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CRENULATION CLEAVAGE FROM THE LOW GRADE METAMORPHITES OF THE LESSER GARHWAL HIMALAYA, INDIA

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Abstract: In the Lesser Garhwal Himalaya, the low-grade metamorphites which have reached up to the biotite zone of greenschist facies, exhibit well developed crenulation cleavages. Different parameters such as pre-existing fabric, metamorphism, grain-size and cleavage spacing have been used to study their influence on the cleavage morphology. The microstructural study reveal that the crenulation cleavage in this part of the Himalayas has developed by the combined mechanism of solution-transfer and metamorphic differentiation with a slight influence of differential plastic flattening.

Key words: Lesser Garhwal Himalaya, low-grade metamorphites, crenulation cleavage, microstructural study.

Introduction

Crenulation cleavage in low-grade metamorphic rocks are thin sharply defined planar discontinuities represented by preferred orientation of layer silicates which truncate the pre-existing fabric. Crenulation cleavages have been observed and described by Cosgrove (1976), Gray (1977a,b,c, 1978, 1979a,b), Gray & Durney (1976, 1979); but there is still a debate on their nature and origin, probably because they represent a diversity in morphology. However, reports on the different morphologies and their probable origin of crenulation cleavage in the Himalayan region are rare (Sengupta 1985; Singh & Thakur 1986).

The present paper records the prominently developed crenulation cleavage from the low-grade metamorphic rocks of the Dudatoli Syncline (Fig. 1) which is one of the largest syncline (approx. 2675 km^2) of the Garhwal Himalaya. On the basis of microstructural studies the morphological types of the crenulation cleavage have been identified. The relationship of crenulation cleavage with the pre-existing fabric, metamorphism, grain-size and cleavage spacing have also been studied. Further, on the basis of microstructures and associated features the authors have tried to discuss the origin of crenulation cleavage from this large part of the Garhwal Himalaya.

Geological setting

The Garhwal region exposes, from south to north, all the four typical lithotectonic subdivisions of the Himalaya (Gansser 1964, Fig.1): 1 - the Outer Himalaya (molassic Siwalik supergroup of Mio-Pliocene ages), demarcated in the south by the Main Frontal Thrust (MFT) from the vast expanse of the Indo-Gangetic Plain and in the north by the Main Boundary Thrust (MBT) from 2 - the Lesser Himalaya - highly folded Precambrian (?) Paleozoic sedimentary/metasedimentary strata demarcated in the north by Main Central Thrust (MCT) from 3 - the Greater Himalaya (with north dipping metamorphics of the Central Crystalline Zone) demarcated by the Martoli Fault in the north from 4 - the Tethys or Tibetan Himalaya (thick pile of sediments of Cambrian to Cretaceous ages). The Trans-Himalayas (further North) and Higher Himalayas with Tethys sediments, are separated by the Indus Tsangpo Suture Zone (I.T.S.Z.).

In the Lesser Garhwal Himalaya, Dudatoli Syncline is regionally folded into a giant synform with an approximately NW - SE trending axis. The southern limit of this synform is bounded by the Garhwal Thrust and South Almora Thrust (SAT), whereas the northern limit is marked by the North Almora Thrust (Heim & Gansser 1939; Gansser 1964). The rocks of this syncline have been named as rocks of Dudatoli Group by Mehdi et al. (1972) who have divided these rocks into three formations. The lower one - Chandpur Formation consists of phyllites and slates, the middle - Nagthat Formation - consists of alternate bands of phyllites and schistose quartzites and the upper - Dudatoli Almora Crystalline Formation - mainly has garnetiferous schist and garnet bearing quartzites. The rocks of the Dudatoli Group are Precambrian in age (Kumar et al. 1974).

In the present work crenulation cleavages have been studied from the rocks of the Chandpur and Nagthat Formations of the Dudatoli Syncline and are associated with the F3-chevron folds of the region. The wave length of the crenulation folds ranges from 200 to 1.5 *mm* (Fig. 3a). The tectonic frame work and structures of different parts of this syncline have been discussed separately (Gairola & Srivastava 1982; Srivastava 1985; Sahai 1987; Srivastava & Sahai 1989, 1990).

Crenulation cleavage

Crenulation cleavage, commonly observed in the multiply deformed low to medium grade metamorphites, is defined by micro scale kinking of an earlier fabric. The earlier fabric may be pre-existing slaty cleavage or finely laminated bedding. Morphologically they are grouped into two main types i.e. discrete and zonal types of crenulation cleavage (Gray 1977a; Cosgrove 1976; Gray & Durney 1979). A cleavage transitional to crenula-

