Structural and metamorphic evolution of the rocks of the Jutogh Group, Chur half-klippe, Himachal Himalayas: A summary and comparison with the Simla area

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The rocks of the Jutogh Group in the Himachal Himalayas and their equivalents elsewhere are now considered to represent a several km thick crustal scale ductile shear zone, the so called Main Central Thrust Zone. In this article we present a summary of structural and metamorphic evolution of the Jutogh Group of rocks in the Chur half-klippe and compare our results with those of Naha and Ray (1972) who worked in the adjacent Simla klippe.

The deformational history of the Jutogh Group of rocks in the area around the Chur-peak, as deduced from small-scale structures, can be segmented into: (**1**) an early event giving rise to two sets of very tight to isoclinal and coaxial folds with gentle dip of axial planes and easterly or westerly trend of axes, (**2**) an event of superimposed progressive ductile shearing during which a plethora of small-scale structures have developed which includes successive generations of strongly non-cylindrical folds, several generations of mylonitic foliation, extensional structures and late-stage small-scale thrusts, and (**3**) a last stage deformation during which a set of open and upright folds developed, but these are regionally unimportant. The structure in the largest scale (tens of km) can be best described in terms of stacked up thin thrust sheets. Km-scale asymmetric recumbent folds with strongly non-cylindrical hinge lines, developed as a consequence of ductile shearing, are present in one of these thrust sheets. The ductile shearing, large-scale folding and thrusting can be related to the development of the Main Central Thrust Zone. The microstructural relations show that the main phase of regional low- to medium-grade metamorphism ($T \approx 430$–$600°$C and $P \approx 4.5$–8.5 kbar) is pre-kinematic with respect to the formation of the Main Central Thrust Zone. Growth zoned garnets with typical bell-shaped Mn profiles and compensating bowl-shaped Fe profiles are compatible with this phase of metamorphism. Some of the larger garnet grains, however, show flat compositional profiles; if they represent homogenization of growth zoning, it would be a possible evidence of a relict high-grade metamorphism. The ductile shearing was accompanied by a low-greenschist facies metamorphism during which mainly chlorite and occasionally biotite porphyroblasts crystallized.

1. Introduction

In their classic memoir on the geology of the Simla-Chur peak area of the Lower Himachal Himalayas (figure 1), Pilgrim and West (1928) made several observations that have played a crucial role in our understanding of the geology of the western Himalayas. (**1**) They recognized two important lithounits, viz., the Jutogh Series and the Chail Series (now Group and Formation respectively, Srikantia and Bhargava 1988) consisting of medium-grade and low-grade metamorphic rocks respectively. These two lithounits or their equivalents have been traced in other parts of the orogen by later workers. (**2**) They also recognized two thrusts from this area: the Jutogh thrust at the base of the Jutogh Group and Chail thrust at the base

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of the Chail Formation. Gansser (1964) considers the Jutogh thrust to be a continuation of the Main Central Thrust (MCT, Heim and Gansser 1939) which is one of the more important intracontinental thrusts in the Himalayas. (**3**) They also suggested that the Jutogh Group of rocks in this area have been involved in large-scale recumbent folding. (**4**) From this area Pilgrim and West *documented* for the first time that the higher-grade metamorphic rocks occur at successively higher structural and topographic levels. This notion of 'inverted metamorphism' in the Himalayas was later made famous by Ray (1947) from the Darjeeling hills.

Many workers now consider that the Jutogh Group and its equivalents elsewhere constitute a several km-thick ductile shear zone, the so-called Main Central Thrust Zone (MCTZ) (e.g., Pecher 1977; Arita 1983). The MCT (or the MCTZ) is supposed to have accommodated a considerable amount of post-collision crustal shortening, and played a key role in the overall geodynamic evolution of the Himalayan orogen. It is, therefore, important to understand in detail the structural and metamorphic evolution of the rock groups in the MCTZ in different sectors of the Himalayas. In the 'Simla klippe' (figure 1), Naha and Ray (1970, 1971, 1972) and Ray and Naha (1971) carried out detailed analyses of structures and microstructures in the Jutogh rocks. As compared to the Simla klippe, a much thicker section of the Jutogh Group is preserved in the area around the Chur peak (3647 m, about 40 km SE of Simla, figure 1). In this area, we have carried out structural (Mukhopadhyay *et al* 1996; 1997a,b) and metamorphic (details to be published elsewhere) studies including geothermobarometric estimates and garnet zoning patterns. A summary of our findings is presented here and our results are compared with the work of Naha and Ray in the Simla Hills. Previous description of the structure and metamorphism of the Chur area have been given by Roy and Mukherjee (1976); Kanwar and Singh (1979); Srikantia and Bhargava (1988); Das and Rastogi (1988) among others.

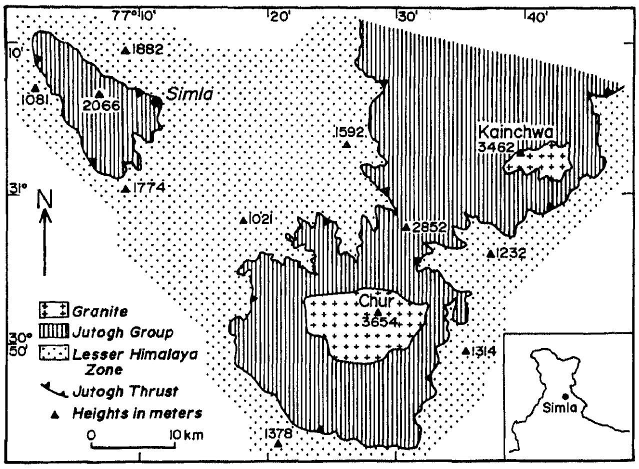

Figure 1. Simplified geological map of the Simla-Chur peak-Kainchwa peak area, Lower Himachal Himalayas showing the extent of the Jutogh thrust sheet (after Pilgrim and West 1928; Srikantia and Bhargava 1988).

