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Influence of micaceous impurity on dynamically recrystallized quartz *c*-axis fabric in *L–S* tectonites from the Singhbhum Shear Zone and its footwall, Eastern India

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Abstract— When temperature and strain rate remain constant the quartz *c*-axis fabric in deformed pure quartz aggregates, is largely dependent on deformation kinematics. Asymmetry of the fabric, e.g. in type-I asymmetric crossed girdle pattern in natural quartz tectonites, simulated fabric or experimentally deformed quartz aggregates is generally related to sense of vorticity for a non-coaxial flow. Natural quartz tectonites, however, often contain micaceous impurities. Measurement on a sample of 59 quartz tectonites with mesoscopic *L–S* fabric and representing low T/T_m deformation under non-coaxial flow, from the Singhbhum Shear Zone and Dhanjori quartzites, Eastern India provides the basic data to quantitatively assess the influence of mica on (i) asymmetry of quartz *c*-axis fabric and (ii) degree of crystallographic preferred orientation, i.e. fabric intensity, taking *c*-axes of dynamically recrystallized quartz grains as a fabric element. A fabric intensity parameter (κ) is defined as the ratio of the greatest eigenvalue to the least eigenvalue of the orientation tensor matrix corresponding to *c*-axis orientations in each measured specimen. The modal percent of mica (μ) in the sample varies from 2 to 35; that of recrystallized quartz grains (v), as opposed to relict clasts, from 45 to 98. The asymmetry of the fabrics in the above sample, measured either as the Am statistic or as the angle between the central segment of the fabric skeleton and direction of mineral elongation lineation, is independent of mica content. Correlation-regression analysis of the variables κ, μ, and v, demonstrate a negative correlation between micaceous impurity and the fabric intensity parameter. The regression equation is of the form $\kappa = 0.13\, v^{1.11}\, \mu^{-0.617}$. © 1998 Elsevier Science Ltd. All rights reserved

INTRODUCTION

Observations on naturally and experimentally deformed quartzites and simulation studies show that the nature and pattern of quartz *c*-axis fabric is largely dependent on temperature, strain rate and deformation kinematics (Etchecopar, 1977; Lister, 1977; Tullis, 1977; Law, 1986, 1987; Schmid and Casey, 1986; Jessell, 1988a,b; Jessell and Lister, 1990; Ralser *et al.*, 1991; Wenk and Christie, 1991). When temperature and strain rate remain constant, the type of fabric (e.g. symmetric or asymmetric) is determined by the symmetry of the causative flow. For example, a type I asymmetric crossed girdle pattern (Lister, 1977; Schmid and Casey, 1986) is often produced under a simple shear type non-coaxial flow where the sense of vorticity is correlatable with the sense of asymmetry in the resultant fabric (e.g. Lister, 1977; Law, 1986).

The above generalizations are based on observations of pure quartz aggregates where the impurity phase has only insignificant volume proportion (< 1%). However, natural quartz tectonites often contain a significant amount (≫1%) of impurities in the form of white mica or chlorite as in micaceous quartzite or quartz–chlorite schists or similar rocks with deformation induced fabric (crystallographic preferred orientation, CPO).

Fifty-nine oriented specimens of quartz tectonites deformed under greenschist facies condition from the Singhbhum Shear Zone (SSZ) and underlying Dhanjori Group outcrops from around Royam–Jublatola–Rohinbera, Singhbhum district, Bihar, Eastern India have been collected and measured for quartz *c*-axis orientation, volumetric proportion of recrystallized and relict quartz grains, and volumetric proportion of white mica (+ chlorite). A majority of the measured fabrics is of asymmetric type I crossed girdle pattern where the acute angle (ϕ) between the central segment of the fabric skeleton and X direction of finite strain ellipsoid is a measure of external asymmetry (Law, 1987). Another available measure of the external asymmetry is the Am statistic based on the intensity of *c*-axis pole distribution in different quadrants of the projection circle (Fernadez-Rodriguez *et al.*, 1994). Fabric intensity (κ) is defined as the ratio of the maximum to minimum eigenvalues of the orientation tensor matrix corresponding to quartz *c*-axis orientations in a specimen (Scheidegger, 1965; Woodcock, 1977; Saha, 1983; Woodcock and Naylor, 1983). An empirical-statistical approach is employed to assess the dependence (or independence) of the fabric asymmetry and fabric intensity as defined earlier on the volumetric proportion of micaceous impurity (μ) in the studied sample of quartz tectonites.

Although other considerations demonstrate that the overall kinematic framework of deformation and ambient $P–T$ conditions are similar for all the specimens in the Singhbhum sample (Saha and Joy, 1995;

Joy, 1996), the measured specimens show a variation in the degree of dynamic recrystallization of quartz. Some earlier works show that the degree of crystallographic preferred orientation is positively influenced by the magnitude of strain (Etchecopar, 1977; Tullis, 1977; Saha, 1983, 1984; Wenk and Christie, 1991). As dynamic recrystallization is strain induced, and a progressive change in the proportion of dynamically recrystallized quartz grains has been reported from zones of natural strain gradient (e.g. Marjoribanks, 1976; Compton, 1980; Saha, 1989), we take into account the variable strain intensity while doing correlation-regression analysis by introducing a third variable, the proportion of recrystallized quartz grains as opposed to relict grains.

GEOLOGICAL AND DEFORMATIONAL BACKGROUND

Geology, deformation history and metamorphic minerals

The specimens belonging to the sample are collected from an area of about 60 km^2 from the central part of the SSZ, including a part of the hanging wall of the SSZ and its footwall comprising the Dhanjori Group (Fig. 1). The hanging wall outcrops of the study area are thought to represent the rocks of the Chaibasa Formation (Dunn and Dey, 1942; Naha, 1961; Gaal, 1964). Singhbhum Granite batholith is outcropped near the southern boundary of the study area (Fig. 2).

The Dhanjori Group is separated from the Chaibasa Formation by a tectonic dislocation zone namely the Singhbhum Shear Zone, marked by intense mylonitization 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 north-easterly) dipping shear zone with a southward thrust movement (Ghosh and Sengupta, 1987). Shortening across the belt is accommodated partly by a number of additional N(NE) dipping shear zones parallel to the SSZ and occurring on its footwall (Fig. 2). One of these dislocations (Jublatola Shear Zone) is internal to the Dhanjori Group but separates strikingly different lithological units (metabasic rocks vs quartzite). The lowermost shear zone (Rohinbera Shear Zone) is placed along the Singhbhum Granite–Dhanjori Group contact (Fig. 2) (Joy, 1996). A layer parallel shortening (LPS) strain (Geiser, 1988) affects the Dhanjori Group in the footwall as well as the Chaibasa Formation rocks of the hanging wall. The near parallelism of schistosity in rocks below and immediately above the SSZ suggests some degree of uniformity in orientation of LPS strain across the Singhbhum Shear Zone (Joy, 1996). On the whole the observations from the present study area show that the structures can be interpreted to have developed in course of a single deformation event by progressive non-coaxial flow (Naha, 1965; Ghosh and Sengupta, 1987; Joy, 1996; cf. Mukhopadhyay *et al.*, 1975; Mukhopadhyay, 1984).

