

DISCUSSION

Prism- and basal-plane parallel subgrain boundaries in quartz: a microstructural geothermobarometer

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INTRODUCTION

In the paper entitled 'Prism- and basal-plane parallel subgrain boundaries in quartz: a microstructural geothermobarometer' by Kruhl (1996), he concluded that the transition in dominant dislocation glide from basal $\langle a \rangle$ to prism $[c]$ slip is caused by the phase transformation from low (α) to high (β) quartz which depends strongly on temperature and pressure (see his Fig. 3). Because the crystallographic orientation of subgrain boundaries (SGBs) in quartz is a useful indicator of the operative slip direction during high-temperature plastic deformation (e.g. Mainprice *et al.*, 1986), he thus suggested that the crystallographic orientation of SGBs indicating either activity of $\langle a \rangle$ or $[c]$ slip in quartz can be used as a practicable geothermobarometer. In reaching this conclusion, it was assumed that the concentration of water or water-related species and other factors have only minor effects on the transition of slip systems. However, after a careful review of his arguments, we have found several problems in the interpretations, and thus we question the validity of Kruhl's conclusions. The aim of the present comment is to show that (1) some natural and experimental data are contradictory to Kruhl's conclusion and (2) the mechanism switch from $\langle a \rangle$ to $[c]$ slip in quartz depends on various factors, which are not simply related to the α - β transformation in quartz as Kruhl (1996) concluded. We believed that the dependence of the mechanism switch from $\langle a \rangle$ to $[c]$ slip in quartz on various physical and chemical variables must be fully explored before the change in SGB microstructure can be used as a practical geothermobarometer.

NATURAL AND EXPERIMENTAL DATA CONTRADICTORY TO KRUHL'S CONCLUSION

The data used in Kruhl (1996) on quartz subgrain patterns from ten metamorphic terranes show that, at least up to 1000 MPa in the stability field of low-quartz, prismatic SGBs indicating the activity of $\langle a \rangle$ slip are dominant, whereas basal SGBs indicating the activity of $[c]$ slip are not developed (see his Fig. 3). Kruhl (1996), on the basis of these data, drew a

straight line that separates these two regions. He further suggested that the line is identical to the experimentally-derived boundary between the stability fields of low- and high-quartz within a range of c. 10 °C and 30 MPa. However, Kruhl (1996) omitted some important natural data (Lister & Dornsiepen, 1982; Garbutt & Teyssier, 1991; Okudaira *et al.*, 1995) reporting the occurrence of prism $[c]$ slip in the low-quartz stability field. To justify omission of these data from his Fig. 3, Kruhl (1996) referred to Okudaira *et al.* (1995), stating that the inferred T_{\max} in the cordierite zone (Fig. 3 and table 1 of Okudaira *et al.*, 1995), where the $\langle a \rangle$ - $[c]$ transition occurred, is uncertain. However, the estimated transition temperatures of c. 550–600 °C (Okudaira *et al.*, 1995), based on two-feldspar thermometry, which were calculated by using an average composition of c. 10 electron-microprobe feldspar analyses performed for each sample, is not likely to be grossly in error, because the temperature range between c. 500 and 850 °C can be accurately assessed by the two-feldspar thermometry (Haselton *et al.*, 1983). Furthermore, Kruhl (1996) argued that the transition temperature range from $\langle a \rangle$ to $[c]$ slip of Okudaira *et al.* (1995) is significantly lower than the temperatures for the $\langle a \rangle$ - $[c]$ transition published previously so far (c. 600–750 °C: e.g. Lister & Dornsiepen, 1982; Blumenfeld *et al.*, 1986; Mainprice *et al.*, 1986). Although the previous investigations reported the occurrence of dominant prism $[c]$ slip in natural quartz deformed at c. 600–750 °C, they did not determine the temperature for the $\langle a \rangle$ - $[c]$ mechanism switch. It should be emphasized that the temperatures estimated by Okudaira *et al.* (1995) were derived from samples collected over a continuous section without any discontinuity of metamorphic grade where the basal-prism mechanism switch occurred. Because the temperature range for the transition estimated by Okudaira *et al.* (1995) includes the lower limit of temperature conditions for the $\langle a \rangle$ - $[c]$ transition, their estimate is not inconsistent with those of the previous studies. Therefore, the temperature estimate for the $\langle a \rangle$ - $[c]$ transition by Okudaira *et al.* (1995) appears reasonable, and they should not then be excluded from the data set used in Kruhl (1996).