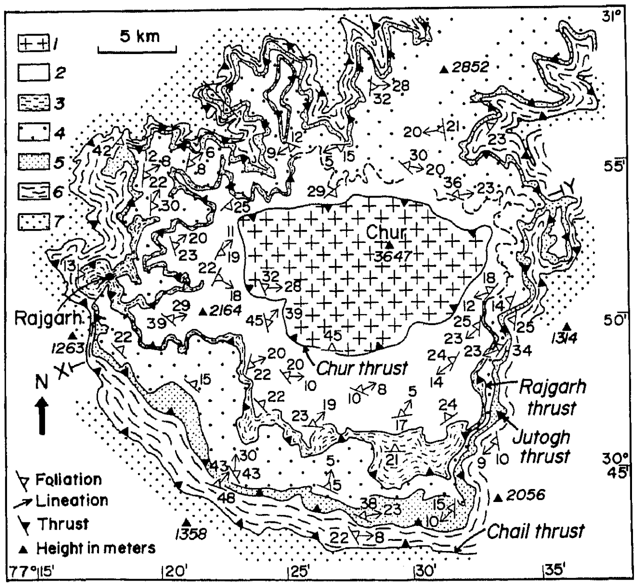

Figure 2. Geological map of the area around the Chur peak (modified after Pilgrim and West 1928). **1**: Chur granite; **2–5**: Jutogh Group; **2**: mica schist; **3**: upper carbonaceous schist (UCS); **4**: quartzite; **5**: lower carbonaceous schist (LCS); **6**: low-grade phyllites of the Chail Formation; **7**: sedimentary rocks of the Lesser Himalaya Zone. Cross section along *X-Y* is given in figure 9.

2. Geology of the area

The approximately circular outcrop pattern of the Jutogh Group around the Chur peak opens out towards NE and merges with the main outcrops further to the north (e.g., Paul 1990; Thakur and Rawat 1992) giving rise to a 'half-klippe' type of outcrop pattern (figure 1). The highest topographic levels around the Chur peak are occupied by the Chur granite. The low- to medium-grade metamorphic rocks of the Jutogh Group, the very low-grade phyllites of the Chail Formation, and the sedimentary rocks of the Lesser Himalaya Zone occur at successively lower topographic levels (figure 2). Pilgrim and West (1928) classified the rocks of the Jutogh Group into Boileaugunge quartzite and carbonaceous schist. However, we recognize that the two carbonaceous schist bands occurring at two topographic levels are two separate units and name them as 'upper carbonaceous schist' (UCS) and a 'lower carbonaceous schist' (LCS) (figure 2). Between the UCS and the Chur granite the rock type is dominantly mica schist whereas between the two carbonaceous schist bands the rock type is essentially quartzite.

3. Structure

3.1 *Ductile shearing*

Microstructures typical of ductile shearing are very common in a majority of more than five hundred thin sections studied but, paradoxically, the evidence for ductile shearing is always equivocal in outcrop. In all the rock types recystallization and neomineralization have resulted in extensive grain-size reduction. This is most commonly shown by quartz grains which are often ribbon shaped, but mica, feldspar and amphibole grains also show similar microstructure. At the initial stage, these minerals show strong anomalous extinction, deformation twins, and kinked cleavage traces. With progressive recrystallization a core-and-mantle texture (cf. White 1976) has developed, followed by 'pseudoporphyritic' texture where highly strained relict porphyroclasts occur in a matrix composed of very small, relatively strain-free grains. At an advanced stage of recrystallization the original fabric is completely destroyed and the rock is composed entirely of small, strain-free polygonal grains showing a 'saccharoidal' texture. This sequence of textural development, that results in reduction in grain size through recrystallization and neomineralization, is characteristic of mylonite which is a common product in ductile shear zones (Bell and Etheridge 1973; Hobbs *et al* 1976; White *et al* 1980). Mylonites vary from protomylonite through orthomylonite to ultramylonite (terminology after Wise *et al* 1984) and this variation is sometimes seen even in a single thin section. All the rock types are mylonitized to varying extent but the LCS, UCS and the granite at the contact with the mica schist are most highly mylonitized.

In the mylonites a mylonitic foliation (S_m) can be easily recognized, traced most commonly by very long and recrystallized quartz ribbons (figure 3). One of the interesting features in this area is that the S_m has been crenulated repeatedly with concomitant development of several generations of crenulation cleavage/ mylonitic foliation during a progressive ductile shearing. The quartz ribbons are often kinked and sometimes they trace refolded isoclinal folds. S–C composite planar fabric (see figure 10, Berthe *et al* 1979) and extension crenulation cleavage (figure 3, Platt 1984) are also present in the mylonitized rocks. A detailed description and the mechanism of development of different types of structures during a progressive ductile shearing have been discussed by Mukhopadhyay *et al* (1997b).

3.2 *Small-scale folds*

A cursory examination of small-scale folds apparently suggests three phases of folding: two generations of coaxial, very tight to isoclinal, and recumbent to gently-plunging reclined/inclined folds superposed by a third set of folds which are open and upright. However, detailed thin section studies of some of the folds show that the deformation history of this area is much more complex than a simple three-phase folding scenario. Some of the important observations in this regard are as follows: (**1**) The axial planar cleavage is a schistosity (continuous cleavage, cf. Davis 1984) in some of the isoclinal folds but in others it is a mylonitic foliation; in many outcrops they have a similar appearance and cannot be easily distinguished from each other in hand specimen. (**2**) Hook-shaped fold interference pattern (type 3 pattern of Ramsay 1967) is a common structure in this area. In some cases the interference structure is traced by *lithological layering only* with the axial planar schistosity of the 'first' generation folded by the 'second' fold. In other instances, however, this interference structure is on mylonitic foliation with the hinge of the 'first' fold

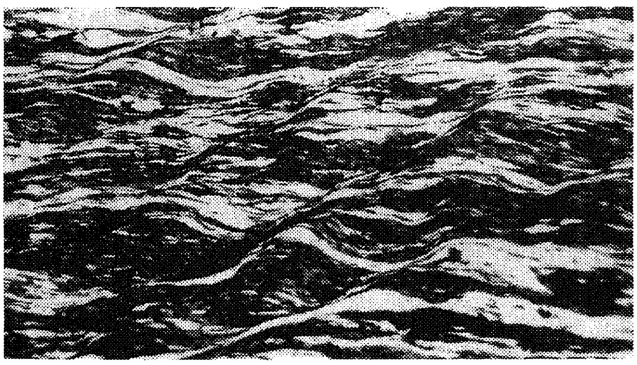

Figure 3. Photomicrograph of mylonitic foliation (S_m) traced by quartz ribbons. The dark portions are rich in mica. A well developed extension crenulation cleavage (ecc) is present, oriented from upper right to lower left. Upper carbonaceous schist, plane polarized light.

