DEFORMATION STYLE IN THE MUNSIARI THRUST DAMAGE ZONE (MCT-II) ALONG MADLAKIYA-MUNSIARI SECTION, KUMAUN HIMALAYA

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree

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By

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CERTIFICATE

I hereby solemnly declare the work presented in this dissertation, entitled ***"STRUCTURAL ANALYSIS ALONG THE SOUTHERN BOUNDARY OF MAIN CENTRAL THRUST"*** *in partial fulfilment of the requirements for the award of the degree of* ***'Integrated Master of Technology'*** *in* ***Geological Technology*** *submitted to the* ***Department of Earth Sciences, Indian Institute of Technology Roorkee,*** *is an authentic record of my own work carried out during the period August 2011 to June 2012, under the supervision of* ***Dr. D.C. Srivastava,*** *Professor, Department of Earth Sciences, I.I.T. Roorkee.*

The matter embodied in this dissertation has not been submitted by me for the award of any other degree of this or any other institute.

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Place: Roorkee

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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Abstract

The southern boundary of the Main Central Thrust zone, identified in the form of Munsiyari Thrust in the north-eastern Kumaon Himalaya, brings Higher Himalayan Crystallines (HHC) over the Tejam Sedimentaries of the Lesser Himalayas (LHS). Detailed mapping and structural analysis shows that the hanging wall and footwall rocks across the Munsiyari Thrust has been deformed by same deformation plan with two phases of folding and a later extensional deformation. Geometry of the Munsiyari Thrust shows a characteristic pattern which has been explained using fold or imbricate model. We find the folding of the Munsiyari Thrust as a more plausible explanation for the identified geometry of the thrust, with the thrust being folded and later modified by early and late folding events along the thrust.

Acknowledgements

I express my profound gratitude to Dr. D.C Srivastava, who gave me this opportunity to work under him, guiding me throughout the project with his useful and valuable insight into the subject. I am deeply indebted to him for expanding my knowledge about the subject and most importantly motivating me to pursue research as a career option in the future.

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Preface

"There is a pleasure in the pathless woods,
There is a rapture on the lonely shore,
There is society, where none intrudes,
By the deep sea, and music in its roar:
I love not man the less, but Nature more."

--Lord Byron

When the area of study in the Kumaon Himalayas was first suggested by our guide Prof. D .C. Srivastava, I had no inkling of what to expect from the field work. Having previously worked in the Garhwal Himalayas., nothing could have prepared me for the long arduous journey that lay ahead. Travelling for two straight days , a snow storm greeted us at arrival in Munsiyari during our first field trip in February. With all the outcrops under a thick snow cover it was difficult to forge ahead and yet our perseverance paid off when the weather improved and we were greeted with beautiful deformation structures, the like of which I had never seen before. The difficult terrain notwithstanding the folds and shear zones were a reward in themselves. The sight of the snow-clad mighty Himalayas which always loomed above us, always managed to uplift our spirits whenever things were going downhill. The tranquility and the idyllic setting of the Munsiyari town coupled with the Main Central Thrust, is like a mecca for budding geologists and I consider myself lucky to have been part of such a project which has been so educating as well as providing me with fond memories that I shall cherish forever

List of Figures and Tables

Chapter 1

Introduction

1. Introduction

The Himalayan mountain range was created by the collision of India and Asia, which began during the Late Cretaceous. The range is characterized by the presence of five laterally continuous large scale structures that separate similar lithologies along its entire ~2400 km length (Le Fort, 1996; Harrison et al., 1999; Upreti, 1999; Hodges, 2000). In the north, the Indus-Tsangpo suture zone separates Asian metasedimentary and igneous rocks from Indian shelf sediments (Tethys Formation) (Beck et al., 1996; Yin et al., 1999). The South Tibetan Detachment System separates the Tethys Formation from a unit of kyanite- to sillimanite-grade gneisses termed the Greater Himalayan Crystallines (Burg et al., 1984; Burchfi el et al., 1992). The Main Central Thrust (MCT) separates the Greater Himalayan Crystallines from Middle Proterozoic phyllites, metaquartzites, and mylonitic augen gneisses of the Lesser Himalayan Formations (Arita, 1983; Pêcher, 1989; Catlos et al., 2001; Martin et al., 2005). At most locations, rocks within the hanging wall of the Main Central Thrust show inverted metamorphism, an increase in metamorphic grade toward structurally shallower levels (Arita, 1983; Pêcher, 1989; Catlos et al., 2001).

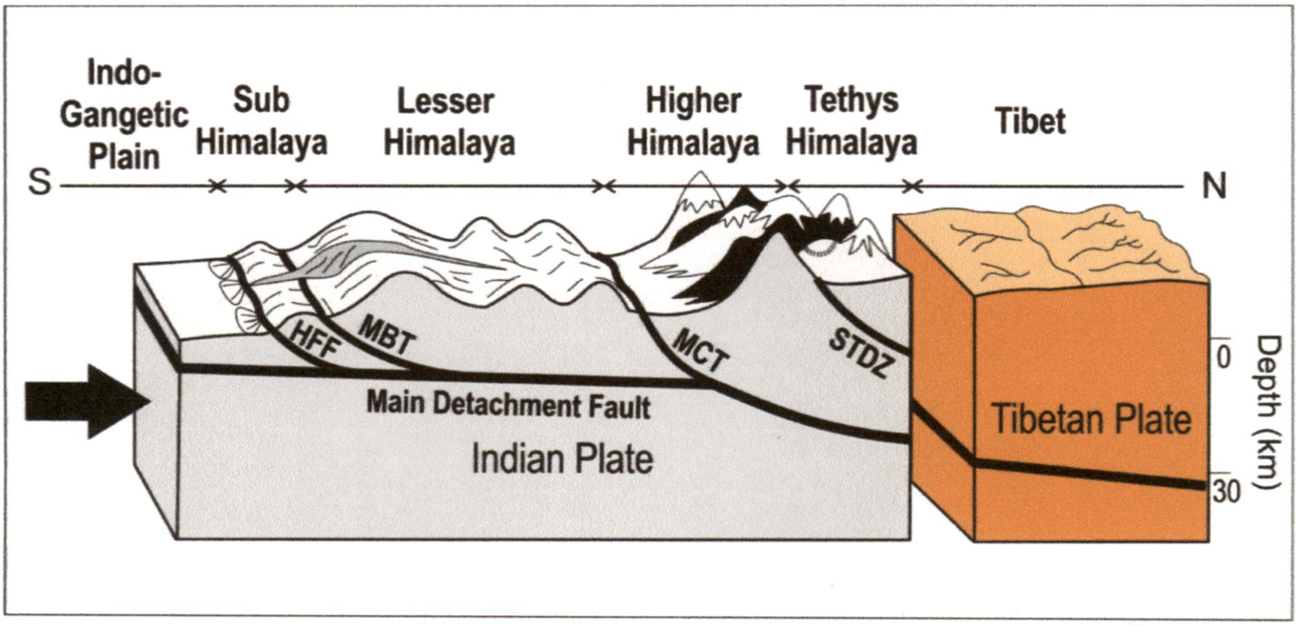

Fig. 1. Structural divisions of the Himalayas (Jackson and Bilham, 1994)

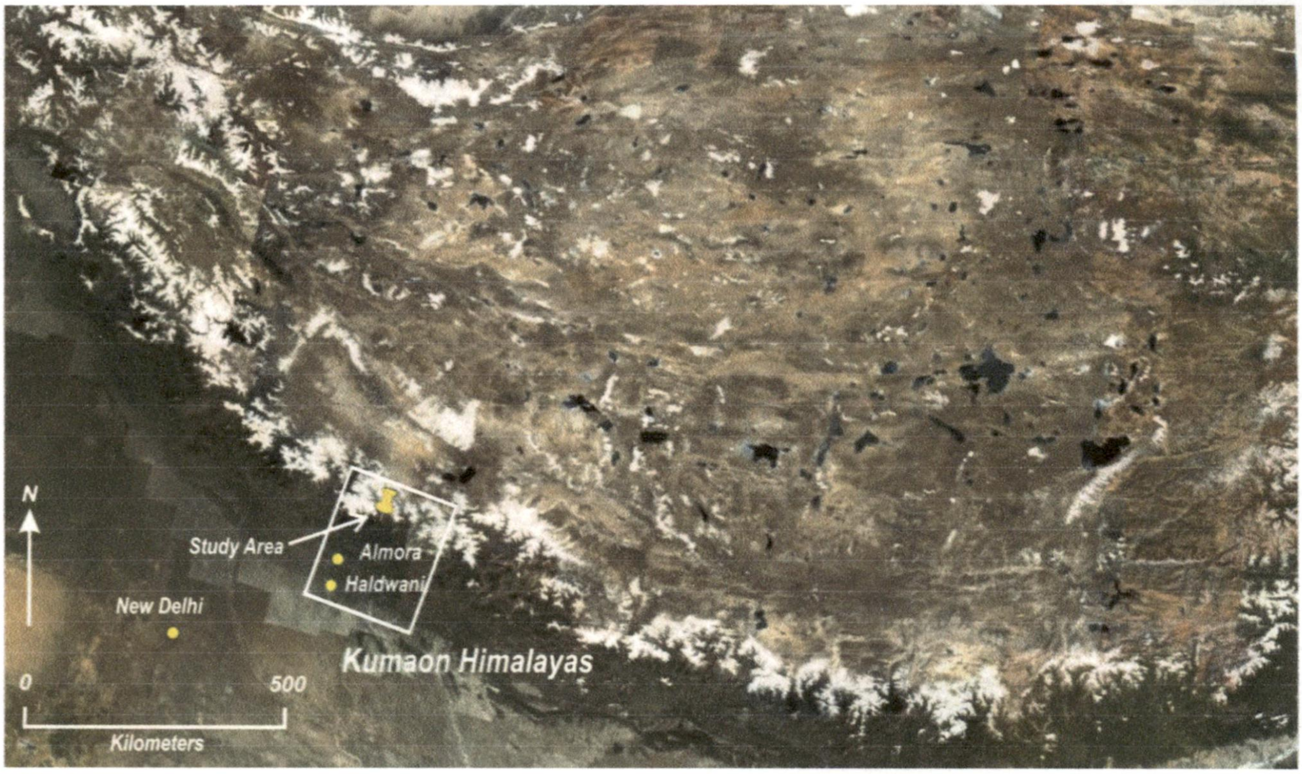

Fig.2: Study area in the Kumaon Himalayas

The MCT is a moderately north-dipping shear zone formed as a result of the southward emplacement of a part of the deeply rooted crust—that now constitutes the Central Crystalline Zone of the Higher Himalaya— over the less-metamorphosed sedimentary rocks of the Lesser Himalaya. The south-directed ductile shearing has affected rocks exposed over a 7– 10-km-wide tract. Rocks of both the Higher Himalayan Crystallines (hanging wall) and the sedimentary rocks of the Lesser Himalaya (footwall) have been affected by strong ductile deformation due to thrusting along the MCT. High-strain zones exist within both the crystalline and sedimentary rocks. The thrust zone therefore constitutes an excellent example of bidirectional strain gradient and the vicinity of the thrust plane represents the zone of highest concentration of ductile shear strain in the region (Bhattacharya, 1987, 1990, 1992, 1999; Bhattacharya and Siawal, 1985).

The sedimentary belt along the MCT is commonly represented by a thick sequence of recrystallized rocks, mainly quartzites. In some sections, however, a recrystallized carbonate sequence, commonly represented by marble, is seen juxtaposed against the MCT. Most of the ductile shear strain induced by emplacement along the MCT has been accommodated in a thick layer of mylonite that developed in rocks of both the crystalline and sedimentary units. The mylonites constitute the most characteristic rocks of the shear zone.

The Main Central Thrust zone was defined by Heim & Gansser (1939) and Gansser (1964) as the thrust fault that places high-grade metamorphic rocks of the Greater Himalayan Sequence southward over low-grade rocks of the Lesser Himalaya. Previous attempts to map the Main Central Thrust have used indirect methods such as:

Criteria for mapping of the Main Central Thrust by different workers	**Reference**
A lithological contrast following a distinctive quartzite unit beneath an orthogneiss unit	Gansser 1983; Daniel et al. 2003
Following the kyanite isograd	Bordet, 1961; LeFort, 1975; Colchen et al., 1986
Differences in U–Pb detrital zircon ages	Parrish & Hodge,s 1996; Ahmad et al., 2000; DeCelles et al., 2000
Differences in Nd isotope compositions	Robinson et al., 2001; Martin et al., 2005; Richards et al., 2005, 2006
Location of young U– Pb and Th–Pb monazite ages	Harrison et al., 1997; Catlos et al., 2001, 2002

Table 1: Basis of definition of Main Central Thrust (After Searle, 2008)

Scope of the present work:

i) Lack of knowledge on the structural style in the Main Central Thrust damage zone

ii) Identification of Pre-Himalayan deformation structures

We have based our definition of the Munsiyari Thrust on the original model proposed by Heim and Ganser (1939) which relies on difference in lithology. Even though a thrust is defined on the basis of structural characteristics, the damage zone due to intense shearing brought about by the Munsiyari Thrust extends both into the gneisses of the Higher Himalayan Crystallines and the recrystallized carbonates of the Lesser Himalayan Sedimentaries. Thus the demarcation based on mesoscopic structures observed in the field is at best subjective and not entirely accurate. Previous work in this region has established the phases of deformation and mapping of the Munsiyari Thrust has been carried on a large scale (Patel and Kumar, 2009; Paul, 1998), but knowledge about the structure of the Munsiyari Thrust as a whole is lacking. While previous workers have identified some of the early deformation structures in this region as Pre-Himalayan, in this thesis, we verify this claim based on our structural data and field observations. We also attempt to prepare a detailed structural map of the MCT zone around Munsiyari and present two hypotheses which provide alternate explanations for the structures and data obtained from the field observations.

Chapter 2

Geological Setting

2. Geological Setting

The Higher Himalayan Crystallines along the Goriganga valley in the Kumaon Himalaya is exposed between Munsiyari and Milam of Pithoragarh district, Uttarakhand. The base of it is bounded by MunsiyariThrust (MT)/Main Central Thrust (MCT) (Heim and Gansser, 1939; Gansser, 1964) and thetop by the Phanerozoic Tethyan Sedimentary Zone (TSZ) (Thakur and Choudhury, 1983). Itcomprises of stacked thrust sheets of greenschist to amphibolite grade of metamorphosed rocksgenerally considered to represent leading northeastern portion of the Indian basement.Southwestward thrusting along the MCT and subsequently along the Main Boundary Thrust(MBT) during the continental collision between the Indian and the Eurasian plates emplacedthese rocks over the Lesser Himalayan meta-sedimentary zone. The Vaikrita Thrust (VT) (Valdiya,1980) evolved as a splay of the HHC along which the Vaikrita Group of rocks thrust over the Munsiyari Formation. The tectono-stratigraphic succession from south to north is shown in the map and described below.

