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Quartz *c*-axis fabric differences between porphyroclasts and recrystallized grains: Reply

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IN PARTIALLY recrystallized quartzites of the White Range duplex, central Australia, the crystallographic preferred orientations (CPOs) of the recrystallized quartz grains differ from the CPOs of the quartz porphyroclasts in the same samples (Kirschner & Teyssier 1991). We assumed the porphyroclast CPOs were the product of, and thus representative of, most of the crystal-plastic deformation. Correspondingly, given the cyclic nature of recrystallization (Means 1981), we proposed the CPOs of recrystallized grains might be more responsive to changes in the fabric-forming parameters (e.g. kinematics, temperature, strain rate, fluid involvement) during deformation. Thus, the CPOs of recrystallized grains would be more representative of the later stages of deformation than the porphyroclast CPOs. We related the observed differences in CPOs between the quartz porphyroclasts and recrystallized quartz of the White Range to changes in incremental strain from flattening to plane or constrictional strain during the closing stages of plastic deformation.

At the onset of our discussion section (Kirschner & Teyssier 1991, p. 107), we acknowledged the potential effects of: (1) heterogeneous flow around porphyroclasts; and (2) host-control recrystallization (which can lead to selective recrystallization) but decided that we did not have suitable constraints to evaluate the importance of these two effects. In their Discussion, Hippertt and Borba propose that our data can be reinterpreted in terms of selective recrystallization. However, their arguments are contingent on several assumptions that need to be correct in order for their hypothesis to adequately explain the White Range Quartzite CPOs. We first identify a few of these assumptions and evaluate their validity for the White Range. Then we test their hypothesis with additional data that we have collected.

In condensed form, the argument of Hippertt and Borba proceeds as follows. First, any CPO developed in the porphyroclasts during the early stages of flattening were "probably erased" by later plane strain deformation. Second, only grains favorably oriented for slip on the prism ⟨*a*⟩ glide system were significantly deforming by intracrystalline slip and these grains preferentially recrystallize. Finally, grains with *c*-axes oriented 45° to the shear plane did not deform by intracrystalline slip nor undergo rigid body rotation during bulk noncoaxial deformation, and the absence of porphyroclasts with *c*-axes subparallel to the intermediate axis of the finite strain ellipsoid is due entirely to preferential recrystallization, and not rotation.

Concerning the first argument, the shape and distribution of porphyroclasts in 14 samples from the White Range document apparent flattening to plane strain (Kirschner & Teyssier 1991). It is reasonable to assume that at least a weak CPO would develop during flattening. What would these fabrics have looked like before they were "erased" as Hippertt and Borba propose? The fabrics of the porphyroclasts are consistent with those found naturally (cf. Price 1985), experimentally (e.g. Tullis *et al.* 1973), and predicted numerically (e.g. Lister & Hobbs 1980) for flattened quartzites. The correlation between porphyroclasts CPO and apparent finite strain is not proof that our interpretation is correct, but an argument in favor of it, which was totally disregarded by Hippertt and Borba.

Concerning the second argument, the porphyroclasts and recrystallized quartz CPOs in the White Range Quartzites are not consistent with prism ⟨*a*⟩ being the most active slip system during deformation, a necessary condition in Hippertt and Borba's hypothesis. Differences between our CPOs of recrystallized grains in the White Range and their 2 m-wide shear zone are of fundamental importance. In the White Range, it is very probable that several glide systems were operative during fabric development. Therefore, a direct comparison with their 2 m-wide shear zone, where the recrystallized grains seem to be dominated by prism ⟨*a*⟩ slip, is not possible. Their hypothesis would be applicable to the White Range data only if different slip systems were operative in the porphyroclasts and the recrystallized grains. We have no knowledge of any study which documents a change in slip system activity with decreasing grain size. In addition, Hippertt and Borba suggest that the only active slip systems are those whose glide planes are oriented so that the resolved shear stress (RSS) is maximized. However, the activity of a specific slip system is also dependent on its yield strength (i.e. its critical resolved shear stress, CRSS). Based on geometric arguments, it is apparent that many of the dominant slip systems in quartz would have high RSS within evolving single and cross-girdle fabrics (e.g. Law *et al.* 1990). Thus, unless they are suggesting that the CRSS of prism ⟨*a*⟩ is significantly lower than other slip systems for low temperatures (which is contrary to the results of many studies), we fail to understand why they imply that grains with *c*-axis subparallel to the *Y*-axis of the finite strain ellipsoid are the only grains significantly deforming by intracrystalline slip.

