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Dynamically recrystallised quartz *c*-axis fabrics in greenschist facies quartzites, Singhbhum shear zone and its footwall, eastern India—influence of high fluid activity

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Abstract

Oriented specimens of quartz tectonites from the Singhbhum shear zone (SSZ), an important tectonic element in the Precambrian eastern Indian shield, and its footwall have been analysed for *c*-axis fabrics of dynamically recrystallised quartz grains. In individual specimens the fabric pattern is either an asymmetric type I cross-girdle or an asymmetric, kinked single-girdle, irrespective of whether the fabric is from the SSZ or its footwall. The asymmetry of the fabric confirms a southward thrust movement of the northern block on a northerly dipping shear zone. The measured fabrics are characterised by a concentration near the Y-axis of the finite strain ellipsoid with an equally or subordinately developed concentration near the Z-axis. Although some earlier works suggest the Y-concentration of the quartz *c*-axis fabric as due to the influence of higher temperature (obtained in amphibolite facies), the occurrence of a similar concentration in the quartz *c*-axis fabric from quartz tectonites of the SSZ and its footwall, interpreted to have formed under greenschist facies condition, is explained by formation of the fabric under high fluid activity during deformation. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

The Singhbhum shear zone (SSZ), originally named the Copper Belt thrust (CBT) by Dunn and Dey (1942), is an important tectonic element in the Precambrian eastern Indian shield (Fig. 1). Dunn and Dey (1942) considered the overturned southern limb of the Singhbhum anticlinorium to be displaced by the CBT; the rocks of the Chaibasa stage (Chaibasa Formation of Sarkar and Saha, 1977) at the core of the Singhbhum anticlinorium were thrust over the supposedly younger Dhanjori Group lying to the south of and below the SSZ. The Dhanjori Group has been considered as older than the Chaibasa Formation (e.g. Mukhopadhyay, 1976; Bose and Chakraborty, 1981; Sarkar, 1982b, 1984; Bose, 1994), while others have considered the Dhanjori Group as a molasse sequence younger than the northern metaflysch sequence (Chaibasa Formation of Dunn and Dey, 1942; Gall, 1964; Sarkar and Saha, 1977; Sarkar, 1982a; Saha and Ray, 1984). Gupta et al. (1980) considered the Dhanjori Group and the Chaibasa Formation to be contemporaneous, but representative of different facies (see also Virnave et al., 1994). In the absence of any radiometric data from these two rock groups, and their correct interpretation, the stratigraphic relation (in its current understanding) cannot be utilised for supporting or refuting the interpretation that the SSZ is a major thrust. Some workers have also suggested continuity of structures across the SSZ (Mukhopadhyay, 1976). The metaflysch sequence has a poly-metamorphic history (Bhattacharyya and Sanayal, 1988). Therefore, the apparently higher metamorphic grade north of the SSZ should also be considered in the light

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of the time relationship between the deformation and metamorphism in the shear zone, the Chaibasa Formation and the Dhanjori Group.

Apart from the obvious copper and uranium mineralisation, the SSZ is marked by the development of a strong foliation and lineation plunging down dip in the foliation plane (cf. *L–S* fabric in mylonites) in rocks varying from pebbly schist (conglomerate), quartzite, quartz–mica schist, to feldspathic chlorite–biotite schist. The strong *L–S* fabric is interpreted to have been induced by strong shearing along the zone (Gall, 1964; Ghosh and Sengupta 1987a,b). For clarity we restrict the use of the term SSZ to the belt of rocks with a strong *L–S* fabric and characterised by copper, uranium, magnetite, apatite and tourmaline mineralisation. The outcrop width of the SSZ passing through the copper and uranium mines of Bhatin, Jaduguda, Rakha Copper Project (Royam), Kendadih, Surda and Musaboni, varies from 500 m to 1 km (Fig. 2).

Development of distinct microstructures and crystallographic preferred orientation (CPO) in minerals including quartz, olivine and calcite have been reported from many large-scale shear zones/thrust zones (e.g. the Moine thrust zone of Scotland). The microstructures and CPO of minerals in such shear zones have been shown to be useful in understanding the kinematics of deformation, as well as in deducing the ambient pressure–temperature condition (Lister, 1977; Lister and Williams, 1979, 1983; White et al., 1980; Lister and Snoke, 1984; Simpson and Schmid, 1983; Law et al., 1984, 1986; Law, 1987; Jessell, 1988a,b; Wenk et al., 1989; Jessell and Lister, 1990; Gleason et al., 1993). Although the SSZ is known to be a major tectonic element in the Eastern Indian shield, there are few detailed microstructural and fabric studies (Banerji, 1959; Sarkar, 1966, 1984; Sarkar and Bhattacharyya, 1978). The present study documents the SSZ fabrics with a view to comparing them with fabrics from other well-documented crustal-scale shear zones. It also considers the development of deformation-induced fabrics in the Dhanjori quartzites lying below the SSZ and thus considers their evolution in relation to the general deformation in the SSZ. The observed patterns of CPO are interpreted in the light of presently available models of CPO development.

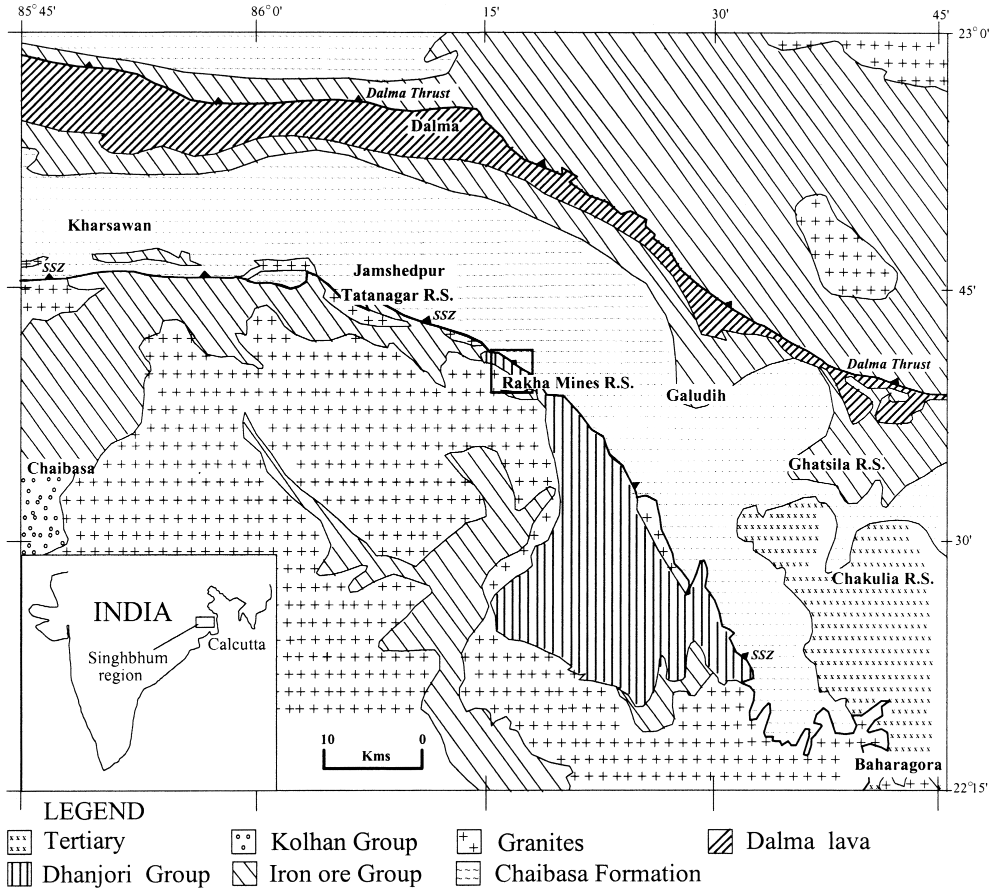

Fig. 1. Geological map of the Singhbhum region (after Dunn and Dey, 1942) with study area outlined. SSZ = Singhbhum shear zone. The Singhbhum shear zone and the Dalma thrust are marked with thick dented lines.