The general lithology could be divided into two major divisions: The Lesser Himalayan Sedimentaries and the Greater Himalayan Crystallines. The various stratigraphic divisions of each of them are as follows:

2.1. The Lesser Himalayan Sedimentaries

The Lesser Himalayan Sedimentaries in this region have been divided into four major units based on their lithology, namely:

i) Argillaceous Unit

ii) Calcareous Unit

iii) Phyllitic Unit

iv) Arenaceous Unit

In the course of the traverse from Kwiti to Munsiyari we have encountered primarily the calcareous unit and arenaceous unit of the Lesser Himalayan Sedimentaries. The calcareous unit includes the typical Calc Zone of Tejam Group (Heim and Gansser, 1939; Gansser, 1964), exposed north of Tejam and constituting of predominantly carbonate rocks overlying the oldest argillaceous Hatsila unit (Paul, 1998). The carbonate rocks of this formation show a gradual increase of metamorphic effects from south (limestone, slate) to the north (marble, schistose marble showing metamorphic differentiation of secondary silica), due to proximity to the Main Central Thrust.

The arenaceous unit is the youngest unit of the sedimentary belt in the Kumaon Himalayas. This formation consists of massive bedded quartzite of white to fawn color. At places occurrence of interbedded chlorite phyllite, amphibolite and basic rocks is common. Lineation of dark colored minerals, mainly biotite, is seen in the upper horizons of this unit. At places due to shearing a phyllonitic texture has been developed which shows distinct green color on the outcrop scale due to development of chlorite. The chlorite phyllonite has been found to be persistent for considerable distance, showing thickening and thinning within 3 to 5 metres. Secondary silica lenses, mostly relict of the original quartzite are commonly found in the phyllonite.

The rocks in Deoban Formation predominantly consist of calc-silicate rocks with alternating layers of silicates within the calcareous rocks. These rocks provide evidence of the deformation pattern in the Tejam Group as the resistant silicate part retains the deformation signature of overturned folds while the less resistant calcareous parts have weathered away. Thus there are many overturned folds that could be seen in this formation which gives us an indication of the large scale structure in the region.

In the Lesser Himalayan Sedimentaries, limestone predominates for major part of the traverse in this area with a few bands of quartzite and phyllonite zones in between. The phyllonite zones are typically formed due to shearing of the rocks in the Munsiyari Thrust (MCT 1). There are small scale evidences of shearing visible with S-C fabrics indicating top to the south direction. The rocks in these shear zones have become phyllonitised and in some cases present a talcose appearance. The phyllitic cleavage is composed mainly of the alignment of muscovite and sericite minerals.

2.2. The Higher Himalayan Crystallines

The rocks in Higher Himalayan Crystallines show distinct contrast with the Lesser Himalayan Sedimentaries. The area of study in the Kumaon Himalayas has been demarcated as the southern extension of the Greater Himalayan crystallines and thus named as the Lower Central Crystallines. The Lower Central Crystallines consist of the belt of low to medium grade metamorphic rocks of the Munsiyari and Rungling Formations whereas the northern division called the Upper Central Crystallines consists of the medium to high grade metamorphic rocks of the Vaikrita Formation. The scope of the present study is limited only to the Munsiyari formation of the Lower Central Crystallines. The Munsiyari formation consists predominantly of greenschist to lower almandine metamorphic facies rocks, namely augen gneiss and schist. It has been divided into 4 major members (Paul,1998) as follows:

i). Phalyati Member

The Phalyati Member is made up of garnet bearing chlorite schist, garnet-bearing sericite schist and sericite-chlorite schist along the Munsiyari Thrust. The garnet crystals are well developed and can range in size from 5-7 mm. quartz veins commonly occur along the foliation planes. It has been named after the village of Phalayti in the Gori River valley.

ii). Baram Member

The Baram Member is primarily composed of well-developed granitic gneiss, characterized by large pinkish quartz phenocrysts (amethyst). Evidence of intrusion is borne by the presence of amphibolite xenoliths in this member. At some places in the Gori Valley the granitic gneisses are highly mylonitised and interbedded with chlorite schist. It is named after the Baram village and forms a transitional contact with the northern Chhiplakot member.

iii) Chhiplakot Member

The Chhiplakot Member consists of low grade metamorphic rocks comprising of augen gneiss, biotite sericite schist, quartzite, quartz sericite schist, phyllonite and foliated amphibolite. It extends from Munsiyari to Polu valley in the Gori Ganga valley.

iv) Khet Member

The Khet Member consists of elongated porphyroblastic gneiss with some of the feldspar porphyroclasts elongated upto 15cm aligned along the foliation plane. There is considerable grain size variation with schist and quartzite intercalated at places with some amphibolite and hornblende schist also present. It is named after the Khet village in the Darma valley.

The prominent lithology type found in this division is that of mylonitised augen gneisses with well-developed gneissic foliation. The feldspar porphyroclasts show deformation structures in the form of sigma and delta porphyroclast thus enabling us to determine the sense of movement in the MCT.

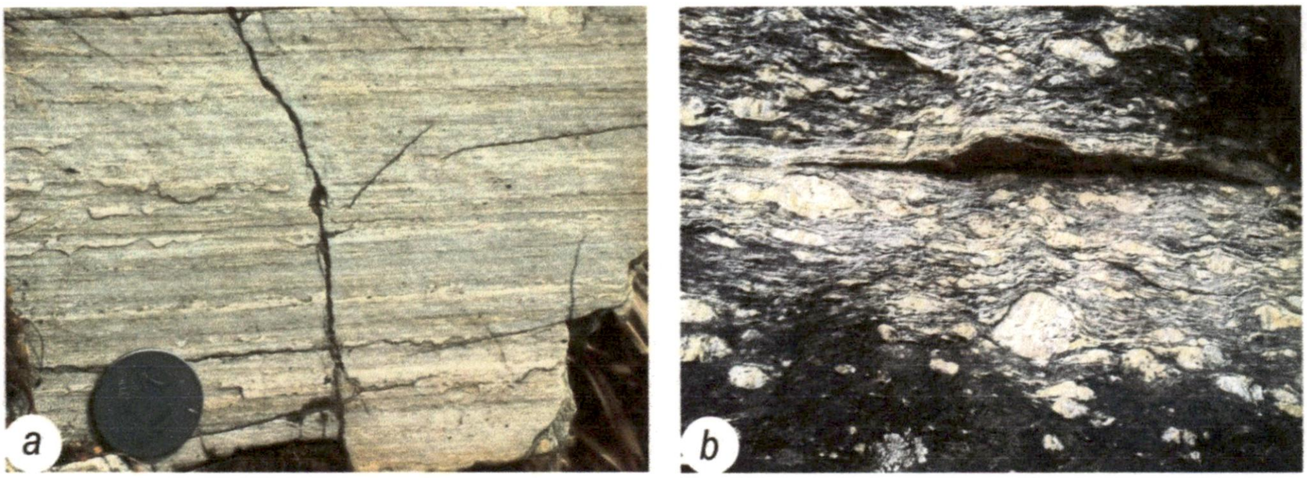

Fig. 3.(a). Laminated Limestone (Calcareous Unit, Lesser Himalayan Sedimentaries) (b). Augen Gneiss, (Munsiyari Formation, Higher Himalayan Crystallines)

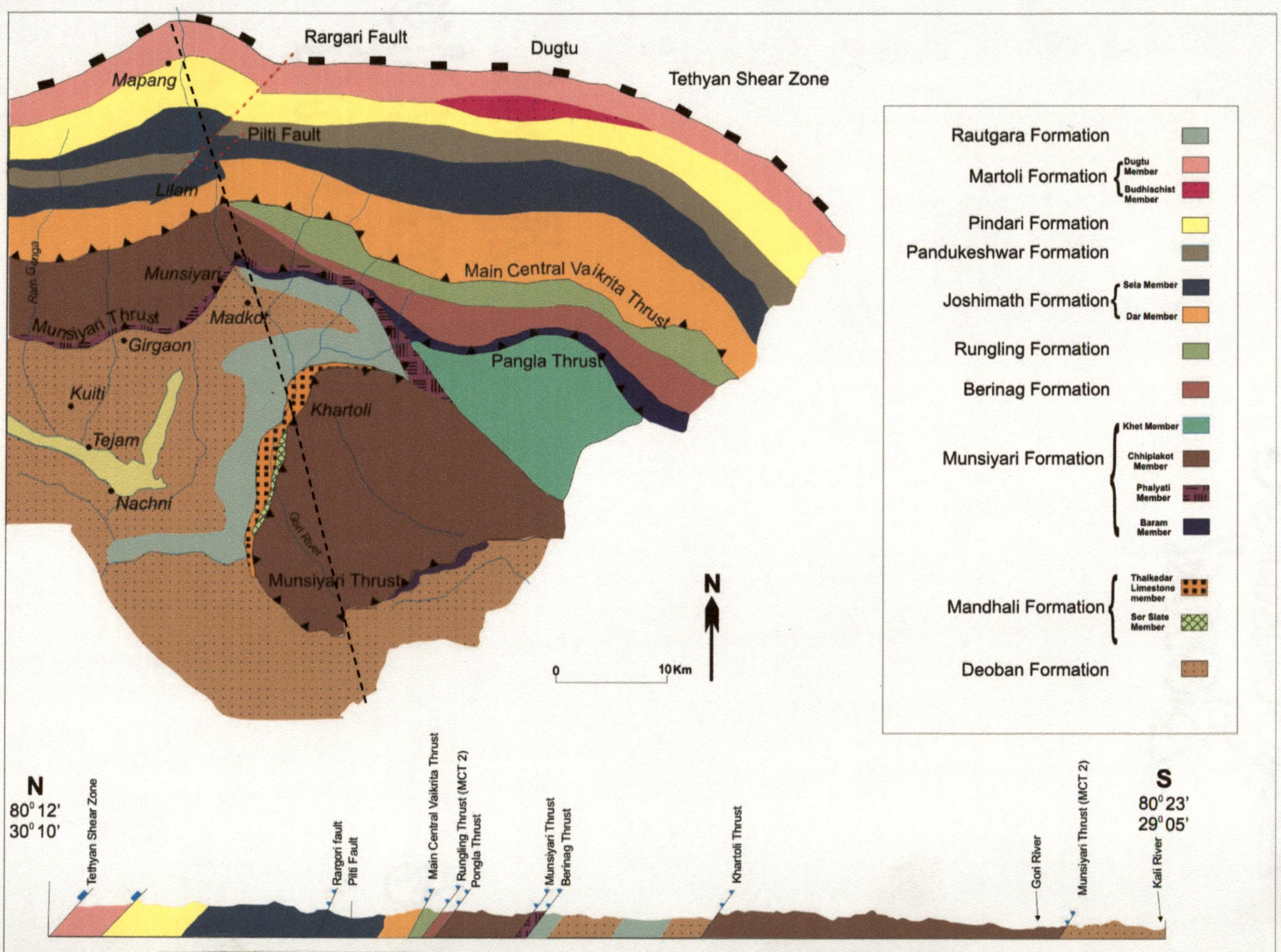

Fig 4: Geological map of the region and cross section along the line. (after Paul 1998)

Chapter 3

Geological and Structural Mapping

3. Geological and Structural Mapping

The study area included the road traverse from the village of Kwiti in the South Eastern Kumaon Himalayas, all the way to the town of Munsiyari, intersecting the Munsiyari Thrust or MCT-I at many points. The structural complications of the thrust become evident when the traverse takes repeated turns going downhill on the mountains. The entire region could be divided into two traverses with distinct deformation patterns, namely: 1) Traverse from Kwiti to Madlakiya 2) Traverse from Madlakiya to Munsiyari. Kwiti, lying in the southern part of the study area, is in the Deoban Sedimentary formation while Munsiyari is situated in the Munsiyari Gneissic formation. The first contact between the two which represents the Munsiyari Thrust or MCT-I is encountered in the village of Madlakiya. The distinctly different deformation pattern between the two formations necessitated the division into the two subareas.

In the traverse from Madlakiya to Girgaon two regions of considerable structural complexity are encountered which have been demarcated as subarea A and subarea B. They have been shown as separate maps with map A covering the region from Girgaon to Ratapani while Map B shows the region from Kalamuni pass to 5 Kms before Munsiyari.

3.1. Madlakiya-Girgaon Subarea (A)

This section of the traverse comprises of predominantly the domain of Lesser Himalayan Sedimentaries with the Munsiyari Thrust and associated gneisses encountered sporadically after the village of Madlakiya, 15 Km from Kwiti towards Munsiyari. The major lithology in this area is of the Calcareous Unit of Lesser Himalayan Sedimentaries comprising of limestone and dolomite. The rocks preserve evidence of deformation in the form of tight isoclinal folds, axial planar cleavage and intersection lineation. The general trend of the lithology in this region is of NW dipping beds with NE plunging intersection lineation. A large scale overturned fold is observed in the map with N dipping axial plane. The rocks exhibit thick bedding feature with prominent laminations. At Madlakiya, the first normal contact of the Munsiyari Thrust is observed with the calcareous unit overlain by fine grain sheared augen gneiss of the Munsiyari formation. An amphibolite dyke in the sheared augen gneiss was also encountered at the Birthi

Waterfall. A few km before Girgaon the Munsiyari Thrust is seen again with phyllonites from the sedimentary unit being developed at this contact. These phyllonites are developed due to the high degree of shearing at the Munsiyari Thrust thus lending them a smooth talcose appearance. The effects of shearing are observed in the form of S-C fabric in the sedimentary unit at the outcrop scale as well as the gradual fining of and subsequent alignment of calcite crystals in the microscopic scale.

