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Joints and shear zones as indicators of principal stress in the area around Bainoli, district Chamoli, Lesser Garhwal Himalaya, India

R.A. Singh and V.K. Gairola
Department of Geology, Banaras Hindu University, Varanasi 221 005, India.

ABSTRACT

The orientation of joints and shear planes have been measured in the rocks around Bainoli, district Chamoli, U.P. For the stress analysis, the area has been divided into 17 subareas with respect to joints and 7 subareas with respect to shear planes. 10°-sector rose diagrams reveal four joint sets in the area, which strike in NW-SE, N-S, NE-SW and E-W directions with a variation of upto 10° in different subareas. Only the NW-SE set is prominent and common to all the subareas. Four sets of the shear planes have been recognised in the area striking in N50°W-S50°E, N-S, N40°E-S40°W and E-W. Of these, two sets are prominent in which one strikes N50°W-S50°E and other strikes N40°E-S40°W with a local variation of upto 10° in different subareas. The analysis of joints and shear planes reveals that joints were mainly developed during the second phase of deformation and shear planes were mainly developed during the third phase of deformation. In the later phases of deformations, earlier joints/shear planes were reactivated and reoriented, as well as new joints/shear planes were also developed. Thus, different orientation of joints and shear planes are observed in the area. The principal stress directions have been also inferred during the second and third phases of deformations with the help of joints and shear zones, respectively.

INTRODUCTION

The area around Bainoli (longitude 79°10'E-79°15'E; latitude 30°08'58" N - 30°13'36"N) lies in the Lesser Garhwal Himalaya of district Chamoli (Fig. 1) where two tectonic units viz., Dudatoli-Almora Crystallines of Kumar et al. (1974) and Garhwal Group of Jain (1971) of diverse lithological characters are separated by a well-defined NW-SE striking tectonic plane, the North Almora Thrust. In the study area, the Dudatoli-Almora Crystallines are represented by quartzites, schistose quartzites and garnet-mica schists, whereas the Garhwal Group by metabasites and massive quartzites. Further, shear zones within the massive metabasites of the Garhwal Group exhibit foliation resulting into schistose metabasites. In comparision to other lithological units, the joints are more prominent in the schistose quartzites and massive metabasites of the Dudatoli-Almora Crystallines and Garhwal Group, respectively. Kumar et al. (1974), Kumar and Agarwal (1975), Valdiya (1980), Saklani (1993) and others have dealt with the regional geology of the northern part of the Garhwal Himalaya including the present area. Detailed structural analysis of the area has been carried out by Singh (1992, 1995), Singh and Gairola (1992, 1994, 1996), and Gairola and Singh (1993, 1995). In the present paper, the joints and shear zones have been classified on the basis of age and are related to two different tectonic phases. The orientations of principal stress directions during these phases have been inferred from the joints and shear planes, respectively.

In the Bainoli area quartzites, the lowermost lithological unit of the Dudatoli-Almora Crystallines tectonic unit, exhibit a general NE-SW strike and dip 30° to 40° towards southeastern direction. Schistose quartzites interlayered with 1 to 3 cm thick fine grained schists at an interval of 1 m defining bedding plane (S_1) conformably overlie these quartzites. Preferred orientation of mica minerals defines the schistosity (S_2), which is parallel to S_1. The strike of $S_1 = S_2$ varies from N-S to NE-SW and E-W with 25° to 70° dip