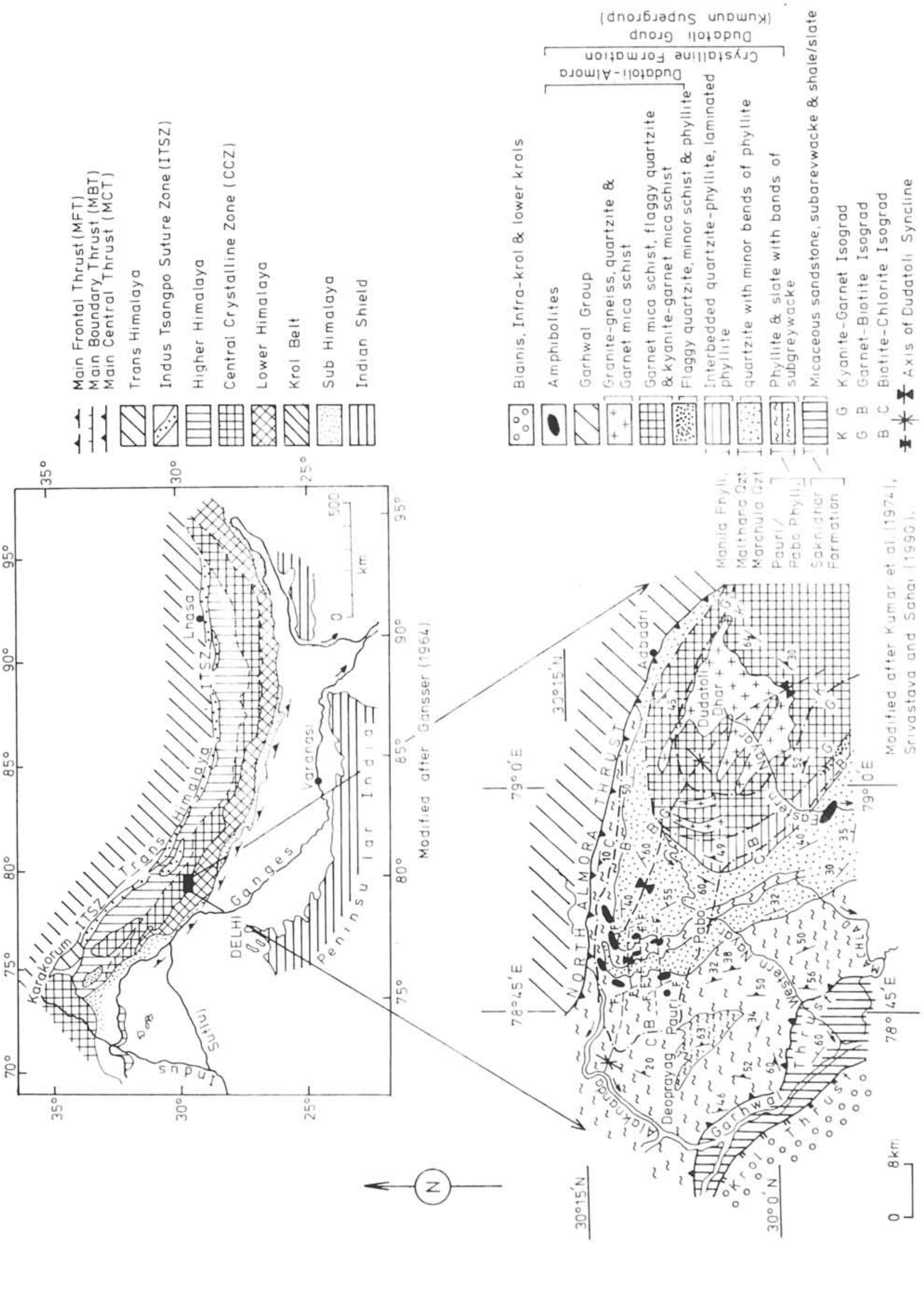

Fig. 1. Outline map of the Himalaya showing the broad lithotectonic subdivisions (Inset): enlargement of geological map of Dudatoli Syncline.

tion cleavage with low initial isotropy has been designated as "rough cleavage" (Gray 1977b) and is commonly observed in multiply deformed psammites. In the low-grade metamorphic rocks of the Lesser Garhwal Himalayas zone, rough and discrete crenulation cleavages have been identified, where the zonal crenulation cleavage gradationally changes to discrete crenulation cleavage. The main feature which distinguishes crenulation cleavage from other cleavages is the ubiquitous association with a microfolded pre-existing fabric (Gray 1977b).

Gray (1977b) has suggested some parameters which affect the crenulation cleavage morphology. In the present work, these parameters have been used to study their influence on the morphology of crenulation cleavage developed in the low-grade metamorphites of the Lesser Garhwal Himalaya. Further, on the basis of microstructural studies probable origin of the crenulation cleavage of this large part of Garhwal Himalaya has been discussed.

Pre-existing fabric

The development of crenulation cleavage requires a pre-existing fabric (Knill 1960, p.318; Rickard 1961, p.329). Thus on the basis of grain size, compaction, nature of grain interaction, degree of preferred dimensional orientation and nature of anisotropy it is suggested that the crenulation cleavages occur in different pelitic and psammitic rocks with characteristic pre-existing fabric (Gray 1977b). In the low-grade metamorphites of the Lesser Garhwal Himalaya the slate (type 1 and 2) Fig. 2a, schist (type 1 and 2) Fig. 2c; 3b,c; 6a,b and 7b; psammite (phase 2 - type A,B and C), Fig. 2b; 3d; and multilayer (type B and C) Fig. 3a, 7a and 8b; microfabric (see Gray 1977b; Fig. 2, p. 767) have been identified.

