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Locating the Main Central Thrust in central Nepal using lithologic, microstructural and metamorphic criteria

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ABSTRACT

Although the Main Central Thrust (MCT) is believed to be an intracrustal thrust extending throughout the length of the Himalaya, its nature and location is very much obscured and debated for many years. In the present work, field observations, microstructural analysis and metamorphic data were combined in a study along the Seti River and Modi Khola valleys in the Pokhara area of central Nepal to figure out recognizable criteria for objectively locating the MCT. The study demonstrates that the MCT is a sharp and discordant tectono-metamorphic boundary separating the Lesser and Higher Himalayas in the Pokhara area. The MCT is marked by changes in 1) lithology, 2) style of microfolding, 3) deformation of quartz and feldspars, 4) garnet texture, compositions and zoning patterns, and 5) muscovite and plagioclase compositions. We believe that some or all of the above changes should be observed across the MCT in other parts of the Himalaya and provide important criteria to locate the MCT.

INTRODUCTION

Major intracrustal thrusts divide the Himalaya into four tectonic zones, i.e., the Tethys Himalaya, Higher Himalaya, Lesser Himalaya and the Sub-Himalaya (Siwaliks), from north to south, respectively (Gansser, 1964) (Fig. 1). Each of these zones is morphologically distinct and shows contrasting lithostratigraphy and tectonic style. The Main Central Thurst (MCT) is one of the major intracrustal thrusts in the Himalaya, dividing the Higher Himalaya in the north from the Lesser Himalaya in the south (Gansser 1964; Le Fort 1975; Valdiya 1980).

The term 'Main Central Thrust' was first used in the Kumaon Himalaya of India by Heim and Gansser (1939). They defined it as a tectonic contact surface between the terrigeneous-carbonate autochthon in the south (the Lesser Himalaya) and the overlying metamorphic complex of mica-schists and gneisses in the north (the Higher Himalaya). All of the subsequent researchers in the Himalaya recognized the MCT as an intracrustal thrust (Gansser 1964; Hashimoto et al. 1973; Le Fort 1975; Valdiya 1980). However, the nature and location of the MCT has remained controversial throughout the Himalayan orogen (Valdiya 1983; Spencer 1995; Upreti 1999).

The main controversial points regarding the MCT are whether it is a single thrust fault or a broad shear zone, and if there are any remarkable structural and metamorphic discontinuities across the MCT. Fuchs and Frank (1970), Frank and Fuchs (1970), Hashimoto et al. (1973), Valdiya (1980) and Arita (1983) show two parallel thrusts in the northern part of the Lesser Himalayan sequence at the level of the MCT. The lower thrust is known as the Lower MCT (LMCT) and the upper one is known as the Upper MCT (UMCT) in the Nepal Himalaya (Upreti 1999). The LMCT and the UMCT are equivalent to the Munsiari and Vaikrita Thrusts, respectively, in India (Valdiya 1980). On the other hand, Le Fort (1975), Pêcher (1975, 1977) and Colchen et al. (1980) consider only one MCT, which is equivalent to the UMCT. Nevertheless, the above researchers believe that the UMCT, which lies at a structural level about 3 km far above the originally defined MCT by Heim and Gansser (1939), is the real MCT dividing the Lesser Himalaya from the Higher Himalaya. The MCT of Heim and Gansser (1939) coincides with the LMCT or the Munsiari Thrust, which has been regarded by some geologists as an imbricate thrust (Hashimoto et al. 1973; Arita 1983; Paudel and Arita 2000), within the Lesser Himalaya.

Some Himalayan geologists argue that locating a discrete MCT is a 'false problem' and one should speak of a MCT zone (e.g., Pêcher 1977). They think that the MCT may be an arbitrary median plane in a broad plastic shear zone. However, others think that it is a distinct tectonic boundary with sharp break in metamorphic grade and structural style (Fuchs and Frank 1970; Stöcklin 1980; Arita 1983). Some geologists suggest the MCT at the base of the first coarse-grained banded gneiss layer, which often marks a sharp lithological change, others place it along a certain isograd, preferably the base of the kyanite zone, which often coincides with the first appearance of gneiss layer.