2. Geological background

The study area (Fig. 1) comprises approximately 60 km^2 and covers the central part of the SSZ. The SSZ is a tectonic dislocation zone which separates the Dhanjori Group (footwall) from the Chaibasa Formation (hanging wall) and is marked by intense mylonitisation and formation of a strong *L–S* fabric in the rock units. The mesoscopic structures from the SSZ indicate that the SSZ is a major northerly (or northeasterly) dipping shear zone with a southward thrust movement (Ghosh and Sengupta, 1987a; Joy, 1996). Even within the Dhanjori Group outcrop there is zonal development of strong *L–S* fabric in quartzites, grits and metabasics (a) close to the contact between lower quartzite and metabasic rock unit and (b) in the gritty quartzites and arkoses immediately overlying the Singhbhum Granite (Joy, 1996). These zones are named here as Jublatola shear zone (JSZ) and Rohinbera shear zone (RSZ), respectively (Fig. 2). Singhbhum Granite outcrops along the southern boundary of the study area.

Rocks occurring north of the SSZ within its hanging wall (Fig. 2) contain muscovite–biotite–quartz–almandine as the prevailing metamorphic mineral assemblage (with retrogression of almandine to chlorite). The Dhanjori Group rocks contain chlorite–muscovite–biotite as metamorphic minerals. Rocks within the SSZ usually have the same paragenesis as those in the Dhanjori Group, except for the local occurrence of kyanite.

3. Fabric measurement procedure

Fifty-nine oriented quartz tectonite specimens were collected from the SSZ, the Dhanjori Group south of the SSZ, and from the Chaibasa Formation immediately north of the SSZ in the Singhbhum District, Bihar, India (Fig. 2). The specimens exhibited extensive grain-size reduction by dynamic recrystallisation with the development of a strong crystallographic preferred orientation in the recrystallised quartz (Saha and Joy, 1995; Joy, 1996).

C-axis orientations of 200 or more recrystallised quartz grains from each quartzite specimen from the SSZ, and its hanging wall and footwall were measured on sections cut parallel to the mineral elongation lineation and perpendicular to the mesoscopic foliation (XZ section) using a Federov Stage assembly fitted to an optical microscope. A repeat set of measurements was obtained from sections cut perpendicular to both foliation and mineral elongation lineation (YZ section) to check the reproducibility of the fabric (Appendix A). Measurements of the *c*-axis orientations of the relict quartz grains were also carried out where they formed a high proportion of the grains.

The *c*-axis orientations were plotted with respect to

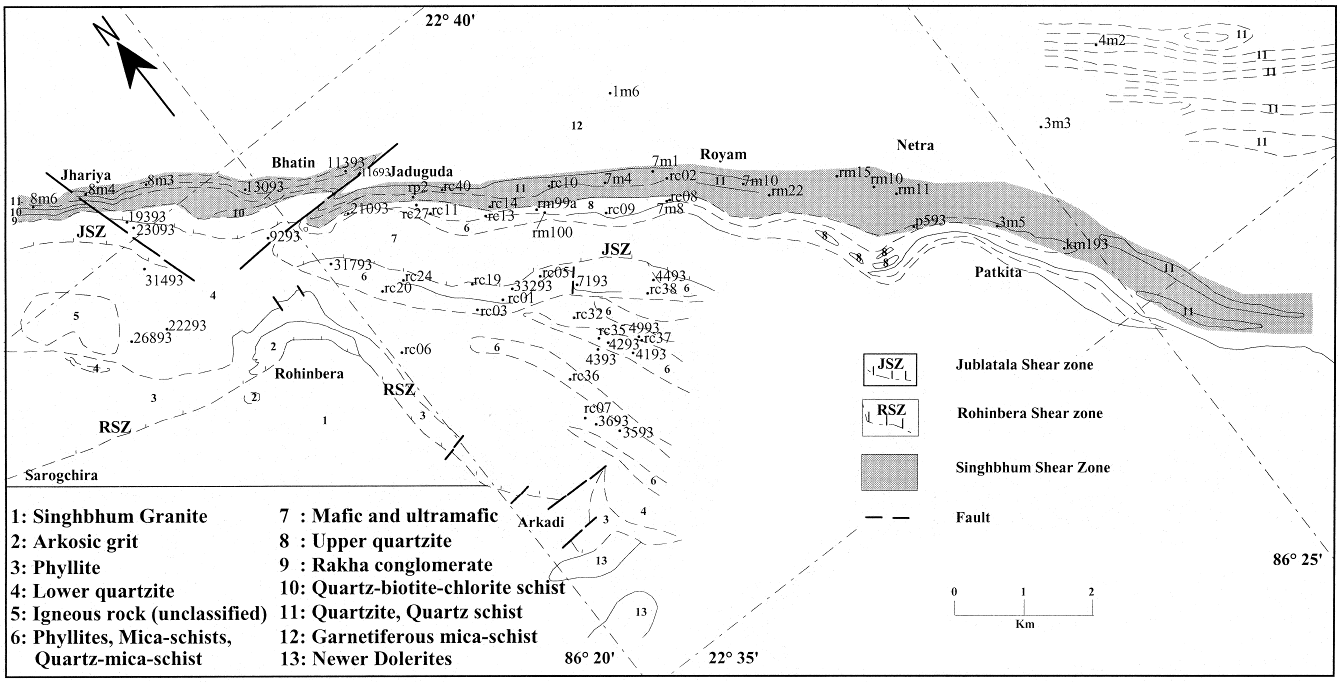

Fig. 2. Location map for specimens collected from the Singhbhum shear zone and the Dhanjori Group.

the mesoscopic foliation–mineral elongation lineation framework on a lower hemisphere equal area projection and contoured using a computer program of Kutty and Joy (1997) to obtain the fabric diagrams presented in this paper. The mineral elongation lineation direction is taken as the principal extension direction (X) of the finite strain ellipsoid. Fabric skeletons were prepared from the contoured fabric diagrams by connecting the crests and ridges (Lister and Williams, 1979; Lister and Hobbs, 1980; Vissers, 1993).