Metamorphic grade

To study the influence of metamorphic grade on the type of crenulation cleavage and pre-existing fabric in the rocks of the Garhwal Himalaya a comparative chart (Tab. 1) has been prepared along with the mineral paragenesis which suggest that:

In the most of thin sections there is a change in the grade of metamorphic minerals (chlorite to biotite) from type 1 to 2 in the schist fabric, type B to C in the psammitic fabric and type B to C in the multilayer fabric. Further mineral parageneses (Tab. 1) suggest that the zonal crenulation cleavage are dominated by biotite minerals suggesting a prograde metamorphism as revealed by the alteration of chlorite to biotite, which probably occurred during microfolding. The discrete crenulation cleavages (Tab. 1) are dominated by the presence of chlorite minerals. In a few thin sections (R86/32; 65 and 35) the chlorite along the discrete cleavage exhibit the alteration of biotite into chlorite (the rim of biotite is altered into chlorite) suggesting a retrograde metamorphism, which is probably a result of solution transfer action.

Thus the grade of metamorphism exhibits its influence in the development of different morphologies of crenulation cleavage particularly in those low-grade metamorphic rocks which show schist, psammites and multilayer pre-existing fabric.

The pelitic and psammitic rocks of this part of the Garhwal Himalaya have suffered two episodes of prograde (M1 and M1b) and one episode of retrograde (M2) metamorphism (Srivastava & Sahai 1990). The PT conditions during metamorphism have been estimated in the western part of Dudatoli syncline (which is represented by the pelitic and psammitic rocks) by comparing the observed mineral assemblage with the experimentally determined mineral equilibria and suggest temperatures between 450 - 550 $^{\circ}C$ and pressure of 4 to 5 *kbs* exhibiting metamorphism in biotite zone of greenschist facies (Srivastava & Sahai 1990). Gray (1977b) has also suggested that this range of PT condition is very much suitable for the development of crenulation cleavage.

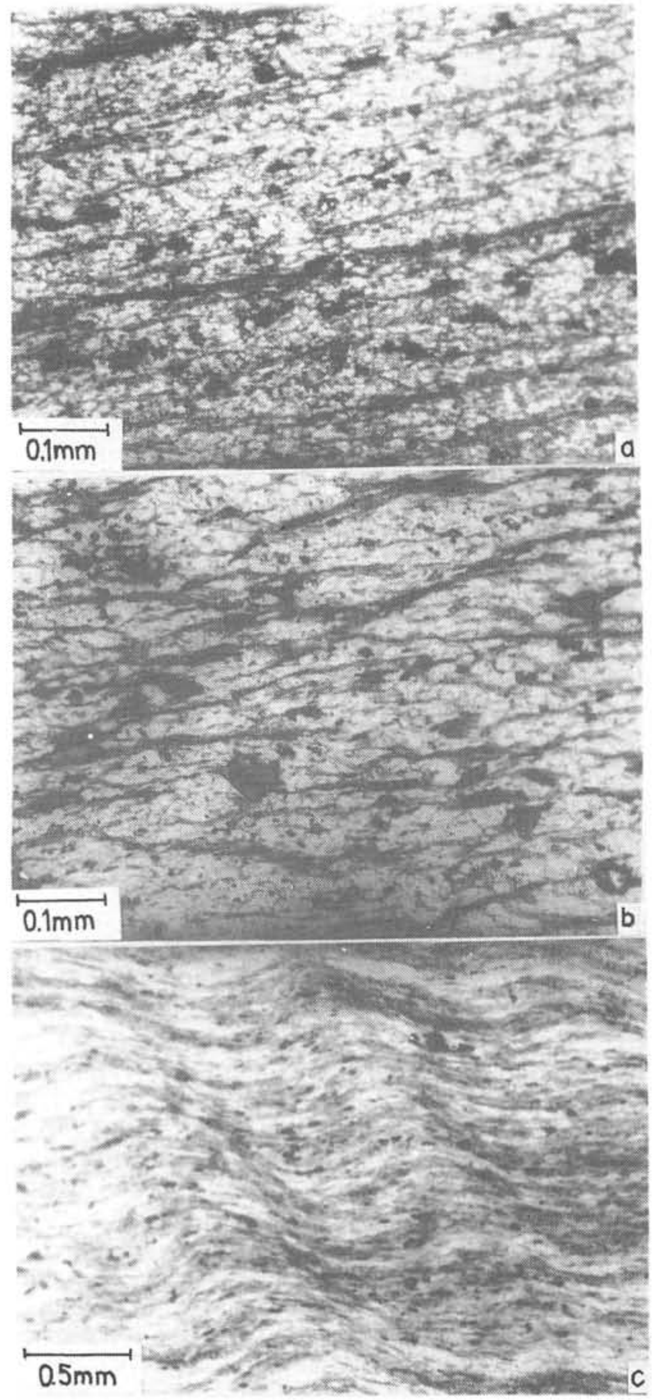

Fig. 2a. Photomicrograph of slate fabric (type 2) in R86/17. (Scale bar = 0.1 *mm*).

Fig. 2b. Photomicrograph of pre-existing psammite fabric (phase-2) type A in R86/966. (Scale bar = 0.1 *mm*).

Fig. 2c. Photomicrograph of pre-existing schist fabric (type 1) showing open folds, a preliminary stage of the development of zonal cleavage. (Scale bar = 0.5 *mm*).