Rocks outcropped in the Garra Nala south of Rakha Mines Railway Station (22° 40′ 26″ N, 86° 21′ 24″ E) and lying above the SSZ show almandine–biotite–muscovite–quartz as the prevailing metamorphic mineral assemblage with retrogression of almandine to chlorite. Pelitic rocks belonging to the Dhanjori Group show chlorite–muscovite–biotite–quartz as metamorphic minerals. Rocks in the SSZ usually have the same paragenesis as the Dhanjori Group, except for the local occurrence of kyanite. However, the kyanite–garnet assemblage of the SSZ and its hanging wall is considered to be pre-tectonic with respect to the shearing in the SSZ (Naha, 1965; Sarkar, 1984). The latter is considered to represent the last phase in the deformation history of the Singhbhum mobile belt (Sarkar and Bhattacharyya, 1978; Sarkar, 1982). The *P–T* condition accompanying the non-coaxial flow in the SSZ and its immediate neighbourhood is therefore lower greenschist facies. The quartz *c*-axis fabric in the analysed specimens is thus thought to have developed under these conditions.

Specimen collection

Oriented quartz tectonite specimens were collected from the SSZ, quartzites of the Dhanjori Group south of the SSZ, and from the Chaibasa Formation immediately north of the SSZ (Fig. 2). All collected specimens contain the mesoscopic foliation, either a mylonitic foliation or a weak schistose grain shape fabric, and a mineral/clast elongation lineation or stretching lineation (*L–S* tectonites: Passchier and Trouw, 1996). In some of the specimens there is a segregation of the phyllosilicates into bands a few grains wide (Fig. 3a). In other cases fine grained muscovite and chlorite are present as a dispersed phase either as inclusions in quartz or at grain boundaries (Fig. 3b).

Microstructures

Quartz tectonites analysed from the study area are generally bimodal aggregates with relatively small dynamically recrystallized (40–120 μm) and larger relict quartz grains (110–425 μm). The relative proportion of recrystallized to relict quartz grains varies across the sample. As dynamic recrystallization is strain induced, specimens with higher proportions of recrystallized quartz grains represent higher strain intensity. The relict quartz grains in general show undulose extinction, either as wavy extinction, or as patchy extinction. Other common microstructures observed in the relict quartz grains are deformation lamellae (Fig. 3c), deformation bands, subgrain structures, creep polygonization textures and core and mantle structure (Fig. 3d) (Carter *et al.*, 1964; Christie *et al.*, 1964; Nicolas and Poirier, 1976; White, 1976; Groshong, 1988). The

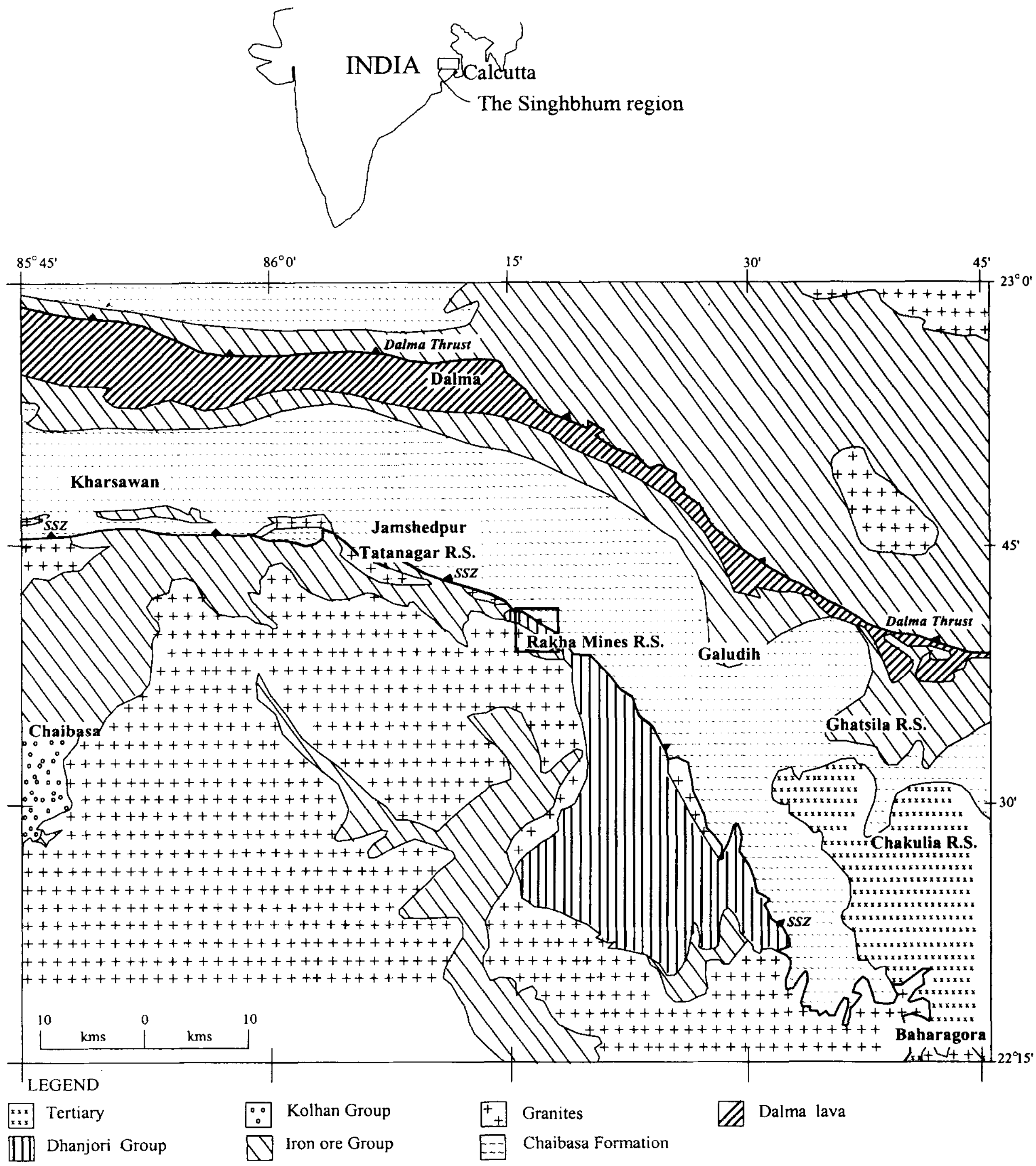


Fig. 1. The geological map of the Singhbhum region, Eastern India (after Dunn and Dey, 1942). The study area is outlined. SSZ = Singhbhum Shear Zone. The Singhbhum Shear Zone and the Dalma thrust are marked with thick tooth-marked lines.

recrystallized quartz grains generally show serrated or sutured grain boundaries. Some of the specimens show castellate microstructure, and rarely dragging microstructure as described by Jessell (1987) in the recrystallized quartz grains. The mesoscopic and microscopic structures including quartz c-axis fabric analysed from the SSZ, from the Chaibasa Formation rocks immediately north of it, and from the Dhanjori Group (footwall of the SSZ) are comparable. Therefore, the deformation in the footwall of the SSZ is considered to be kinematically related to the general deformation in the SSZ (Joy, 1996).