Thrust faults are usually defined and recognized by the presence of older lithological units resting on top of younger lithological units. However, in the case of the MCT, both the hanging wall and footwall rocks are plastically deformed, sheared, recrystallized and metamorphosed (Le Fort 1975; Pêcher 1977; Arita 1983; Brunel and Kienast 1986; Hubbard

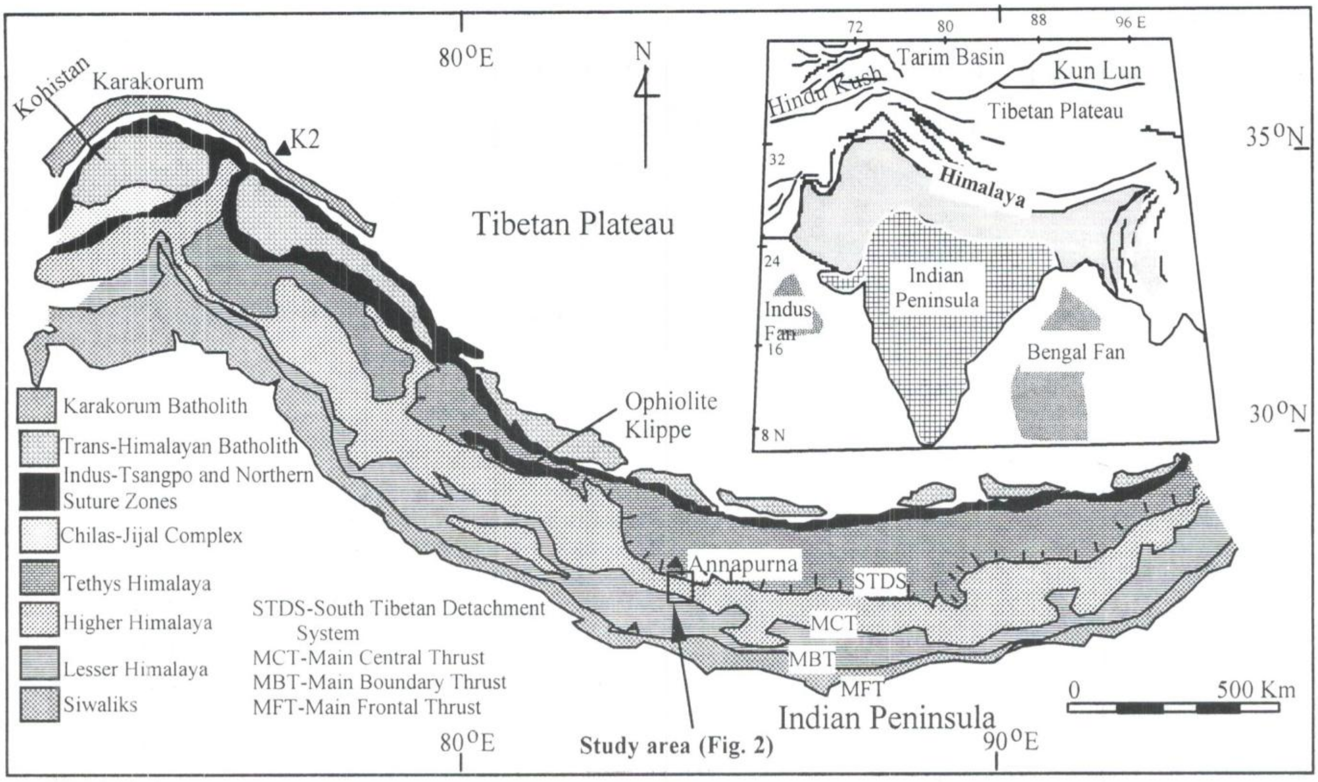

Fig. 1: A simplified geological map of the Himalaya showing major lithotectonic divisions and the location of the present study area (modified from Gansser 1964; Sorkhabi et al. 1997).

1996). Therefore, the structural style and grade of metamorphism at the hanging wall and the footwall of the MCT appear to be similar in the field.

Regardless of the above situation, the MCT should maintain some recognizable characteristics for at least a given section if it had emplaced older rocks over the younger, as thrusts normally do. The older rocks lie at deeper level and hence at higher P-T field in the crust. Hence the rheological properties of the older rocks lying at deeper levels and the younger rocks lying at shallower levels of the crust should be different. When older rocks slide over the younger rocks along a thrust, the footwall is intensely bulldozed by the hanging wall. Due to the difference in rheological properties and deformation intensity at the footwall and hanging wall, the resultant microstructures should also differ in the footwall and the hanging wall of the thrust. Similarly, the deeper rocks should have already metamorphosed to certain grade before thrusting. Therefore, the hangingwall rocks should show metamorphic history different from that of the footwall. The ultimate result should be a recognizable tectono-metamorphic discontinuity across the thrust.