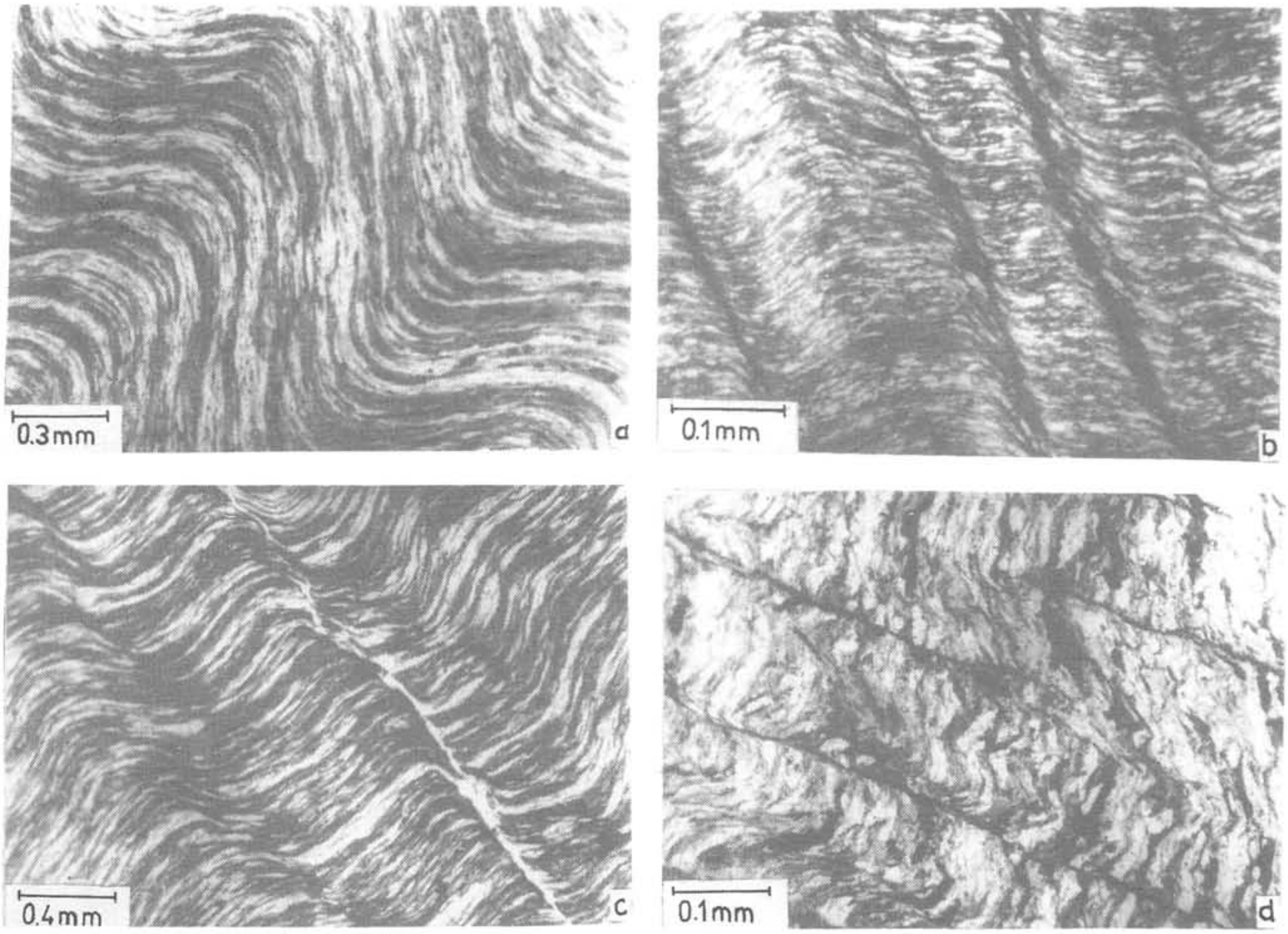

Fig. 3a. Photomicrograph of multilayer fabric, exhibiting symmetrical zonal crenulation cleavage. (Scale bar = 0.3 *mm*).

Fig. 3b. Photomicrograph of a schist fabric (type 2) showing the development of asymmetrical zonal cleavage along the steeper limb of a fold. (Scale bar = 0.1 *mm*).

Fig. 3c. Photomicrograph of a schist fabric (type 1) exhibiting the development of discrete cleavage from zonal cleavage 1. (Scale bar = 0.4 *mm*).

Fig. 3d. Photomicrograph of psammite fabric (phase 2 - type B) exhibiting the discrete cleavage (linear traces).(Scale bar = 0.1 *mm*).

Grain size and cleavage spacings

Histograms of length, width, length/width ratio (for grain shape) with cleavage spacings have been plotted and studied for quartz, mica and magnetite grains. These grains are invariably associated with cleavage zones as well as in the mineralogy of the host rock. Grain sizes are studied in psammitic and schist pre-existing fabric of the low-grade metamorphites of Lesser Garhwal Himalaya (Figs. 4 and 5).

Length: The length of quartz (500 to 2000) and mica (300 - 2500) grains in zonal crenulation cleavage associated with type 1 and type 2 of schist fabric (Fig. 5, R86/49 R86/65) are greater, as compared to discrete crenulation cleavage (grading into zonal) associated with rough cleavage of psammites (type A, B and C; Fig. 4, R86/21; R86/44 and R86/67).

The length of magnetite exhibits a practical uniformity with all the pre-existing fabric and shows no appreciable influence on cleavage type. However, in schist fabric type 1 (zonal crenulation cleavage) magnetite grains are longer than in type 2 (Fig. 3).