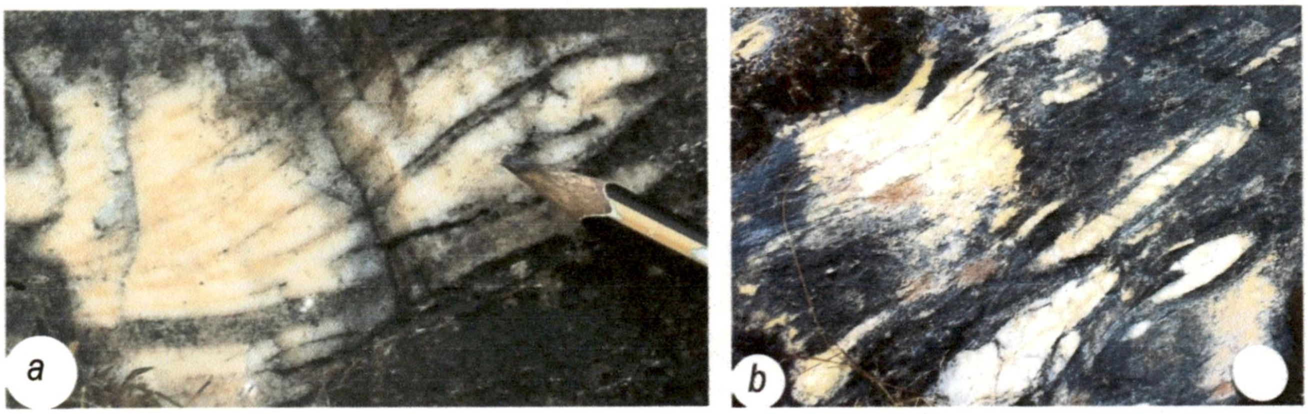

Fig. 5. Structures in Lesser Himalayan Sedimentaries. (a). Dextral Shear zone in calcareous unit (b). Rootless hinges of the isoclinal folds near Girgaon

3.1.1. Girgaon-Kalamuni traverse (Map A)

After Girgaon we again enter into the domain of the calcareous unit which continues upto some distance from the village Banik. At about 1km from Banik sheared gneisses are observed again but with some degree of migmatization present in them. Mylonitic foliation is prominent and also exposure of sheath folds with elliptical sections on the outcrops is seen.

A 2 km thick zone of phyllonites from the sedimentary unit was mapped in the road section from Banik to Ratapani which tapers towards Ratapani. As the structural features seen in this traverse cannot be suitably represented on the scale of the first map they were shown with much higher detail as the subarea Map A.

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Fig. 6. Sheath fold in augen gneiss near Banik.

From the map it can be seen that the major deformation pattern of the Munsiyari Thrust involves tight isoclinal overturned folds even in the map scale. Because of the shearing tight folds with rootless hinges belonging to an earlier deformation episode are observed in the outcrops. The structures formed in both the hanging wall and footwall are similar with both exhibiting S-C fabrics and tight folds. The later deformation episodes which have brought about large scale open kink type folds and extensional shearing in the rocks is also prominently seen in the calc silicate unit of the Lesser Himalayan Sedimentaries.

Fig. 7. Large scale open fold in calcareous unit of Lesser Himalayan Sedimentaries

Fig. 8 a-b. Style of folding in calc-silicate rock. Tight isoclinal folds near Ratapani

Fig. 9. Kink Folds in dolomite at Banik

The Kink folds with large scale extensional feature like normal fault shows the typical signature of the D_3 deformation pattern with broad open folds having two long limbs and the short limb in between. At Ratapani the last of phyllonites from the calcareous unit of Lesser Himalayan Sedimentaries are mapped.

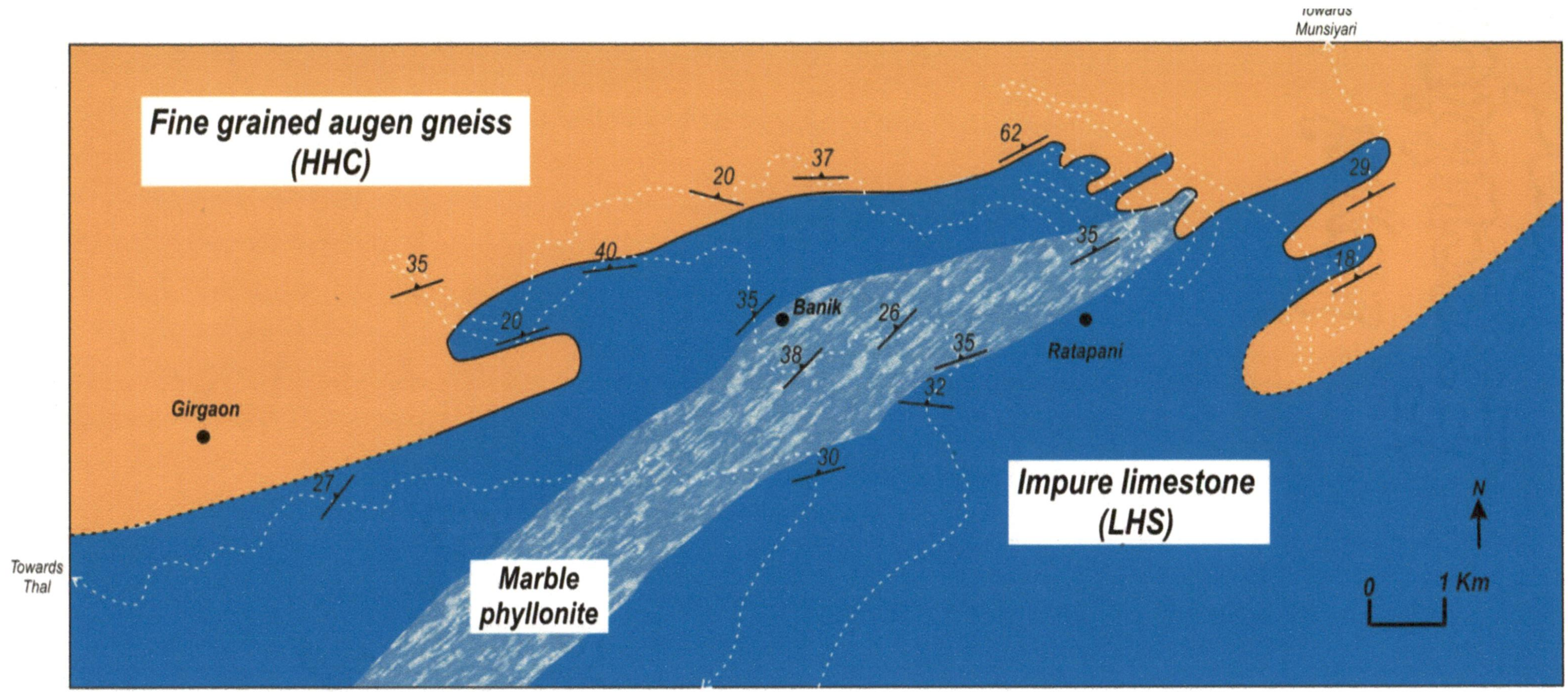
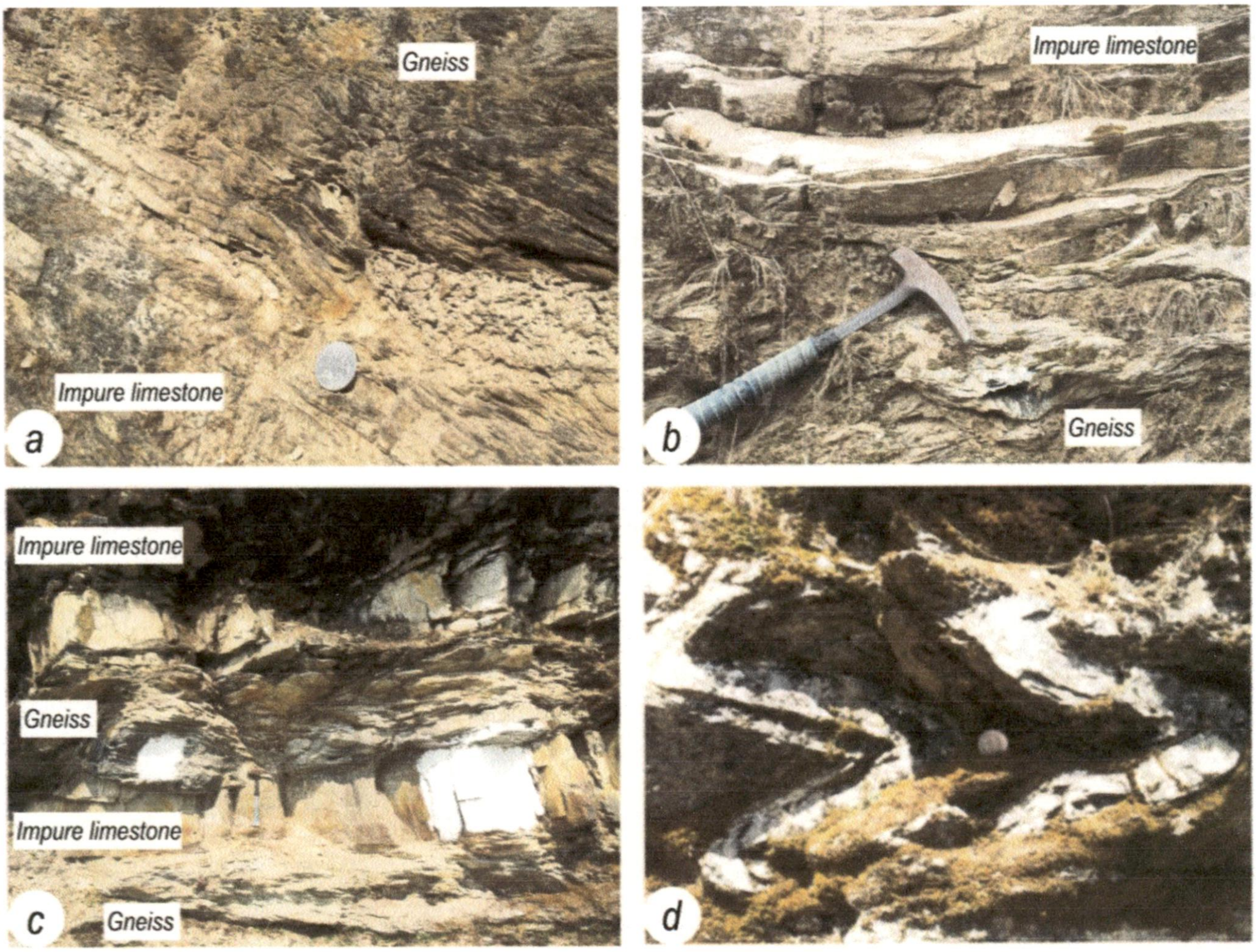


Fig. 10. Detailed map of a part of subarea A showing the intricately folded nature of the Munsiyari Thrust and phyllonite zone in the footwall rocks.

3.2 Kalamuni-Munsiyari Subarea (B)

Kalamuni pass provides a distinct contact between the calcareous unit of the Lesser Himalayan Sedimentaries and the sheared augen gneisses of the Munsiyari Formation exposed just in front of the temple at the point. Travelling towards Munsiyari, MCT is exposed sporadically in both normal as well as overturned contacts between the gneissic phyllonite of Munsiyari Formation and relatively undeformed calc silicate rocks of the Lesser Himalayan Sedimentaries. At places the imbrication of calcareous units into the gneissic phyllonites occurs showing the effect of large scale shearing. This exposure has abundant exposure of gneiss phyllonites with lenses of undeformed protolith in between. The phyllonites exhibit a schistose appearance with deformational features like S-C fabrics abundant in them. There are also exposures of kink type folds which are characteristic of later stage of deformation.



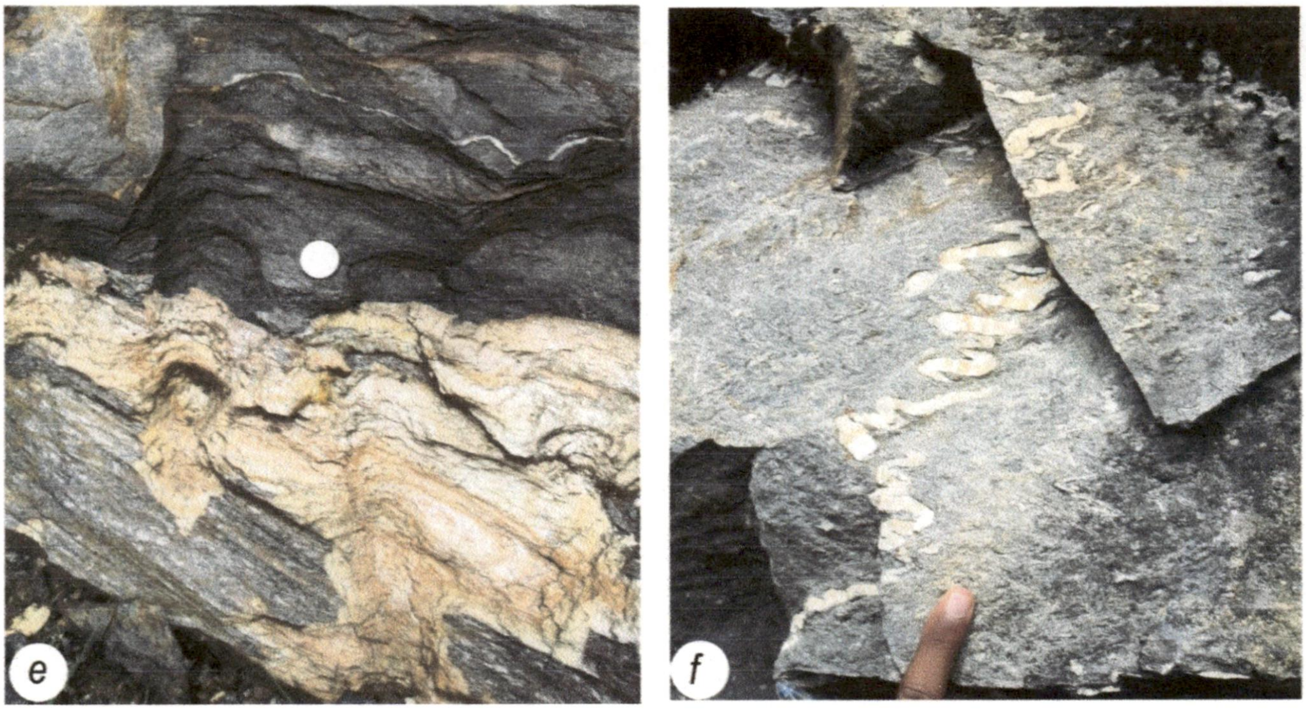


Fig. 11. (a) Normal contact of Munsiyari Thrust with gneiss representing Munsiyari Formation (HHC) and Impure limestone from the Deoban Formation (LHS) (b) Overturned Contact of Munsiyari Thrust (c) Imbrication of phyllonitised gneiss into the Lesser Himalayan Sedimentaries (d) Kink Folds in Munsiyari Formation (e) Migmatization of gneisses in Munsiyari Formation (f) Folding of quartz veins in gneiss of Munsiyari Formation