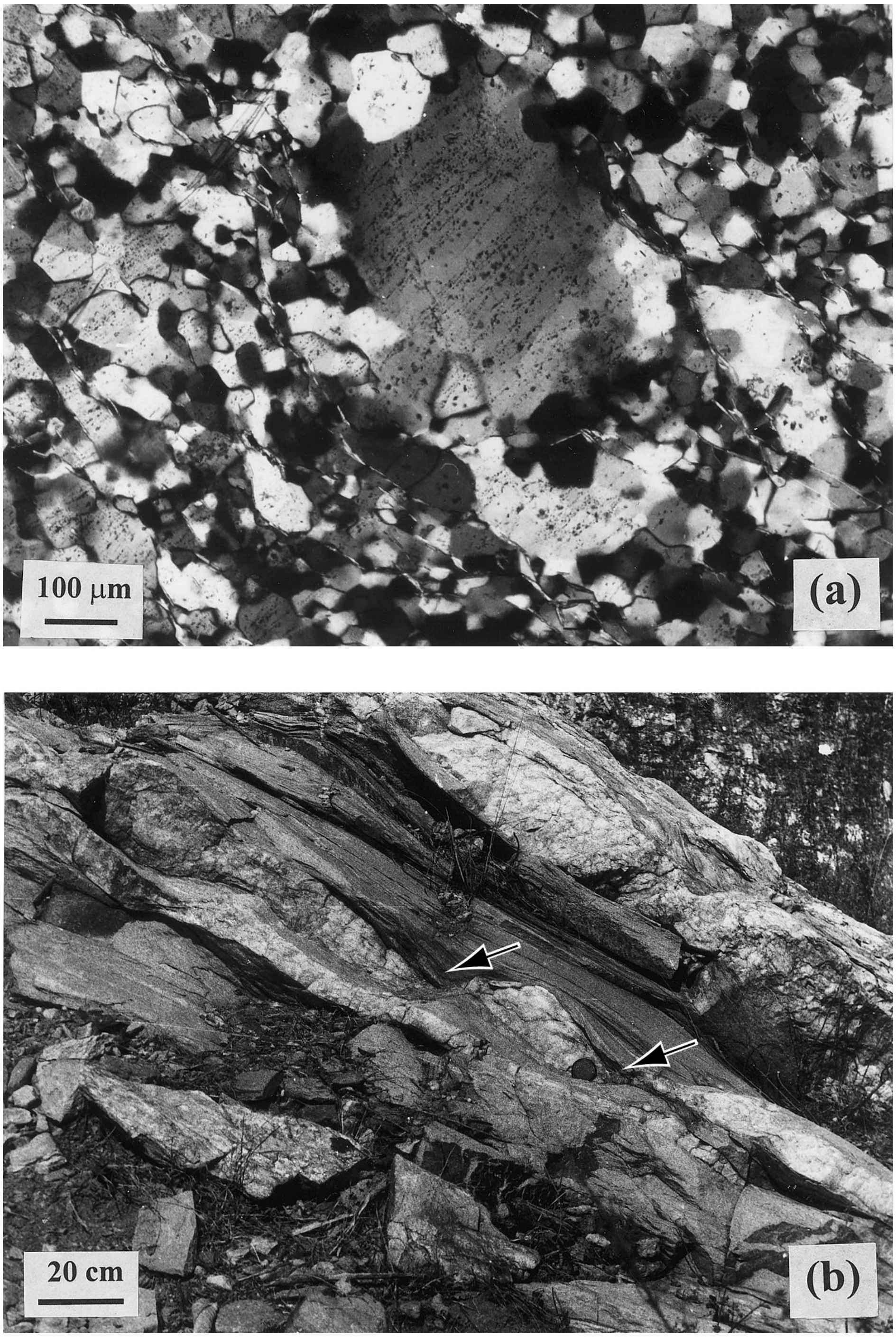

Fig. 3. Micro-structures indicative of high fluid pressure in the Singhbhum shear zone and its footwall. (a) Tuttle lamellae appearing as fine parallel dust inclusion trails in relict and some recrystallised quartz grains, specimen no. rc07, photomicrograph under cross polars. (b) Asymmetric boudin in quartz veins emplaced sub-parallel to mylonitic foliation in the Singhbhum shear zone (white arrows at boudin necks indicate apparent top-to-the-south displacement comparable to that on *C′* shears of Passchier and Trouw, 1996). Field photo on a NNE joint surface perpendicular to mylonitic foliation.

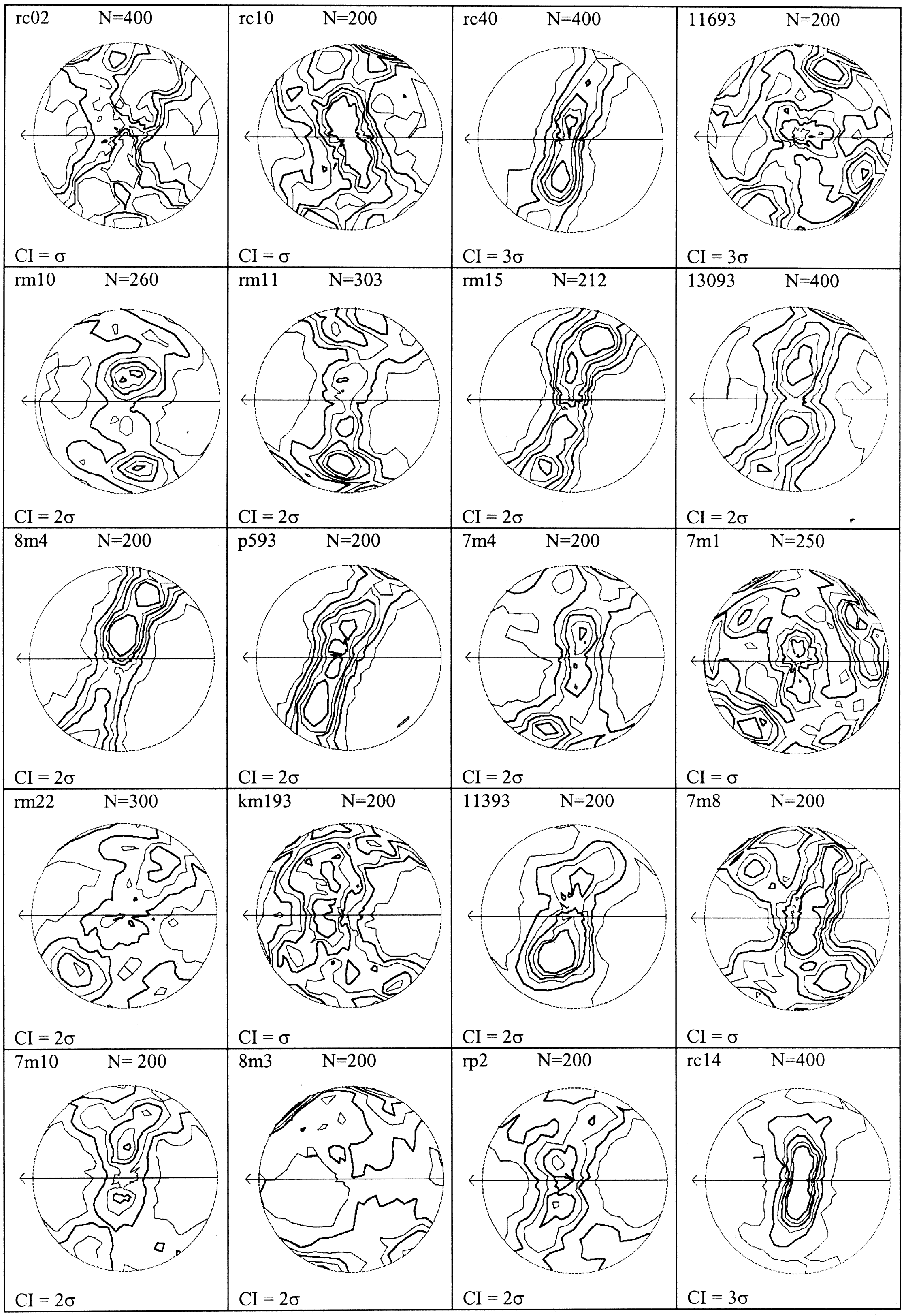

Fig. 4. Quartz *c*-axis fabric of the Singhbhum shear zone specimens. Lower hemisphere equal area projections for *c*-axis orientations in dynamically recrystallised grains, N is the total number of *c*-axes measured. Fabric patterns are contoured using a computer program of Kutty and Joy (1997) following the Kamb method with $E = 3\sigma$. Lowest contour in all fabric diagram corresponds to $(E–2\sigma)$. CI is contour interval. The foliation trace is E–W, and the arrow is pointing in the down plunge of mineral elongation lineation direction (taken here as the X direction of the finite strain ellipsoid). Viewing towards east or south-east. Top of foliation is towards north side of the foliation trace. A similar convention is followed for Figs. 5–9. The specimen number is at the top left corner of each fabric diagram. Specimen number rp2 is a quartzite pebble from the Rakha conglomerate and specimen number rc14 is matrix of the Rakha conglomerate.

4. Petrography of the specimens

Quartz tectonites analysed from the study area are composed of quartz as the main constituent with phyllosilicates (white mica and/or chlorite) varying from 2 to 35 modal percent. The quartz tectonites are generally bimodal aggregates with relatively smaller dynamically recrystallised grains (40–120 μm) and larger relict quartz grains (110–425 μm). The proportion of the relict grains is typically higher in specimens from the Dhanjori Group (footwall); however, specimens with near to complete recrystallisation are noted from the JSZ also. The relict grains show undulose extinction, deformation bands, subgrain structures, and core-and-mantle structures (White, 1976) and sometimes deformation lamellae (Fairbairn lamellae). The recrystallised quartz grains generally show serrated or sutured grain boundaries, castellate microstructures and, rarely, dragging microstructures (Jessell, 1987). Some of the recrystallised quartz grains also show undulose extinction and incipient subgrain structures (Joy, 1996). A few samples from the Dhanjori Group also show Tuttle lamellae (Tuttle, 1949), which are healed microfractures remaining visible as planes of solid and/or fluid inclusions (Fig. 3a). Quartz veins occurring sub-parallel to mylonitic foliation in the SSZ, but retaining their coarse texture and internal fractures, often show asymmetric boudins with apparent displacement at boudin necks comparable to C' shears of Passchier and Trouw (1996) (Fig. 3b).

The dynamic recrystallisation is apparently controlled by a combination of both progressive grain-boundary-rotation and grain-boundary-migration recrystallisation. Microstructures indicative of progressive grain boundary rotation—core-and-mantle structure (White, 1976), grain polygonisation (Nicholas and Poirier, 1976); and microstructures indicative of grain-boundary-migration recrystallisation—grain boundary bulging (White, 1976; Bell and Etheridge, 1976), castellate microstructures, dragging microstructures, serrate grain boundaries (Jessell, 1987), and small strain-free grains (White, 1976), are observed in the analysed specimens, either individually or in combination within the same specimen.