The development of lattice preferred orientation (LPO) of *c*-axes in experimentally deformed quartzites in α -quartz stability field (800 °C, 1.02 GPa, 10^{-6} s $^{-1}$) and β -quartz stability field (1100 °C, 0.90 GPa, 10^{-5} s $^{-1}$) were measured by Gleason *et al.* (1993). Gleason *et al.* (1993) concluded that there is no abrupt change in the LPOs corresponding to the α - β transition, which suggests that the slip systems active in α - and β -quartz are essentially the same.

EFFECT OF H₂O AND STRAIN RATE ON THE $\langle a \rangle$ -[*c*] TRANSITION

Kruhl (1996), on the basis of his observations of quartz deformed under various H₂O-content conditions but with the transition temperatures from $\langle a \rangle$ to [*c*] glide not deviating from the α - β transformation boundary, argued that a 'water'-rich fluid phase had no substantial effect on the transition. However, many experimental studies using single crystals and aggregates of quartz (e.g. Griggs & Blacic, 1965; Blacic, 1975) have shown that the $\langle a \rangle$ -[*c*] transition depends strongly on concentration of water or water-related species, and may depend on fugacity of H₂O ($f_{\text{H}_2\text{O}}$). Griggs & Blacic (1965) experimentally showed that the strength of synthetic quartz containing a trace amount of water (c. 0.1 wt%) dramatically decreased from c. 500 MPa at 200–300 °C to 100 MPa at 400–600 °C at a strain rate of 8×10^{-4} s $^{-1}$. The sudden decrease of strength of the synthetic quartz at 400–600 °C was interpreted by Griggs & Blacic as due to the mechanism switch from basal $\langle a \rangle$ to prism [*c*] slip systems, associated with the intracrystalline water weakening of prism [*c*] slip system. This is believed to be caused by the replacement of the strong Si–O bonding by weak hydrogen bonding (Si–OH·HO–Si). On the other hand, the experimental work of Kronenberg & Tullis (1984) indicated a continuous

reduction of creep strength with increasing confining pressure. The effect of confining pressure on the strength of quartz may be directly related to an effect of $f_{\text{H}_2\text{O}}$, because the rates of dislocation climb, grain boundary migration and oxygen self-diffusion in quartz strongly depend on $f_{\text{H}_2\text{O}}$ (Paterson, 1989; Tullis & Yund, 1989; Post *et al.*, 1996).

Furthermore, several experiments (e.g. Blacic, 1975) have shown that the temperature for the transition from $\langle a \rangle$ to [*c*] slip greatly reduces with decreasing strain rates. For example, one order of magnitude change of strain rate is equivalent to a change of c. 40 °C in the transition temperature (Blacic, 1975). Consequently, the temperature for the transition from $\langle a \rangle$ to [*c*] slip depends on H₂O content (or $f_{\text{H}_2\text{O}}$) and strain rate, while the α - β transformation does not correlate to these parameters (cf. Coe & Paterson, 1969).

CONCLUSION

We question the validity of Kruhl's conclusion because of two reasons. First, Kruhl has ignored estimates of the conditions for the $\langle a \rangle$ -[*c*] transition in naturally deformed quartz which are inconsistent with his conclusion. Second, experimental studies indicate that the amount of H₂O (or $f_{\text{H}_2\text{O}}$) and strain rate greatly influence the temperature for the $\langle a \rangle$ -[*c*] slip transition, although the α - β phase transformation does not depend on these factors. It is also concluded that the $\langle a \rangle$ -[*c*] transition does not correlate with the low- to high-quartz transformation. Finally, we suggest that the microstructural geothermobarometer proposed by Kruhl (1996) cannot be used as a practical geothermobarometer for naturally deformed quartz-rich tectonites until the dependence of $\langle a \rangle$ -[*c*] transition on various physical and chemical conditions is more fully explored.