CPOs develop as a result of intracrystalline slip, rigid grain rotation, and preferential growth/annihilation of grains via recrystallization. Hippertt and Borba focus entirely on the annihilation of a group of grains via selective recrystallization to the near exclusion of rigid grain rotation. They suggest that grains which rotate into "metastable" positions are removed from subsequent deformation due to low RSS on their basal planes, and that strain then localizes in the recrystallized quartz–mica matrix surrounding these grains. They assume these least deformed clasts do not experience intracrystalline slip or rigid body rotation, and thus do not 'escape' from metastable orientations. Tullis *et al.* (1973) and Ralser (1990) have shown from experiments on pure quartzites that anomalously unstrained augen grains are commonly preserved in zones of bulk coaxial deformation, while in zones of non-coaxial flow (i.e. at the corners of the pistons) all of the grains are deformed, rotated, and recrystallized; however, Dell'Angelo & Tullis (1989) have also observed quartz augens in non-coaxially deformed samples. In naturally deformed rocks (Fig. 1), several authors have suggested that quartz augens in strained quartzites persist only when bulk deformation is coaxial. In order for augen grains not to rotate rigidly in a bulk non-coaxial deformation, as required in the Hippertt and Borba hypothesis, strain would have to be partitioned in a manner such that the clasts experienced coaxial deformation in a non-coaxially deforming matrix. This situation is reminiscent of the controversial strain partitioning hypothesis put forth by Bell (1985) and Bell *et al.* (1986) concerning non-rotating porphyroblasts embedded in a matrix undergoing non-coaxial deformation.

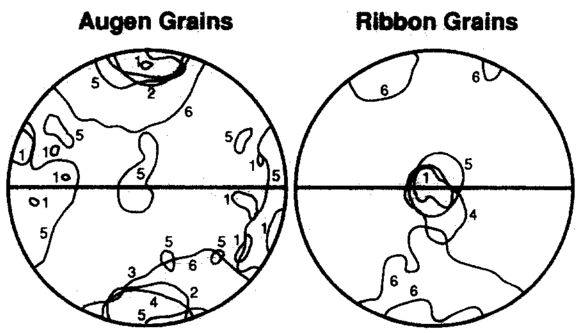
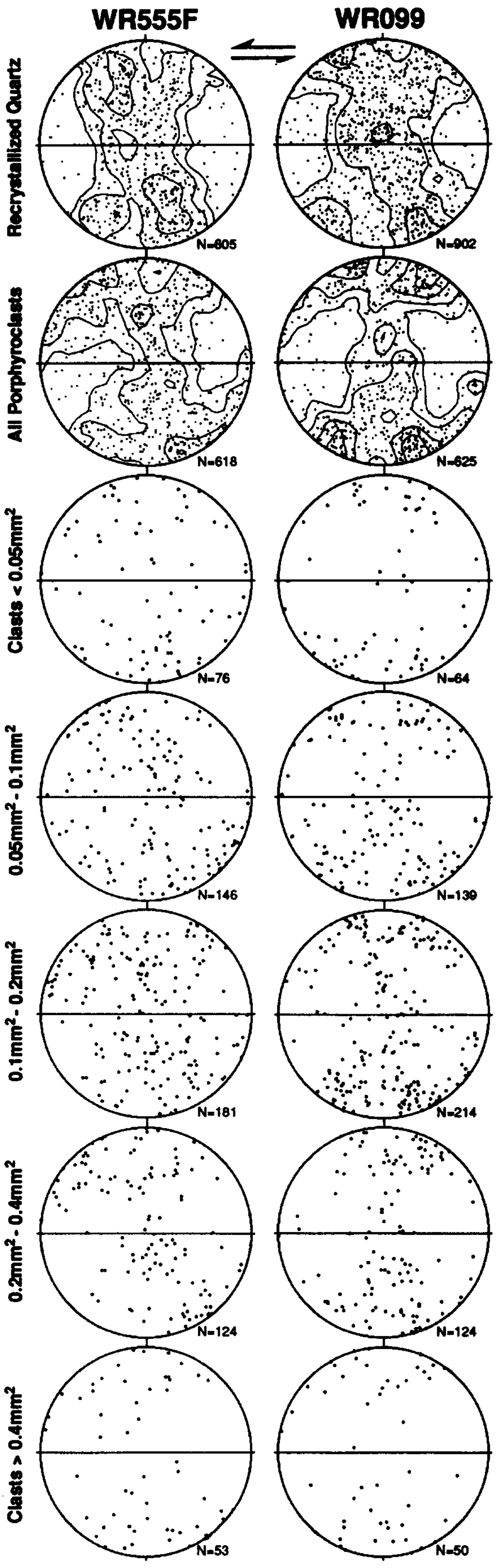