Flow stress

The reported flow stress measurement using the recrystallized quartz grain size from the SSZ is 23–49 MPa (Sen Gupta, 1995) using the relationship of Twiss (1977). Mean recrystallized quartz grain size in 15 of the analysed specimens is shown in Fig. 4. The chart

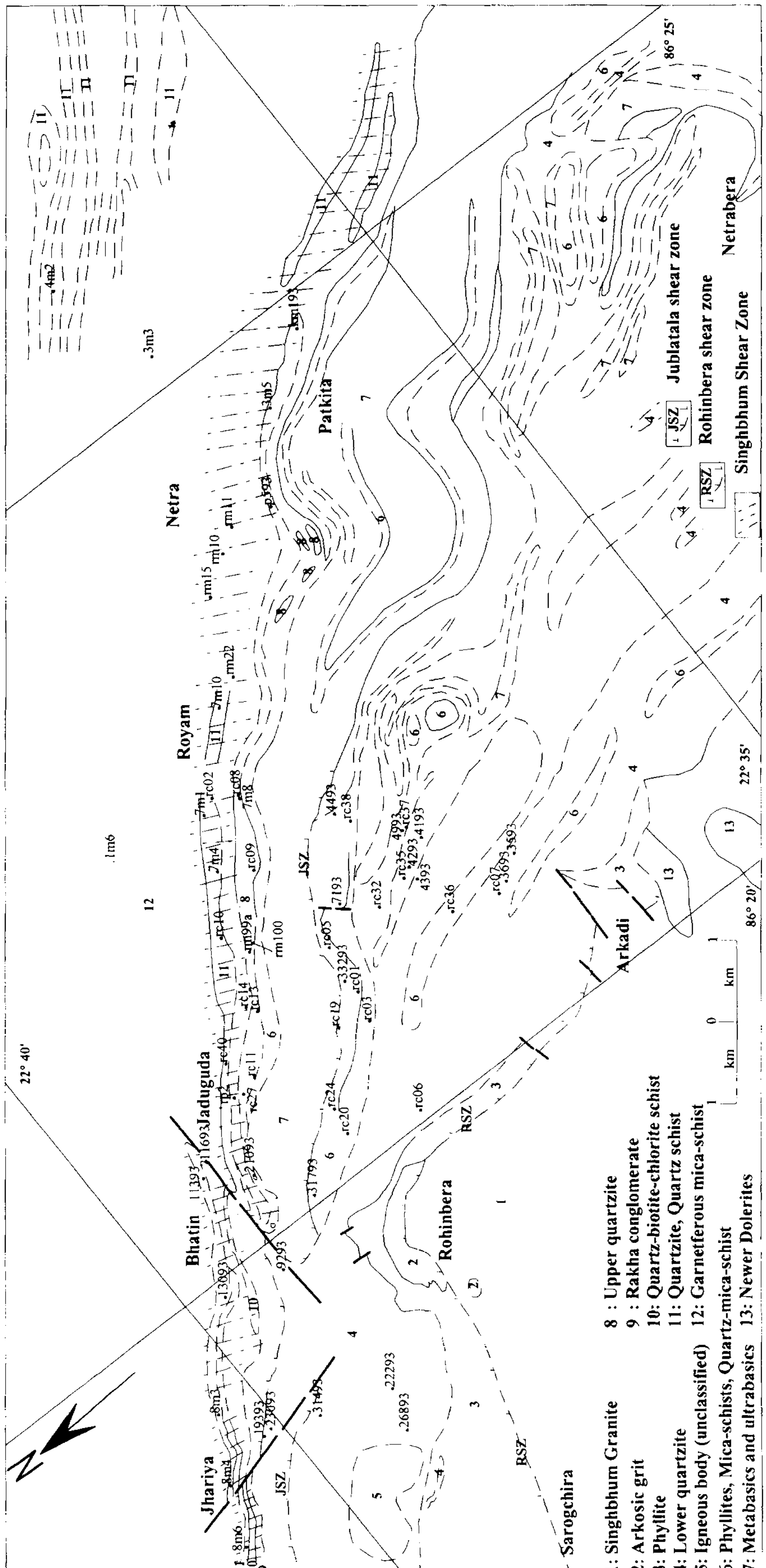


Fig. 2. Geological map of the study area with specimen locations.