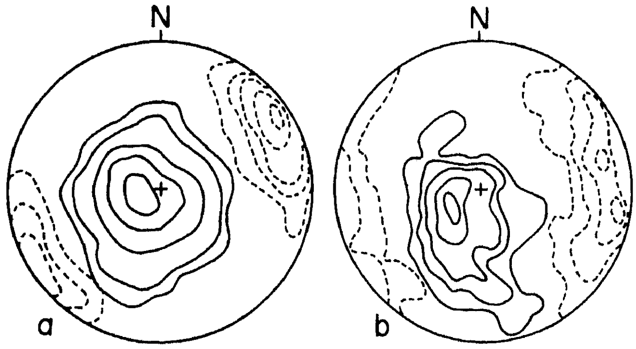

Figure 4. Synoptic stereograms showing orientations of (**a**) foliation and lineation, and (**b**) axial planes and axes of early (F_1–F_2) folds measured in mica schist/quartzite units. (**a**) Continuous contours: 2086 poles to foliation, 0.5-1-3-5-7% per 1% area; dashed contours: 677 lineations, 1-3-5-10-13% per 1% area. (**b**) Continuous contours: 139 poles to axial planes, 1-3-5-8-11% per 1% area; dashed contours: 185 axes, 0.6-3-6-9% per 1% area.

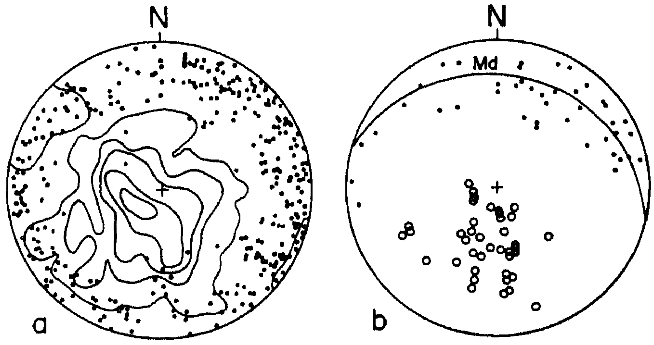

Figure 5. Orientations of axial planes and axes of small-scale folds in carbonaceous schist. (**a**) Whole area, continuous contours: 217 poles to axial planes, contours: 0.5-2-3-5-6% per 1% area, dots: axes. (**b**). Data from one outcrop in the UCS, open circles: poles to axial planes, dots: axes, **Md**: approximate modal axial plane.

also traced by the mylonitic foliation. Therefore, type-3 interference patterns developed both prior to and during ductile shearing. In the shear zones, type-1 (akin to sheath folds) and type-2 interference structures have also been observed. (**3**) The dominantly flat-lying 'foliation' planes in a major part of the area (figures 2, 4a) includes schistosity and several generations of crenulation cleavage and mylonitic foliation. (**4**) In the mica schist/quartzite the hinge lines of the tight to isoclinal folds generally plunge gently towards E or W (figure 4b) and they are traced by lithological layering with well preserved axial planar schistosity in many instances. In the carbonaceous schist, the gently-plunging hinge lines of small-scale folds show extreme variation in trend (figure 5a), the orientation of axial planes of folds show large scatter, and the folds are invariably traced by mylonitic foliation. Therefore, a contrast between the small-scale folds present in the mica schist/quartzite and in the carbonaceous schist is obvious. (**5**) Sheath folds with elliptical cross sections are present in several outcrops in highly sheared rocks. It has been observed in the carbonaceous schist that the small-scale folds in a particular outcrop have similar orientation of axial planes but their hinge lines have variable orientation but lie on the axial plane giving rise to sheath-like geometry in the scale of outcrop (figure 5b). These folds are invariably traced by mylonitic foliation.

We have grouped the folds directly observable in thin sections and outcrops into early folds, folds related to ductile shearing, and late folds (Mukhopadhyay *et al* 1997a). The early folds include two phases of nearly coaxial folding (F_1–F_2) with similar geometry and orientation. In most of the cases they are very tight to isoclinal with subhorizontal to gentle dip of axial planes (figure 4b). The F_1 folds, developed on lithological layering only, are characterized by axial planar schistosity (S_1) whereas the F_2 folds are traced by the S_1 surfaces with or without the development of an axial planar crenulation cleavage (S_2). These folds are pre-ductile shearing and are well-preserved only in areas least affected by the ductile shearing. In ductile shear zones, the early folds have been extensively modified or completely obliterated (for details see Mukhopadhyay *et al* 1997b). Several (but unknown number) generations of folds, mostly of the nature of crenulation folds, have developed during the progressive ductile shearing. In each stage of folding a new crenulation cleavage/mylonitic foliation has developed leading to several generations of S_m. It is neither possible to determine how many generations of folds and S_m are present in the ductile shear zones nor do we consider it to be important. Therefore, all the folds in the shear zones have been grouped together and designated, for the purpose of brevity, as F_{sz}. *In outcrops*, it is often difficult to distinguish the early folds from F_{sz}, primarily because the S_1–S_2 and S_m have a similar appearance. The regionally unimportant late folds include a set of open and upright folds (F_3) that affect all the early structures as well as the structures developed during shearing.