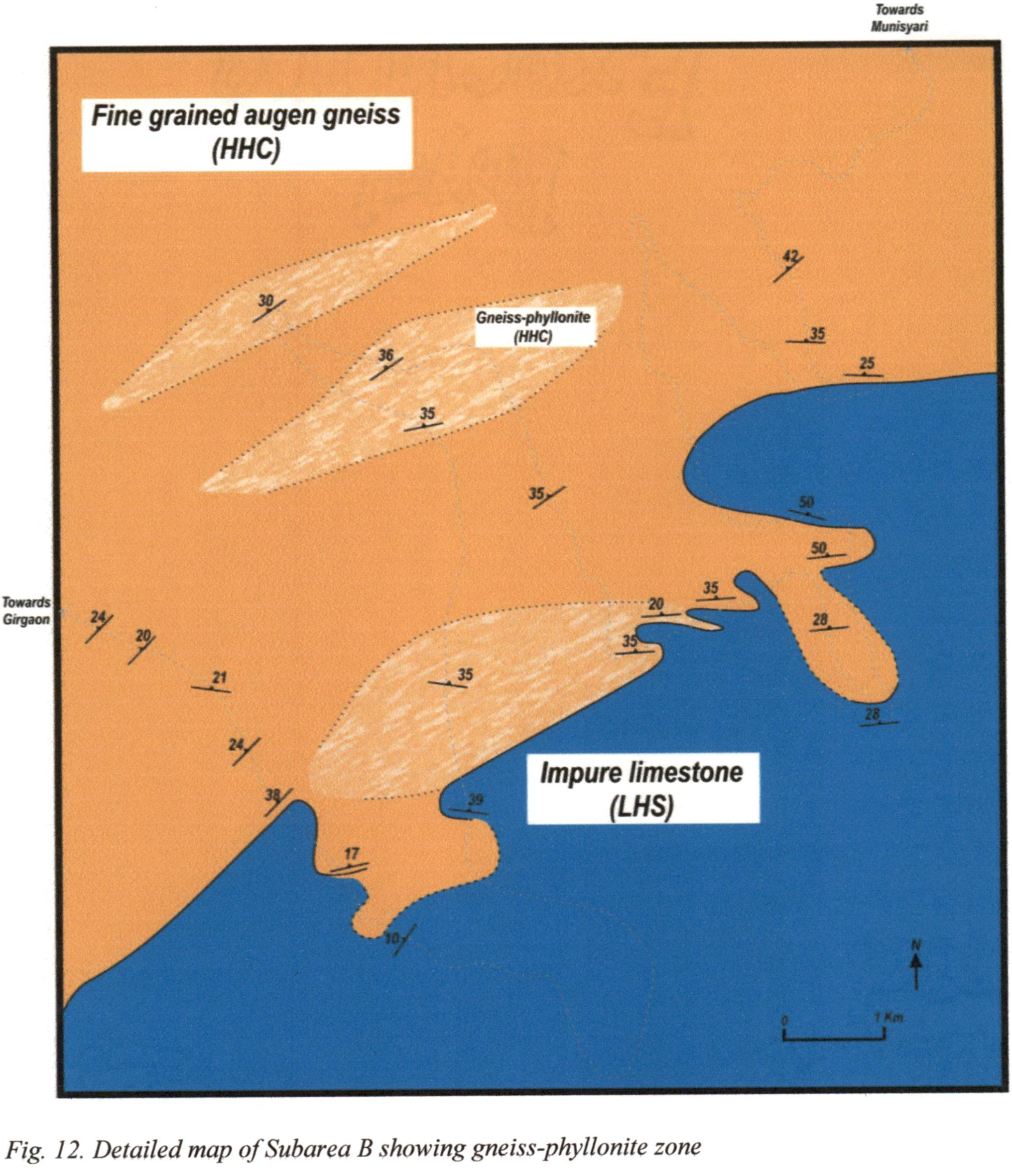


Fig. 12. Detailed map of Subarea B showing gneiss-phyllonite zone

Chapter 4

Structural Geometry of the Munsiyari Thrust

4. Structural Geometry of Munsiyari Thrust

The basic aim of the outcrop scale mapping was to obtain a better understanding of the structural complications occurring along the Main Central Thrust. Previously it has been reported that the degree of deformation increases as one moves towards the Munsiyari Thrust (Singh and Thakur, 2001) but in the present study it has been observed that there is instead of following a gradual pattern the deformation and shearing is concentrated in various pockets wherein the rocks show structures like rootless hinges and S-C fabric. The characteristic S-C fabrics were mostly found in the phyllonitic rocks where they had developed a schistose foliation due to the extreme shearing conditions. As one moves from the Lesser Himalayan Sedimentaries towards the MCT-1 or Munsiyari thrust some evidence of migmatization is seen in the form of quartz veins. The veins were mostly of the S- shaped form showing sinistral sense of shearing with the shear direction being top to the SW. There were also evidences of rotated porphyroclasts with both sigma and delta porphyroclasts from which the shear sense could be inferred as well. All of these structures were dominant in the coarse grained augen gneiss between the Kalamuni Pass and Munsiyari town wherein the Munsiyari Thrust contact was encountered several times. The augen gneisses showed definite evidence of shearing with their mylonite texture and at places of low competency they had developed a near schistose foliation with lenses of the original gneisses in between and planar alignment of the mica in the gneiss. In almost all the cases we found that the bedding was generally parallel to the foliation plane, thus the foliation data has been collected to infer about the large scale folds.

The deformation history can be broadly classified into four phases, with three being compressional and one extensional in nature. The compressional phases are classified into two categories namely: a) Early Folding which encompasses the first two compressional phases and b) Late Folding which includes the later compressional deformation.

1. Early Folding: This phase of deformation is syn-shearing i.e. developed during the formation of the Munsiyari Thrust in the Himalayas. Based on their deformation pattern we could discern two different phases of deformation which have been named as D_1 and D_2

(a) D_1 Deformation: These are the folds that represent the first phase of deformation wherein the folds occur along the bedding (S_0). The intensity of the second phase of deformation and strong metamorphic overprinting make the identification of these structures difficult but they have been identified by numerous workers in different parts of the Higher Himalayan Crystallines (HHC) in the Himalaya (Srikantia et al., 1978; Thakur, 1980; Pognante et al., 1987; Williams et al., 1988; Pognante and Lambardo, 1989; Treloaret al., 1989; Purkayastha et al., 1999; Jain and Patel, 1999; Paudel and Arita, 2000; Kumar and Patel, 2004). We refer to the folds formed by this deformation as F_{1A} folds which are tight isoclinal folds developed along the bedding. Due to the high intensity of deformation their axial planes have been oriented along the bedding and the fold hinges not preserved thus making it very difficult to recognize these structures in the field. S_1 is moderately NE-dipping, axial planar to F_1 folds and these parallel the S_0 layering. S_1 is well developed in psammitic and pelitic layers but not clearly developed in other rocks showing instead a first set of quartz veins which trend roughly parallel to S_0 and S_1. The structures related to D_1 have largely been overprinted and transposed by later folding and shear strain.

Fig. 13. F_{1A} folds in calc-silicate rocks of Lesser Himalayan Sedimentaries

(b) D_2 Deformation.: In the HHC, the main structure is a penetrative, moderately dipping, planar-linear fabric developed during D_2. These parallel the axial plane and fold axis of NE-plunging F_{1B} folds respectively. The original layering S_0 is obliterated by the penetrative foliation (S_1). The earlier F_{1A} folds and its associated structures are overprinted by tight to isoclinal reclined F_{1B} folds of D_2 deformation. The orientation of F_{1B} fold hinges across the HHC consistently plunges gently to moderately due NE. The S_1 defined by alternate alignment of the fine grained quartz-feldspar and biotite muscovite layers and are marked by quartzo-feldspathic segregated layers alternating with mica layers, which are consistently oriented parallel to axial plane of F_{1B} folds. These are essentially a ductile shear fabric, having regional dips between 20° and 40° due NE. In the schist/phyllonite, the foliation is composed of S surfaces that are progressively deflected and become sub-parallel to the ductile C foliation of high strain. In various deformed rocks, this typically resembles the S-C mylonitic foliation. Throughout the HHC in the Kumaon Himalaya, kinematic indicators such as shear bands (S-C), asymmetric quartz, feldspar augen, asymmetric lenses, brittle-ductile reverse shear zone , sheared porphyroblasts and asymmetric folds indicate a consistent non-coaxial flow illustrating a well regulated top-to-SW sense of shear. During the field traverse an example of Type-3 fold interference pattern was found which provides evidence of the fact that the initial bedding and foliation is refolded along the later developed S_2 foliation. The above figure conforms to the tight isoclinal fold pattern observed in the first phase of deformation F_{1A} with initial foliation folded along a newly developing S_2 foliation which is parallel to the axial plane of the second generation of folds. Two outcrops with sheath folds were observed in which the gneissic foliation S_1 was folded forming a test-tube like structure. Thus this points evidence to the fact that in addition to tight isoclinal folds, the second phase of deformation D_2 also played host to sheath folding. Due to the high intensity of shearing the F_{1A} folds are getting rotated to follow the axial planar cleavage of the new foliation S_2 owing to which at most places it is difficult to distinguish between the axial planar data of the two generations of folding.

2. Late Folding: At shallow structural level, compressional brittle-ductile D_3 deformation folded the earlier fabrics and the NE-plunging mineral/stretching lineation. F_2 folds are more easily distinguished from F_{1A} and F_{1B} on the basis of style. They represent the large scale open fold kink type folds which are exposed in the schistose rocks. They consist of a pair of antiform and synform with two long limbs on the side and the shorter one in between. In most of the cases, the data was obtained from the longer limb of the folds. The short limb was inferred by the change in direction of the stretching lineation of the folds with respect to the axial plane of the fold, and some outcrops where it was adequately exposed. A large exposure of this type of fold can be observed about half a kilometer from the KMVN guest house at Munsiyari.

3. Extensional Deformation: This forms the phase of extensional shearing leading to extensional shear zone and normal faults in the region. They are superimposed on the existing structures with shear zones forming at an high angle to the existing foliation S_2. a normal fault is observed passing through the axial plane of the kink folds exposed near Banik. Exposures of this deformation episode are rare in the region of study.

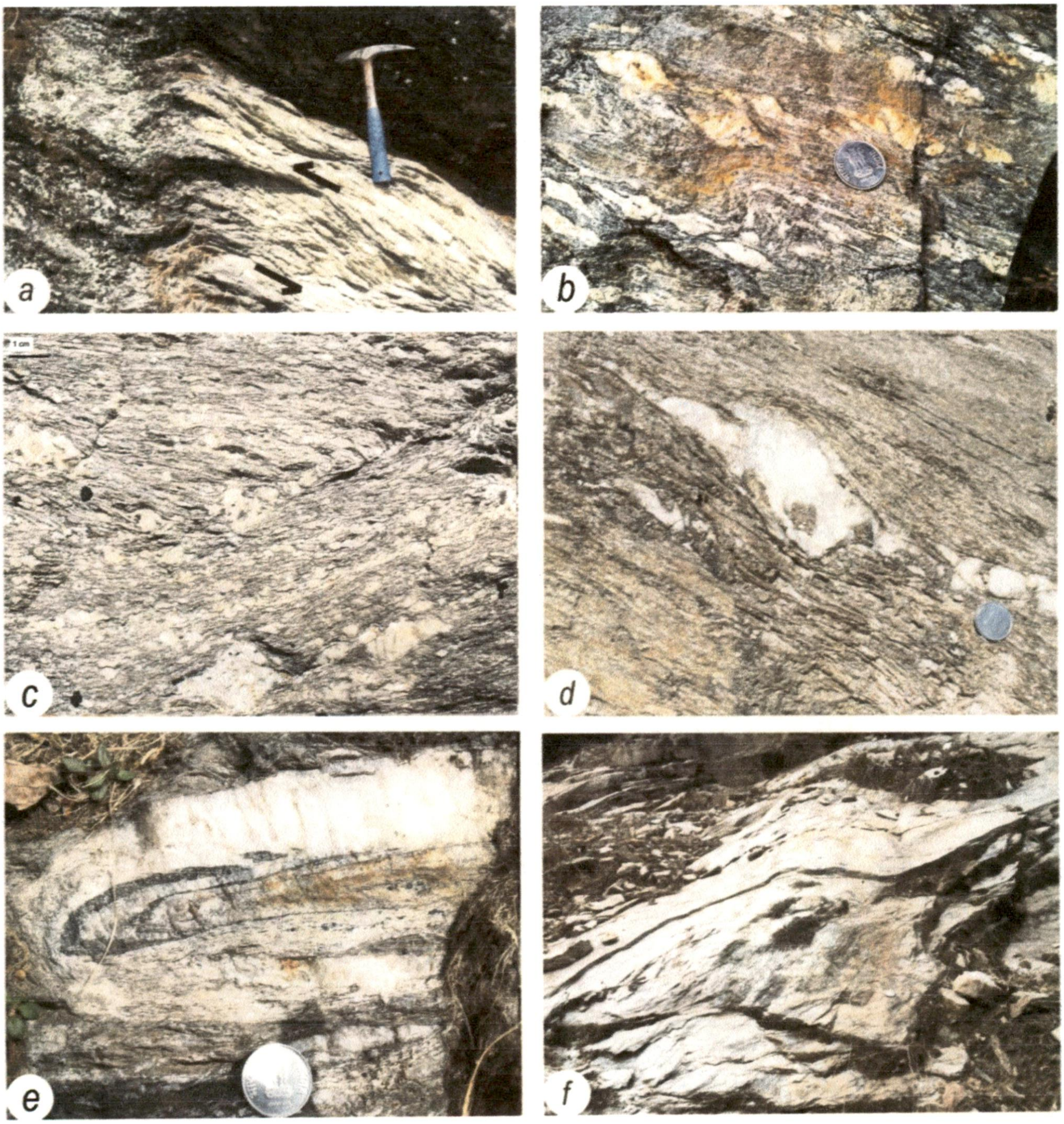


Fig. 14. (a) Sinistral shear zone (top to SW) (b) σ-porphyroclast showing top-to-south sense of movement (c) Development of secondary foliation (S_2) fabric at an angle to the original foliation (S_1) (d) Rotated porphyroclast (e) Isoclinal fold (F_{1B}) (f) Large scale F_2 folds of Late Folding