5. Description of the quartz *c*-axis fabric

5.1. Specimens from the Singhbhum shear zone

Individual specimens collected from the SSZ are characterised by either of two patterns: (1) an asymmetric, kinked single-girdle pattern oriented at a high angle to the trace of foliation and mineral elongation lineation, with or without the vestige of the trailing edge of a type I cross-girdle, as exemplified by 7m4 and rm15 (Fig. 4) or (2) an asymmetric type I cross-girdle, exemplified by 7m8 (Fig. 4, definitions of fabric types after Lister, 1977). A few specimens display more discontinuous girdles, especially the ones with high mica content, but the connected fabric skeleton of the specimens remains asymmetric (7m1, 11693, Fig. 4).

The fabric point maxima have several locations: close to Y (p593, Fig. 4), close to XZ plane at an angle less than 45° to Z, the foliation normal (e.g. rm11, Fig. 4), or at nearly 45° from Y and Z (e.g. 7m10, Fig. 4). All three types of fabric maxima are equally well developed in some of the analysed specimens (e.g. rm15 and rp2, Fig. 4). Other specimens generally display one or two maxima with or without a submaximum at the other positions described. The central segment of the type I fabric skeleton is oriented at a high angle (80–85°) to the foliation trace (e.g. rm15, Fig. 4).

5.2. Specimens from the footwall and hanging wall

Specimens with L–S fabrics from the footwall display *c*-axis fabrics similar to those obtained from the SSZ specimens, except for the details of internal asymmetry and locations of point maxima within the girdle. The specimens from the upper quartzite (Fig. 2) are characterised by either an asymmetric, kinked single-girdle (rm100 and rm99a, Fig. 5), or an asymmetric type I cross-girdle (21093 and rc11, Fig. 5). The point maximum within the girdle is oriented either near Y (rm100, Fig. 5), or close to XZ plane at low angle (< 45°) to Z (rc09, Fig. 5), or occasionally at an intermediate orientation (rc13, Fig. 5). Specimens from the JSZ display more strongly developed single-girdle fabrics (9293, rc24, rc03, and 33293, Fig. 6), which are morphologically close to those from the SSZ. The main fabric type in specimens away from the lower quartzite–metabasic rock contact, i.e. the JSZ (Fig. 2), is an asymmetric type I cross-girdle (rc07, Fig. 7). Occasionally fabrics in the lower quartzite away from the JSZ are nearly symmetric type I cross-girdle fabrics (rc37, Fig. 7). A few specimens from the lower quartzite display a more diffused fabric (e.g. rc06 and rc36, Fig. 7), although strongly developed single girdle fabric is also recorded from the lower quartzite (e.g. 4393 and 4993 of Fig. 7).

Only two specimens were analysed for *c*-axis fabric from the hanging wall of the SSZ, both specimens containing a very high proportion of mica. One of them (3m3, Fig. 8) displays a poorly developed (type I?) girdle, and the other (4m2, Fig. 8), displays a girdle fabric with a slightly asymmetric central segment, but with point maxima both at Y and at low angle to Z.

6. *c*-Axis fabric in the relict grains

With progressive plastic deformation and dynamic recrystallisation, quartzite evolves into a rock with bimodal grain-size distribution consisting of recrystallised quartz and relict porphyroclasts (Marjoribanks, 1976; White, 1976). Krischner and Teyssier (1991) have suggested that the CPO in the relict grains would be influenced by (and thus indicative of) the kinematic framework present during most of the crystal-plastic deformation history while the fabric of the recrystallised aggregates reflects the last stages of plastic deformation.

To gain information on the variations, if any, between the *c*-axis fabric of the recrystallised and relict quartz grains, a few specimens from SSZ with relatively high proportions of relict quartz grains were selected for measurement of *c*-axes in relict quartz grains. Where the relict porphyroclasts display undulose extinction, the vector mean of measurements from different parts of the same grain was taken as the average orientation of the relict porphyroclast. The measured fabrics do not indicate any noticeable variation from the fabric of the recrystallised quartz grains (Fig. 9).

7. Discussion

The *c*-axis fabric from Singhbhum with the central segment of the fabric skeleton oriented at a high angle (80–85°) to the mesoscopic foliation may be inter-

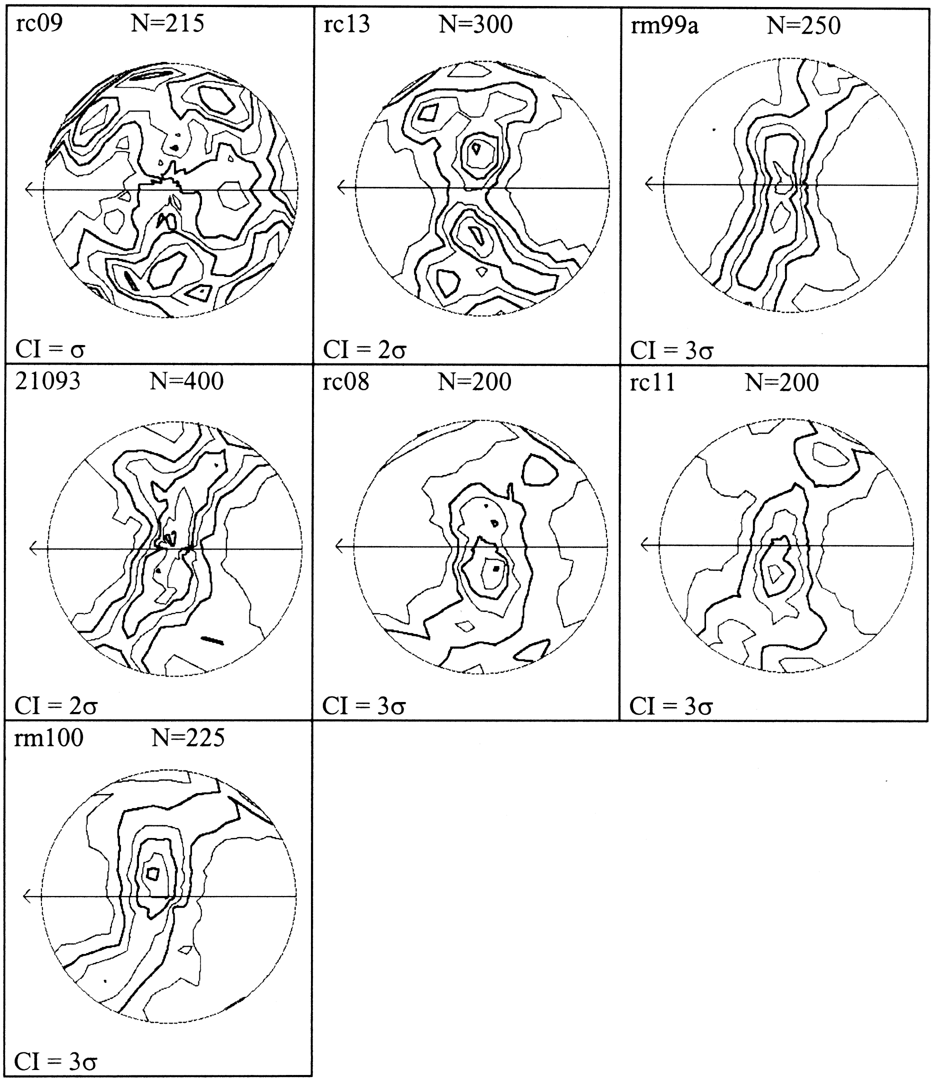

Fig. 5. Quartz *c*-axis fabric diagrams for the specimens of ‘upper quartzite’ of the Dhanjori Group (in the eastern part of the study area the Singhbhum shear zone affects the ‘upper quartzite’ and thus some specimens like p593 may be considered as belonging to the Singhbhum shear zone and the corresponding fabric is included in Fig. 4).

preted in terms of a progressive simple-shear deformation with high shear strain (Lister and Williams, 1979; Bouchez et al., 1983; Lister and Snoke, 1984; Davis et al., 1987). However, it should be noted that *c*-axis fabrics often record only the last episodes of strain (Lister and Price, 1978; Lister and Williams, 1979; Lister and Hobbs, 1980).

