, 1999; Newton & Manning, 2000;

Schneider *et al.*, 2000; Shmulovich *et al.*, 2001; Zotov & Keppler, 2002; Gerya *et al.*, 2005; Kessel *et al.*, 2005; Manning, 2006). The wide variety of silicate, oxide and carbonate phases found in fluid inclusions and as polyphase solid inclusions in natural HP/UHP rocks points directly to the existence of complex, multicomponent fluids at high pressure (Philippot & Selverstone, 1991; Thomas, 1991; Ferrando *et al.*, 2005; Malaspina *et al.*, 2006). Supersaturation resulting from changes in pressure, temperature or overall fluid composition could lead to precipitation of garnet $\pm$ quartz ($\pm$ other phases included within honeycomb garnet) from such a fluid. Alternatively, if the fluid is highly polymerized, it could potentially go through a spontaneous sol-gel process that directly produces one or more solid phases (e.g. Klein, 1985).

The physical and chemical properties of fluids at high-pressure conditions are not well known, but will clearly play a major role in controlling mass transport processes and rock rheology. Experimental studies show that dihedral angles for H_2O – CO_2 and H_2O – NaCl fluids decrease markedly at pressures above 0.6 GPa in quartzites (Holness, 1993), but increase in carbonate rocks (Holness & Graham, 1995). Experimental studies also demonstrate that solubilities of silica, albite, diopside, corundum and wollastonite in $\text{H}_2\text{O} \pm \text{CO}_2 \pm \text{NaCl}$ fluids increase with pressure (Newton & Manning, 2000; Shmulovich *et al.*, 2001; Gerya *et al.*, 2005; Fockenberg *et al.*, 2006; Manning, 2006), although no pressure correlation was observed for alkali aluminosilicate components (Mysen & Armstrong, 2002). Wetting properties of such complex fluids in natural polyminerals undergoing simultaneous deformation and reaction are unknown. However, several experimental studies in systems involving silicate melt or aqueous fluid have shown that dynamic wetting – in which the fluid phase spreads out as a nearly continuous film along grain faces – can occur in response to deformation at low differential stress (Jin *et al.*, 1994; Laporte, 1994; Kohlstedt & Zimmerman, 1996; Tullis *et al.*, 1996). Reinecke *et al.* (2000) described evidence from natural high-pressure rocks for dynamic wetting of calcite–quartz and calcite–white mica grain boundaries during deformation. By analogy, even if equilibrium dihedral angles are high for silicate-rich aqueous fluids in high-pressure schists, dynamic conditions could distribute fluid along mineral surfaces, which would both weaken the rocks and enhance mass transport.

Direct precipitation of garnet from a dynamically wetting fluid could have significant implications for interpretation of the random CPO recorded by quartz inclusions in garnet. If such a fluid precipitated honeycomb garnet around preexisting quartz (Fig. 10c), the random CPO of the quartz could have resulted from free rotation of quartz grains in a slurry prior to garnet precipitation and does not require prior development of a quartz foam texture. Alternatively, both garnet and quartz could have precipitated

Fig. 10. Schematic illustrations of models for formation of honeycomb garnet. (a) Hypothesis 1: solid reaction producing garnet and quartz in abundances that match honeycomb regions. (b) Hypothesis 2: Dissolution-precipitation creep of preexisting garnet and quartz, followed by fracture of garnet. Stress drop results in precipitation of garnet + quartz within low-stress region along fracture. BSE image shows example of honeycomb region that could have resulted from this mechanism. (c) Hypothesis 3: Garnet precipitates from fully wetting fluid along grain boundaries of preexisting quartz. (d) Hypothesis 3: Both garnet and quartz precipitate directly from silicate-rich fluid. BSE images in (c) and (d) show garnet composed entirely of honeycomb material that is most easily explained by either form of Hypothesis 3.



simultaneously from the fluid (Fig. 10d), leading to the cellular intergrowths; however, a mechanism for organizing the cellular structure during simultaneous precipitation is not easily conceived. The random CPO of the quartz included within the garnet thus need not indicate that low differential stresses prevailed at peak pressures conditions (Stöckhert *et al.*, 1997; Stöckhert, 2002). The lack of a quartz CPO implies only that the cellular garnet structure enclosing the quartz was very strong and protected the inclusions from subsequent deformation, rather than providing information on stress conditions at $P_{\max}$.

Precipitation of cm-scale garnet porphyroblasts from a fluid phase presents a potential space problem in rocks undergoing high-pressure metamorphism. However, mafic eclogites from adjacent outcrops contain 10-cm knots of euhedral omphacite + kyanite + clinozoisite + rutile + quartz that apparently grew into fluid-filled pockets (Thomas, 1991; Selverstone *et al.*, 1992). The presence of these segregations indicates that significant fluid volumes were locally present at high pressure and made room for themselves in the rocks. Honeycomb garnet may also have precipitated from fluid-filled pockets, or via diffusive mass

transfer in a grain-boundary fluid. In the latter case, there need not have been a significant volume of fluid present at any one time. Deformation associated with subduction likely played a key role in creating space and channelling fluids to garnet growth sites, via fracturing of preexisting garnet (hypothesis 2) and/or by triggering dynamic wetting of grain boundaries.