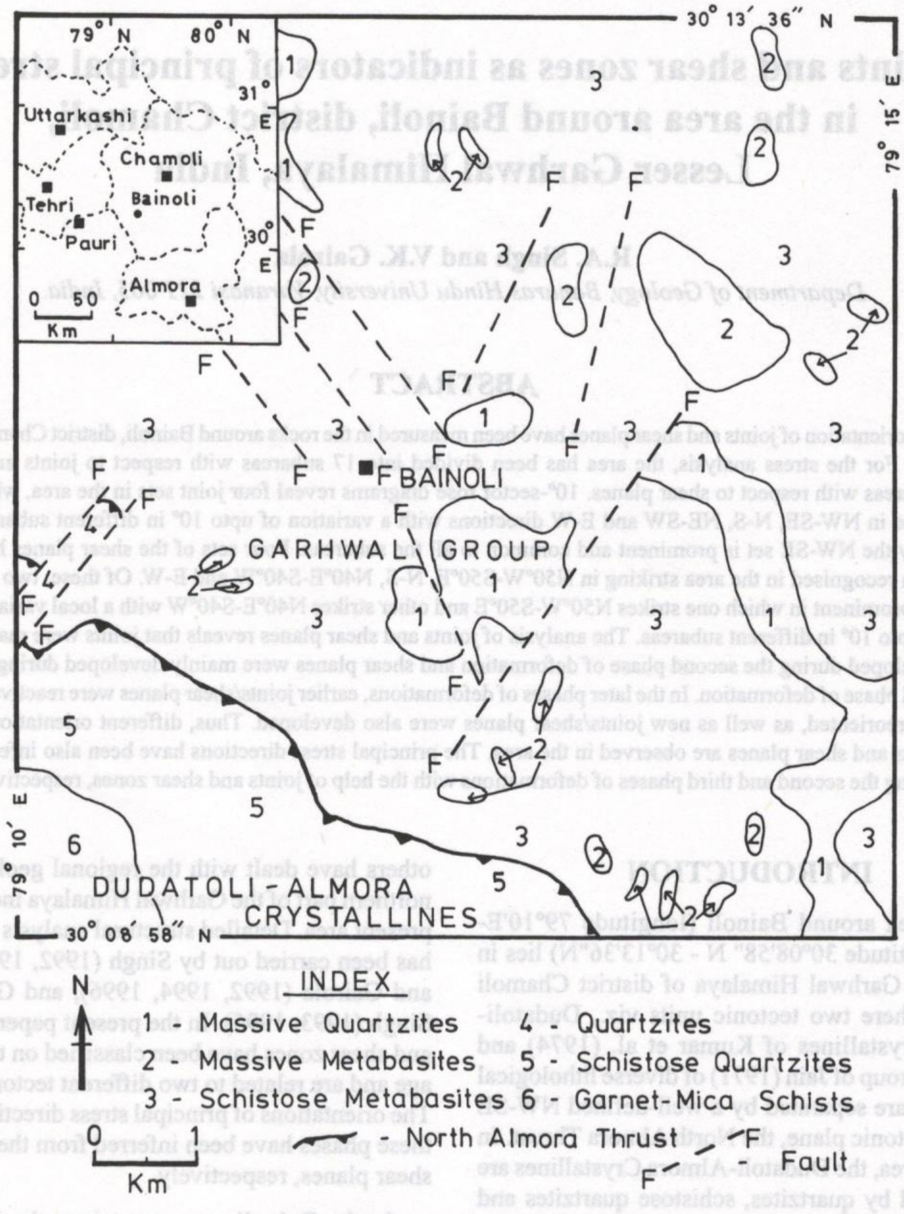

Fig. 1: General geological map of the area. The inset map shows the location of the Bainoli area in district Chamoli, U.P.

towards southwestern, southern and southeastern directions. Schistose quartzites are highly sheared and mylonitised (Gairola and Singh, 1995). Joints are frequently observed in this lithological unit. Garnet-mica schists constitute the topmost lithological unit of the Dudatoli-Almora Crystallines and conformably overlie schistose quartzites. At places, garnet-mica schists are intercalated with thin quartzite bands (similar as schistose quartzites), which define the bedding (S_1). The schistosity in the garnet-mica schists is defined by the preferred orientation of muscovite, biotite and chlorite minerals and is almost parallel to the schistosity developed in schistose quartzites.

Massive quartzites of the Garhwal Group are interlayered with metabasites. In massive quartzites, the strike of the bedding varies from E-W to NE-SW and NNW-SSE directions and the dip varies from 40° to 70° towards south. At times, massive quartzites are sheared. The metabasites have been subjected to intense shearing as a result of which they have developed foliation within the shear zones. The foliation in metabasites is defined by preferred orientation of chlorite, has a general strike of NW-SE with a variation of dip from 20° to 50° towards northeastern direction. However, the dip direction varies due to locally developed folds. The less-deformed metabasites away from the shear zones are massive, highly jointed and fractured (Singh and Gairola, 1996).

The Dudatoli-Almora Crystallines exhibit one set of systematic joints (Fig. 2 and 7A), whereas four sets of systematic joints (Fig. 2 and 7B) have been observed in the rocks of the Garhwal Group. The joint planes form a continuum, which covers more than 200 m in the schistose quartzites of the Dudatoli-Almora Crystallines and 3 m to 200 m in the rocks of the Garhwal Group. The continuities of joint planes of earlier generation are intercepted by the shear zones of later origin. The size of the joint planes of the present area is related to the rock types in both the tectonic units. In schistose quartzites of the Dudatoli-Almora Crystallines and schistose metabasites of the Garhwal Group, the joints are closely spaced, whereas in the massive quartzites and massive metabasites joints are wide apart with the interval varying from 1 cm to 10 cm. Shear joints occur as conjugate sets and at places characterised by slickensided surfaces. Tension joints characterised by quartz filled veins are present at a few places and have not been included for the determination of stress directions in the present work.

Shear zones which are observed in the area are of three types viz., ductile shear zones, brittle-ductile shear zones and brittle shear zones. In ductile shear zones, conjugate set of shear planes are present in which the deformation and differential displacement along the wall of the shear planes are accomplished by ductile flow. In brittle-ductile shear zones the boundary exhibit strain effects in a limited area. Within the domain of brittle-ductile shear zones, vergent drag folds are developed in schistose quartzites of the Dudatoli-Almora Crystallines and en-echelon quartz veins are observed in the massive quartzites of the Garhwal Group. The brittle shear zones are characterised by parallel and clear-cut discontinuity existing on either side of the shear planes as observed in metabasites of the Garhwal Group. These shear zones are either abruptly dissected by other shear zones or gradually die out in the massive metabasites.

DATA ANALYSIS AND RESULTS

The orientation of representative joints and shear planes in the Bainoli area has been shown in Fig. 2 and 4, respectively. For dynamic analysis, the area has been divided into 17 subareas on the basis of orientation of prominent set of joint planes. Among them, four subareas (XIV to XVII, Fig. 2) include the rocks of the Dudatoli-Almora Crystallines and thirteen (I to XIII, Fig. 2) include the rocks of the Garhwal Group. On the basis of orientation of prominent set of shear planes, the area has been divided into 7 subareas where one subarea (VII, Fig. 4) include the rocks of the Dudatoli-Almora Crystallines and six subareas (I to VI, Fig. 4) include the rocks of the Garhwal Group. The analysis of joint/shear planes has been carried out statistically by preparing 10°-sector rose diagrams (Fig. 2 and 4) for each subarea with the radius vector proportional to the total number of joint/shear planes in each sector.