Fig. 1. Quartz *c*-axis fabrics for relatively unstrained (augen) and highly strained (ribbon) porphyroclasts in partially recrystallized quartzites and a metasiltstone. For none of these samples is it reported that the ribbon grains are more recrystallized than the augen grains. Labelled contours in augen grain stereonet are from: (1) Bouchez 1977, Contour (C) = 3% per 1% area; (2) Law *et al.* 1984, C = 5%; (3) Law *et al.* 1986, C = 5%; (4) Law 1986, C = 5%; (5) Mancktelow 1981, C = 1.4%; (6) Marjoribanks 1976, 2σ contour = 14. Labelled contours in ribbon grain stereonet are from: (1) Bouchez 1977, C = 6%; (4) Law 1986, C = 4%; (5) Mancktelow 1981, C = 5.6%; (6) Marjoribanks 1976, 2σ contour = 16 (Schmidt, lower-hemisphere stereonets).

Hippertt and Borba's proposed role of mica on quartz CPO development (via grain boundary sliding and stress reduction) in the White Range Quartzite samples with 8–26% mica content by volume is not strongly supported by the results of other studies. For example, in experimentally deformed quartzites shortened up to 55%, the CPOs of quartzites with 25% muscovite are similar to those fabrics developed in pure quartzites (Wenk *et al.* 1990). Similarly, White *et al.* (1982) found no difference in CPO development between a mica–feldspar–quartz-rich layer and a pure quartz layer in a mylonite from the Moine thrust zone. Also, Etheridge & Vernon (1981) found no significant differences in the CPOs between recrystallized quartz clasts with 40% mica ± albite and those with 10% mica ± albite by volume in a polymictic conglomerate deformed under greenschist-grade conditions. Conversely, Kronenberg (1981) documents in a conglomerate well developed CPOs in pure quartz cobbles and a random crystallographic pattern in the fine-grained matrix with 17% micas plus chlorite. Similarly, Starkey & Cutforth (1978) observed a linear relation between degree of quartz CPO development and percentage of quartz in samples collected from many structural and metamorphic environments. The results of these studies suggest that the effects of mica on the development of quartz CPO fabrics are not simply a function of the mica content, but probably a combination of mica content, distribution, and interconnection, plus the kinematics and physical conditions of the deformation. So without more studies to clarify these issues, the proposed role of mica on the CPO fabric development of the White Range Quartzite is tenuous.