The aim of the present work is to emphasize the importance of lithologic, microstructural and metamorphic criteria to objectively locate the MCT in the Pokhara area, central Nepal. For this purpose, detailed field mapping was carried out in the Pokhara area, and samples were collected systematically along the Seti River valley (Figs. 2 and 3). The samples were subjected to petrographic study, microstructural analyses and mineral compositional studies. The results of the study and their implications for the MCT are discussed in this paper.

GEOLOGICAL OUTLINE OF THE POKHARA AREA

The Pokhara area, south of the Annapurna Range, comprises greenschist-facies metasediments of the Lesser Himalaya in the south and amphibolite-facies rocks of the Higher Himalaya in the north (Hashimoto et al. 1973; Le Fort 1975; Colchen et al. 1980; Arita et al. 1982). The Lesser Himalaya is overthrust by the Higher Himalaya along the UMCT (note that the UMCT is equivalent to MCT of Le Fort 1975; Pêcher 1975; Colchen et al. 1980; MCT II of Arita et al. 1982; the Mahabharat Thrust of Stöcklin 1980; and the Vaikrita Thrust of Valdiya 1980).

Lesser Himalaya

The Lesser Himalaya is basically divided into the outer and inner belts (Arita et al. 1982; Sakai 1985). The Pokhara area lies in the inner belt and is further divided from south to north into the Thrust sheet I (TS I), Thrust sheet II (TS II) and the MCT zone by the Phalebas Thrust (PT) and the LMCT (Figs. 2 and 3), respectively (Paudel and Arita 2000). The inner Lesser Himalaya is made up of Late Precambrian-Early Paleozoic Nawakot Complex (Stöcklin 1980). The TS I comprises the middle part of the Nawakot Complex, namely the Nourpul Formation, Dhading Dolomite and the Benighat