7.1. Shear sense from quartz *c*-axis fabric

The external asymmetry (as defined by Law, 1987) in the studied quartz *c*-axis fabrics from the SSZ indicate a north-side-up displacement (Fig. 10) consistent with southward thrust movement along a northerly dipping SSZ. The specimens from the Jublatola shear

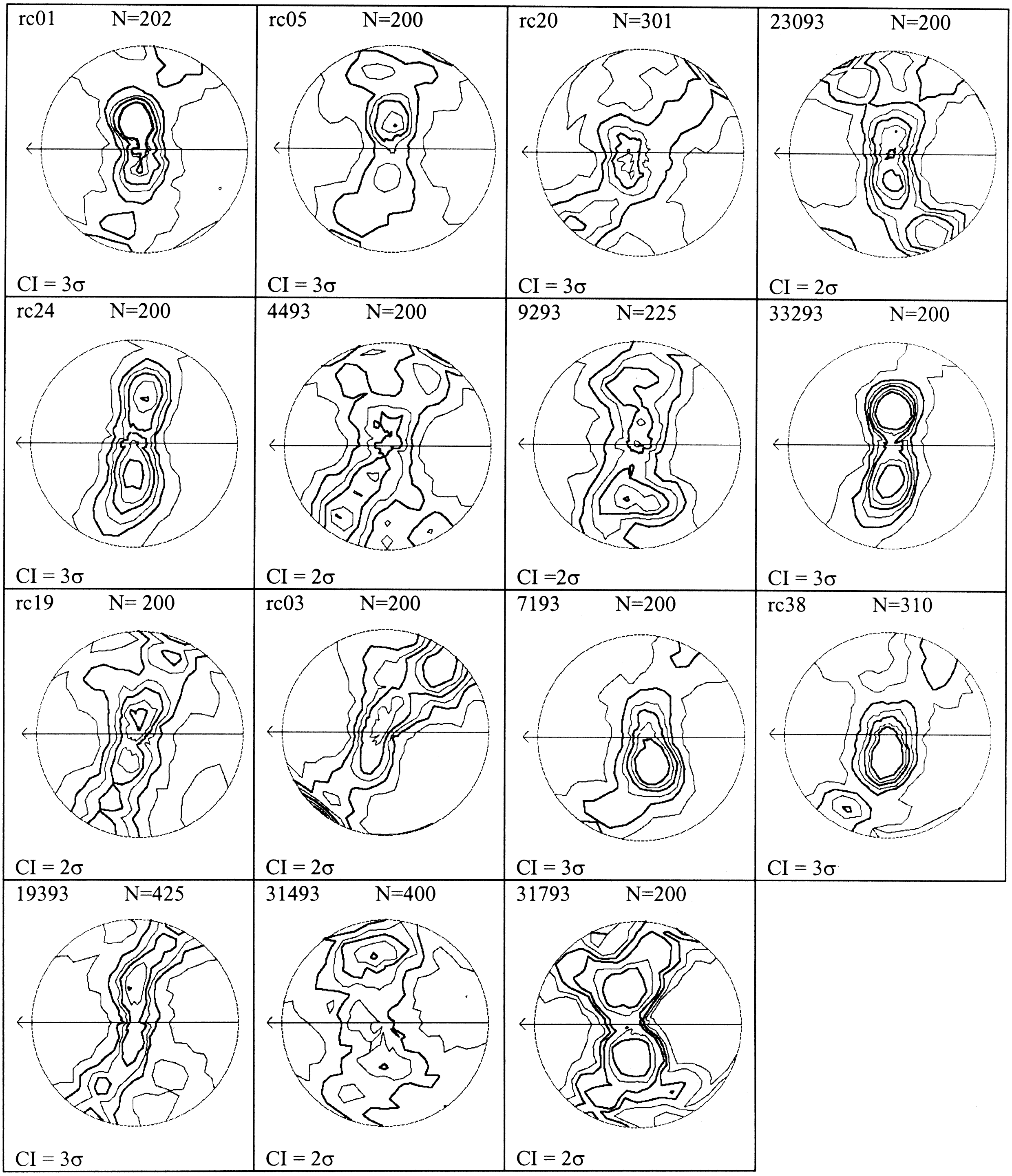

Fig. 6. Quartz *c*-axis fabric diagrams of the quartz tectonite specimens from the Jublatola shear zone (Dhanjori Group).

zone, except, 23093, also have external asymmetry which can be interpreted in terms of top-to-south displacement (Fig. 6). The opposite sense of asymmetry displayed by 23093 might be due to local aberration in the flow pattern (Passchier, 1983). Some workers anticipate such heterogeneity of flow in 'real' rocks (Jiang and White, 1995).

7.2. CPO, slip systems and ambient deformation temperature

Crystallographic preferred orientation in quartz aggregates is an indicator of deformation temperature since the fabric pattern is controlled by the relative importance of different slip systems, which in turn are

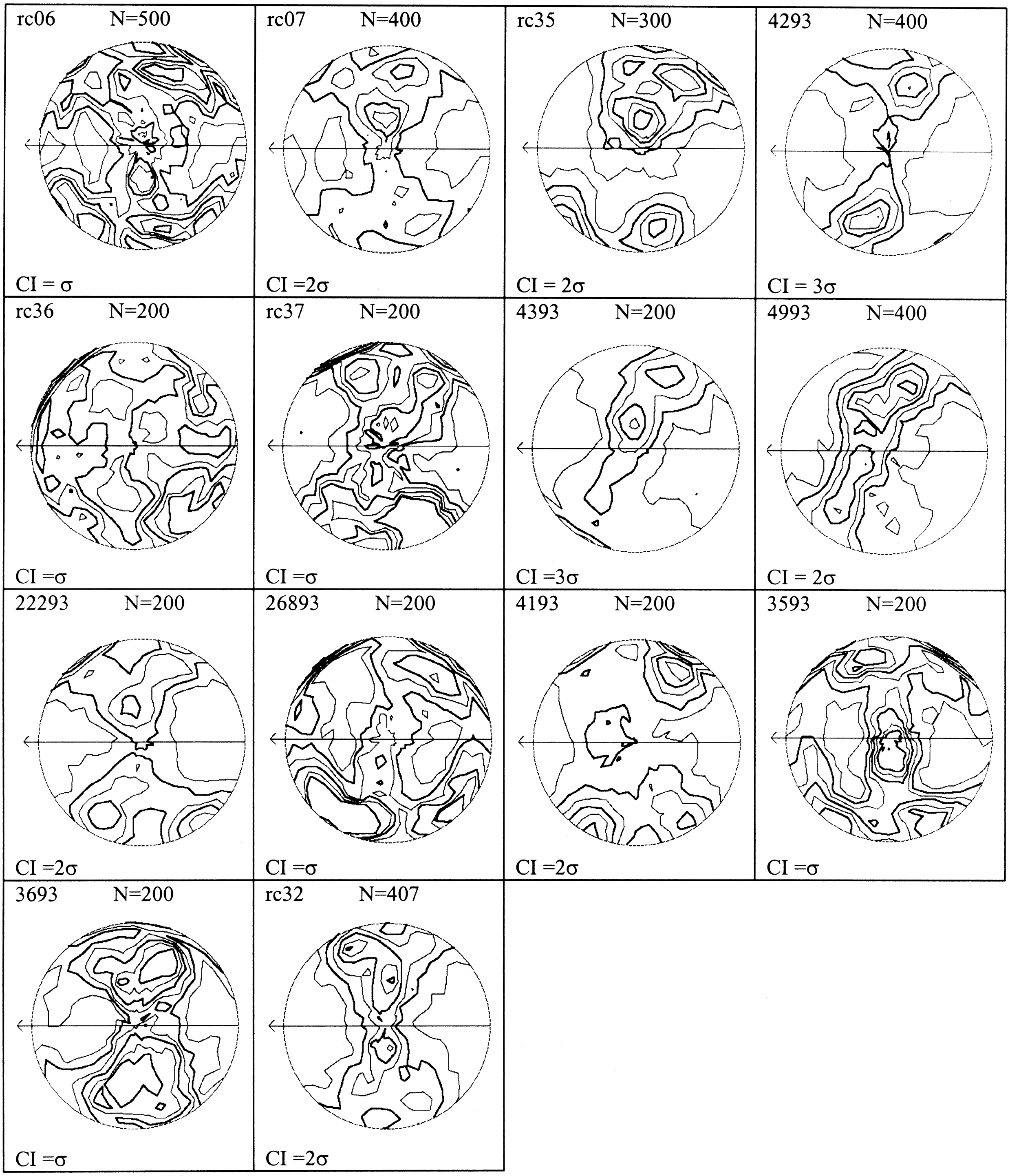

Fig. 7. Quartz *c*-axis fabric diagrams of the 'lower quartzite' specimens of the Dhanjori Group.