Width: The width of the quartz is practically uniform (100 - 600 in schist fabric - types 1 and 2; Fig. 5) whereas in psammitic fabric there is an increase in the width of quartz grains (up to 1000 ; Fig. 4). The width of mica exhibits uniformity in all the pre-existing fabrics (Figs. 4 and 5). At times there is an increase in the width of mica when the schist fabric grades from type 1 to type 2. This increase in the width of mica is probably due to recrystallization, with an increase in the grade of metamorphism. Magnetite grains ranging in the width from 200 - 500 have a uniform thickness in all the cleavage types.

Grain shape: the length-width ratio of quartz is higher (2 to 7) in the schist fabric type 1 whereas the ratio is reduced to 2 - 4.50 in type 2 (Fig. 5). There is a general increase in the L/W ratio of the grains in psammites when the rock grades from type A to C of pre-existing fabric, with cleavage grading from discrete to zonal type (Fig. 4).

- The histograms reveal that there is a sharp increase in ratio of mica grains from schist fabric type 1 to type 2 (Fig. 5) probably due to solution transfer and differential plastic flattening. Mica has a uniform L/W ratio ranging from 3.5 to 7.0 in the psammites.

- A slight lowering of L/W ratio in the magnetite has been observed when pre-existing schist fabric grades from type 1 to 2. In the psammites there is no apparent influence on cleavage type, except a slight variation in type B (Fig. 4).

Pre-existing Fabric Type (& Transitional)		Slide No.	Folding	Discrete	Zonal	Rough	Mineral assemblage
SLATE FABRIC	Type 1	R 86/12	No. minor to moderate				Chlorite-muscovite-quartz-plagioclase
	Between Type 1 & 2	R 86/935					
		R 86/978					
	Type 2	R 86/17					
SCHIST FABRIC	Type 1	R 86/27	No.				Sericite-chlorite-biotite-quartz (± albite ± epidote)
		R 86/64					
		R 86/32	moderate to high				Biotite-muscovite-chlorite-quartz (±albite ±epidote)
		R 86/50					Chlorite-muscovite-quartz-plagioclase
		R 86/1010					Chlorite-muscovite-quartz-sericite-plagioclase-K-feldspar
		R 86/39					Chlorite-muscovite-biotite-quartz-K-feldspar
	Type 2	R 86/10					Chlorite-muscovite-quartz-plagioclase; Biotite-muscovite-chlorite-quartz (±albite ±epidote)
		R 86/13					Chlorite-muscovite-quartz-plagioclase-K-feldspar (with biotite in S.No. R86/65)
		R 86/49					
		R 86/65					
		R 86/915					
PSAMMITIC FABRIC	Type A	R 86/14	Not appreciable				Chlorite-muscovite-quartz-sericite-plagioclase
		R 86/21					
		R 86/40					
		R 86/41					
		R 86/43					
		R 86/63					
		R 86/961					Biotite-chlorite-sericite-quartz (± albite ± epidote)
		R 86/966					Chlorite-biotite-quartz (±albite± epidote)
		R 86/981					Chlorite-muscovite-quartz (± plagioclase)
	Transitional between A & B	R 86/35					Biotite-muscovite-chlorite-quartz (± albite ±epidote)
		R 86/37					Chlorite-muscovite-biotite-quartz-K-feldspar
		R 86/51					Chlorite-muscovite-quartz
	Type B	R 86/19					Chlorite-muscovite-quartz-sericite-plagioclase (± albite± epidote)
		R 86/44					
		R 86/56					
	Transitional between B & C	R 86/23					Chlorite-muscovite-quartz (± plagioclase); Biotite-muscovite-quartz (±albite±epidote)
		R 86/962					
		R 86/979					
	Type C	R 86/60					Biotite-muscovite-chlorite-quartz (± albite ±epidote)
		R 86/61					
		R 86/67	minor				
MULTI-LAYER FABRIC	Type B	R 86/18	moderate to high				Biotite-muscovite-chlorite-quartz (± albite ±epidote)
		R 86/47					
		R 86/971					
	Type C	R 86/48					Biotite-muscovite-quartz (±albite±epidote)
		R 86/952					Chlorite-muscovite-biotite-quartz-K-feldspar
		R 86/954					Biotite-muscovite-chlorite-quartz (±albite ±epidote)

Cleavage spacing: The schist fabric type 2, with discrete crenulation cleavage, has a wider cleavage spacing (2200) as compared to zonal crenulation cleavage (schist fabric - type 1; ; Fig. 5). In psammites there is a gradual decrease in cleavage spacing with pre-existing fabric grading from type A (cleavage spacing, 400 - 3000) to type B (1700 - 2400) to type C (300 - 1200). This is due to gradual enhancement of cleavage seams, from short discontinuous seams around randomly oriented grains of psammite fabric - type A, to continuous cleavage seams around strongly oriented detrital grains in psammite fabric - type B and to psammite - type C, which has a cleavage fabric characterized by several continuous cleavage seams in specific isolated zones (Figs. 2b; 3d and Fig. 4; compare with Gray 1977b, p. 767; Fig. 2).