The 10°-sector rose diagrams (Fig. 2) reveal four joint sets in the area, out of which the NW-SE set is prominent in almost all the subareas with a minor variation in strike. The other sets of joints are not common to all the subareas and exhibit a mean strike orientation in N-S (subareas I, II, III, VI, IX, X, XI and XII, Fig. 2), NE-SW (subareas IV, VII, IX, X, XIII, XIV and XVII, Fig. 2) and E-W (subareas I, II, IX, XI and XII, Fig. 2) with a variation in strike up to 10° in different subareas. A composite 10°-sector rose diagram has also been prepared from all the data of joints in the Dudatoli-Almora Crystallines (339 data, Fig. 7A) and another composite diagram of joints in the Garhwal Group (974 data, Fig. 7B) tectonic unit. From Fig 7A and 7B, it is evident that the NW-SE striking set is prominent in the Dudatoli-Almora Crystallines, however, four joint sets are

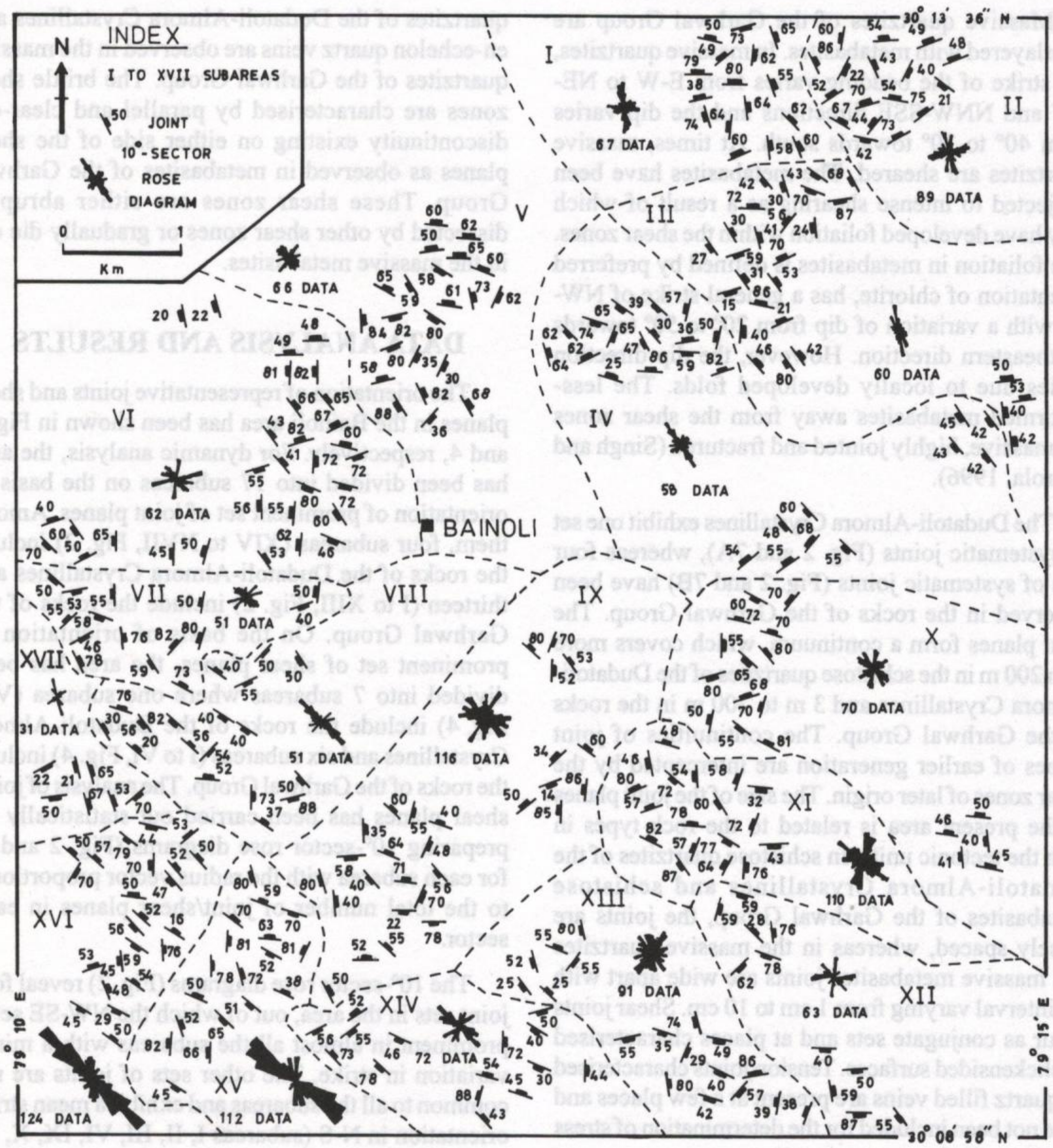

Fig. 2: Orientation of joints with rose diagrams in different subareas around Bainoli, District Chamoli, U.P.

observed in the Garhwal Group viz., NW-SE, N-S, NE-SW and E-W directions. The NW-SE striking set is most prominent and present in both the tectonic units.