3.3 *Recumbent folding in large scale*

Pilgrim and West (1928, see also Kanwar and Singh 1979) postulated that the flat-lying carbonaceous bands occurring at different topographic levels indicate recumbent folding in large scale although they were unable to demonstrate any large-scale hinge zone. Stereographic plots of 'foliation' and 'lineation' from the whole area give point maxima indicating gentle dip and gentle plunge of modal foliation and lineation respectively (figure 4a). The axial planes of small-scale tight to isoclinal folds also show similar orientation but with an imperfect partial girdle (figure 4b). These, together with the gentle plunge of hinge lines of small-scale folds can be interpreted to suggest recumbent to gently-plunging reclined/inclined folding in large scale also. But there are several difficulties with this interpretation: (**1**) as mentioned earlier, the 'foliation' includes different types of planar elements all of which cannot be axial planar to the same set of folds, (**2**) the 'lineation' is dominantly a stretching lineation which may or may not be parallel to fold axes, and (**3**) the mica schist and the quartzite units do not show repetition either in the Simla area or in the Chur-peak area. Therefore, the postulate that the *two carbonaceous schist bands represent two limbs of a huge recumbent fold* is untenable.

The map pattern in the area as a whole is rather simple with each rock unit restricted to a certain topographic level (see figure 2). But around Rajgarh the UCS shows a rather complex outcrop pattern (figure 6). After making allowance for topography, the repetition of UCS along the same hill slope (e.g., between Bhanot and Thaina) indicate folding in the scale of the map. The LCS, however, remains

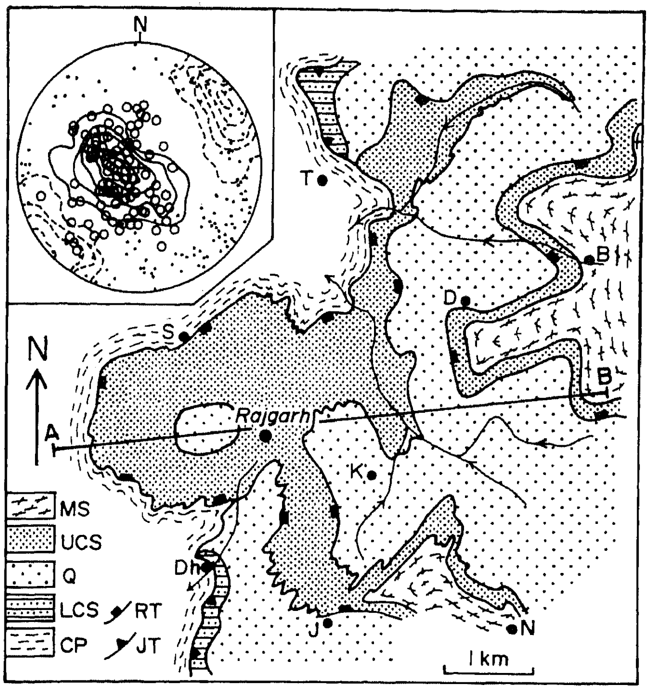

Figure 6. Geological map of the area around Rajgarh in the eastern part of area. **MS**: mica schist; **UCS**: upper carbonaceous schist; **Q**: quartzite; **LCS**: lower carbonaceous schist; **CP**: phyllites of the Chail Formation; **RT**: Rajgarh thrust; **JT**: Jutogh thrust; **B**: Bhanot; **D**: Dohar; **Dh**: Dharoti; **J**: Jon; **K**: Karyut; **N**: Nalog; **S**: Sidhori; **T**: Thaina. Cross-section along **A-B** is shown in figure 7. The main drainage is shown by thin lines with arrows. Inset shows the orientations of planar and linear structures from this area. **Continuous contours**: 383 poles to foliation (mainly mylonitic) planes, 1-2-5-10-12% per 1% area; **dashed contours**: 151 stretching lineations, 1-3-5-10-15% per 1% area; **open circles**: axial planes, **dots**: axes.

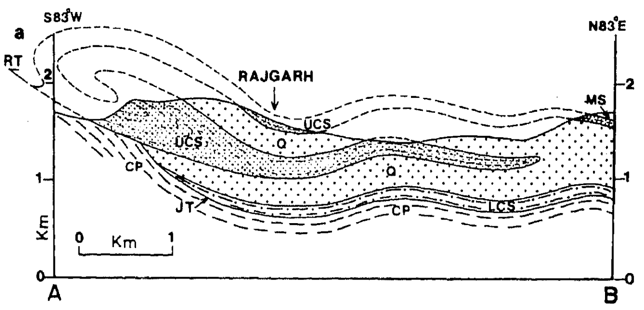

Figure 7. Approximately E-W cross-section through Rajgarh showing refolded isoclinal recumbent fold on UCS and truncated LCS at JT. Abbreviations and line of section as in figure 6.

unaffected by this folding but gets truncated against the Jutogh thrust (near Thaina and Dharoti). In thin sections it has been seen that the foliation surfaces in this area are essentially mylonitic foliation, the stereographic plot gives a well-defined point maximum corresponding to a gently-dipping (16°/N86°) modal plane (figure 6, inset). Thin section studies show that the small-scale folds in this sector are

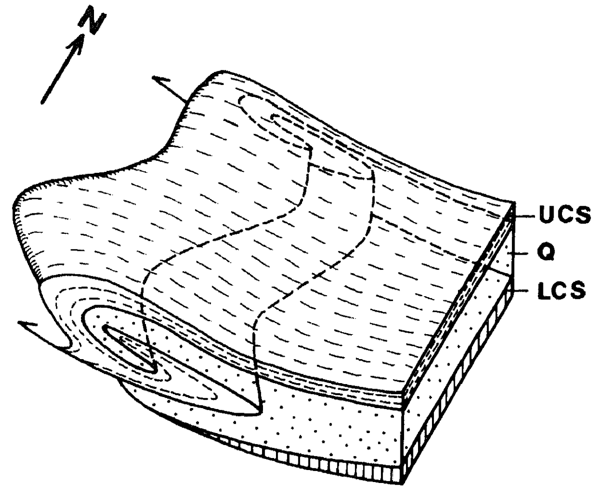

Figure 8. Schematic three-dimensional representation of the structure in the area around Rajgarh. Abbreviations as in figure 6.