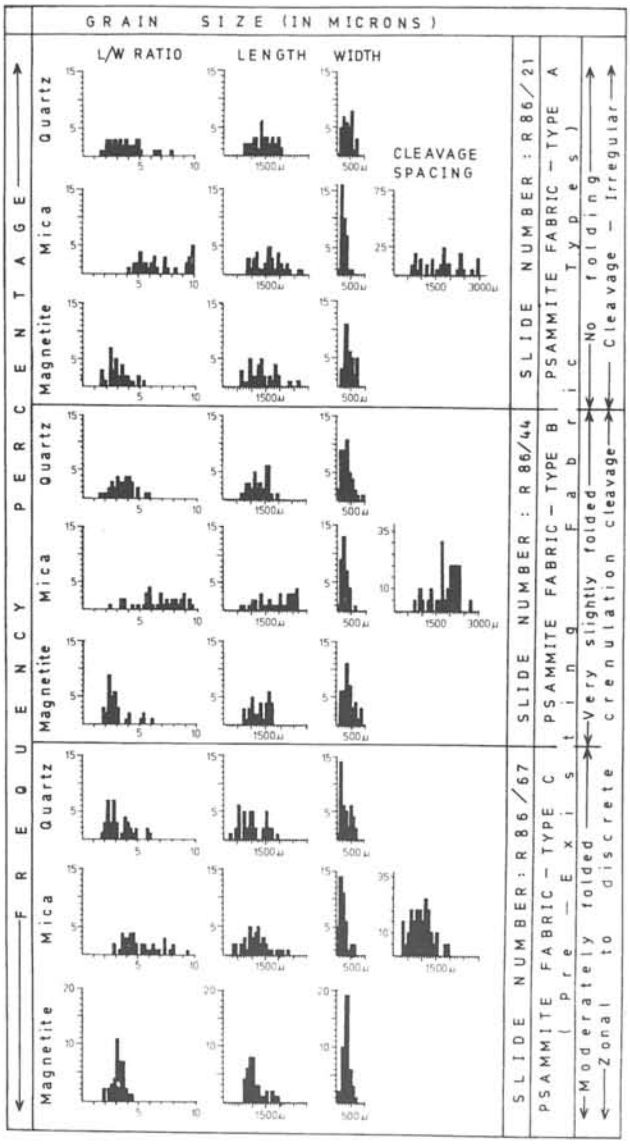

Fig. 4. Histograms of grain size; L/W ratio and cleavage spacings in quartz, magnetite and mica in pre-existing psammite fabric - type A, B and C.

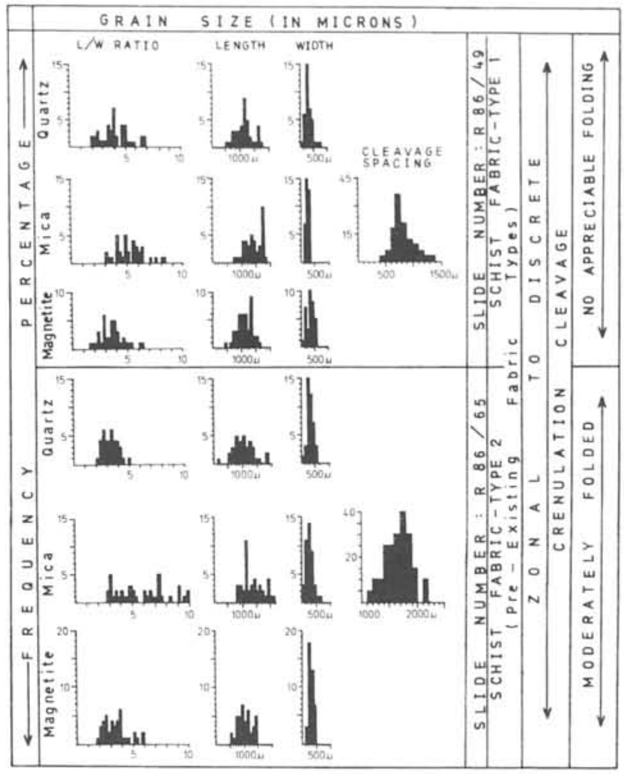

Fig. 5. Histograms of grain shape/size (L/W ratio) and cleavage spacings in schist fabric type 1 and 2.

Microstructure

Cleavage microstructure is one of the important parameter and provide detailed information on the deformation mechanism responsible for their development (Gray 1977c; Marshak & Mitra 1988). In the following lines, both discrete and zonal crenulation cleavage observed in low-grade metamorphites of the Garhwal Himalaya, have been included.