The 10°-sector rose diagrams (Fig. 4) reveal four sets of shear planes in the Garhwal Group. Among them, two sets are prominent, in which one strikes N50°W-S50°E (subareas II, IV and VI, Fig. 4) and the other strikes N40°E-S40°W (subareas I, III, V and VI, Fig. 4) with a local variation of strike upto 10° in different subareas. The two other sets in which shear planes strike are N-S (subareas I, II, IV and V, Fig. 4) and E-W (subareas I and VI, Fig. 4) with a local variation in strike from 10° to 20° in different subareas. In view of insufficient data for statistical analysis, the rose diagram has not been presented in the subarea VII which includes the rocks of the Dudatoli-Almora Crystallines. The synoptic 10°-

sector rose diagram of data on shear planes from the Garhwal Group reveals that N40°W-S40°E and N40°E-S40°W striking shears occur as conjugate sets.

The rose diagrams reveal only general direction of principal stress axis σ_1. However, to obtain the precise orientation of σ_1, σ_2 and σ_3 the poles to the joint/shear planes have been plotted on the lower hemisphere of the equal area net. The plots in each subarea were contoured to obtain the maxima. Planes normal to these maxima were determined. Out of these planes, those two planes which made an angle of approximately 60° were considered to be the mean orientation of conjugate set of joint/shear planes formed during the same phase of deformation (Badgley, 1965; Singh and Gairola, 1994). The orientation of the intersection of these two planes denotes the σ_2 (Fig. 3, 5, 6 and 8A). The bisectors of the acute angle and obtuse angle made by conjugate set of joint/shear planes, contain σ_1 and σ_3, respectively, and lie at 90° to σ_2 (Fig. 3, 5, 6 and 8A). The values of the mean plunge and direction of σ_1, σ_2 and σ_3 in different subareas obtained with the help of joint poles (Fig. 3) and the poles of shear planes (Fig. 5) are given in Table 1 and 2, respectively.

The poles to all joint planes in the rocks of the Dudatoli-Almora Crystallines and the Garhwal Group have been plotted separately in one diagram (Fig. 6A and 6B), which give the mean plunge and direction of σ_1, σ_2 and σ_3 in both the tectonic units separately. In the Dudatoli-Almora Crystallines, the mean plunge and direction of σ_1, σ_2 and σ_3 are 45/S30E, 45/N15W and 02/S73W, respectively (Fig. 6A). In Garhwal Group, the mean plunge and direction of σ_1, σ_2 and σ_3 are 67/S16E, 22/N37W and 06/N54E, respectively (Fig. 6B). The poles to all shear planes in the rocks of the Garhwal Group have been plotted on one diagram (Fig. 8A) which reveals the mean plunge and direction of σ_1, σ_2 and σ_3 to be 0/N60E or 0/S60W, 12/S30E and 78/N30W, respectively.

DISCUSSION AND CONCLUSIONS

The joint set locally exhibits a variation of 10 in each subarea. Joints have been observed parallel to the locally developed foliation in subareas I, II, III, IV, V, IX, X, XI and XII and have an oblique relationship with the locally developed foliation in the subareas VI, VII, VIII, XIII, XIV, XV, XVI and XVII. Badgley (1965) has dealt with the fracture patterns in of the Colorado Plateau and related them to vertical uplift, compression and rotation, lateral compression and vertical horsting, and vertical horsting with extension effects. Interpretation of the rose diagrams in different subareas of the Bainoli area has been carried out after the method of Badgley (1965) and it is suggested that in subareas III, IV, VIII, XIV, XV, XVI and XVII joints were developed due to vertical upliftment and in subareas I, II, V, VI, IX, X, XI, XII and XIII joints were developed mainly due to compression and rotation effects, and in subarea VII, the joints were developed due to both lateral compression and vertical horsting. The σ_1 inferred from joints makes an angle of 60°±15° in all the subareas (Fig. 3 and Table 1). Out of 17 subareas, in eight subareas σ_1 lies on a plane almost parallel to the north Almora Thrust, and plunges in NW-SE direction (subareas I, VI, VIII, IX, X, XIII, XV and XVI, Fig. 3). In other subareas, it is oblique to the thrust plane and lies in N-S direction (subareas I and III, Fig. 3) in NE-SW direction (subareas IV, V, XI, XII and XVII, Fig. 3) and in E-W direction (subareas VII and XIV, Fig. 3). The variation in the orientation of σ_1 (and corresponding σ_2 and σ_3 also) may be probably due to local variation in the stress directions and rotation of the rocks during folding, thrusting and faulting in the later deformational phases. The other joints are the old reactivated joint patterns or new joints developed during the subsequent phases of deformation and have not been used for the stress analysis. Similar observations have also been made by Badgley (1965) on the basis of rose diagrams from Colorado Plateau.

σ_1 inferred with all the joints from the Garhwal Group tectonic unit (Fig. 6B) and the Dudatoli-Almora Crystalline tectonic unit (Fig. 6A) confirm that the maximum principal stress direction plunges in NW-SE direction and lies on a plane almost parallel to the thrust plane. This reveals that joints were not contemporaneous with thrusting. Further, the joint sets, which have been used for dynamic analysis, are symmetrically oriented with respect to hinge lines of folds of second generation which have been related to D_2 deformation (Singh, 1992; Singh and Gairola, 1996).