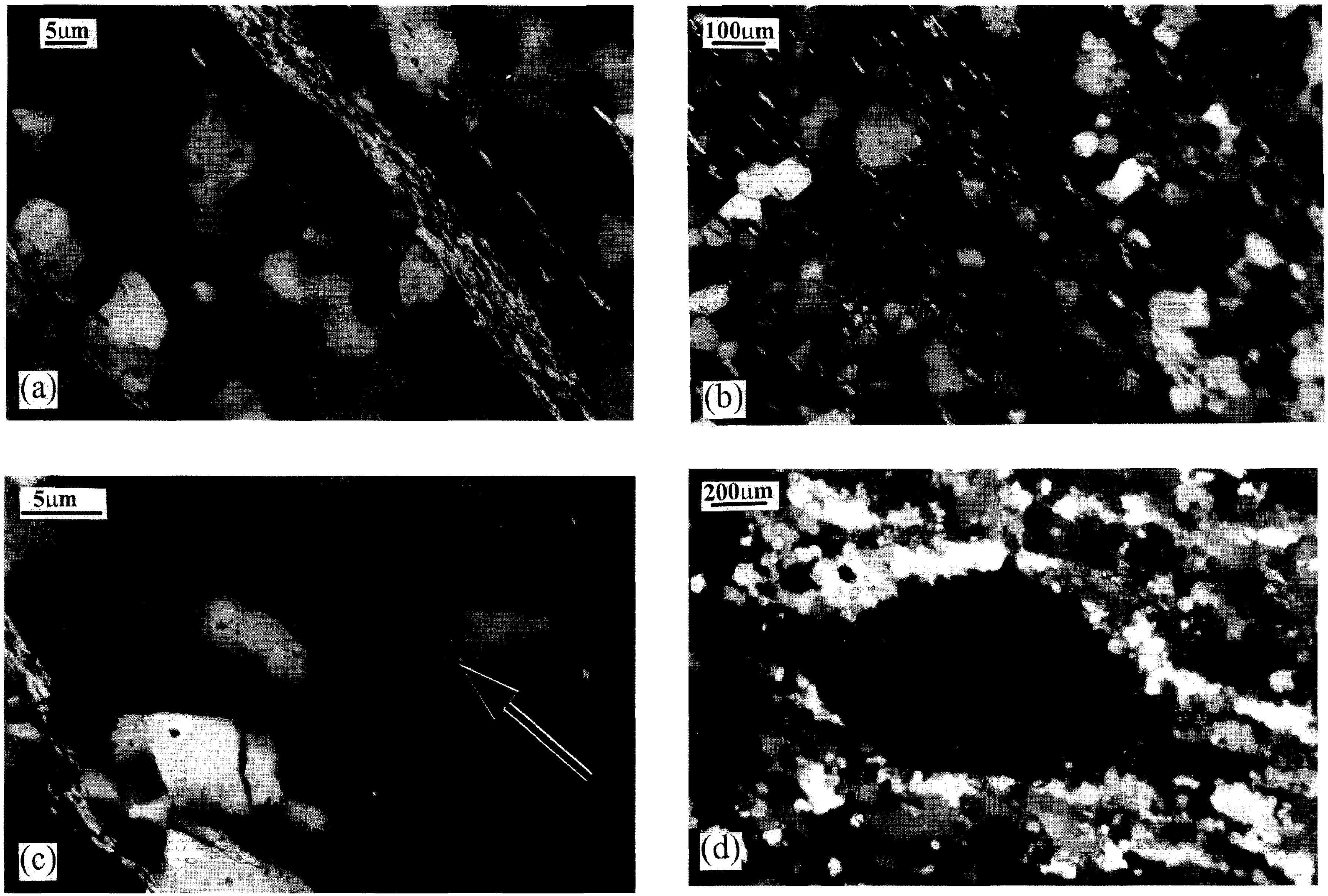


Fig. 3. Photomicrographs under cross polars illustrating texture and microstructure of studied quartz tectonites. (a) Segregation of mica into bands of few grains wide (specimen no. rc24). (b) Very fine grained muscovite and chlorite as a dispersed phase either as inclusions or at quartz grain boundaries (specimen no. rc20). (c) Deformation lamellae (arrow) in a quartz grain (specimen no. 9293). (d) Core and mantle structure (specimen no. rc13).

indicates that the mean recrystallized quartz grain size, an indicator of the flow stress (White, 1979), is comparable in different specimens collected from the study area. Thus the sample represents specimens of quartz tectonites with comparable geological background, kinematic history, ambient P–T condition, and differential stress.

ASYMMETRY OF THE FABRIC

Measurement of quartz c-axis orientation and representation of fabric asymmetry

In each specimen of quartz tectonite collected from the Singhbhum region 200 or more quartz c-axis (Fernandez-Rodriguez *et al.*, 1994) orientations are measured using a Federov universal stage fitted to an optical microscope. A reference co-ordinate frame is defined by the mesoscopic foliation plane, its normal, and the clast elongation lineation ($\approx X$ direction of finite strain ellipsoid) lying on foliation. The c-axis orientations are plotted on a lower hemisphere equal area projection and contoured using a computer program (Kutty and Joy, 1997). The c-axis fabric can be characterized by their skeletal outline by constructing a set of straight lines connecting the ridges and crests on the contoured fabric diagram (fig. 1 of Lister and Williams, 1979; Lister and Hobbs, 1980; Vissers, 1993). Representative patterns of the contoured c-axis fabric diagrams from the study area are shown in Fig. 5.

The degree of external fabric asymmetry (of fabric skeleton) can be expressed as (a) $c_1{\sim}c_2$, where c_1 is the obliquity of the leading edge with respect to Z (foliation normal) and c_2 is the obliquity of the trailing edge with respect to Z (Law, 1987); (b) obliquity, ϕ, of central segment with respect to X (measured anticlockwise) (Law, 1987) and (c) the Am statistic of Fernandez-Rodriguez *et al.* (1994). The angle defining the obliquity in each of the above cases is measured on the XZ plane, a plane perpendicular to foliation but containing X (mineral/clast elongation lineation) (Platt and Behrmann, 1986; table 1 of Law, 1987).

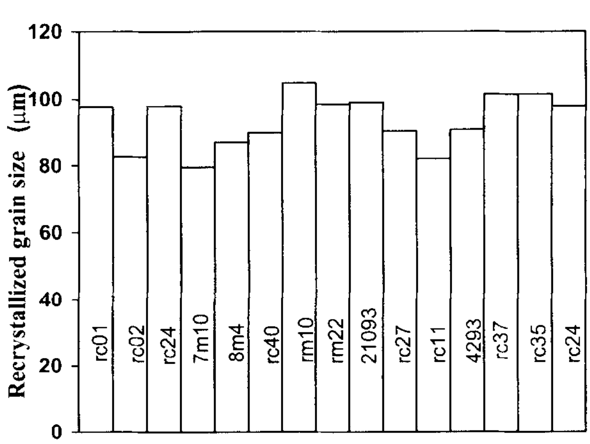


Fig. 4. Column chart showing average recrystallized quartz grain size (in microns) in specimens from the Singhbhum Shear Zone and its footwall. The specimen numbers are indicated within each bar. Number of grains considered in each specimen is 100.

In the measured Singhbhum specimens, ϕ and Am are utilized as a measure of fabric asymmetry. The measure ($c_1{\sim}c_2$) is not utilized as a number of measured fabrics lack a trailing edge. As shown in Table 1, the quartz c-axis fabric is distinctly asymmetric with ϕ values in the range 54–90°. Other features attesting to the asymmetry of the fabric are listed in Table 1. Scatter diagrams of ϕ vs volume percent of micaceous impurity (μ) and Am vs μ provide a graphic demonstration of the independence of ϕ and Am from μ (Fig. 6). Statistical evaluation also shows that there is not enough evidence to reject the hypothesis of independence between the fabric asymmetry and μ (Appendix A).