temperature sensitive. Slip in quartz occurs primarily in the <*a*> crystallographic direction, predominantly on the basal and prism planes (Schmid and Casey, 1986; Ralser et al., 1991). Basal <*a*> slip is dominant at lower temperatures and at faster strain rates, causing a *c*-axis fabric maximum near the Z-axis of the finite strain ellipsoid. With increasing temperature, rhombohedral <*a*> slip system becomes activated, causing a fabric maximum at an intermediate orientation between the Y- and Z-axes. Ultimately, at still higher temperature and slower strain rates, the prism <*a*> slip system operates, causing a fabric maximum near the Y-axis of the finite strain ellipsoid (Tullis et al., 1973; Nicholas and Poirier, 1976; Bouchez, 1977; Tullis, 1977; Lister and Dornsiepen, 1982; Hobbs, 1985; Mainprice et al., 1986; Schmid and Casey, 1986; Culshaw, 1987; Wenk et al., 1989; Jessell and Lister, 1990). Experimental data indicate that the transition temperature from basal <*a*> to prism <*a*> slip occurs at about 700–800°C, under a strain rate of 10^{-5} s^{-1} (Blacic, 1975). Prism <*c*> slip system may be activated at very high temperatures and causes a *c*-axis fabric concentration near the X direction (Blacic, 1975; Garbutt and Teyssier, 1991). High temperature (700–800°C) and a high partial pressure of water is invoked to explain the activation of prism <*c*> slip (Blumenfeld et al., 1986; Duebendrofer and Housten, 1987). Quartz *c*-axis fabrics with girdles through Y and containing a Y-maximum have been reported from naturally deformed quartzites under amphibolite facies condition (Bunge and Wenk, 1977; Schmid and Casey, 1986), and from granites deformed under subsolidus condition at a temperature of 650–700°C (Blumenfeld et al., 1986). However, Lister and Dornsiepen (1982) recorded notable *c*-axis maxima at the Y-axis in quartzites deformed in greenschist to mid-amphibolite facies condition from Saxony granulite terrain.

Specimens from the SSZ and in its footwall are characterised by either asymmetric, kinked single-girdle or asymmetric type I cross-girdle fabrics passing through Y, at a high angle to the foliation. Often the fabric girdles contain a strong Y-maximum together with equally well developed maxima or submaxima at low angles to Z or at an intermediate orientation in the girdle (Fig. 11).

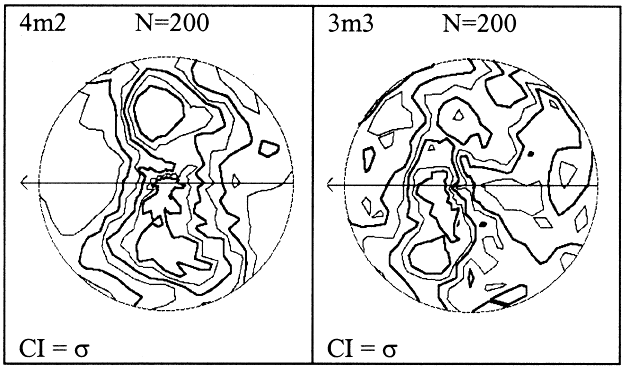

Fig. 8. Quartz *c*-axis fabric diagrams of the specimens from the Chaibasa Formation immediately north of the Singhbhum shear zone.

The metamorphic mineral paragenesis in the Ghatsila–Galudih region indicates that the garnet zone rocks of Ghatsila are replaced southward (still in the hanging wall of the SSZ) by staurolite–kyanite zone rocks (Naha, 1965). According to Naha (1965) these staurolite–kyanite zone rocks (supposedly of amphibolite facies) have suffered retrogression along the SSZ due to dislocation metamorphism. However, Ghosh and Sengupta (1987b) interpreted the development of kyanite as broadly synchronous with progressive deformation in the SSZ. One could explain the Y-maximum as due to supposedly amphibolite facies condition during deformation in the SSZ. However, the Y-maximum fabrics are also present in the JSZ and the lower quartzite in the footwall (Figs. 5–7), where the mineral paragenesis of quartz–chlorite–biotite indicates lower ambient temperature of greenschist facies condition.

Various alternative interpretations regarding the relationship between the metamorphism and deformation in the SSZ have also been put forward (Naha, 1965; Mukhopadhyay et al., 1975; Bhattacharyya and Sanayal, 1988). If higher grade metamorphism in the SSZ and in the northern belt (hanging wall of the SSZ) predates (Naha, 1965), or post-dates (Mukhopadhyay et al., 1975) the deformation responsible for the development of grain-shape fabric and CPO in the SSZ, then activation of the prism <*a*> slip system and the Y-maximum should have been controlled by factors other than temperature, especially when the CPO from the footwall quartzites are also taken into account.

Alternatively, it has been suggested that temperature may not be the only parameter influencing activation of different slip system (Hobbs, 1985). Fluids may have an important effect on the operative slip systems in natural quartzites (Lister and Dornsiepen, 1982; Bouchez et al., 1984; Blumenfeld et al., 1986). Hippertt (1994a,b) has correlated increasing mica enrichment (phyllonitisation) and access of water during progressive strain to a change in operative slip system from basal <*a*> to prism <*a*>, through dislocation-assisted diffusion. Prism <*c*> slip is shown to be facilitated at high temperatures and high fluid pressure (Blacic, 1975; Blumenfeld et al., 1986; Garbutt and Teyssier, 1991). However, to our knowledge, independent influence of the fluid activity on the activation of different slip system in quartzite has not so far been sufficiently evaluated.

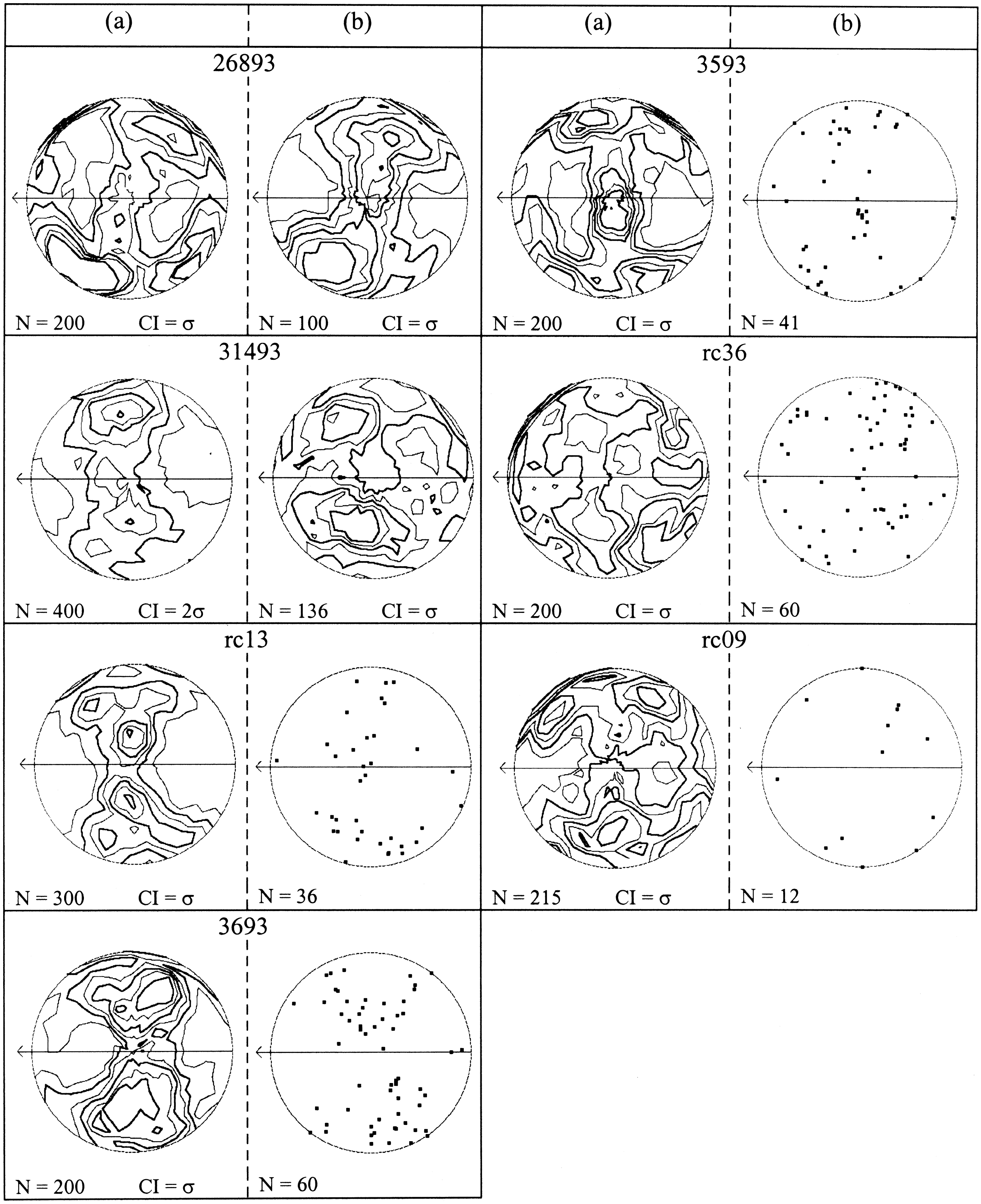

Fig. 9. Quartz *c*-axis fabric for the recrystallised quartz grains (column a) vis-a-vis the relict quartz grains (column b). Lower hemisphere equal area projections. *N* is total number of *c*-axis measured in each specimen. Contouring after Kamb method with $E = 3\sigma$. Lowest contour corresponds to $(E - 2\sigma)$. CI is contour interval. Viewing towards east or southeast. The fabric diagram is not contoured when *N* is less than 100 for relict grains.