Significance

All of the honeycomb garnet examined in this study is consistent with formation via some combination of processes outlined in hypotheses 2 and 3, but not with solid-state transformations described in hypothesis 1. Viable explanations for the formation of the cellular garnet morphology thus require involvement of a silicate-rich aqueous fluid that precipitated either garnet alone or garnet + quartz ($\pm$ phases included within the honeycomb quartz). The presence of such a fluid has several implications for mass transport processes and rock rheology at high pressures:

1. Evidence for transport and deposition of garnet by fluid at high-pressure conditions is in accord with experimental and fluid inclusion studies pointing to in-

creased solubilities for many species and to the stability of highly polymerized aqueous-silicate fluids at high pressure (Shen & Keppler, 1997; Mysen, 1998; Bureau & Keppler, 1999; Newton & Manning, 2000; Schneider *et al.*, 2000; Shmulovich *et al.*, 2001; Zotov & Keppler, 2002; Ferrando *et al.*, 2005; Gerya *et al.*, 2005; Kessel *et al.*, 2005; Manning, 2006). The boundaries between fluid and melt and between solid and fluid appear to blur under conditions of subduction zone metamorphism and deformation. Dense, polymerized fluids are likely to migrate and react with surrounding minerals in very different ways from aqueous fluids in low-pressure environments. As a result, it becomes difficult to apply data on strain accommodation mechanisms, porphyroblast growth, and reactive transport obtained at more moderate pressures to these conditions.

2. If garnet grew around preexisting quartz, the garnet-precipitating medium must have had a near-zero dihedral angle with respect to quartz-quartz grain boundaries (e.g. Fig. 4). Very low dihedral angles have not previously been described in equilibrated geological materials, but experimental studies show that increasing pressure can lead to a decrease in equilibrium dihedral angle, depending on the temperature conditions (Holness, 1993). If this is the case, mass transfer processes may be at least locally enhanced by high-pressure metamorphism. Transient reductions in dihedral angle (dynamic wetting) have been demonstrated for melt-rock and fluid-rock systems during deformation (e.g. Jin *et al.*, 1994; Schenk & Urai, 2005; Hier-Majumder & Kohlstedt, 2006). In a dry system, the absence of a quartz CPO would imply low differential stresses prior to garnet nucleation. In a fluid-rich system, however, no such conclusions can be drawn. Strain localization into the metasedimentary units of the EZ could have been facilitated by the presence of a wetting silicate fluid that lubricated grain edges and allowed for grain-boundary sliding in what would have effectively been a quartz-rich slurry. Strength contrasts between the metasedimentary and mafic units of the EZ may have been magnified as a result.

3. If both quartz and garnet precipitated from the same fluid, quartz would not be expected to exhibit a CPO. Synchronous enclosure of the quartz within cellular garnet would protect the quartz from subsequent deformation. The absence of a CPO in the quartz inclusions thus need not imply low differential stresses during HP/UHP metamorphism, in contrast to the interpretations of Stöckhert (2002).

4. If silicate-rich aqueous fluids are volumetrically significant at high-pressure conditions, interpretations based on solid-state theory of microstructural development may be in error. Goldsby & Tullis (2002) and Di Toro *et al.* (2004) documented experimental evidence for production of a thixotropic silica gel at elevated slip velocities. It is interesting to speculate about the possibility that the honeycomb garnets and their quartz inclusions could have existed as a weakening gel during deformation, and then recovered to a more

structured, high-viscosity state following cessation of shearing. Small changes in P - T conditions could also have affected fluid structure and hence rheology. Textural evidence that the honeycomb garnet morphology developed both before and after growth of more massive garnet is consistent with high-pressure switching of rheologies within these rocks.

Detailed studies of porphyroblast growth mechanisms in high-pressure rocks have the potential to provide new insight into the interactions between metamorphism, deformation and mass transfer processes during subduction. At present, however, our limited knowledge of the physical and chemical properties of natural fluids at high pressure hampers interpretation of the textural data.

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SUPPLEMENTARY MATERIALS

Movies of HRXCT images of honeycomb garnets.

Movie S1. File DT102A.wmv (6.5 Mb). Computed 3-D model of scanned sample DT102A showing two honeycomb garnets (light grey). Note that garnet completely encloses quartz inclusions (dark grey) in three dimensions, and thus displays a cellular

honeycomb structure rather than a web present along quartz triple junctions. Garnet on right is 5 mm across.

Movie S2. File FT105A.wmv (6.8 Mb). Computed 3-D model of large honeycomb garnet (light grey) encasing quartz (dark grey) and oxide (white) inclusions. Garnet coats all surfaces of inclusions, indicating that it forms a 3-D cellular structure. Garnet is 9 mm across.