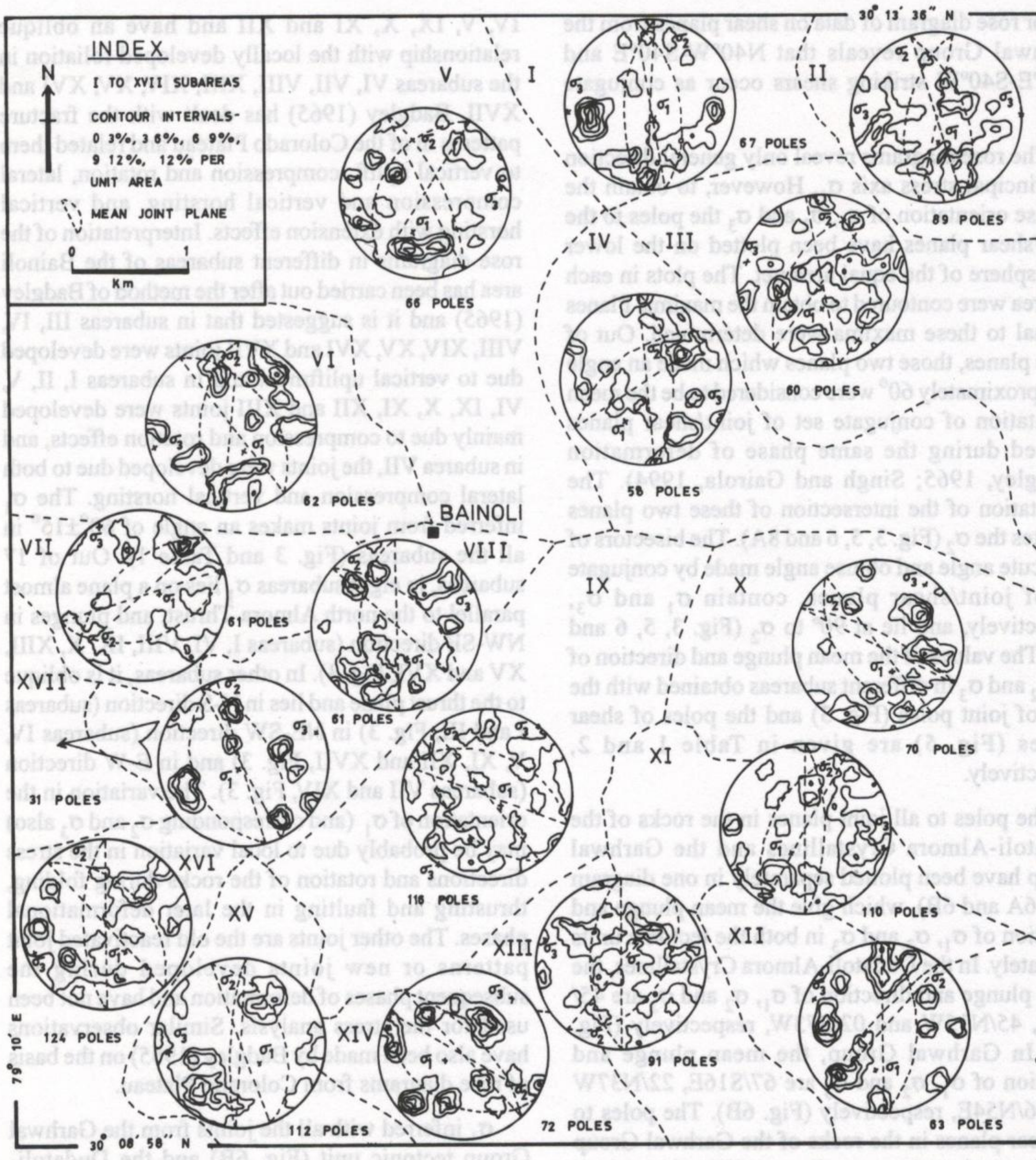

Fig. 3: Synoptic contour diagrams of joints around Bainoli, district Chamoli, U.P. 1, 2 and 3 show the direction of inferred maximum, intermediate and minimum principal stress directions.

σ_1 inferred from the shear planes is nearly horizontal (from 2° to 18° in different subareas Fig. 5 and Table 2) and σ_2 plunges in the direction of the strike of the thrust plane, i.e. in NW-SE direction except in subarea VI (Fig. 5) where it is inclined, probably due to rotation of rocks during faulting in the later phase of deformation. The data on shear planes (Fig. 8A) from the Garhwal Group tectonic unit show that σ_1 was horizontal and σ_2 was parallel to the strike of thrust plane. σ_1 was nearly horizontal and σ_2 was oriented nearly parallel to the strike of the thrust plane. This suggests that the shear planes were contemporaneous with the thrusting. The old reactivated shear planes as well as new shear planes