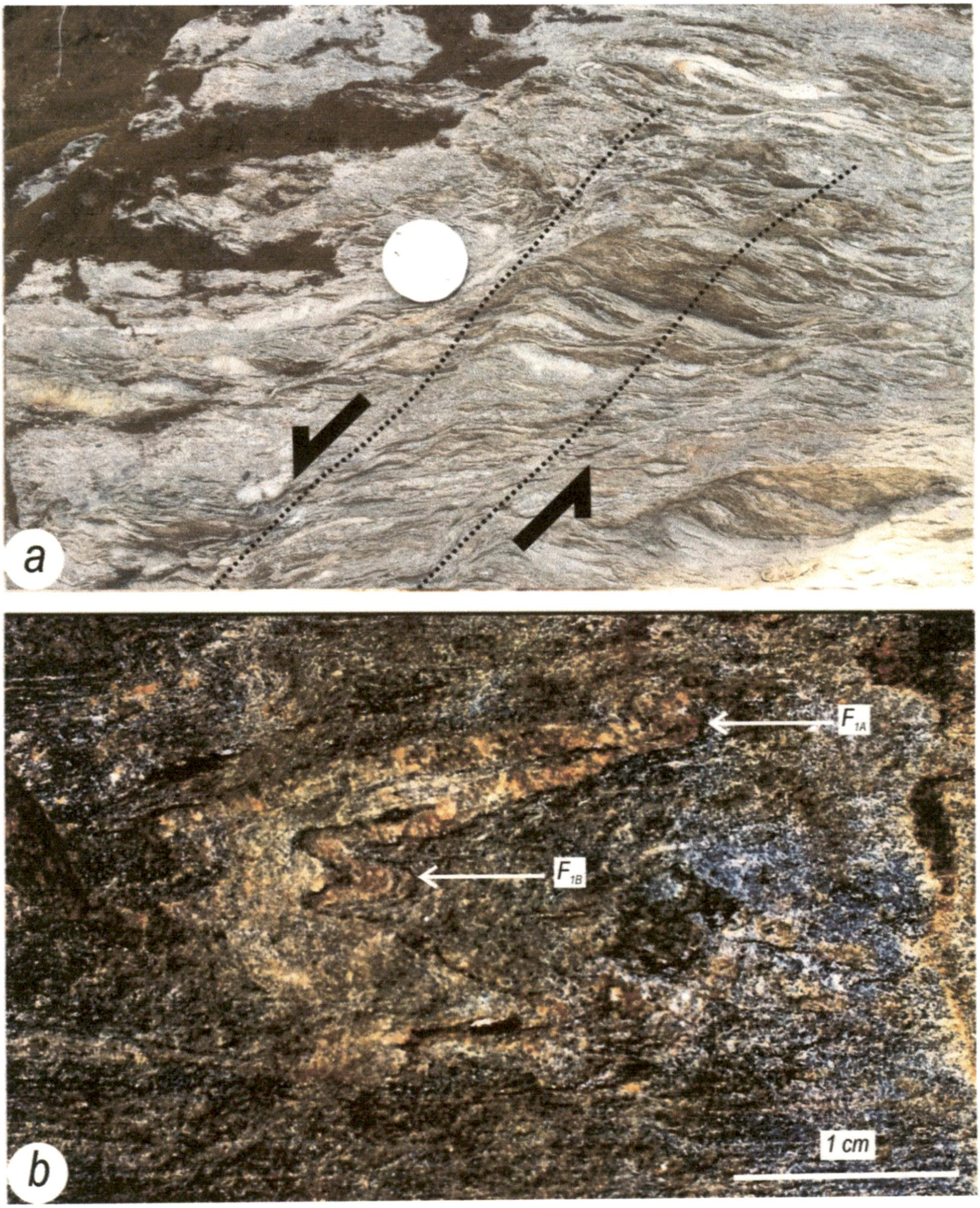


Fig. 15. (a) Extensional shear zone (D_4 deformation) near Kalamuni. (b) Type 3 fold interference near Banik.

Thus in the present terrain especially in the gneissic lithology belonging to the Munsiyari Formation, the initial phase of deformation D_I created tight isoclinal reclined folds which were developed in the original bedding within which metamorphic foliation was developed parallel to the axial plane of the folds. In the second phase of deformation D_2 the original mylonitic foliation is refolded again in a Type 3 (hook shaped) interference pattern where the second stage of deformation also brought about the same tight isoclinal type of folds as the first stage. Thus as the intensity of deformation increases the folds of the first deformation episode D_1 are rotated more tightly to align themselves parallel to the to the axial planar fabric of the folds of D_2, making it extremely difficult to differentiate between the folds generated by either deformation episode. But due to their parallel alignment the axial planar data obtained for both the folds are similar. In case of the folds generated by D_2 at some locations it was observed that with the original fabric being folded, a new axial planar cleavage was developed which was sub-parallel to the original mylonite foliation. The last stage of deformation causes large scale open kink folds which are rarely observed in the outcrop scale. The data collected from the limbs and axial plane of this large scale fold conform to the data obtained from the overall S_1 data from the Munsiyari gneisses. There are some evidences of brittle faulting and extensional shear zones which may have occurred at a later stage.

Chapter 5

Structural Analysis

5. Structural Analysis

Based on the homogeneity of the main foliation (S_1) the entire region has been divided into two sub-areas which have distinctly different deformation pattern. The bedding and cleavage data for each of the sub-area has been plotted on a stereogram along with their respective lineations wherever available. The cleavage (S_1) is the pervasive foliation and is generally parallel to the bedding. The bedding is preserved mostly in the laminated limestone and some of the quartzite while in the gneisses the bedding is overprinted by the gneissic foliation. The two stereograms for rocks from the Lesser Himalayan Sedimentaries (footwall) and those of the Munsiyari Thrust (hanging wall) show two different deformation patterns which have been shown. The deformation episodes in the region suggest that of the 4 phases of deformation the most intense was that of the second phase D_2 which causes the tight isoclinal folds with development of axial plane parallel foliation.

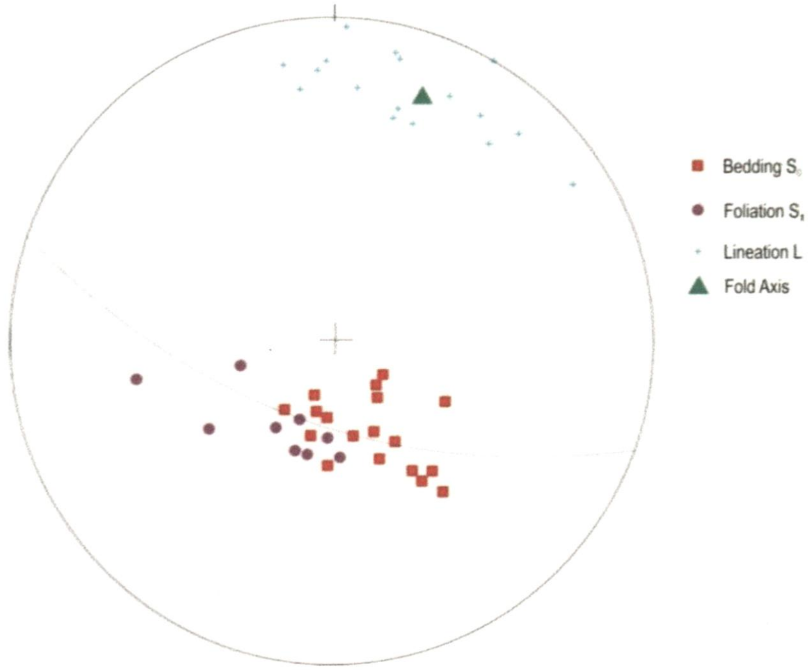


Fig. 16. Poles to bedding plot of (S_0), foliation (S_1) & lineation (L) data for the Kwiti-Madlakiya traverse in the undeformed Lesser Himalayan Sedimentaries. Total 34 data points were plotted for S_0 & S_1 with calculated girdle being 104/67 and fold axis plunging 23^0 towards 014^0. 17 data points for lineation were plotted with Mean Principal direction being towards 16^0 and plunging at 18^0.

For the stereoplot from Madlakiya to Munsiyari traverse, a merged plot for both the foliation and bedding data was plotted. This traverse intersects the Munsiyari Thrust at various points thus giving an indication of the structural deformation of the MCT-1. The bedding and foliation data were taken from both the hanging wall and footwall of the thrust.

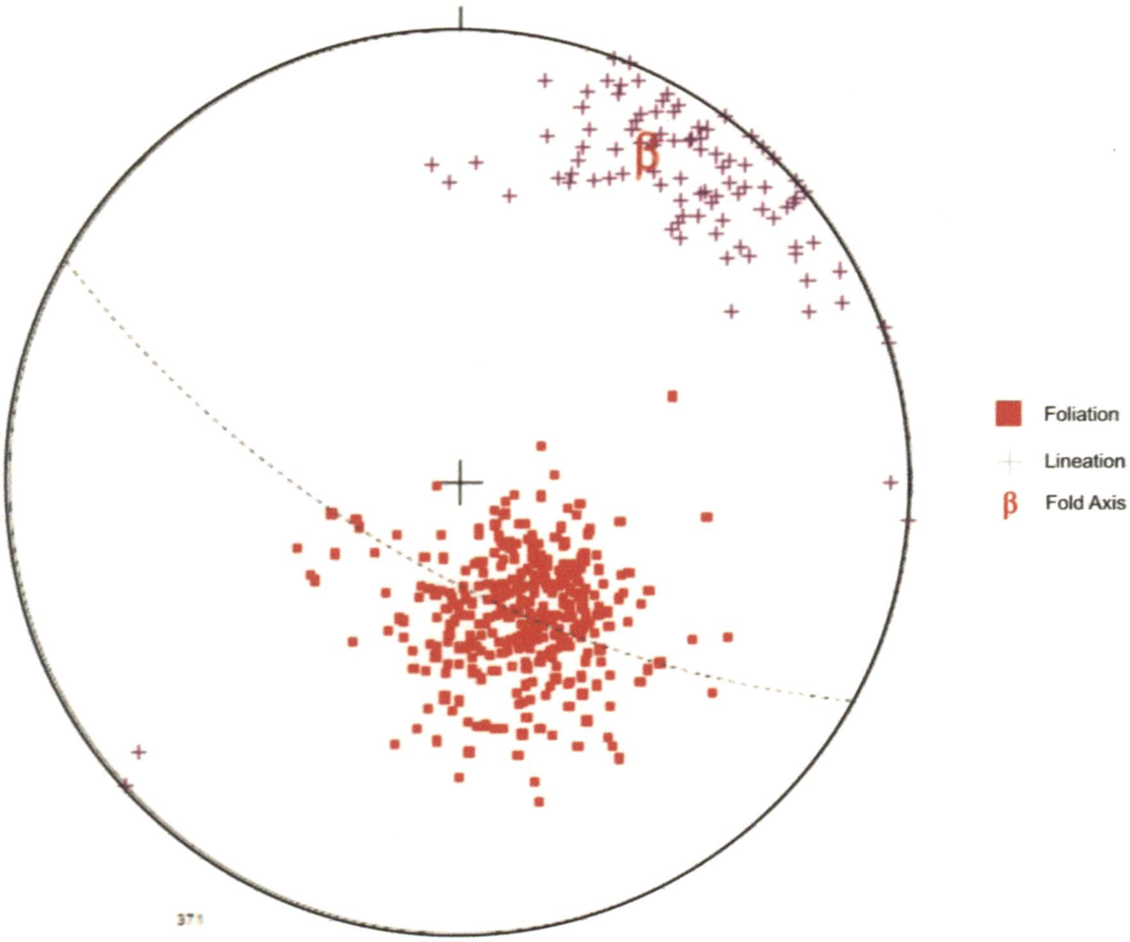


Fig. 17. Poles to bedding plot of 371 data points for the combined bedding and foliation data are plotted with 107 data points for the lineation. The calculated girdle for the foliation data comes at 119/73 with fold axis at 17^0 plunging towards 29^0. For the foliation data plotted the mean direction 13^0 plunging towards 37^0.

From the above plot we can say that while in the previous traverse (Kwiti to Madlakiya) the fold axis as well as the mean lineation generally conformed to each other, here the lineation is at an angle to the general fold axis. This could be due to rotation of stretching and intersection lineation which are oblique to the fold axis. The general trend of folding in the region however remains the same with only minor difference between the two. Thus there is scarce difference between the deformation of the rocks of the footwall and the rocks within the thrust zone. This goes to show that the effects of MCT-1 extend southwards farther than has been earlier reported in this area.

Data for individual plots was obtained for the later folding phase (D_3 Deformation) and plotting the poles to bedding on stereoplot (Fig. 20) reveals a pattern for two different generations of folding within the later fold as the fold axis for both the types are distinctly different from each other. We have classified the two generations as F_2 and $F_{2'}$. Since no overprinting relationships between the two could be observed in the field , the sequence of folding cannot be conclusively said on the basis of present evidence.