Are there empirical tests capable of evaluating the hypothesis of Hippertt and Borba concerning preferential recrystallization in the White Range Quartzite of our earlier study? Their hypothesis would predict that the *c*-axis orientations of the least strained and least recrystallized clasts would be aligned 45° to the shear plane in simple shear. Conversely, the *c*-axis orientations of the most strained and most recrystallized clasts would lie in the shear plane and perpendicular to the shear direction (Hippertt & Borba, fig. 2). Because recrystallization reduces the size of the original detrital clasts in medium- to coarse-grain quartzites, their hypothesis would also predict a direct correlation between the volume reduction of individual clasts due to recrystallization and *c*-axis orientations. And volume reduction in three dimensions would, in general, result in surface area reductions of clasts in two-dimensional sections.

In order to test their hypothesis, we have separated the CPOs of porphyroclasts in two samples according to surface area of unrecrystallized clast remnants (Fig. 2). We do not use apparent finite strain in testing the hypothesis for two reasons: (1) partial recrystallization always alters clast surface area, but not necessarily the shape of the unrecrystallized clast remnant; and (2) degree of recrystallization does not always correlate



with clast finite strain. The second reason is exemplified in many partially recrystallized quartzites that contain both unrecrystallized, unstrained augen grains and unrecrystallized, highly strained ribbon grains (Fig. 1). In addition, we have chosen not to use volume of unrecrystallized clasts in the comparisons because of the difficulties involved with acquiring accurate volumetric data. However, in using surface area in the comparisons, both the two-dimensional cut effect through a three-dimensional packed aggregate (cf. Graton & Fraser 1935) and the finite strain of the sample must be considered. A *c*-axis orientation to surface area correlation is most applicable for well sorted quartzites which have experienced plane strain deformation. It is not possible to know whether the White Range Quartzite was well sorted, although the undeformed Heavitree Quartzite protolith in general is described as being so. Also, the finite strain of sample WR555F records apparent flattening, not plane strain, thus complicating the interpretation of the results for that sample. Within these limits, there is no obvious correlation between *c*-axis orientation and size fraction of unrecrystallized clast remnants, in contradiction to what would be expected from the Hippertt and Borba hypothesis.

The new CPOs presented here (Fig. 2) are similar to, though not as distinct as, those formerly presented in Kirschner & Teyssier (1991). The porphyroclast CPOs are representative of two populations, intact porphyroclasts and remnants that were clearly of porphyroclast affinity. All remnants of questionable origin were disregarded during the initial survey. The new CPO data presented here were determined for all clasts and remnants that are of probable porphyroclast affinity. This change in criterion from definite to probable clast affinity has resulted in the less distinct patterns. The recrystallized quartz CPOs presented here and in Kirschner & Teyssier (1991) are representative of grains that are not within or adjacent to porphyroclasts or clasts' remnants.

In conclusion, we do not think that Hippertt and Borba's hypothesis is valid for the White Range fabrics of our study, but we find their results on the 2 m-wide shear zone in the Bonfim metamorphic complex provocative. We are looking forward to reading a more thorough description of the microstructural relations observed in that shear zone, where a combination of lower modal quartz content and higher temperature of deformation could have led to a difference in CPO between porphyroclasts and recrystallized grains brought about by selective recrystallization.

Fig. 2. Quartz *c*-axes fabrics for two partially recrystallized White Range Quartzite samples. The porphyroclast populations were subdivided according to surface area of unrecrystallized clasts' remnants. Surface area was measured on sections oriented perpendicular to foliation and parallel to lineation. Error associated with digitizing process did not exceed $1\sigma = 5\%$ of measured surface area; a larger indeterminable error was associated with defining the boundaries of the unrecrystallized clasts' remnants. Sample WR555F contains 20% mica and 84% of the quartz is recrystallized; sample WR099 contains 10% mica and 80% of the quartz is recrystallized ($1\sigma = 3\%$ for point counts with $n > 1000$ for both samples; cf. van der Plass & Tobi 1965). Contours are 0.5, 1, 2 and 3% per 1% area on a Schmidt, lower-hemisphere stereonet.

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