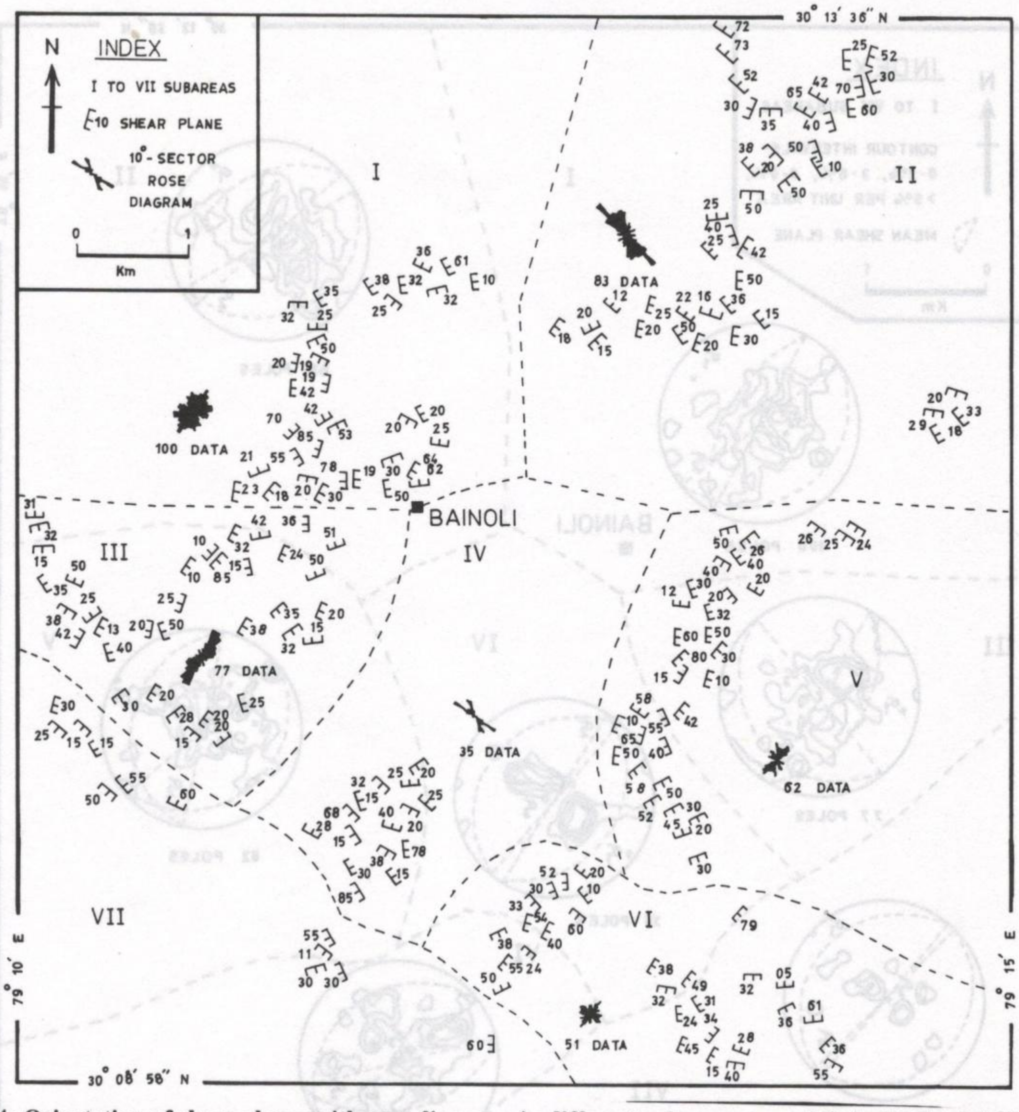

Fig. 4: Orientation of shear planes with rose diagrams in different subareas around Bainoli, district Chamoli, U.P.

developed during subsequent phases of deformation have not been used for stress analysis.

The first phase of deformation (D_1) was responsible for the development of isoclinal folding in the Himalaya (Powell and Conaghan, 1973a; Gairola, 1982; Saklani, 1978; Singh, 1992; Singh and Gairola, 1996 and others) under high temperature and Pressure conditions which resulted in plastic deformation. Hence joints which are brittle to brittle-ductile structure can not be prominently developed during D_1. In the second phase of deformation (D_2), when the open folds were developed in the rocks of Garhwal Himalaya (Gairola, 1992; Singh and Gairola, 1996), was at a lower temperature (Powell and Conaghan, 1973a) during the Upper Eocene to Oligocene times (Gairola, 1992; Kumar and Singh, 1992). The lower temperature during D_2 resulted in a brittle deformation when the rocks of both the tectonic units developed joints. Further, the relationship of joints with the second phase of folding shows that joints were developed during the second phase of deformation. The thrusting in the Himalaya has been related to the D_3 phase of deformation