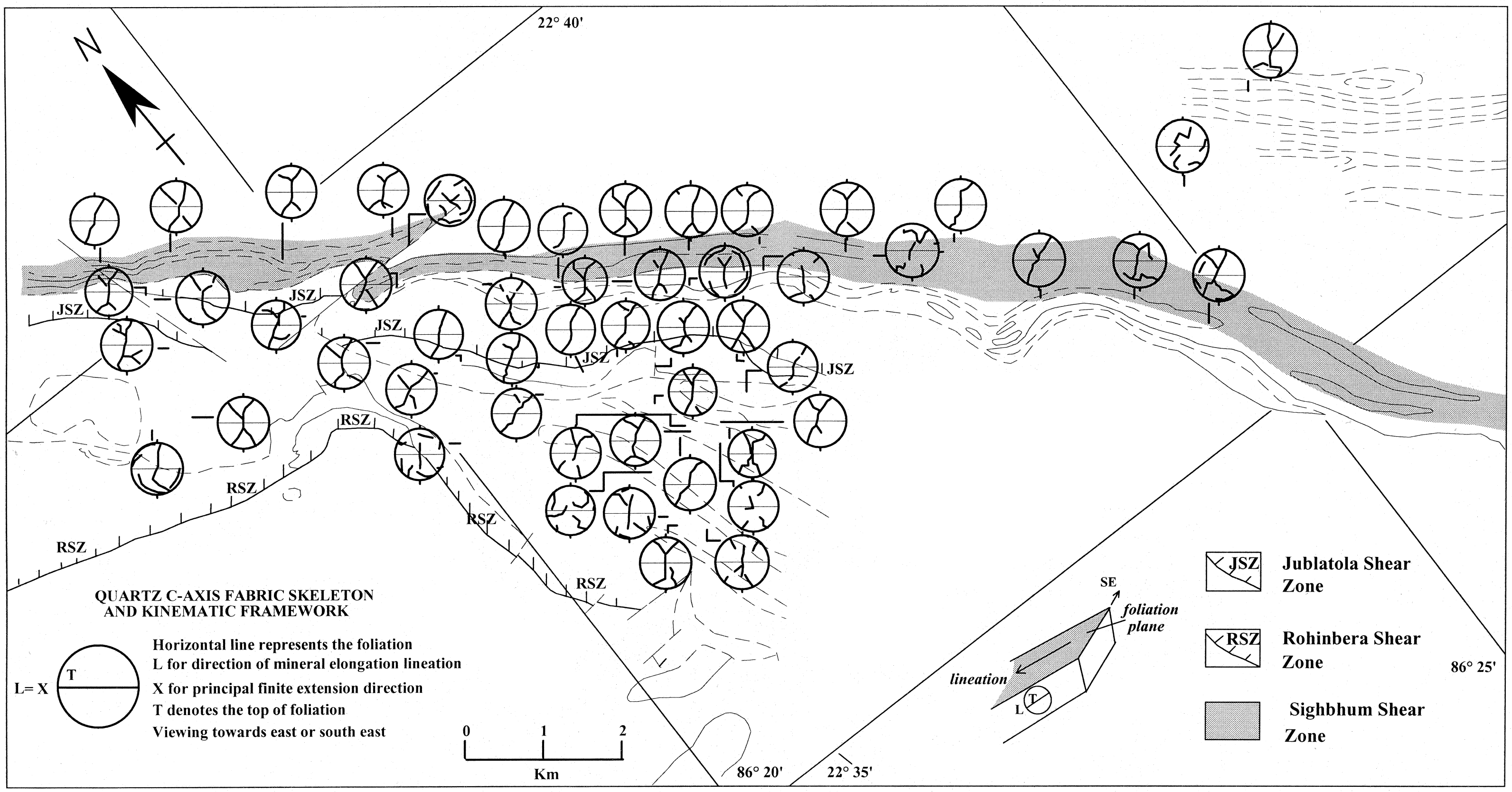

Fig. 10. *c*-Axis fabric skeletons of the analysed specimens. Viewing towards east or southeast. Note persistent asymmetry of fabric skeletons, particularly among the SSZ and the JSZ specimens.

7.3. Comparable c-axis fabric in recrystallised and relict quartz grains

The *c*-axis fabrics measured from relict quartz grains display a pattern and asymmetry comparable to those from their recrystallised counterparts. Experimental observations demonstrate that CPO of dynamically recrystallised quartzites depends on the mechanism of recrystallisation (Gleason et al., 1993). Dominance of grain-boundary-migration recrystallisation driven by local difference in strain-induced dislocation density leads to CPO of dynamically recrystallised quartz grains distinct from that of deformed original grains (regime I of Hirth and Tullis, 1992). On the other hand dynamic recrystallisation by progressive subgrain rotation leads to a CPO in dynamically recrystallised quartz grains mimicking that of the relict grains because of host control on subgrain orientations (regime II of Hirth and Tullis, 1992). In the regime III of Hirth and Tullis (1992), there is again a preponderance of grain boundary migration, but now driven by surface energy reduction through increased grain boundary mobility at elevated temperature. In regime III as there is no preferential orientation for growth, the CPO of dynamically recrystallised quartz grains is similar to that of relict quartz grains (Gleason et al., 1993). The apparent similarity of *c*-axis fabrics of recrystallised and relict quartz grains from the SSZ and its footwall may be interpreted as a case of regime II or regime III recrystallisation. However, one should keep in mind that fabric patterns or kinematic framework of experimentally deformed quartzites (Gleason et al., 1993) is different from that of the SSZ sample.

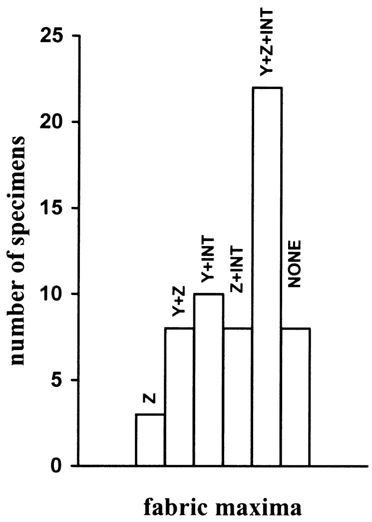

Fig. 11. Bar chart indicating frequency of measured quartz *c*-axis fabrics with different combinations of maximum types. Different maximum types (or their combinations) are labelled according to the relative positions of point maximum with respect to the X-, Y- and Z-axes of the finite strain ellipsoid (see text). 'NONE' refers to specimens with no noticeable point concentration in the fabric diagram.

7.4. Fluid activity in the Singhbhum shear zone

In the present sample, the Y-axis maxima are not associated with an increase in the mica content as suggested by Hippertt (1994a). On the other hand, the role of fluids in the SSZ is demonstrated by the presence of stable hydrous phase such as muscovite and common syntectonic quartz veins. Also the ore minerals in the shear zone are interpreted to be of hydrothermal origin (Sarkar, 1984). Asymmetrically boudinaged quartz veins, whose asymmetry can be related to the syntectonic *C′* shears (Passchier and Trouw, 1996) in the SSZ, are quite common in the mylonites of Singhbhum region (Fig. 3b). This intensity of syntectonic veining could be correlated with a high fluid pressure during deformation. Experimental works demonstrate that the Tuttle lamellae formation is enhanced by either high temperature (Lemmleyn and Kliya, 1960) or by the presence of reactive pore fluid (Smith and Evans, 1984).