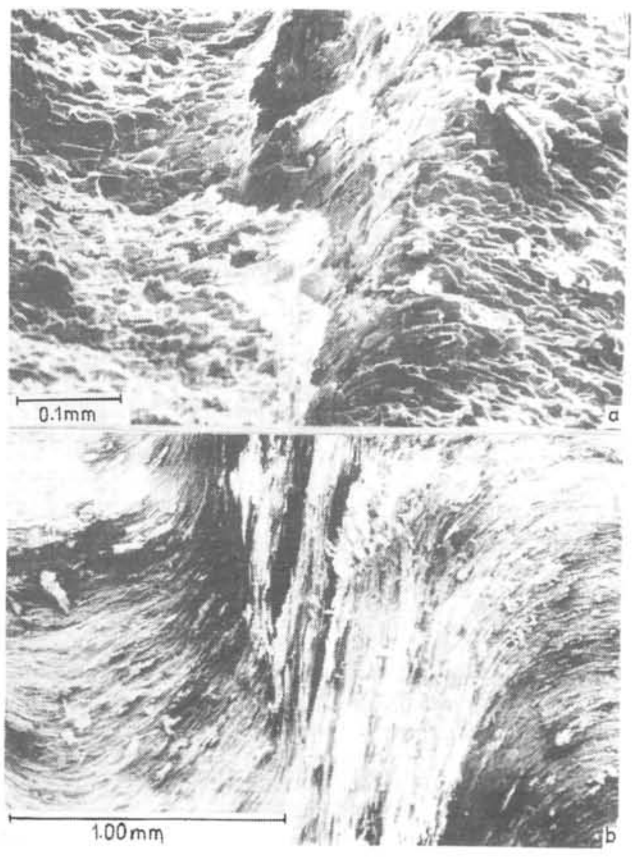

Fig. 6a. SEM photograph of a limb of a microfold in schist 1. Steep limb gradually grades into discrete cleavage. (Scale bar = 0.1 *mm*).

Fig. 6b. SEM photograph of schist fabric - type 1, exhibiting the zonal crenulation cleavage changing to discrete cleavage along the steep limb of a microfold. Note the constant size/shape of phyllosilicate grains. (Scale bar = 1 *mm*).

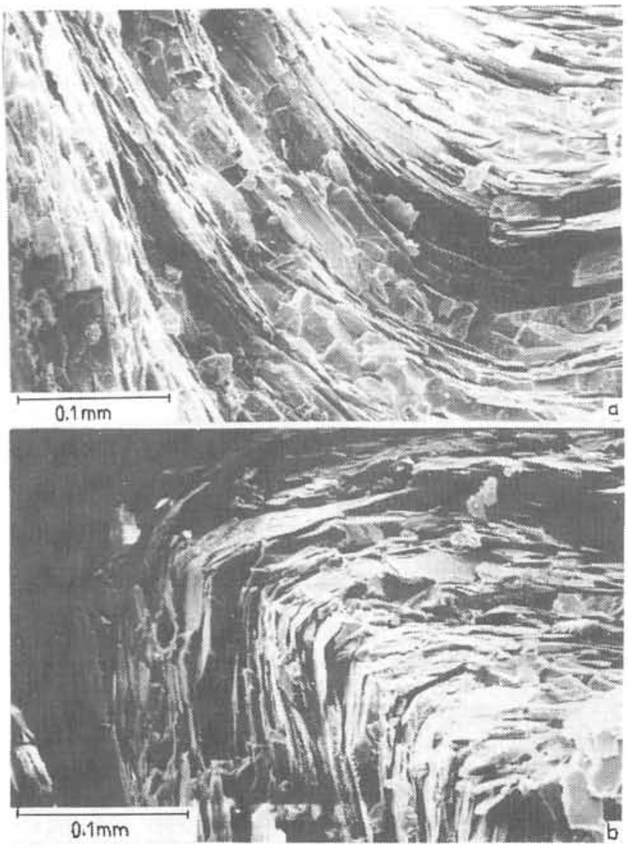

Fig. 7a. SEM photograph of a multilayer fabric (type C) exhibiting alternate layers of quartz and mica in a discrete zone developed due to dissolution and precipitation in layers. (Scale bar = 0.1 *mm*).

Fig. 7b. SEM photograph of a zonal symmetrical cleavage along close fold in schist fabric type 2. (Scale bar = 0.1 *mm*).

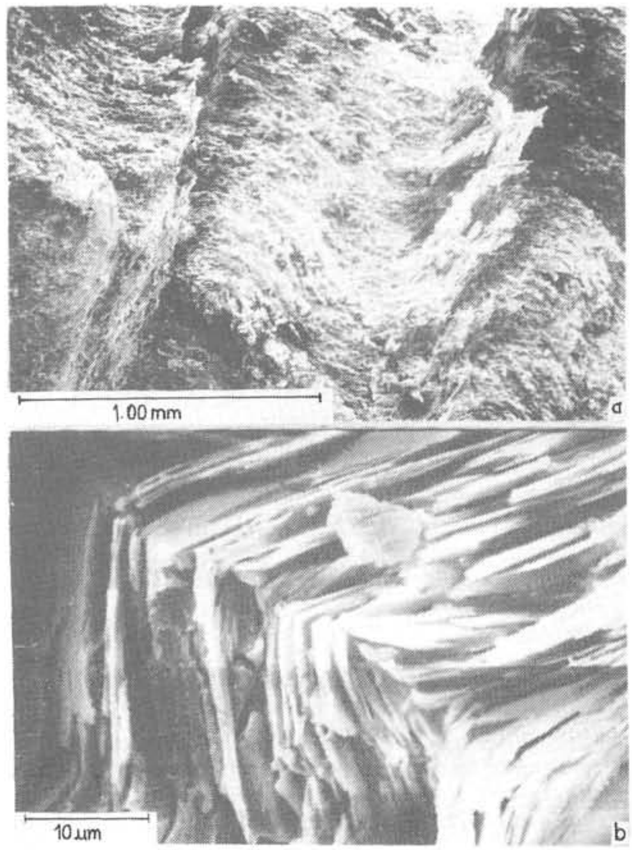

Fig. 8a. SEM photograph of a schist fabric exhibiting excellent development of discrete cleavages. (Scale bar = 1 *mm*).