mostly traced by mylonitic foliation and they are very tight to isoclinal with gentle dip of axial planes. In some of the exposures near Rajgarh coaxially refolded isoclinal folds and steeply-dipping axial planes of isoclinal folds have been observed. All these taken together suggest that in the scale of the map there is a refolded isoclinal folding on approximately subhorizontal axial plane which is depicted in an idealized E-W cross section through Rajgarh (figure 7). Since the axial planes are very gently dipping we have not attempted to draw the axial traces in figure 6. The extreme variation in the trend of the hinge lines of small-scale folds together with northeasterly trending subhorizontal stretching lineations (figure 6, inset) suggest that the map-scale fold cannot have the shape of a simple hook (type 3 interference pattern). The large-scale fold is likely to be strongly non-cylindrical and, with approximately planar axial plane, should have sheath-like geometry. Figure 8 is a schematic three-dimensional representation of the geometry of large-scale structure around Rajgarh. This structure is traced entirely by mylonitic foliation and, therefore, cannot be related to the early (i.e., F_1–F_2) deformation episode but must have formed during ductile shearing. The km-scale folding depicted in figures 7 and 8 is restricted to Rajgarh area and affects the UCS but not the LCS. This is in contrast to the interpretation of Pilgrim and West (1928) who suggested recumbent folding in the scale of tens of km that affects both the carbonaceous bands.

3.4 *Large-scale thrusts*

The Jutogh and Chail thrusts were originally recognized by Pilgrim and West (1928). The most important evidence for the Jutogh thrust in the Chur area is the sharp metamorphic break between the chlorite-zone phyllites of the Chail Formation and the

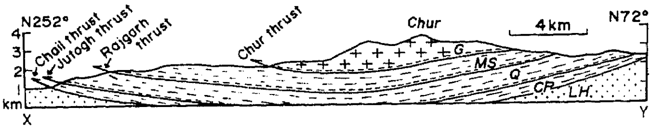

Figure 9. Cross-section across Chur peak showing stacking of thin thrust slices. Line of section as in figure 2. **G**: Chur granite; **MS**: mica schist; **Q**: quartzite; **CP**: Chail phyllite; **LH**: Lesser Himalaya Zone. Carbonaceous schist are too thin to show in this scale.

overlying garnet-zone Jutogh rocks with the biotite zone missing at the Jutogh thrust.

Figures 6 and 7 show that near Rajgarh the LCS is truncated by the Jutogh thrust, and the Jutogh quartzite and the UCS directly overlie the Chail Formation. This is in contrast to the rest of the area where the UCS is always sandwiched between the Jutogh quartzite and mica schist. This demonstrates that, like the LCS, the UCS also marks a structural discontinuity. Further, the UCS is as intensely sheared as the LCS and the UCS separates the underlying garnet-zone quartzite from the staurolite-zone mica schist (no break in metamorphic grade though). Therefore, the lower contact of the gently dipping UCS marks another thrust which we have named as Rajgarh thrust (figure 2, Mukhopadhyay *et al* 1997a). In addition, we have already presented several lines of evidence to prove that the contact of the Chur granite with the underlying mica schist represents a thrust, called the Chur thrust (Mukhopadhyay *et al* 1996). Therefore, in this area there is a stacking of four thin thrust sheets in large scale (figure 9). The stacking of a number of thin (few tens of cm thick) thrust slices riding over each other has been observed in outcrop scale also. These small-scale thrusts usually slice up the mylonitized rocks suggesting that the thrusts formed at the late stage of the shearing movement. The Rajgarh thrust is itself folded (figure 7) and, therefore, the thrusting event could not be completely post-ductile shearing.

4. Metamorphism

In order to understand the metamorphic history of the area, the microstructural relations between the porphyroblasts and the matrix foliation(s) were studied followed by estimation of P-T using microprobe data on coexisting phases and analyses of chemical zoning patterns of garnet porphyroblasts.

Garnet is the most important metamorphic mineral in this area and occurs in almost all the outcrops of the rocks of the Jutogh Group. The mica schist above the UCS usually contain staurolite, and kyanite and/or sillimanite have been observed in a few samples collected from very close to the contact of the mica schist with granite. In the ductile shear zones the

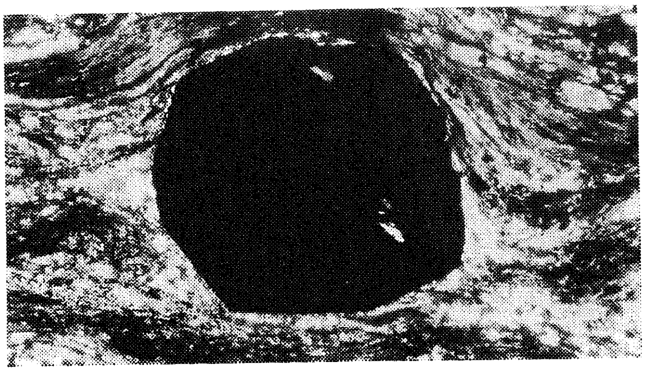

Figure 10. Mylonitic foliation (S_m) swerving around garnet porphyroblasts (dark) in mica schist. Pressure shadow zones, filled with small polygonal quartz grains, are noticeable. Crossed nicols.

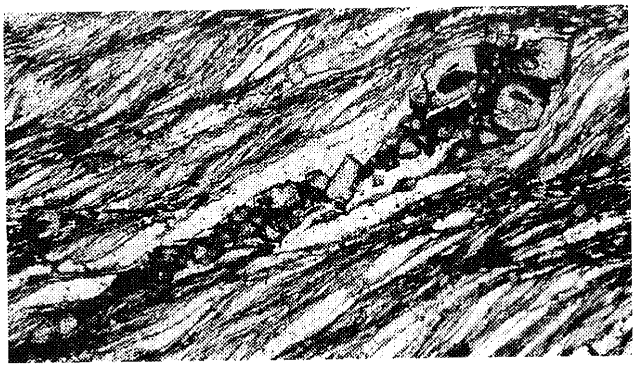

Figure 11. Garnet porphyroblast is boudinaged and broken into small polygonal pieces which are strewn along S-surfaces in an S-C mylonite. The S-surfaces (upper right to lower left) are traced by quartz ribbons. The C-surfaces are oriented from left to right. Plane polarized light.

mylonitic foliation (S_m) invariably swerves around the porphyroblasts of garnet (figure 10), staurolite and kyanite. Garnet (figure 11) and staurolite porphyroblasts are often boudinaged or broken into small pieces and are strewn along the mylonite foliation. Staurolite, kyanite and sillimanite needles (fibrolite) show evidence of strong post-crystalline deformation such as anomalous extinction, bent crystals and kinked cleavage traces. These microstructural relations indicate that the garnet, staurolite, kyanite and sillimanite are pre-kinematic with respect to the ductile shearing.