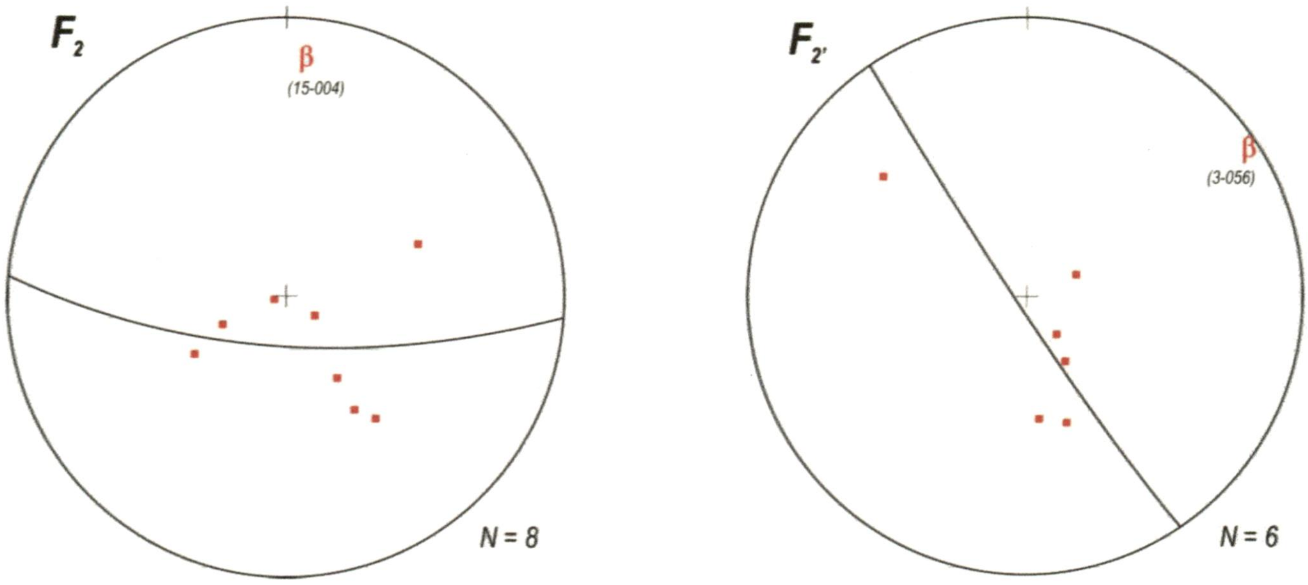


Fig. 18. Poles to bedding plot of 14 data obtained from individual fold measurements for two different classes of folds F_2 and $F_{2'}$

Chapter 6

Discussions and Conclusions

6. Discussion and Conclusions

Study of the deformation pattern of the Munsiyari Thrust in the Kumaon Himalayas suggests that the region has undergone four phases of deformation. The first phase represented by D_1 represents the folding on the bedding S_0 of the underlying Higher Himalayan Crystallines. The deformation pattern here is tight isoclinal folds which have been more or leass obliterated by the intense second phase of deformation. Previous workers (Bhanot et al., 1977; Singh et al. 1985) have ascertained the age of the gneisses in this region by Rb/Sr whole rock dating, thus implying the deformation to be of Pre-Himalayan origin. But our mapping of the Munsiyari Thrust suggests that the general pattern of deformation in the region is that of tight isoclinal overturned folds which are not dissimilar to the pre-Himalayan deformation suggested by (Patel and Kumar, 2009).While it could be possible that the pre-Himalayan deformation structures were obliterated during the shearing accompanying the MCT, we are inclined to suggest that the generations of coaxial folding were formed during the formation of MCT. The second phase of folding represented by D_2 has a penetrative planar fabric which encompasses tight isoclinal folds (F_{1B}) formed by refolding of the original F_{1A} folds thus exhibiting Type 3 interference patterns. Few isolated F_{1A} folds are found coaxial with the later F_{1B} folds implying passive rotation of earlier folds close to the stretching direction during simple shear. The third phase of deformation D_3 causes formation of large scale open kink folds while the fourth phase D_4 is of brittle ductile extensional deformation.

The stereoplots for both the hanging wall as well as the footwall show same deformation pattern with both fold axes plunging at low angles towards the NNE. Thus, the deformation due to Munsiyari Thrust is not localized at only the hanging wall i.e. the Munsiyari Formation but extends farther south well into the Deoban Formation, posing an important question as to the demarcation of the southern extent of the MCT zone. The strain observed is also not gradually increased as one approaches the Munsiyari Thrust, but is rather localized in discrete phyllonite zones found in both the Munsiyari and Lesser Himalayan Sedimentariess. The phyllonites of the MCT zone are mainly composed of quartz, muscovite, biotite and chlorite. The present mineral assemblages, and hence the gross lithological composition of the rocks of the MCT zone appear to be quite different from those occurring outside the shear zone. Previously the zones of phyllonites have been classified as separate units of mica schist in the Higher Himalayan Crystallines but on the basis of our mapping wherein we observe the truncation of the formations into the original protoliths of gneisses and calcareous rocks with development of micaceous minerals in the direction of shearing from the original protolith, we believe the formation of the schistosity was syn-deformational with the Munsiyari Thrust.

The structural analysis of the Munsiyari Thrust poses important questions regarding its evolution. At places of detailed mapping of contacts of MCT-1 it could be observed that they form a veritable pattern which could be explained on the basis of two hypotheses. Based on our field observations, the contacts could be part of a large scale folding of the Munsiyari Thrust mirroring the structures that have been observed at a smaller scale ranging from outcrops to microscopic scale in the field. The contacts also present a picture for imbricates which are quite common for a zone of intense ramp and flat thrusting. Based on the above framework, two different maps could be prepared Fig. 20, showing folding of the Munsiyari Thrust and Fig. 21 showing imbricate thrusting. Here we investigate the evidence in support of both the hypotheses and suggest which is most suitable for explaining the structure of the Munsiyari Thrust.

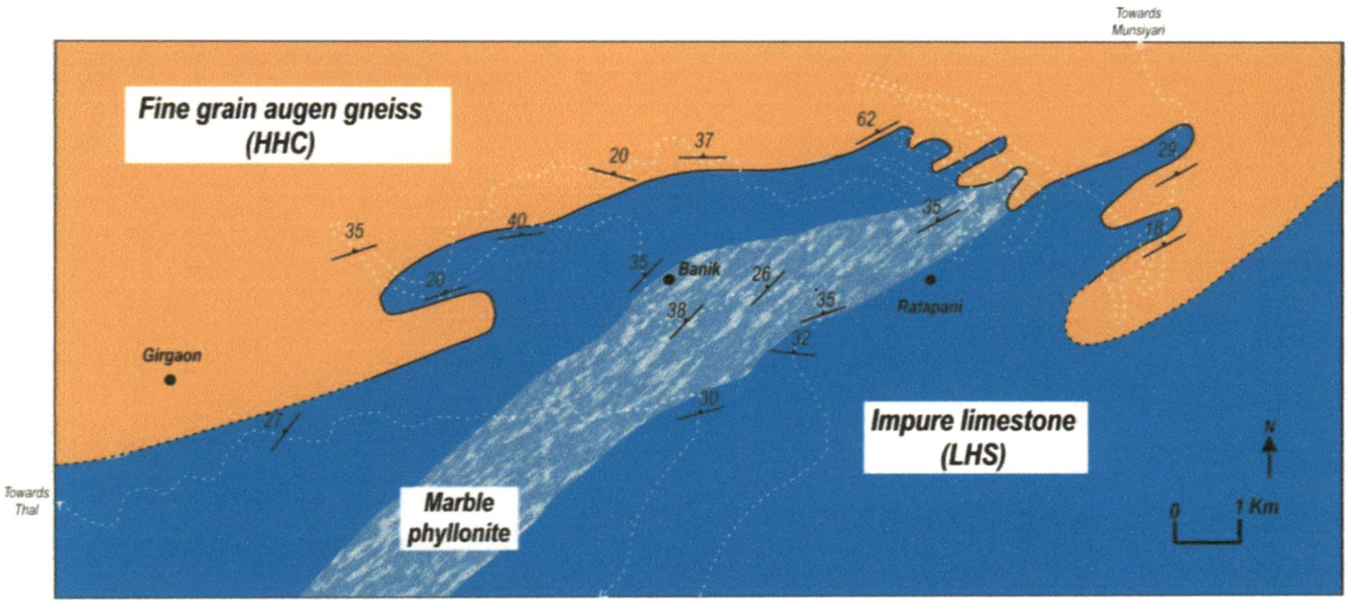


Fig. 19. Map showing folded Munsiyari Thrust

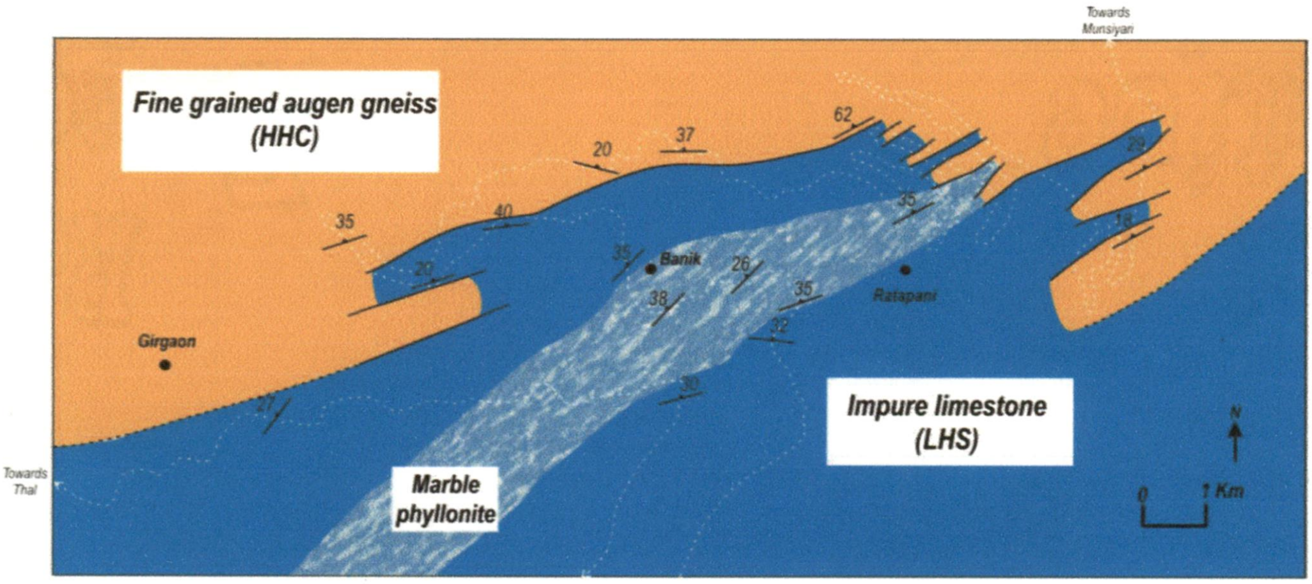


Fig. 20. Map showing Munsiyari Thrust based on imbricate hypothesis

Evidence in favor of folding of Munsiyari Thrust:

a) Foliation parallel to Munsiyari Thrust:

During our field traverse through the Munsiyari region, it was observed that the bedding and foliation are generally parallel throughout the region, which has also been reported by previous workers (Paul, 1998; Patel and Kumar, 2009). Thus we have taken the Munsiyari Thrust to bethe contact between the gneisses of the Higher Himalayan Crystallines (HHC) and the calc-silicate member of the Lesser Himalayan Sedimentaries (LHS) (Arita, 1983; Pêcher, 1989; Catlos et al., 2001; Martin et al., 2005). The contact between the two formations is parallel to the mylonitic foliation throughout the region and at no place any evidence of a discordant contact could be observed. Having plotted the foliation data collected from both the hanging wall (HHC), footwall (LHS) as well as the contact points of the Munsiyari Thrust (Fig. 22) it can be observed that the structures are generally concordant in both parts of the thrust. Our field observations show evidence of folding of mylonitic foliation in both the rocks of Lesser Himalayan Sedimentaries and the Higher Himalayan Crystallines. As the foliation on both sides of the thrust is folded and thrust contact parallels the foliation at all places, it could be concluded that the Munsiyari Thrust in itself is folded.

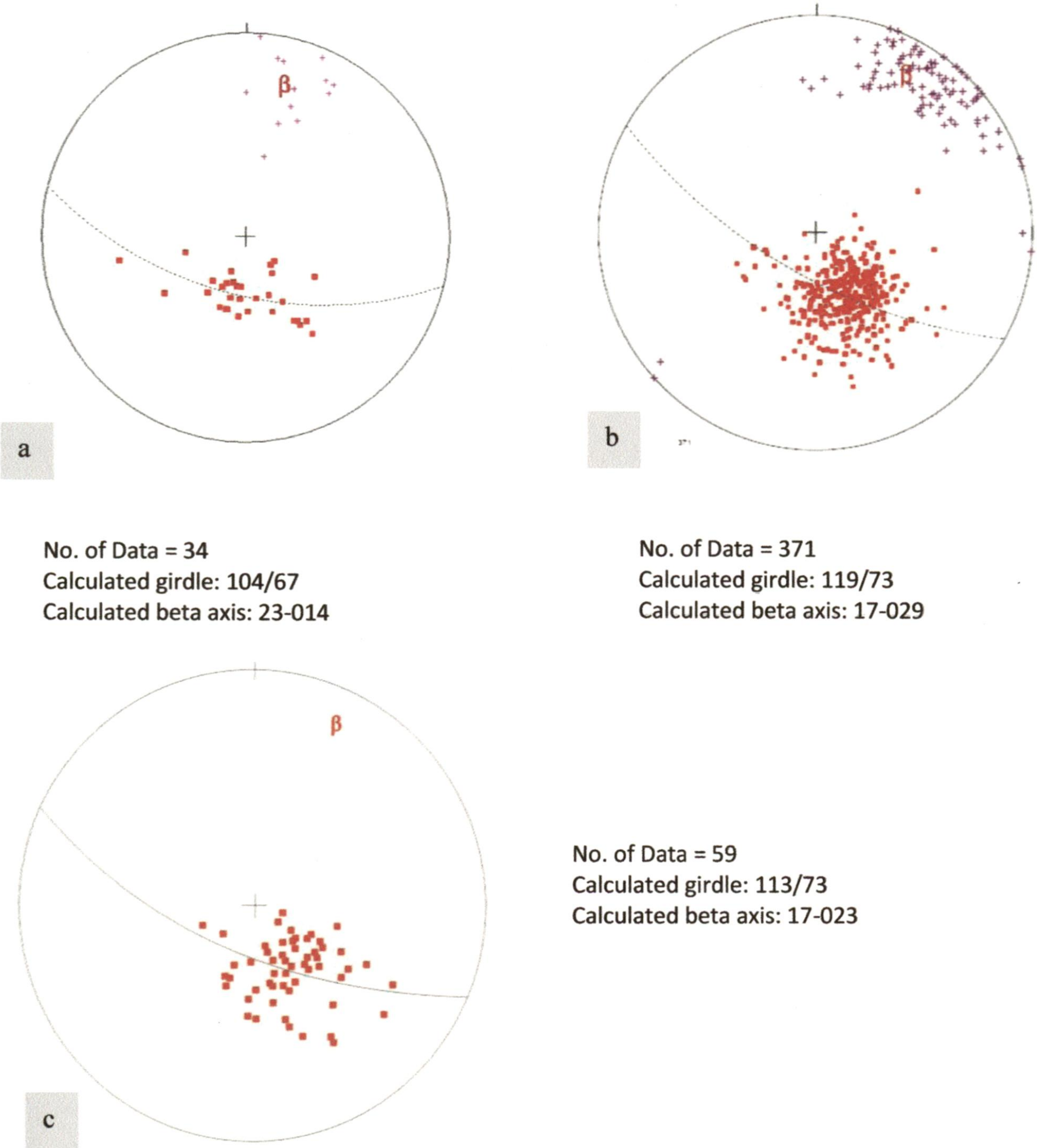


Fig. 21. Stereoplots for (a) Footwall (LHS) (b) Hanging wall (HHC) (c) Contact points of MCT-1

The nature of imbricates in a duplex structure is such that they always occur at an angle to both the roof and floor thrust (Fig. 23). Thus it can be safely surmised that the foliation is either parallel to the roof and/or floor thrust or imbricates themselves and never both at the same time, which has been encountered in the field (Fig. 11c). As the Munsiyari Thrust is the contact between the mylonitic foliations of the HHC and the LHS, foliation inside the imbricated cannot be parallel to the contacts. Plotting the data obtained only from the MCT-1 represented by the contact between the fine grained gneiss of Higher Himalayan Crystallines and calc-silicate rocks of Lesser Himalayan Sedimentaries, we find that the deformation of the contact could be divided into three discrete domains with point maximas and the calculated girdle being concordant to that found in the rocks of both the hanging wall as well as footwall. Now, assuming that the Muniyari Thrust has indeed has caused imbrications which have been erroneously mapped as contacts, it could be argued that alignment of imbricates parallel to either the roof thrust or the floor thrust is highly improbable in the field. This can never be the case for imbricates and thus point towards a folded Munsiyari Thrust.