FABRIC INTENSITY AND MICACEOUS IMPURITY CONTENT

As described earlier, the sample from the Singhbhum region represents asymmetric type I crossed girdle or asymmetric kinked single girdle c-axis fabric with variable intensity. For each fabric measured the fabric intensity parameter (κ) was computed by considering the orientation tensor matrix corresponding to the c-axis orientations. In order to test whether the fabric intensity is influenced by mica content (μ) in the quartz tectonite sample a regression analysis is performed using a bivariate approach, i.e. μ as the only independent variable and κ as the dependent variable. Although the sample includes specimens with similar kinematic history the actual deformation intensity across the belt varies. As strain magnitude is known to affect the quartz c-axis fabric (Etchecopar, 1977; Tullis, 1977; Saha, 1983, 1984; Wenk and Christie, 1991), a part of the variation in κ in the Singhbhum sample may be related to strain intensity. The influence of the latter factor is assessed through a consideration of the effect of variation in volumetric proportion of recrystallized quartz grains (ν) on κ in a trivariate regression analysis where both μ and ν are considered to be independent variables.

Bivariate approach

Results of regression analysis attempting to fit an intrinsically linear model (Draper and Smith, 1981) to the relationship between dependent variable κ and the independent variable μ are summarized in Table 2. The best among the analysed models is the multiplicative model (Fig. 7) with an R^2 value of 0.3970 (39.7%). Statistical tests for the correlation coefficient

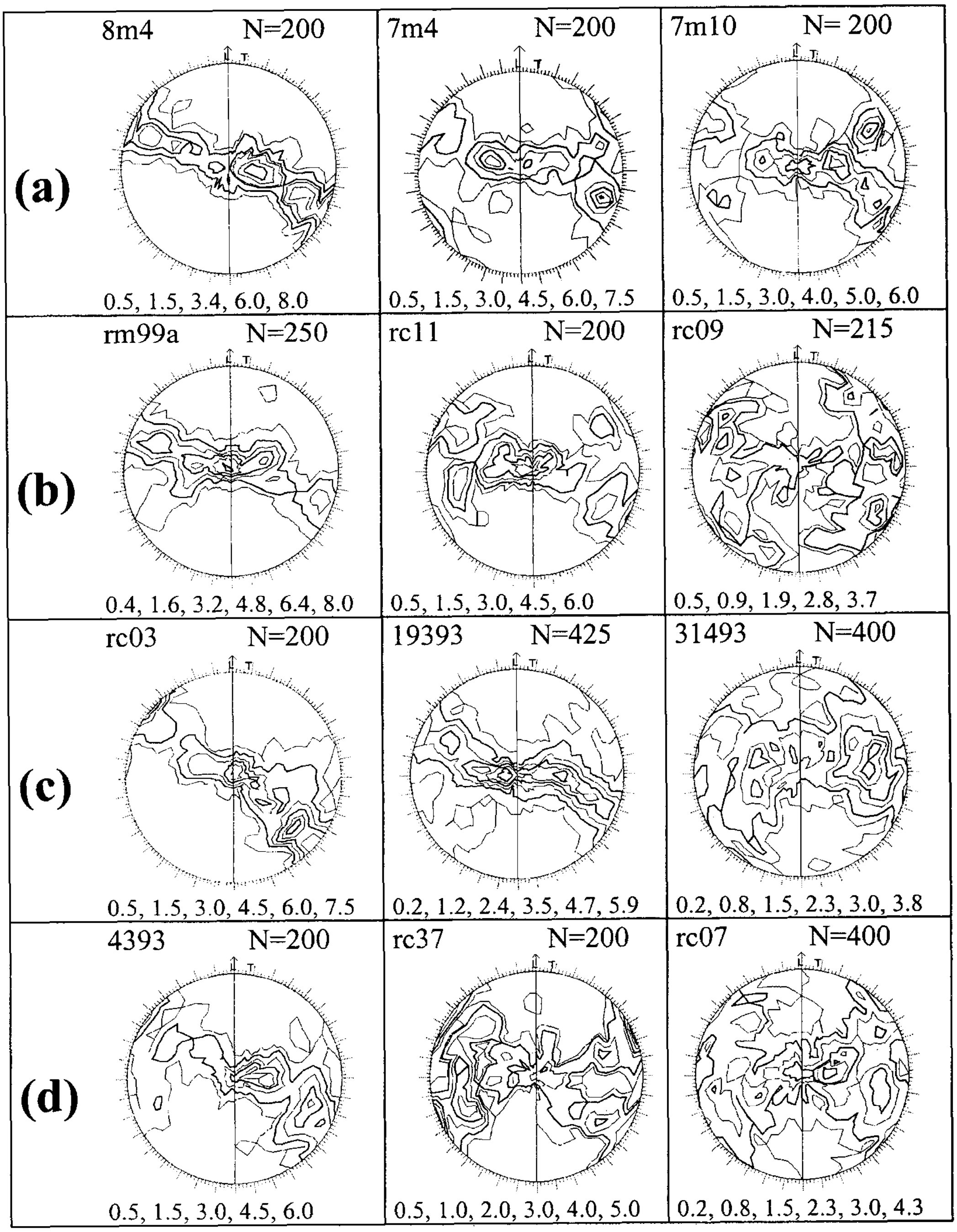


Fig. 5. Representative quartz c-axis fabric diagrams of the samples from Singhbhum Shear Zone and its footwall. The specimen number is at the top left corner of each diagram. Lower hemisphere equal area projection. N is the number of c-axes measured in each specimen. Contour levels are indicated at the bottom of each diagram as percentage of data points per one percent area. The foliation trace is N–S and the arrow is pointing toward the down plunge direction of mineral elongation lineation (taken here as the X direction of the finite strain ellipsoid). Top of foliation is towards the right of N–S foliation trace. (a) Singhbhum Shear Zone. (b) Upper quartzite, Dhanjori Group. (c) Jublatola shear zone. (d) Lower quarzite, Dhanjori Group.

(Appendix B) show that the null hypothesis of zero correlation between κ and μ has to be rejected. A linear negative correlation between ln (κ) and ln (μ) is upheld by the test. Similarly, analysis of variance (ANOVA) test for the significance of the regression coefficient (β) shows that β is significantly different form zero (Appendix B). The regression equation between κ and μ can be written as

$$\kappa = 17.99\,\mu^{-0.618}. \quad (1)$$

Trivariate approach

Volumetric fraction of recrystallized quartz grains relative to relict grains quartz grains varies within the

Table 1. Data for the measurement of symmetry of quartz *c*-axis fabric in specimens from the Singhbhum Shear Zone