Many of the garnet porphyroblasts are texturally zoned in the sense that they have inclusion-rich core and inclusion-poor rim (figure 12). This texture is sometimes taken to indicate two phases of metamorphism (e.g., Chakrabarti 1983) but we consider this interpretation to be equivocal. The formation of a poikiloblast is suggestive of rapid growth of the host in a high-energy environment and a homogeneous porphyroblast indicate slow growth in a low-energy environment (Spry 1969; Tracy 1982). Therefore, if a garnet starts to grow syn-kinematically with a

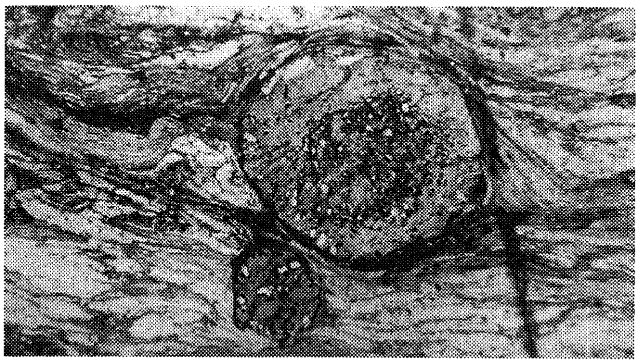

Figure 12. Texturally zoned garnet with inclusion-rich core and relatively inclusion-free rim. Note that the inclusions are mainly quartz which do not show any internal fabric. In the rim very fine graphite needles aligned parallel to the grain boundary are present. The garnet occurs in a highly mylonitized mica schist. Plane polarized light.

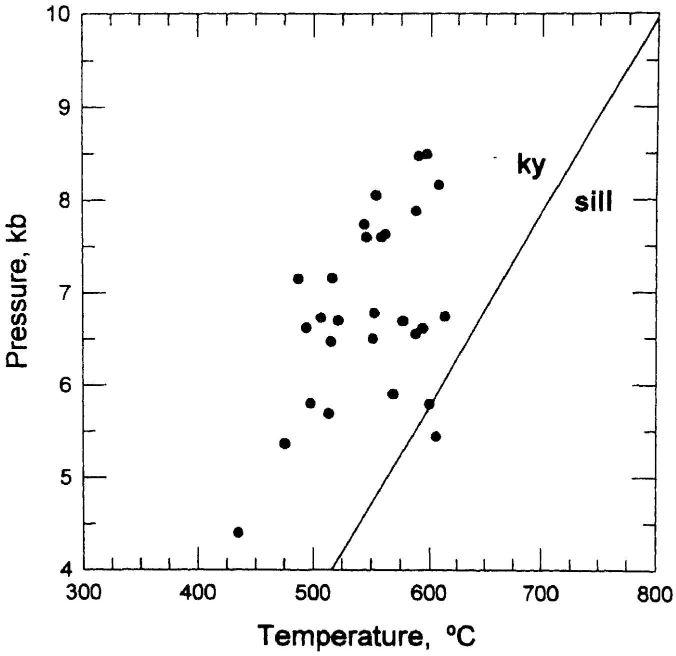

Figure 13. Pressure-temperature diagram showing the results of geothermo barometric estimates obtained through simultaneous solutions of garnet-biotite geothermometer and garnet-muscovite-biotite-plagioclase geobarometer. The kyanite (ky)-sillimanite (sill) phase diagram is after Holdaway and Mukhopadhyay (1993).

deformation episode but eventually outlasts it, then the garnet may become texturally zoned. Further, overgrowth on a garnet porphyroblast during a second metamorphic event should lead to compositional discontinuity across the interface (e.g., Rumble and Finnerty 1974). The compositional profiles determined on several texturally zoned garnet porphyroblasts from this area do not show any such discontinuity.

Chlorite and sometimes biotite are the only minerals that have crystallized syn-kinematically with reference to the ductile shearing. Chlorite porphyroblasts often overgrow and incorporate S_m where S_i is continuous with $S_e(= S_m)$. In some cases, both S_i and $S_e(= S_m)$ are crenulated and the chlorite porphyroblasts are strongly deformed. Within some chlorite grains S_i represents an early mylonitic foliation which has been overprinted and obliterated by a later mylonitic foliation in the matrix. These microstructural relations suggest that a very low-grade metamorphism, locally reaching up to biotite-grade, accompanied the ductile shearing.

In summary, microstructural relations suggest metamorphism in two phases in the Jutogh Group. The first metamorphic phase, represented by the mineral assemblage garnet + biotite ± staurolite ± kyanite/sillimanite, is pre-ductile shearing in age. Since the ductile shearing has been related to the formation of the MCT by many workers (e.g., Pecher 1977), this progressive medium-grade metamorphism is also pre-MCT. The MCT related metamorphism was of very low grade (chlorite/biotite zone).

Twenty eight samples were chosen for microprobe analyses on coexisting mineral phases. The chosen samples had the appropriate equilibrium assemblages for simultaneous solution of garnet-biotite geothermometer and garnet-biotite-muscovite-plagioclase geobarometer. We calculated rim-to-rim P and T using all the calibrations available to date but the P-T data presented here were calculated using Hodges and Crowley (1985) calibration for pressure, Hodges and McKenna (1987) for temperature with Berman (1990), Hoisch (1991) and Chatterjee and Flux (1986) solution models for garnet, biotite and muscovite respectively.