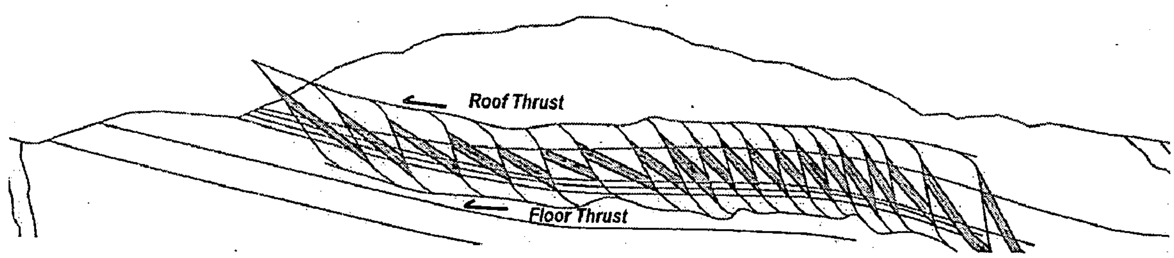


Fig.22 Formation of imbricates and relationship with foliation (after www.sp.lyellcollection.org)

b) Absence of Floor Thrust:

An imbricate structure in the field, necessitates the presence of both the roof thrust as well as floor thrust. Throughout our field traverses we have not encountered the presence of any floor thrust or any evidence of discordance between the boundaries which would have been the case had imbricates been developed in the region. The foliation being parallel throughout the region, with all structures concordant in the LHS and HHC, presence of imbricates at the contacts seems improbable.

c) Evidence from Field Outcrops

In the field traverses, various generations of folding were observed which could be broadly classified into two categories:

i) The Early Folds (F_{1A} and F_{1B}) (Fig. 8)

ii) The Late Folds (F_{2A} & F_{2B}) (Fig. 16f)

The Early Folds are of tight isoclinal nature with bedding folded, foliation axial planar (F_{1A}) or both bedding and foliation folded (F_{1B}). The later folds are characterized by large scale open kink folds which refold the foliation as well as the axial planar fabric of the early folds. A schematic diagram of the deformation occurring in the region is shown in (Fig. 24) Since the outcrops show abundant evidence of folding at all scales and large scale structures essentially mimic those at a smaller scale, it could be safely assumed that on a larger scale the fold geometry would be essentially that of the later kink type folds which is observed in the map pattern of the Munsiyari Thrust as well.

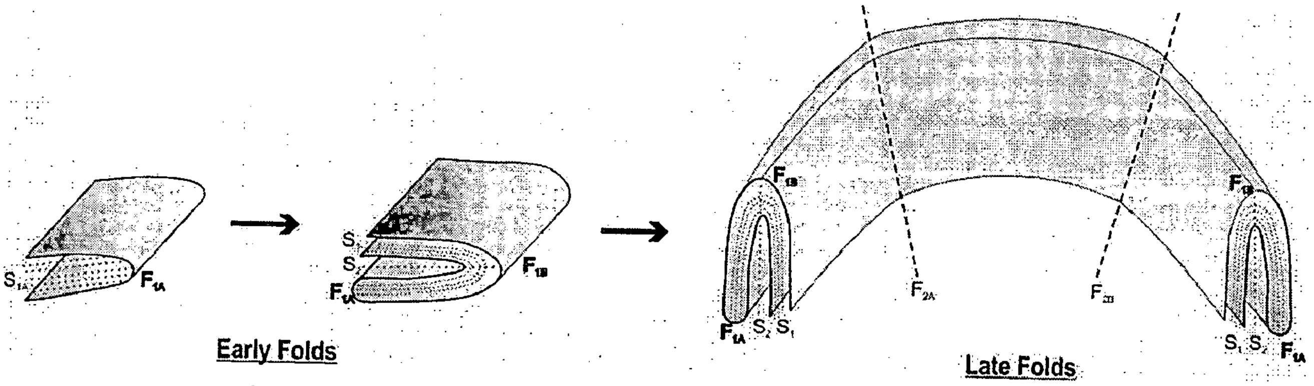


Fig. 23. Deformation episodes in the region

d) Problem of joining of contacts

On plotting the foliation data for more than 60 contact points around the Munsiyari Thrust, there are at least two points where the strike lines are converging which could only be explained by a fold. The presence of imbricates requires a series of parallel faults which could not be drawn in any way for contact points at that place leaving the only alternative that the Munsiyari Thrust is folded in itself.

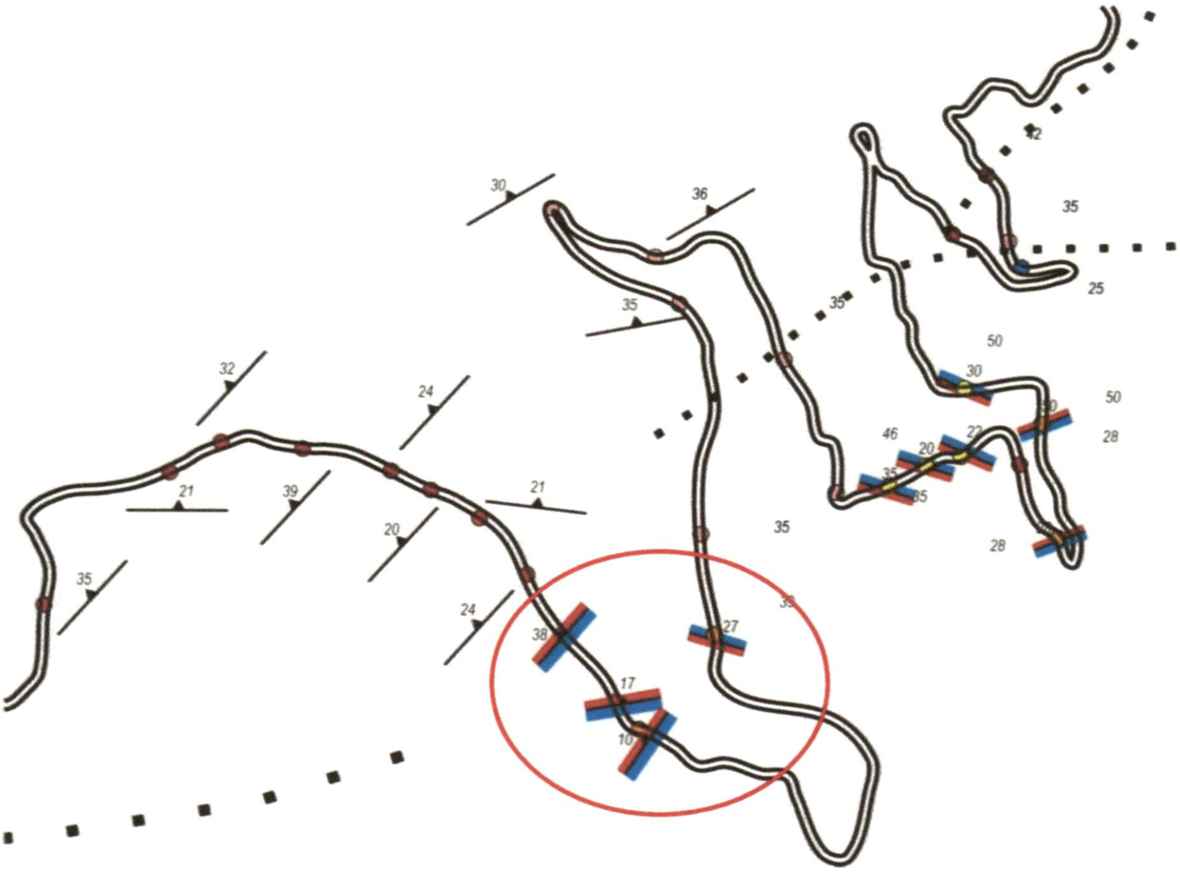


Fig. 24 Rough map showing contact points of the Munsiyari Thrust, with points which cannot be explained by imbricate thrusts

e) Clustering of points obtained for data from the Munsiyari Thrust

When the 60 data points obtained only for the contact between the mylonitic foliation of the LHS and the HHC which we have identified as Munsiyari Thrust is plotted on the stereo net, we divide them into 3 classes based on their orientation, namely

i) SE ($< 255^0$)

ii) S ($255^0 <$ and $< 275^0$)

iii) SW ($> 275^0$)

Plotting the data for the three different classes and contouring them individually, we obtain a clustering of points with three maxima oriented SSE, S and SSW respectively. For imbricates formed in a ramp flat structure, the contacts between them are generally parallel, thus providing no reason for the three maxima obtained from the plots. The only explanation along these lines is presence of oblique ramps in addition to a frontal ramp. But this explanation does not hold good as it requires the bedding or foliation to be discordant to the contact at the ramp structure which is not encountered in the field. A folded contact on the other hand encompasses the field evidence of parallel foliation with the stereoplot reiterating what has already been observed for the contact data i.e. it parallels the data for both the hanging wall and footwall (Fig 22) thus also having the same structure as both of them which are folded in the form of large scale kink folds of the later generation. Thus the above arguments prove that a folded contact hypothesis is a better explanation than the hypothesis involving imbricates.

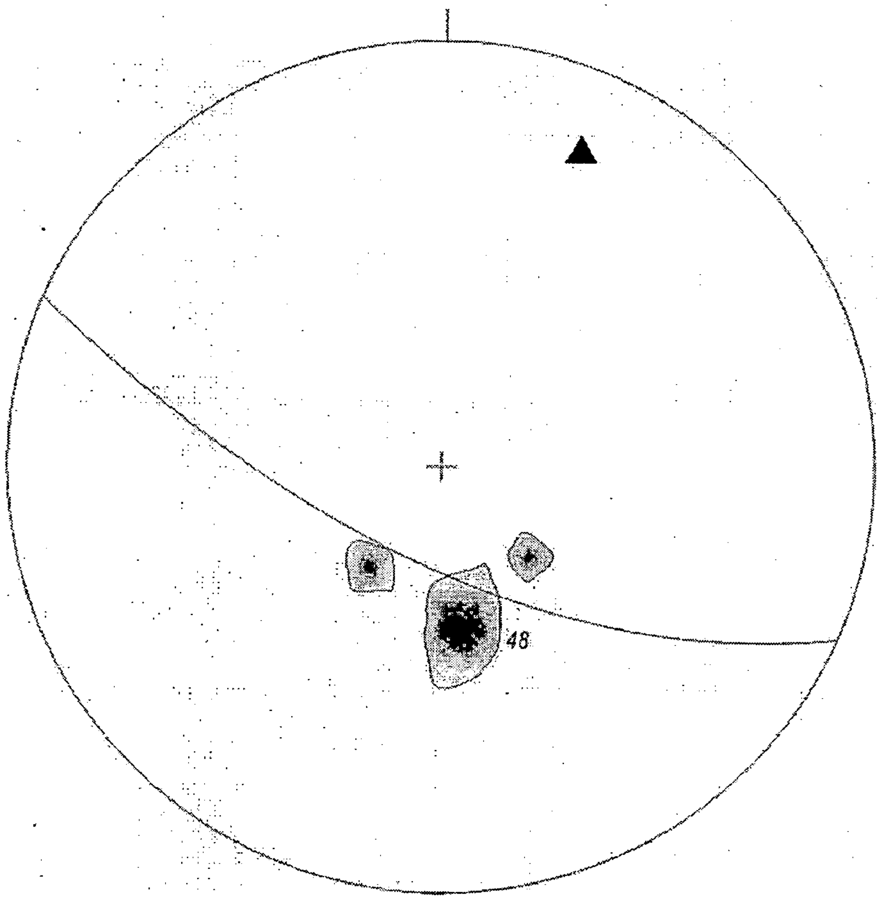


Fig. 25. Contouring of points for different classes showing three maxima with 48% of point density in them.