Specimen number	Angle with X in degrees: Central segment	Leading edge	Trailing edge	Am statistic	Specimen number	Angle with X in degrees: Central segment	Leading edge	Trailing edge	Am statistic
rc02	86	60	115	1.8	31493		70	145	−14.0*
rc10	90	70	130	2.6	31793	90	55	135	−2.0
rc40	82	70		29*	33293	87	68		−23.7
rm10	82	65	110	−5.5	rc38	88	60	110	11.8*
rm11	82	45	105	9.8*	rc03	88	50		37.8*
rm15	85	63		43.9*	rc06		50	130	−4.2
rm22	54	54	120	17.3*	rc07		60	118	−9.0*
km193	84	55	126	−2.9	rc32	85	70	118	−12.5*
p593	60	64		37.2*	rc35	84	50	105	8.9*
11393	86	55		3.5	rc36		60	140	−5.7
11693		55	150	8.6*	rc37	84	60	112	−6.4
13093	88	70		8.7*	3593	89	50	115	−7.2
7m1	89	65	115	3.7	3693		70	117	−13.7*
7m4	76	74	124	16.8*	4293	90	65	120	16.4*
7m8	89	70	130	3.0	4393	84	60	110	21.8*
7m10	85	65	20	13.3*	4993	72	60	105	16.8*
8m3		70	125	0.6	22293	88	65	120	1.2
8m4	75	70		43.3*	26893	70	70	145	18.4*
rc14‡	82	60		−9.0*	rc08	90	55	115	−11.3*
rp2‡‡	78	65	120	2.1	rc09	85	70	130	0.8
rc01	86	70	120	−9.5*	rc13	82	70	125	−3.3
rc05	85	62	110	0.2	rm99a	85	70	117	20.9*
rc19	88	70		21.3*	rm100	82	55	120	2.8
rc20	80	50	105	18.6*	21093	84	64	120	8.3*
rc24	86	70		2.8	3m3		70	135	13.56*
4493	86	60	120	17.4*	4193		62	124	9.14*
7193	78	55		−1.5	4m2		60	120	−2.71
9293	60	64		−5.618	8m6	70	62		40.77*
19393	86	65	125	14.8*	rc11	80	65	120	15.685*
23093	90	60	120	−11.7*					

‡ Matrix of Rakha conglomerate; ‡‡ Pebble of Rakha conglomerate. X, Y and Z are the principal axes of the finite strain ellipsoid. The foliation plane is considered as the XY plane. The mineral elongation lineation is taken as the X direction. All angles are measured anticlockwise from X on XZ section. The asterisk over Am statistic values indicate fabric asymmetry at a significance level of 0.05.

sample. As dynamic recrystallization is strain induced, the proportion of recrystallized grains increases with increasing strain intensity. Therefore, we consider the effect of the volume proportion of recrystallized quartz grains (v) in the regression analysis as a third variable. (v in the present case varies from 44.9% to 98.4%.) Here also only intrinsically linear models are considered, i.e. models which could be transformed into linear form (Draper and Smith, 1981). The results are given in Table 3. The multiplicative model with multiple $R^2 = 0.455$ (45.5%) is the best of all the analysed regressions (Table 3), through which 45.5% total variation in the dependent variable is explained. ANOVA test for significance of the regression relation is given in Appendix C (Table 4). The regression equation relating the three variables can be written as

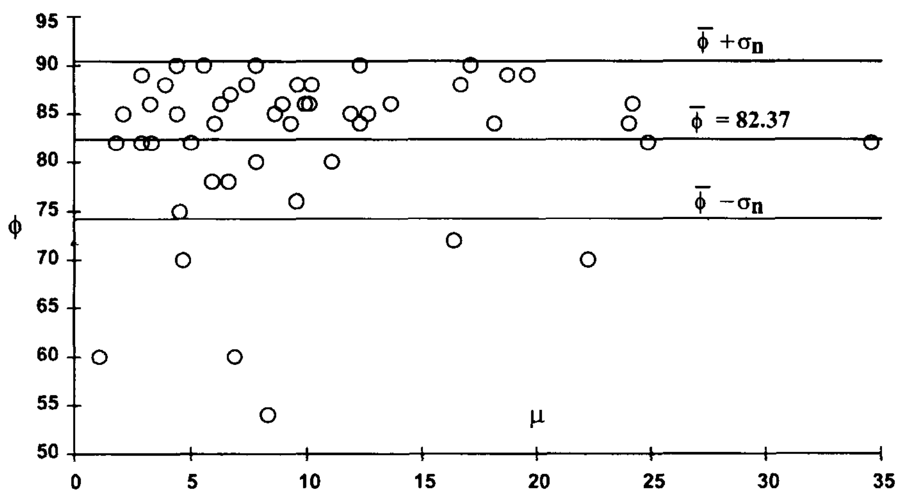
$$\kappa = 0.13\, v^{1.11}\, \mu^{-0.617}. \tag{2}$$

Table 2. Results of regression between κ and μ, see text for details

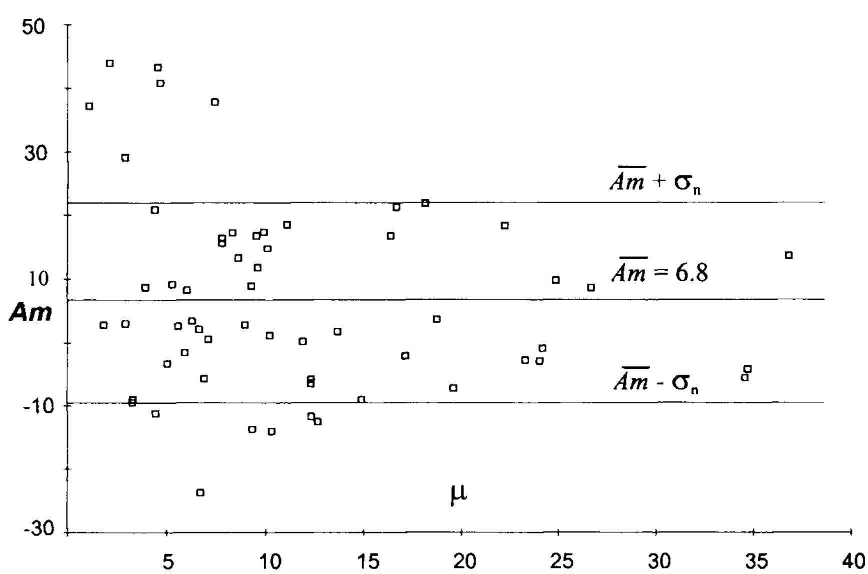
No	Model	Estimated values	R^2
1	Linear $\kappa = \beta_0 + \beta_1 \mu + \varepsilon$	$\beta_0 = 10.000$ $\beta_1 = -0.3180$	19.9%
2	Quadratic (second order) $\kappa = \beta_0 + \beta_1 \mu + \beta_{11} \mu^2 + \varepsilon$	$\beta_0 = 13.400$ $\beta_1 = -0.9170$	26.2%
3	Exponential $\kappa = \alpha\, e^{\beta\mu}$ $\ln \kappa = \ln \alpha + \beta\mu$	$\ln \alpha = 2.1300$ $\beta = -0.0515$	34.5%
4	Logarithmic transformation $\kappa = \beta_0 + \beta_1 \ln \mu + \varepsilon$	$\beta_0 = 15.300$ $\beta_1 = -4.0800$	24.9%
5	Reciprocal transformation $\kappa = \beta_0 + \beta_1 (\mu)^{-1} + \varepsilon$	$\beta_0 = 3.5800$ $\beta_1 = 18.300$	19.5%
6	Multiplicative Model $\kappa = \alpha\, \mu^{\beta} \varepsilon$ $\ln \kappa = \ln \alpha + \beta \ln \mu + \ln \varepsilon$	$\ln \alpha = 2.8900$ $\beta = -0.6180$	39.7%