The calculated P-T are plotted in figure 13 which shows that the estimated temperature and pressure fall within the range of about 430–600°C and 4.5–8.5 kbar respectively. Within the limits of the uncertainties the range in P-T accords well with the mineral assemblages present in the area. Figure 13 also shows that, although there is an approximately positive correlation between the estimated pressures and temperatures, the data points show quite a large scatter and do not trace a well-defined P-T path. The scatter of data points is not a manifestation of estimated uncertainties. A plot of estimated P and T on the map shows that the variation in estimated P and T in space is rather chaotic. There is no definitive correlation between P and T and structural distance from the Jutogh thrust; neither do the estimated temperatures smoothly increase upsection nor does the variation in estimated pressure with structural distance define a normal lithostatic gradient (cf. Hubbard 1989). This is most surprising because, as mentioned earlier, the metamorphic grade increases from the Jutogh thrust towards higher topographic and structural levels showing the so-called inverted metamorphism. We interpret the chaotic variation in

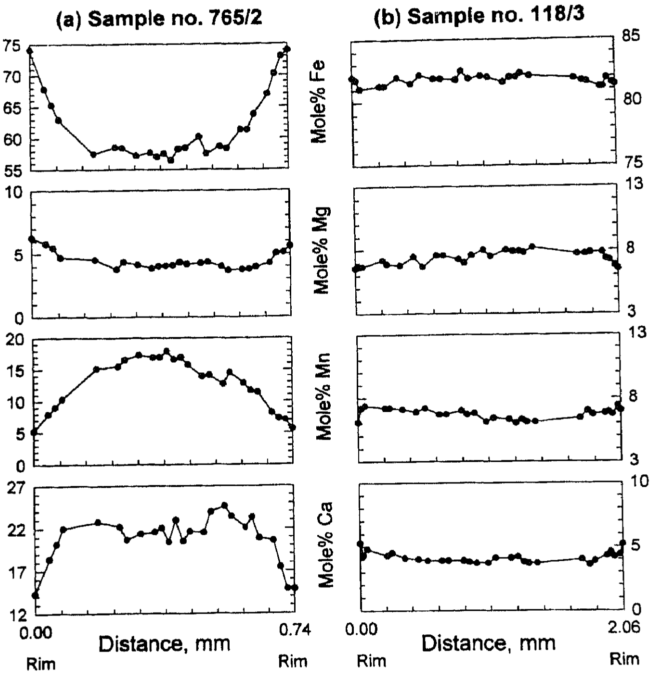

Figure 14. Contrasting zoning patterns as shown by representative compositional profiles of two garnet porphyroblasts. (a) Growth zoning. (b) Flat compositional profiles.

P and T in space to be due to stacking of thin thrust sheets which have been observed in scales ranging from outcrop to map. With this structural pattern it is not possible to decide which sample is located at a higher structural level than the other. This interpretation is also consistent with our conclusion that the main phase of metamorphism is pre-ductile shearing.

We have also determined fifty rim-core-rim chemical profiles on twentynine garnets from nineteen thin sections; most of the garnets were step scanned along two perpendicular directions. The composition profiles of Fe, Mn and Ca show wide variation in both shape and composition gradient. One of the interesting aspects is that some of the garnets show strong compositional zoning but others show flat patterns, that is, they are compositionally homogeneous (figure 14). These two types are not spatially separable and in some cases two garnets in the same thin section show these contrasting zoning patterns. In the zoned garnets, the most common Mn and/or Ca zoning profile is bell-shaped (concentrations decreasing from core to rim) with compensating bowl-shaped (concentrations increasing from core to rim) Fe and/or Mg profiles (figure 14a). This type of zoning pattern is called growth zoning (or normal zoning) and forms during growth of the garnet in pelitic rocks at low to medium-grade (up to kyanite/sillimanite grade) metamorphism with T_{max} less than about 600°–650°C (cf. Tracy 1982; Chakraborty and Ganguly 1991). Therefore, the zoned garnets of this area are compatible with the mineral assemblages as well as geothermometric estimates. The flat composition profiles in garnet are characteristic of high-grade metamorphic event at or above the 'second sillimanite' grade with T_{max} greater than about 650°C. This is because at elevated temperatures the volume diffusion becomes important and the garnets with growth zoning formed at lower grade are homogenized (e.g., Tracy 1982; Spear 1988; Chakraborty and Ganguly 1991). Implicit in this interpretation is the assumption that the garnets with flat composition profiles were previously growth zoned. *If this assumption is valid* in this area, then the garnets with flat composition profiles (figure 13b) may suggest a relict high-grade metamorphism, the evidence for which has not survived in mineral assemblages, texture or in rim-to-rim geothermobarometric estimates due to later metamorphism and intense ductile shearing.

5. Conclusions

Detailed analyses of structures from the scale of thin section to the scale of the map show that the Jutogh Group of rocks around the Chur peak may be considered to represent about 5-6 km thick ductile shear zone. This is in accordance with the present day notion of the MCT being a several-km thick ductile shear zone, the so-called Main Central Thrust Zone (MCTZ). Within this zone, however, we have recognized two generations of pre-ductile shearing coaxial folds which have been extensively modified and in parts totally obliterated during ductile shearing. In addition, several sets of folds and mylonitic foliation have formed during ductile shearing. The structure in largest scale can be best described in terms of stacked up thin thrust slices.

Microstructural relations and the mineral assemblages suggest that the low- to medium-grade regional metamorphism (reaching up to kyanite/sillimanite zones) is pre-kinematic with reference to the ductile shearing. Geothermobarometric estimates and growth zoned garnets are compatible with this metamorphism. A very low-grade greenschist (chlorite/biotite zones) facies metamorphism accompanied the ductile shearing event.