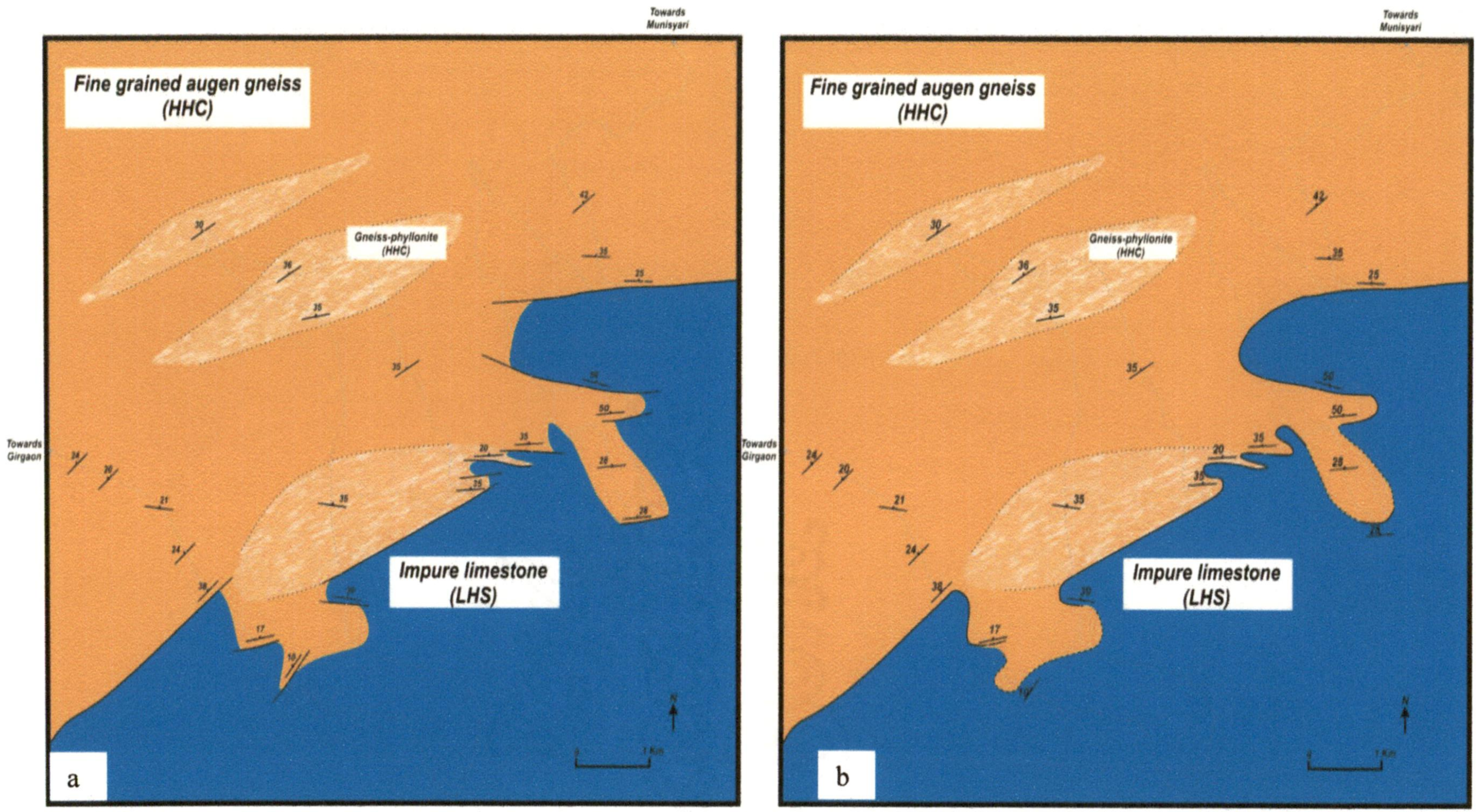


Fig. 26. A comparative picture showing the maps obtained by the two hypotheses and showing how a folded Munsiyari Thrust fits the obtained field data much better than the imbricate hypothesis. a) Map obtained by drawing parallel thrusts b) Map obtained by large scale folding

Thus from the present work the four deformation patterns have been established by the mapping of the Munsiyari Thrust (MCT-1) which shows the same structure on the map scale as those shown by the rocks of the hanging-wall and footwall. The development of the schistosity parallel to the Munsiyari thrust and their concentration in and around Munsiyari thrust also suggests that the development of all the structures in the region is syn-thrusting with the Munsiyari Thrust

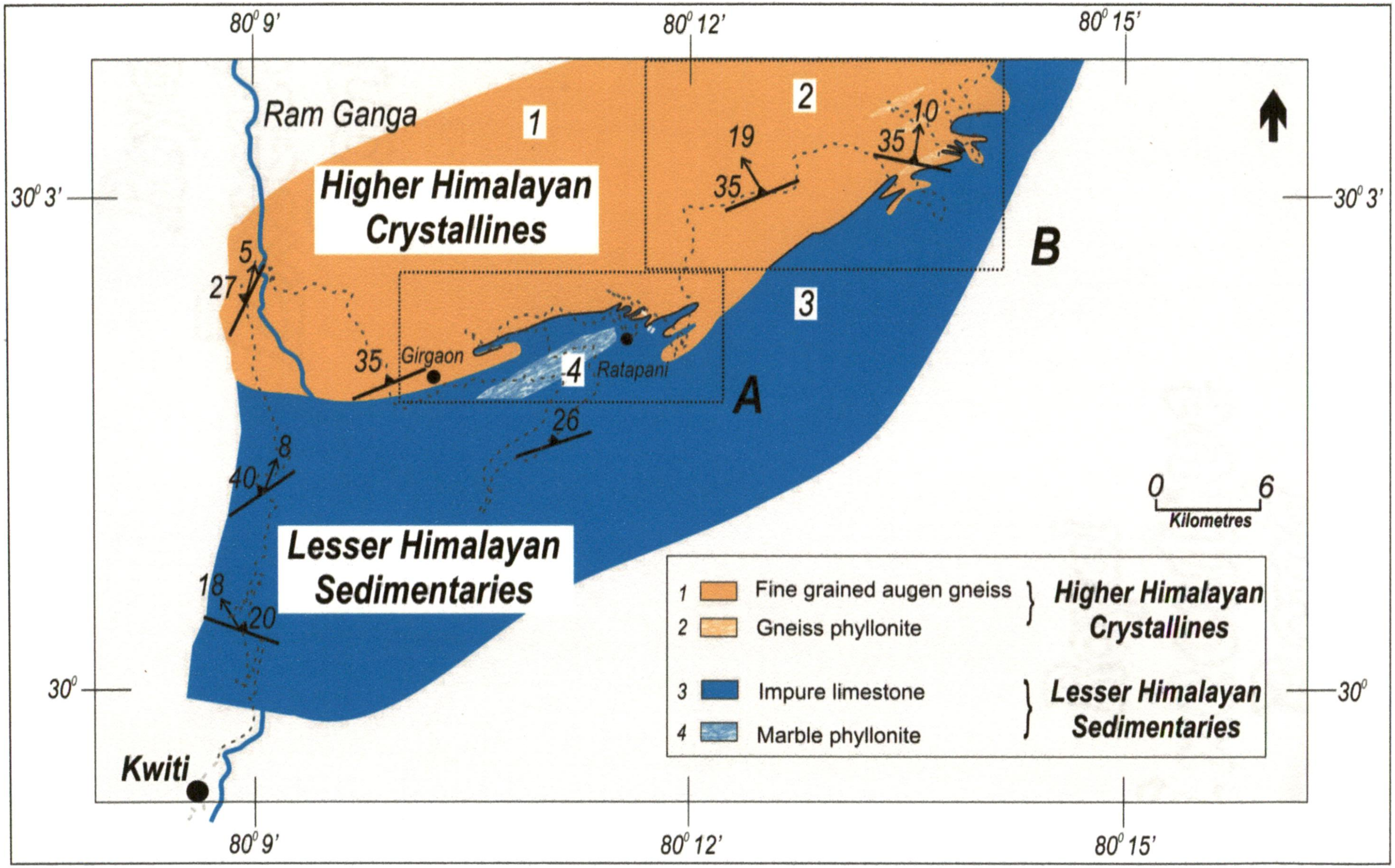


Fig. 27. Final large scale map prepared for the region

Chapter 7

References

7. References

Ahmad, T., Harris, N., Bickle, M., Chapman, H., Bunbury, J. and Prince, C. 2000. Isotopic constraints on the structural relationships between Lesser Himalayan series and High Himalayan crystalline series, Garhwal Himalaya. Tectonophysics 112, 467–477.

Arita, K., 1983, Origin of the inverted metamorphism of the Lower Himalaya, central Nepal: Tectonophysics, 95, 43–60.

Beck, R.A., Burbank, D.W., Sercombe, W.J., Khan, A.M., and Lawrence, R.D., 1996, Late Cretaceous ophiolite obduction and Paleocene India-Asia collision in the westernmost Himalaya: Geodinamica Acta, 9, 114–144.

Bhattacharya, A.R., Weber, K. 2004. Fabric development during shear deformation in the Main Central Thrust Zone, NW-Himalaya, India Tectonophysics 387. 23–46.

Bordet, P. 1961. Recherches Ge´ologiques dans l'Himalaya du Ne´pal, Re´gion du Makalu. CNRS, Paris.

Burchfi el, C.B., Zhiliang, C., Hodges, K.V., Yuping, L., Royden, L.H., Changrong, D., and Jiene, X., 1992, The South Tibetan Detachment System, Himalayan orogen: Extension contemporaneous with and parallel to shortening in a collisional mountain belt: U.S. Geological Survey Special Paper 269, 1–40.

Burg, J.P., Brunel, M., Gapais, D., Chen, G.M., and Liu, G.H., 1984, Deformation of leucogranites of the crystalline Main Central Sheet in southern Tibet (China): Journal of Structural Geology 6, 535–542

Catlos, E.J., Harrison, T.M. and Kohn, M.J. et al. 2001. Geochronologic and thermobarometric constraints on the evolution of the Main central thrust, central Nepal Himalaya. Journal of Geophysical Research, 106, 16177–16204.

Catlos, E.J., Harrison, T.M., Kohn, M.J., Grove, M., Ryerson, F.J., Manning, C.E., and Upreti, B.N., 2001, Geochronologic and thermobarometric constraints on the evolution of the Main Central Thrust, central Nepal Himalaya: Journal of Geophysical Research 106, 16,177–16,204.

Catlos, E.J., Harrison, T.M., Manning, C.E., Grove, M., Rai, S.M., Hubbard, M.S. and Upreti, B.N., 2002. Records of the evolution of the Himalayan orogen from in situ Th–Pb ion microprobe dating of monazite: Eastern Nepal and western Garhwal. Journal of Asian Earth Sciences 20, 459–479.

Colchen, M., LeFort, P. and Pe^cher, A. 1986. Carte Ge´ologique Annapurna– Manaslu–Ganesh, Himalaya du Ne´pal. CNRS, Paris.

Daniel, C.G., Hollister, L., Parrish, R.R. and Grujic, D. 2003. Exhumation of the Main Central thrust from lower crustal depths, Eastern Bhutan Himalaya. Journal of Metamorphic Geology 21, 317–334.

De Celles, P.G., Gehrels, G.E., Quade, J., Lareau, B. and Spurlin, M. 2000. Tectonic implications of U–Pb zircon ages of the Himalayan orogenic belt in Nepal. Science, 288, 497–499.

Gansser, A. 1964. Geology of the Himalaya. Wiley, Chichester. Gansser, A. 1983. Geology of the Bhutan Himalaya. Birkhauser, Basel. Geology 7, 31–41.

Harrison, T.M., Grove, M., Lovera, O.M., Catlos, E.J., and D'Andrea, J., 1999, The origin of Himalayan anatexis and inverted metamorphism: Models and constraints: Journal of Asian Earth Sciences, 17, 755–772.

Harrison, T.M., Ryerson, F.J., LeFort, P., Yin, A., Lovera, O.M. and Catlos, E.J. 1997. A Late Miocene–Pliocene origin for the central Himalayan inverted metamorphism. Earth and Planetary Science Letters 146, E1–E7.

Heim, A. and Gansser, A. 1939. Central Himalaya: Geological Observations of the Swiss Expedition, 1936. Memoires de la Socie´te´ helvetique des Sciences Naturelles 73.

Hodges, K.V., 2000, Tectonics of the Himalaya and southern Tibet from two perspectives: Geological Society of America Bulletin 112, 324–350.

Jackson, M., Bilham., 1994. Constraints on Himalayan Deformation inferred from Vertical Velocity Fields in the Nepal and Tibet. Journal of Geophysical Research 99 (B7), 13897-13912.

Le Fort, P., 1996, Evolution of the Himalaya, in Yin, A., and Harrison, T.M., eds., The tectonic evolution of Asia: Cambridge, UK, Cambridge University Press, 95–109.

Le Fort, P. 1975. Himalayas, the collided range: present knowledge of the continental arc. American Journal of Science 275, 1–44.

Martin, A.J., DeCelles, P.G., Gehrels, G.E., Patchett, P.J. and Isachsen, C. 2005. Isotopic and structural constraints on the location of the Main central thrust in the Annapurna Range, central Nepal Himalaya. Geological Society of America Bulletin 117, 926–944.

Martin, A.J., DeCelles, P.G., Gehrels, G.E., Patchett, P.J., and Isachsen, C., 2005, Isotopic and structural constraints on the location of the Main Central Thrust in the Annapurna Range, central Nepal Himalaya: Geological Society of America Bulletin 117, 926–944.

Parrish, R.R. and Hodges, K.V. 1996. Isotopic constraints on the age and provenance of the Lesser and Greater Himalayan sequences, Nepalese Himalaya. Geological Society of America Bulletin 108, 904–911.

Patel, R.C., Kumar, Y. 2009. Deformation and Structural Analysis of the Higher Himalayan Crystallines along Goriganga Valley, Kumaon Himalaya, India. Magmatism, Tectonism and Mineralization. Macmillan Publishers India Ltd. 146-166.

Paul, S.K. 1998. Geology and tectonics of the Central Crystallines of northeastern Kumaun Himalaya, India. Journal of Nepal Geological Society 18, 151-167.

Pêcher, A., 1989. The metamorphism in the Central Himalaya. Journal of Metamorphic Geology 7, 31–41.

Richards, A., Argles, T., Harris, N., Parrish, R., Ahmad, T., Darbyshire, F. and Draganits, E. 2005. Himalayan architecture constrained by isotopic tracers from clastic sediments. Earth and Planetary Science Letters 236, 773–796.

Richards, A., Parrish, R., Harris, N., Argles, T. and Zhang, L. 2006. Correlation of lithotectonic units across the eastern Himalaya, Bhutan. Geology, 34, 341–344.

Robinson, D.M., DeCelles, P.G., Garzione, C.N., Pearson, O.N., Harrison, T.M. and Catlos, E.J. 2001. The kinematic evolution of the Nepalese Himalaya interpreted from Nd isotopes. Earth and Planetary Science Letters 192, 507–521.

Searle, M.P., Law, R.D., Godin, L., Larson, K.P., Streule, M.J., Cottle, J.M., Jessup, M.J., 2008. Defining the Main Central Thrust in Nepal. Journal of the Geological Society, London 165, 523-534.

Srivastava, D.C. 2010. Geometrical similarity in successively developed folds and sheath folds in the basement rocks of the northwestern Indian Shield. Geol. Mag. 148 (1), 2011, 171–182. Cambridge University Press 2010.

Thakur, V.C and Chudhury, B.K.,1983, Deformation, metamorphism and tectonic relations of Central Crystallines and Main Central Thrust in eastern Kumaun Himalaya. In: Saklani, P.S. (ed), Himalayan Shears, Himalayan Books, New Delhi, 45-57.

Upreti, B.N., 1999, An overview of the stratigraphy and tectonics of the Nepal Himalaya: Journal of Asian Earth Sciences 17, 577–606.

Valdiya, K.S. 1980 (b) Geology of Kumaun Lesser Himalaya. Wadia Inst. Him. Geol.,Dehradun, U.P., 291p.

Yin, A., Harrison, T.M., Murphy, M.A., Grove, M., Nie, S., Ryerson, F.J., Feng, W.X., and Le, C.Z., 1999, Tertiary deformation history of southeastern and southwestern Tibet during the Indo-Asian collision: Geological Society of America Bulletin 111, 1644–1664.