Table 3. Results of the trivariate regression of κ, μ and v, see text for details

No	Model	Estimated values	Multiple R^2
1	Linear $\kappa = \beta_0 + \beta_1 + \beta_2 \mu + \varepsilon$	$\beta_0 = 1.6300$ $\beta_1 = 0.0983$ $\beta_2 = -0.3065$	23.6%
2	Second order $\kappa = \beta_0 + \beta_1 v + \beta_2 \mu + \beta_{11} v^2 + \beta_{22} \mu^2 + \beta_{12} \mu v + \varepsilon$	$\beta_0 = 2.0000$ $\beta_1 = 0.0610$ $\beta_2 = -0.4820$ $\beta_{11} = 0.0009$ $\beta_{22} = 0.0188$ $\beta_{12} = 0.0058$	33.8%
3	Exponential $\kappa = e^{\beta_0 + \beta_1 v + \beta_2 \mu} \varepsilon$ $\ln \kappa = \beta_0 + \beta_1 v + \beta_2 + \ln \varepsilon$	$\beta_0 = 1.0600$ $\beta_1 = 0.0126$ $\beta_2 = -0.0500$	38.5%
4	Logarithmic transformation $\kappa = \beta_0 + \beta_1 \ln v + \beta_2 \ln \mu + \varepsilon$	$\beta_0 = -21.300$ $\beta_1 = 8.2700$ $\beta_2 = -4.0700$	31.1%
5	Multiplicative Model $\kappa = \alpha\, v^{\beta} \mu^{\gamma} \varepsilon$ $\ln \kappa = \ln \alpha + \beta \ln v + \gamma \ln \mu + \ln \varepsilon$	$\ln \alpha = -2.0300$ $\beta = 1.1100$ $\gamma = -0.6170$	45.5%



(a)



(b)

Fig. 6. Scatter plots showing independence of quartz c-axis fabric asymmetry from mica impurity. (a) ϕ vs mica percent (μ). ϕ is the angle between the central segment of fabric skeleton and the X direction (mineral elongation lineation direction) measured anti-clockwise from X. (b) Am vs μ. $\bar{\phi}$ and Am are the mean of ϕ and $\overline{Am}$ values, respectively; σ_n is the standard deviation of each.

DISCUSSION AND CONCLUSIONS

Within the studied range of variation of micaceous impurity (white mica plus chlorite, 2–35 vol.%) in the quartz tectonites from the Singhbhum regions Eastern India, the asymmetry of the quartz c-axis fabric is independent of the impurity content. Although the actual values of ϕ and Am, measures of the external asymmetry of the fabric, vary from specimen to specimen they are uncorrelated with μ, the volume percent of micaceous impurity (Fig. 6). Therefore, the sense of asymmetry in the deformation induced fabric can be utilized in deducing the sense of vorticity associated with deformation, irrespective of whether the L–S tectonite is a pure quartzite, a micaceous quartzite or a mica–chlorite–quartz schist.

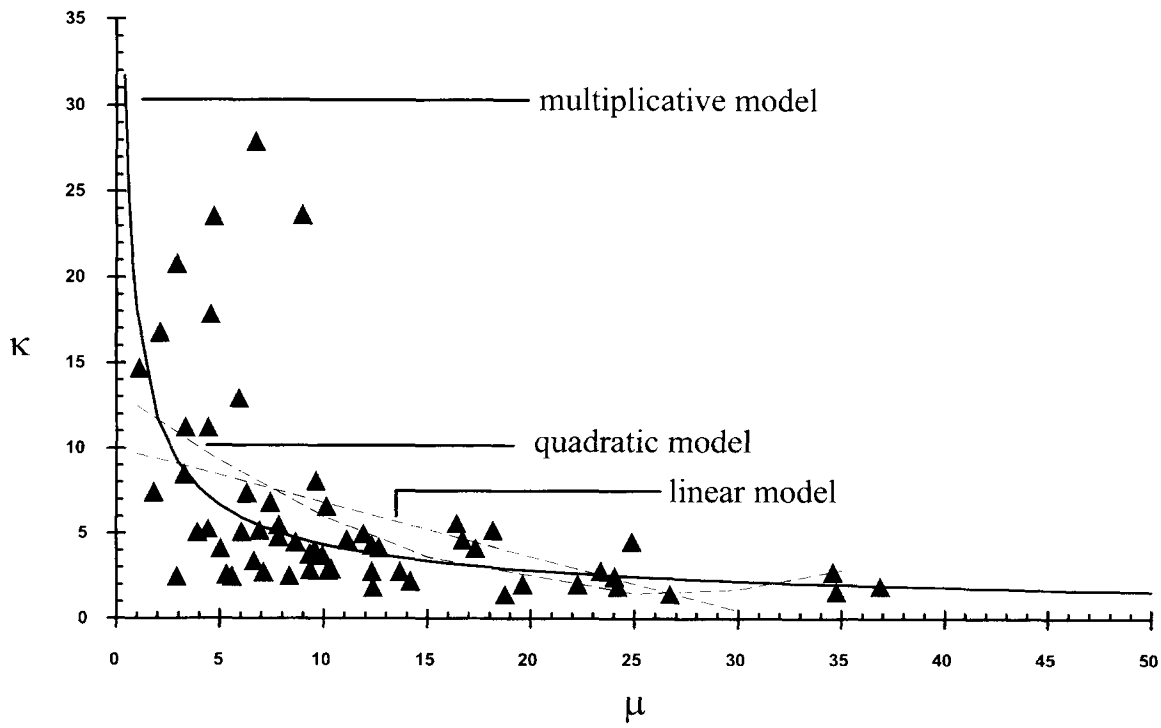


Fig. 7. Influence of micaceous impurity (μ) content on quartz c-axis fabric intensity (κ). Regression lines corresponding to a linear model and a quadratic model are shown as dashed lines and the regression line corresponding to a multiplicative model is shown as a continuous line.