Fig. 8b. SEM photograph of a multilayer fabric, showing the dissolved quartz layer along the hinge zone (zonal symmetrical cleavage).(Scale bar = 10 μm).

Discrete crenulation cleavage

The discrete crenulation cleavages of the Garhwal Himalaya (Figs. 3c,d; 6a,b; 7a and 8a) are defined by siliceous minerals, opaques and phyllosilicates. It is mainly developed in slaty and psammitic pre-existing fabric (Tab. 1). The folded quartz vein associated with crenulation cleavage often show off setting along steeper limb of the microfold. However, along the discrete crenulation cleavage zone, the following observations have been made:

a - The micaceous minerals which are oriented along the discrete cleavage plane exhibit no evidence of deformation (Fig. 3d and 7a).

b - The quartz grains near the cleavage plane exhibit no increase in undulose extinction or development of deformation lamellae (Fig. 3d).

c - The offset of the quartz vein exhibits sutured or corroded boundaries and does not show any evidence of fracturing and faulting (i.e. crushing/cataclastic texture) related to brittle deformation (Figs. 3c,d and 7a). Similar observations have been also made by Gray (1977a,b).

d - The micaceous minerals/phyllosilicates are of practically the same size in the cleavage zones in comparison to these along pre-existing cleavage i.e. schistosity (Fig. 3c, 6b and 7a).

Zonal crenulation cleavage

The microstructure of zonal crenulation cleavage varies with the fabric in which it occur. Since these cleavages are mainly developed due to folding in schist and multilayer fabric (Figs. 3a,b,c; 6a,b; 7b and 8b) their microstructure will be described in reference to these fabrics only.

In schist fabric, the cleavage is generally developed along the steeper limb (Figs. 3b, 6a,b) of microfolds. The cleavage zone consists of parallel closely packed phyllosilicates, with small grains of quartz. The quartz grains are elongated (stretched) and show undulose extinction (R86/1010; R86/39; R86/915).

The multilayer fabric mainly consists of mica and quartz rich layers (Fig. 7b), where the quartz and mica grains are aligned parallel to the slaty cleavage plane. The crenulation cleavage is developed in micaceous layer (R86/27; 32; 1010; 65; 961; 37 and 56) whereas the quartzose layers are devoid of it (R86/12; 17; 41; 51; 44 and 56). However, where the deformation is more intense the crenulation cleavage entering from mica-rich layer to quartz-rich layer shows a refraction in the cleavage plane direction (R86/18; R86/971; Figs. 3c and 7a). At times, the elongated quartz grains show further elongation as they become aligned to the crenulation cleavage. The thinning and truncation of quartz layer along the limbs of the microfolds in buckled multilayer fabric observed in few thin sections (R86/18; R86/971; 952 and 954), is probably due to the homogenous flattening caused by ductile deformation (Ramsay 1967, p. 434). The development of crenulation cleavage along the steeper limb of crenulation folds is readily observed (R86/48; R86/9562; R86/954; Fig. 3c) in several sections.

The quartzose layers along the limbs of microfolds show evidence of boudinage as well as pinch and swell structure and suggest a strong differential movement occurred between adjacent fold hinges (R86/50; 1010; 65; 952). The process by which these microstructures have been formed is named as a differential plastic flattening. The relationship of crenulation cleavage with chevron folds (F3) has been studied in many thin sections from this region (R86/50; 1010; 39; 49; 65; 915; 48; 952 and 954).

Conclusion

The microstructural studies in the rocks of low-grade metamorphits of the Garhwal Himalaya exhibit both the discrete and zonal types of crenulation cleavages, where the zonal crenulation cleavage gradationally changes into discrete the type. The zonal crenulation cleavage is developed due to folding, followed by dissolution and diffusion of soluble minerals. The presence of boudinage, pinch and swell structure and the thinning of layers along the limb of buckled multilayered fabrics suggest that the zonal crenulation cleavages are formed due to differential plastic flattening followed by diffusion and dissolution of soluble minerals, which leave behind insolubles as phyllosilicates.

The discrete crenulation cleavage exhibits no deformational feature, hence the absence of cataclastic texture, and the presence of corroded irregular grains along or adjacent to the cleavages, supports the solution mechanism to explain the development of crenulation cleavages in deformed pelitic rocks of the Lesser Garhwal Himalayas. Whereas, earlier, it was considered that the discrete crenulation cleavages were formed due to microfaulting along the limbs of microfolds i.e. due to brittle deformation (Sorby 1880; Harker 1886; Greenly 1930; Woodland 1965; Williams 1972). Further, the absence of deformational features and gradational change from zonal to discrete type suggests that the discrete crenulation cleavage are developed at later stages than zonal crenulation cleavages. The metamorphic differentiation was probably more active during the late stages of cleavage formation and helped in solution transfer by dissolving the already weakened quartz and other grains (Gray 1979). In this part of the Himalayas, these crenulation cleavages are invariably associated with F3-chevron folds which were developed during the D3 phase of deformation (Simurian phase - Middle Miocene). This phase was associated with the M1b phase of prograde regional metamorphism in the area (Srivastava & Sahai 1989, 1990).

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