Microstructures indicating a coupling of progressive subgrain rotation and grain boundary migration recrystallisation mechanisms, specimens having extensive dynamic recrystallisation and the presence of *S–C* fabrics from the SSZ sample may be interpreted as a result of deformation in the regime III or in a transitional regime between regimes II and III (Hirth and Tullis, 1992). Microstructural evolution in such a regime could have occurred at elevated temperature or through the influence of fluids (Hirth and Tullis, 1992). The latter may be the case of water weakening (Blacic, 1975; Mainprice et al., 1986: Paterson, 1989) or transient high fluid pressure leading to brittle effects and consequent water penetration and weakening of quartz. Alternatively, the presence of stable hydrous phases, such as muscovite, indicates that the ambient temperature in the SSZ and JSZ was not too high.

Difficulties remain in attempting to explain the Y-maximum fabric from the SSZ and the JSZ in terms of higher ambient temperature of deformation. On the other hand, experiments (Blacic, 1975) and natural examples of Y-maximum fabric supposedly formed under high fluid activity (e.g. Blumenfeld et al., 1986; cf. Mainprice et al., 1986), suggest that the high partial pressure of water prevalent in the SSZ and its footwall may account for mechanical effects which facilitate water penetration and consequent hydrolytic weakening of quartz leading to the prism $<a>$ slip in addition to the basal $<a>$ and rhomb $<a>$ slips under greenschist facies condition.

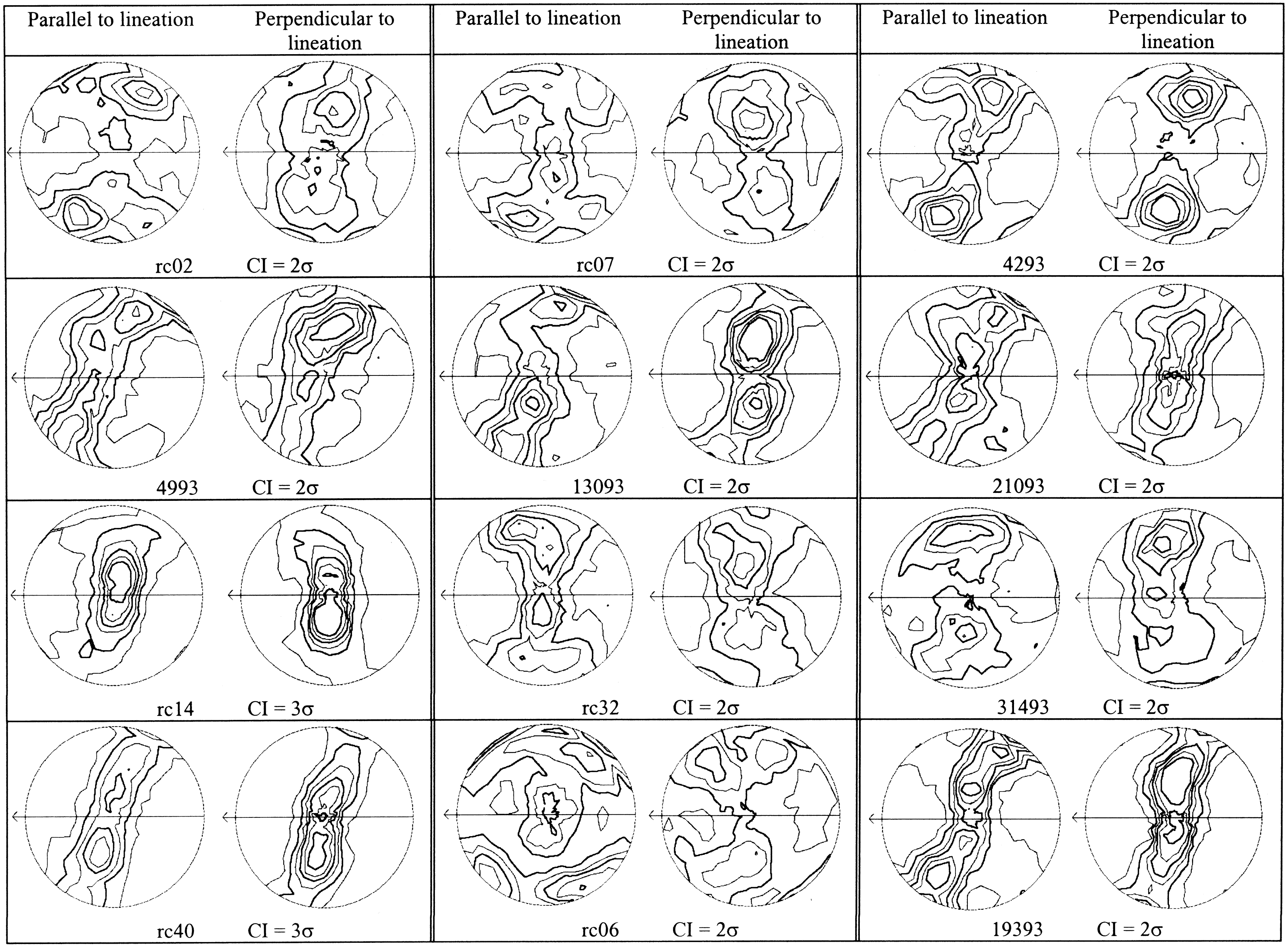

Fig. A1. Comparison of quartz *c*-axis fabric from two mutually perpendicular sections for individual specimens. Orientations measured in sections perpendicular to lineation are rotated before presentation. E–W horizontal line represents the trace of foliation with top of foliation on the north side; arrow at the western end represents down plunge direction of stretching/mineral lineation. Viewing is towards east or southeast. Contouring after Kamb method with $E = 3\sigma$. Lowest contour is for E–2σ. CI is contour interval.

7.5. Comparison of c-axis fabrics from the SSZ with those from its footwall

The dynamically recrystallised quartz *c*-axis fabrics in the SSZ and the Dhanjori Group quartzites (the footwall rocks of the SSZ) display comparable patterns (Fig. 10), although the actual positions of the fabric point-maxima and the angles made by the leading edge, trailing edge and central segment of the fabrics within individual specimens vary with respect to finite strain axes. Therefore, the deformation responsible for the *c*-axis fabric development in the SSZ and in the Dhanjori Group may be kinematically linked.

8. Conclusions

Specimens from the Singhbhum shear zone and its footwall display either asymmetric, type I cross-girdle or asymmetric, kinked single-girdle *c*-axis fabrics measured in dynamically recrystallised quartz grains. The *c*-axis fabric and its asymmetry in the relict quartz grain is apparently very similar to that of the recrystallised quartz grain counterparts. The fabrics are characterised by a concentration near the Y-axis of the finite strain ellipsoid, with an equally well, or subordinately developed, concentration at a small angle to the Z-axis and at an intermediate orientation. The asymmetry of the fabric indicates a general southward thrust sense of movement of the northern block on both the northerly dipping SSZ and subsidiary shear zones such as the JSZ. The formation of quartz CPO with Y-maximum and simultaneous concentration near Z or at an intermediate orientation under greenschist facies condition of the Singhbhum shear zone and its footwall is attributed to influence of higher fluid activity in these large shear zones.

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Appendix A. Homogeneity of the quartz *c*-axis fabric in the hand specimen scale: A visual check

In order to check the homogeneity of quartz *c*-axis orientations at the hand specimen scale, two thin sections of different orientations were prepared from each specimen—one cut parallel to the mineral elongation lineation and perpendicular to the foliation and the other perpendicular to both foliation and mineral elongation lineation. *C*-axis orientations of 200 dynamically recrystallised quartz grains were measured in each thin section using a Federov stage fixed to an optical microscope. The measured *c*-axes were then plotted on a lower hemisphere equal area projection and contoured. Necessary rotations were applied so that prepared fabric diagrams refer to the same orientation framework, i.e. with the E–W axis of the fabric diagram as the trace of foliation, the W (left) as the mineral elongation lineation direction, and the north (top) side of the E–W line as the top of the foliation. The viewing direction is towards SE or E. Visual comparison of such fabric diagrams for 12 specimens (a pair for each) show that they are comparable (Fig. A1) and the assumption of homogeneity in quartz *c*-axis fabric at the hand specimen scale could be accepted by the visual comparison method.

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