The addition of mica and chlorite into quartz aggregates (*sensu* lato quartzites) has a general effect of weakening the fabric intensity (Starkey and Cutforth, 1978; Kronenberg, 1981; Boullier, 1986; Wenk and Christie, 1991). It has been suggested that grain boundary sliding between quartz and matrix mineral grains may be a causative factor for such fabric dispersion. But the importance of grain boundary sliding at low temperatures (as in greenschist facies) and in the grain size range 40–120 μm (Singhbhum examples) is not very marked even under higher fluid pressure. As increased fluid pressure at low temperature facilitates intracrystalline glide (Paterson, 1989) rather than grain boundary sliding, and mica is known to have a well developed [001] glide system. The weakening of quartz c-axis fabric with increase in mica–chlorite content may be related to partitioning of strain in a manner so that a significant part of the bulk strain is accommodated by intracrystalline glide in mica, and thus relative lowering of grain scale strain in quartz. It has been shown that the degree of strain partitioning in a deforming rock depends strongly on proportion, shape and distribution of the mineral phases (Handy, 1994). However, one has to take into account the influence of variation in strain intensity. At lower strain the intensity of quartz c-axis fabric is low even in pure quartz aggregates (Marjoribanks, 1976; Bouchez, 1977; Tullis, 1977; Compton, 1980; Miller and Christie, 1981; Saha, 1983, 1989; Wenk and Christie, 1991).

A linear correlation between quartz content and the degree of quartz c-axis preferred orientation in quartzite specimens with biotite and feldspar as impurity phases has been proposed (Starkey and Cutforth, 1978). The present correlation-regression analysis shows that a multiplicative model (Stoodley *et al.*,

Table 4. Analysis of variance (ANOVA) table for testing the significance. (a) The (bivariate) regression coefficient. (b) The trivariate regression relation

Source of variation	Degrees of freedom	Sum of Square	Mean Square	F ratio
(a)				
Regression	1	12.709	12.709	37.51
Residual	57	19.312	0.339	
Total	58	32.021		
(b)				
Regression	2	14.5819	07.2910	23.41
Residual	56	17.4394	0.3114	
Total	58	32.0213		

1980) of the form $\kappa = \alpha\mu^{\beta}$, provides a better fit as far as the relationship between fabric intensity and impurity content is concerned. The exponent β has a negative value (−0.618) and $\alpha = 17.99$ for the studied sample. As earlier works (e.g. Saha, 1983) demonstrate the influence of strain on fabric intensity, the present regression analysis also takes into account the variation in the proportion of recrystallized (or relict) quartz grains in the sample. It should be noted that with increasing strain the proportion of relict grains decreases and that of dynamically recrystallized grains (v) increases. A regression equation of the form $\kappa = \alpha v^{\beta}\mu^{\gamma}$ explains the sample variation in a better manner ($\alpha = 0.13$, $\beta = 1.11$, $\gamma = -0.617$). The above relationship is valid for quartz aggregates deformed under low greenschist facies condition, the ambient condition of fabric development in the Singhbhum region, Eastern India.

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APPENDIX

Appendix A: Test for dependence of asymmetry of fabric and μ

Correlation coefficient test for dependence ϕ on μ.

Under the assumption of bivariate normal distribution of two variables x and y, let their population correlation coefficient be ρ, under an $H_0{:}\rho = 0$. The statistic $r^* (n-2)^{0.5}/(1-r^2)^{0.5}$ is shown to be distributed as a 't' with $n-2$ degrees of freedom, r being the sample correlation coefficient and n the sample size, (Goon *et al.*, 1993). Out of the 59 measured specimens only 49 are showing a distinct central segment of asymmetric type I crossed girdle or kinked single girdle quartz c-axis fabric. Hence, ϕ was measured in only these fabrics and therefore the sample size is 49. Let our alternative hypothesis be $H_1{:}\rho \neq 0$. The correlation coefficient (r) between ϕ and μ is 0.118.

$$t = r(n-2)^{0.5}/(1-r^2)^{0.5} = 0.8089672/0.9930136 = 0.814659. \quad \text{(A1)}$$

The tabulated value for two tailed $t(t_{.05,\ 47}) = 1.6795$. The observed value (0.814659) is insignificant at a test level of 0.05 probability and, therefore, there is not enough evidence in the data to reject the null hypothesis at this test level.

Correlation coefficient test for dependence Am on μ

The null hypothesis (and the alternative hypothesis) being similar to those in the previous test, the correlation coefficient (r) between Am and μ, is −0.1922. Here the sample size (n) being 59 the t statistic is obtained using equation (A1) as $t = -1.478646$. The tabulated value for two-tailed $t(t_{.05,\ 57}) = 1.67295$. The observed value of $t(-1.466691)$ is insignificant at this test level and therefore, the null hypothesis cannot be rejected. In other words the test does not show any evidence to reject the hypothesis that Am and μ are independent of each other.

Appendix B: Bivariate regression

Test for the correlation coefficient between ln (κ) and ln (μ)

The null hypothesis (and the alternative hypothesis) is similar to those in the previous tests (Appendix A). The correlation coefficient (r) between ln (κ) and ln (μ) is −0.630. The sample size (n) being 59, the t statistic is obtained using equation (A1) as $t = -6.124679$. The tabulated value of two-tailed t is $(t_{.01,\ 57}) = 2.39497$. The observed value (−6.124679) is significant at 0.01 probability level of testing and therefore, the null hypothesis has to be rejected, and concluded that there is a strong negative correlation between ln (κ) and ln (μ).

ANOVA test for the significance of regression coefficient

Consider a simple regression model $\ln y = \ln \alpha + \beta \ln x + \ln \varepsilon$, then let the null hypothesis $H_0{:}\beta = 0$ and the alternative hypothesis $H_1{:}\beta \neq 0$ (Stoodley *et al.*, 1980). The F ratio which is obtained as the mean square due to regression/residual mean square (Table 4a) follows an F distribution with 1 and $n-2$ degrees of freedom under H_0, where n is the sample size (Stoodley *et al.*, 1980). The tabulated value of F $(F_{.01\ (1,\ 57)}) = 7.1145$. The observed value of 37.5 (Table 4a) is significant at 99% confidence levels and therefore H_0 is rejected, in other words β significantly differs from 0.

Appendix C: Trivariate regression

Test for the significance of the regression relation

Consider a regression model $\ln \kappa = \ln \alpha + \beta \ln v + \gamma \ln \mu + \ln \varepsilon$, then let the null hypothesis H_0: β or $\gamma = 0$ and the alternative hypothesis H_1: at least one of β or $\gamma \neq 0$ (Stoodley *et al.*, 1980). The F ratio (Table 4b) follows an F distribution with 2 and $n-3$ degrees of freedom under H_0, where n is the sample size (Stoodley *et al.*, 1980). The tabulated value of F is $F_{.01\ (2,\ 56)} = 5.112$. The observed value of 23.41 (Table 4b) is significant at 0.01 level of significance and therefore the null hypothesis has to be rejected.