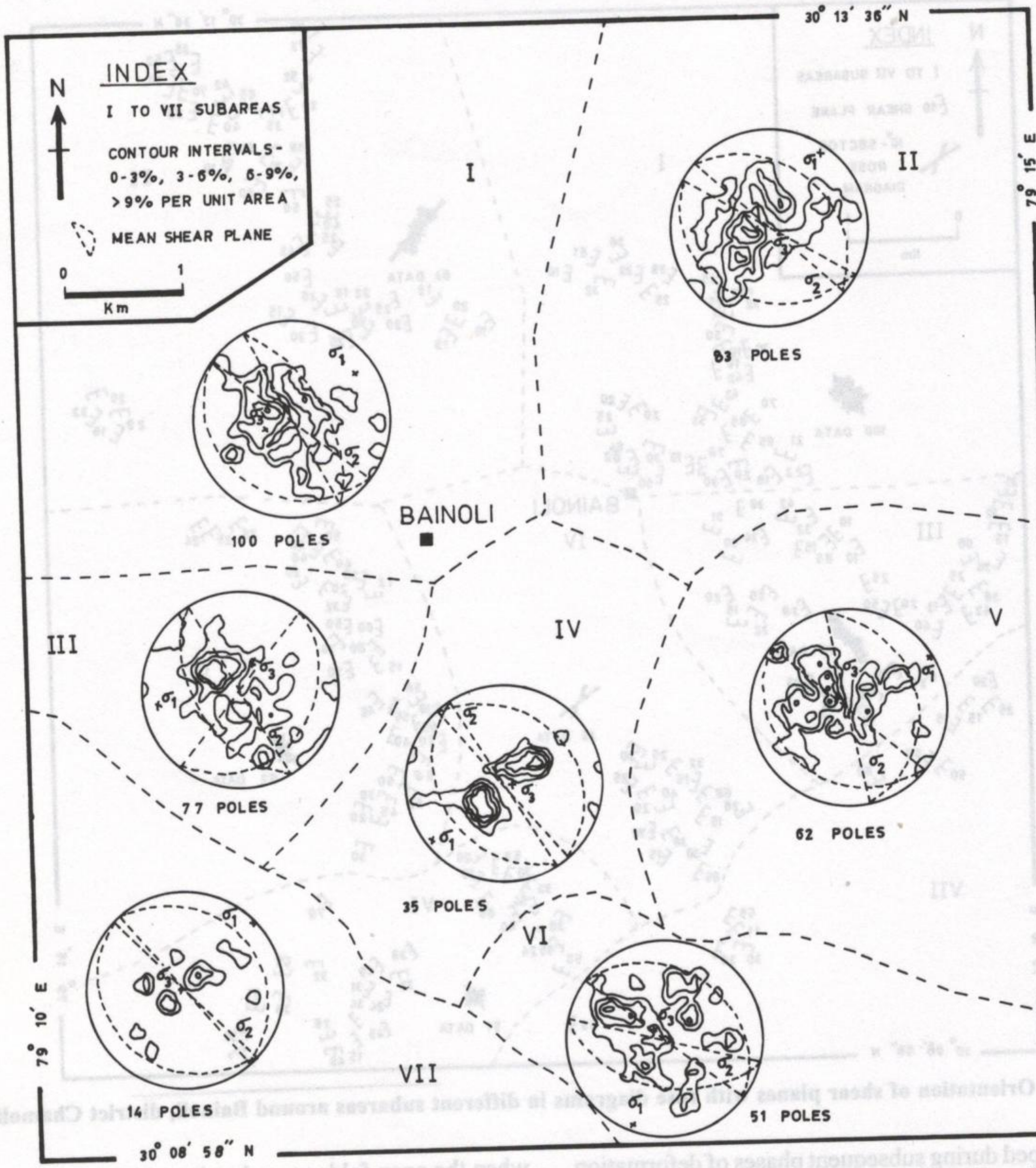

Fig. 5: Synoptic contour diagrams of shear planes around Bainoli, district Chamoli, U.P. σ_1, σ_2 and σ_3 show the direction of inferred maximum, intermediate and minimum principal stress directions.

(Powell and Conaghan, 1973a, Gairola, 1982; Singh and Gairola, 1996) during Middle Miocene (Powell and Conaghan, 1973b; Valdiya, 1980; Gairola, 1982). The stresses responsible for the development of shear planes suggest that these are contemporaneous with thrusting. Further, third phase of deformation (D_3) was also responsible for the development of foliation in the metabasites along and within the shear zones during thrusting (Singh, 1992; Singh and Gairola, 1996). In D_3, orientation of pre-existing joint patterns developed during the D_2 phase, were rotated near the thrust zone and new joints related to the new stresses were also developed, whereas away from the thrust plane the pre-existing joints were reactivated. The fourth phase of deformation (D_4) which has been related to Pliocene

Table 1: Principal stress directions inferred from joint planes

Subarea	Rock type	Direction and plunge of stress		
		σ_1	σ_2	σ_3
I	Metabasites	76° due S16°E	14° due N02°W	04° due S86°W
II	Metabasites	65° due S03°W	25° due N04°W	00° due S87°W 00° due N87°E
III	Metabasites	63° due S02°W	26° due N18°E	08° due N76°W
IV	Metabasites and massive quartzites	45° due S27°W	45° due N22°E	03° due S67°E
V	Metabasites	50° due S16°W	36° due N14°W	14° due N88°E
VI	Metabasites	62° due S25°E	27° due N12°W	07° due S74°W
VII	Metabasites	72° due N82°E	16° due S58°W	06° due N32°W
VIII	Metabasites	57° due S17°E	32° due N28°W	04° due N64°E
IX	Metabasites and massive quartzites	74° due S54°E	16° due N54°W	00° due N37°E 00° due S37°W
X	Metabasites	62° due S26°E	24° due N58°W	11° due N37°E
XI	Metabasites	63° due S28°W	26° due N11°E	06° due S77°E
XII	Metabasites	48° due S10°W	40° due N33°E	14° due N68°W
XIII	Metabasites	64° due N30°E	26° due S16°W	06° due N72°W
XIV	Schistose quartzites	72° due S76°W	10° due S47°E	14° due N40°E
XV	Schistose quartzites	64° due S45°E	20° towards N	18° due S82°W
XVI	Schistose quartzites	58° due S34°E	31° due N14°W	10° due S68°W
XVII	Schistose quartzites	78° due S24°W	08° due N24°W	08° due N66°E

Table 2: Principal stress directions inferred from shear planes.