6. Comparison of structure and metamorphism between Simla klippe and Chur area

Naha and Ray (1971, 1972) and Ray and Naha (1971) showed that the rocks of the Jutogh Group in the Simla Klippe (figure 15a) have been involved in folding of three generations (F_1–F_3) the second (F_2) of which is absent in the Chail Formation. The F_1 folds are isoclinal on gently plunging E-W axes where least reoriented, and are generally recumbent/reclined (figure 15b). The axial planes of the F_1 folds have

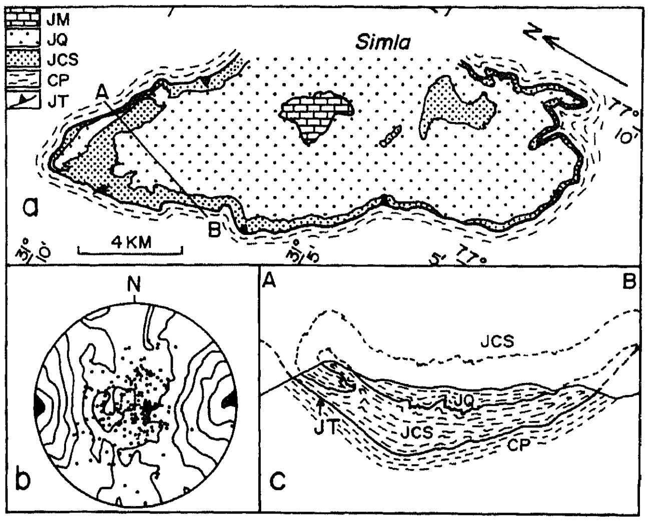

Figure 15. Geology and structure in the Simla klippe (after Naha and Ray 1971, 1972). (**a**) Geological map. **JM**: Jutogh marble; **JQ**: Jutogh quartzite; **JCS**: Jutogh carbonaceous schist; **CP**: Chail phyllite; **JT**: Jutogh thrust. JM is equivalent of UCS and JCS is equivalent to LCS (see figure 2). (**b**) Synoptic stereogram showing orientation of axial planes of isoclinal folds of the first generation (**dots**: poles to axial planes) and early linear structures (2096 readings, **contours**: 0.05-0.5-1-2.5-5-7.5% per 1% area). (**c**) Cross-section along **A-B** (figure 15a) showing refolded isoclinal fold in large scale.

been refolded coaxially by the folds of the second generation (F_2) into open upright antiforms and synforms which are overturned and isoclinal in the north resulting in fold involution (figure 15c). A set of upright, conjugate and chevron folds (F_3) with NNW to N strike of axial planes have overprinted the F_1–F_2 folds. The most pervasive planar structure is the axial planar schistosity of the first generation. In the largest scale, the structure of the Jutogh rocks is an EW-trending, recumbent syncline; the remnants of the overturned limb are preserved in the peaks of Jutogh, Taradevi and Prospect Hill. They also presented a large body of evidence to prove that the contact between the Jutogh Group and Chail Formation is indeed a thrust, the Jutogh thrust (Naha and Ray 1971). Naha and Ray (1970) also showed that the main phase of regional metamorphism, reaching up to amphibolite facies (staurolite zone) condition, is late- to post-tectonic with the first deformation but pre-tectonic with the second deformation. The second greenschist-facies metamorphism started late in the second deformation, with metamorphism outlasting the deformation.

As mentioned earlier, a much thicker section is preserved around the Chur peak than in the Simla klippe. This is because the highest altitudes near Simla barely exceed 2000 m whereas the altitude of the Chur peak is 3647 m. In the Simla area the entire Jutogh mica schist and the Chur granite have been eroded away and only a few isolated exposures of UCS are preserved around Jutogh and Taradevi peaks (compare figure 2 with figure 15a). A comparison between the work of Naha and Ray with that of our findings and interpretations brings out the following:

(1) In the Simla area Naha and Ray interpret the structure in terms of three phases of folding and a thrusting event synchronous with the second deformation episode. However, we recognize an important ductile shearing event subsequent to the early deformation episodes (F_1–F_2).

(2) The map pattern of the carbonaceous schist in the northwestern part of the Simla klippe (JCS, left hand side of figure 15a) is remarkably similar to the map pattern of the UCS around Rajgarh in the Chur area (figure 6). The cross section drawn by Naha and Ray (figure 14c) as well as our cross section through the Rajgarh area (figure 7) show refolded isoclinal recumbent folds. However, Naha and Ray concluded that the large-scale folding is on stratification only and, therefore, represents folds of earliest generation. In contrast, we show that the large-scale fold in the area around Rajgarh is on mylonitic foliation (which is parallel to the formational boundaries) and, therefore, of later generation related to ductile shearing; the large-scale folding affects only the UCS. The large-scale folds shown in figures 7 and 15(c) occur in two different but successive thrust sheets (cf. figure 9). This leads us to suggest that the so-called Main Central Thrust Zone is made up of stacked up thrust slices and in different sectors of each of these thrust sheets we should expect to get km-scale asymmetric isoclinal folds developed during ductile shearing/thrusting. The line of section of Naha and Ray is approximately N-S but our line of section is approximately E-W but both show similar structural style. This confirms our interpretation that the large-scale folds are plane but strongly non-cylindrical, possibly with sheath-like geometry. This should not be a problem even if we assume a constant orientation of tectonic transport (from NE to SW) because hinge lines of folds can be perpendicular, oblique or even parallel to the shear direction (cf. Dennis and Secor 1987, 1990).

(3) Naha and Ray (1971) listed a number of evidences to prove that the base of the Jutogh Group is indeed a thrust (Jutogh thrust). In addition to Jutogh thrust, we have recognized two new thrusts in the Chur area, viz., Chur thrust and Rajgarh thrust. In the Simla area the two topmost thrust sheets have not been preserved (compare figure 2 with 15a). We conclude that the structure in the largest scale can be best described in terms of stacked up thin thrust slices (figure 9) whereas Naha and Ray interpret the large-scale structure in terms of a huge recumbent fold.

(4) Naha and Ray conclude that the main phase of regional metamorphism is post-kinematic with reference to recumbent folding but pre-kinematic with respect to thrusting. Further, they also argue that folding, thrusting and regional metamorphism are

related to Tertiary Himalayan orogeny. In the Chur area the medium-grade metamorphism is completely pre-ductile shearing and, therefore, pre-MCT in age; it appears to be broadly synchronous with the early deformation episodes. The ductile shearing has been correlated with the Tertiary Himalayan orogeny by many workers (e.g., Hubbard and Harrison 1989) but we consider that the age of regional medium-grade metamorphism (and early deformations i.e., F_1–F_2) in the Chur area is uncertain at present and could even be pre-Himalayan.

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