Subarea	Rock type	Direction and plunge of stress		
		σ_1	σ_2	σ_3
I	Metabasites	18° due N52°E	08° due S34°E	68° due S74°W
II	Metabasites	07° due N36°E	06° due S53°E	81° due S78°W
III	Metabasites	16° due S80°W	20° due S14°E	64° due N26°E
IV	Metabasites	05° due S53°W	04° due N36°W	84° due N82°E
V	Metabasites	03° due N58°E	11° due S30°E	78° due N46°W
VI	Metabasites	06° due S22°W	10° due S70°E	80° due N36°W
VII	Schistose quartzites	02° due N45°E	02° due S45°E	88° due N82°W

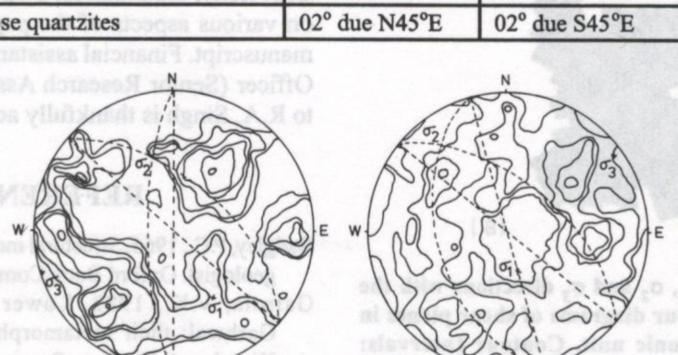

Fig. 6: Inferred σ_1, σ_2 and σ_3 directions with the help of synoptic contour diagrams of joints. A: Dudatoli-Almora Crystallines tectonic units. Contour Intervals: 0.25%, 0.25-0.75%, 0.75-1.5%, 1.5-2.25%, 2.25-3%, 3-3.75%, >3.75% per unit area. B: Garhwal Group tectonic unit. Contour Intervals: 0.17%, 0.17-0.75%, 0.75-1.5%, 1.5-2.25%, 2.25-3%, >3% per unit area.

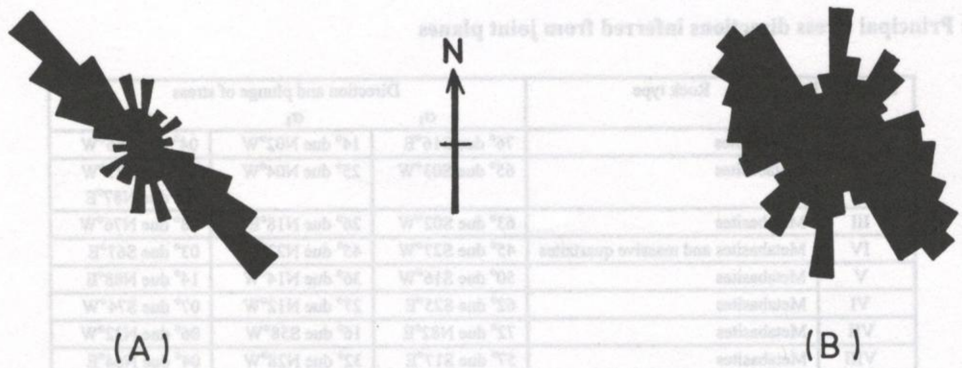

Fig. 7: Synoptic 10-sector rose diagrams of joints. A: Dudatoli-Almora Crystallines tectonic unit. B: Garhwal Group tectonic unit.

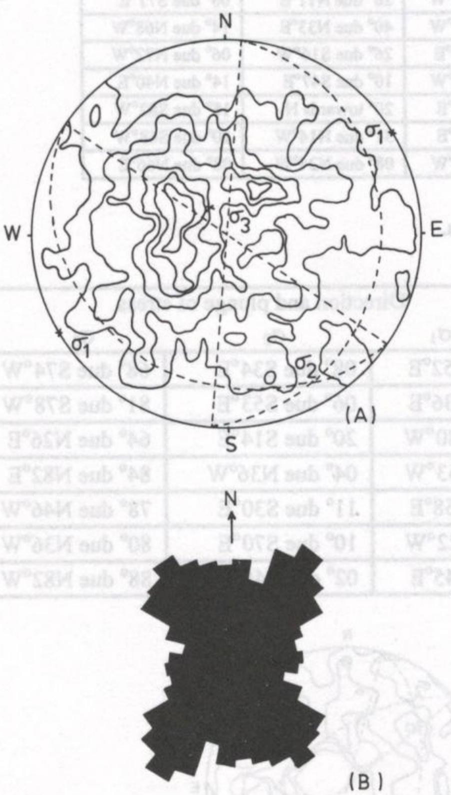

Fig. 8: A- Inferred σ_1, σ_2 and σ_3 directions with the help of synoptic contour diagrams of shear planes in Garhwal Group tectonic unit. Contour Intervals: 0.25%, 0.25-1%, 1-2%, 2-3%, 3-4%, 4-5%, >5% per unit area. B: Synoptic 10σ-sector rose diagrams of shear planes in Garhwal Group tectonic unit.

times, was responsible for the faulting as well as new joints and shear zones. The rocks have been rotated during faulting and may have modified the orientation of the principal stress axes which existed during the second and third phase of deformations.

In the Upper Eocene to Oligocene times, joints were mainly developed during D_2 and shear zones were mainly developed during the D_3 phase of deformation at the time of thrusting in the Middle Miocene times. The joints were reactivated, reoriented and new joints were developed during the D_3 and D_4 phases of deformations, and the shear zones were reactivated, reoriented and new shear zones were developed in D_4 phase of deformation.

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