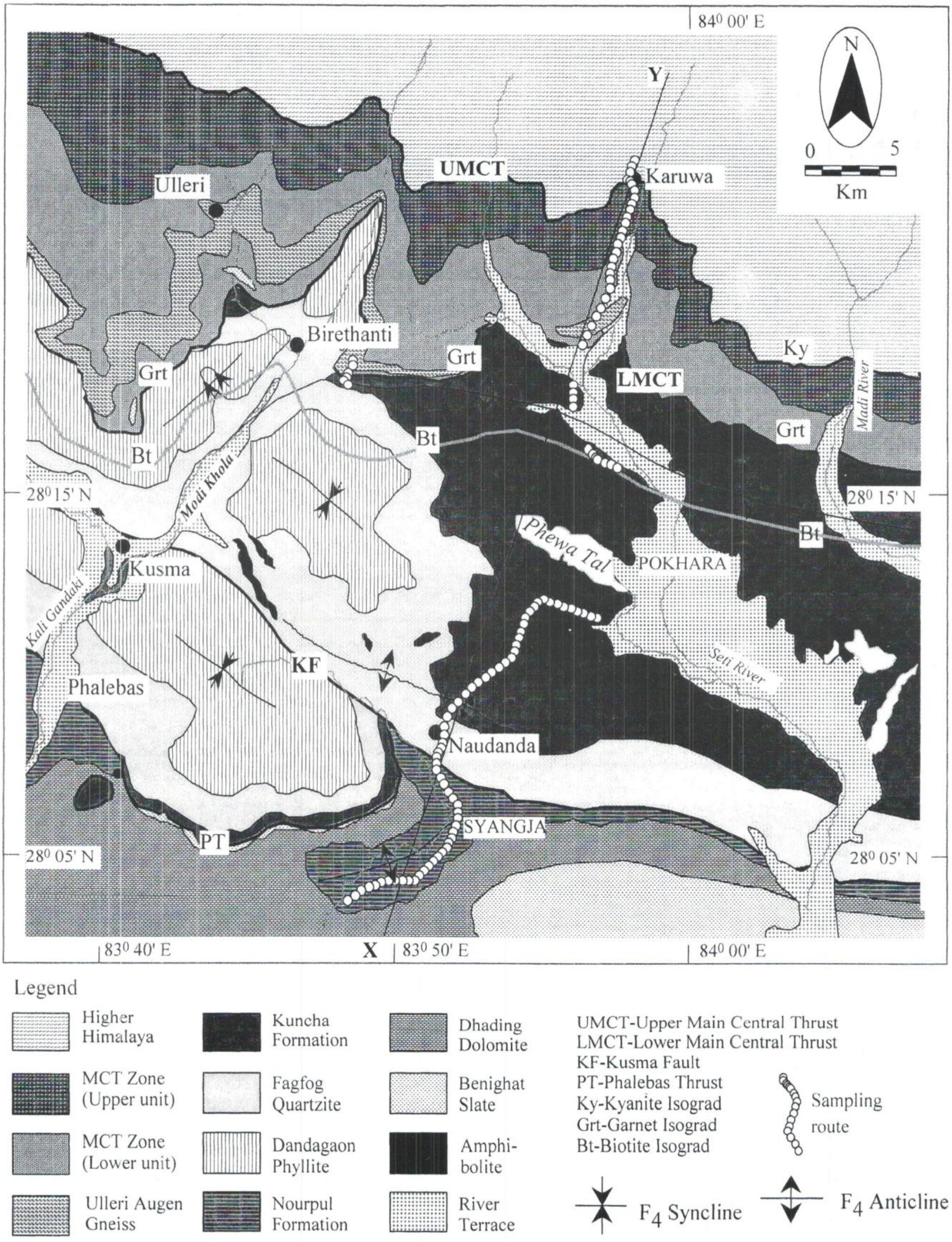

Fig. 2: Geological map of the Pokhara area (after Paudel and Arita 1998). Biotite (Bt) isograd is shown. Garnet (Grt) and Kyanite (Ky) isograds coincide with the LMCT and the UMCT, respectively. X-Y: line of cross-section shown in Fig. 3.

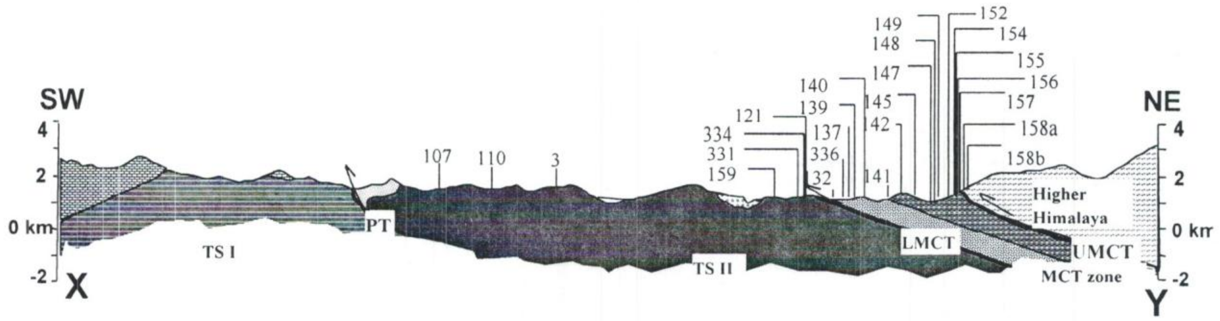

Fig. 3: Geological cross-section of the Pokhara area showing the approximate positions of samples. PT-Phalebas Thrust, LMCT- Lower Main Central Thrust, UMCT-Upper Main Central Thrust, TS I- Thrust Sheet I, TS II- Thrust Sheet II. Patterns and line of cross-section as in Fig. 2.

Slate. These formations consist of alternating varicoloured phyllites, slates and dolomites. The TS II comprises the lower part of the Nawakot Complex, i.e., the Kuncha Formation, Fagfog Quartzite and Dandagaon Phyllite (Fig. 2). These formations comprise alternating sequence of metasandstones, quartzose phyllites, gray-green phyllites and white quartzites. Sill-like bodies of amphibolites are also commonly found in the Fagfog Quartzite. The northern part of the Lesser Himalaya, which is delimited by the UMCT, is a thick ductile shear zone (MCT zone). The MCT zone is generally supposed to have been most active at 22 to 20 Ma (Hubbard and Harrison 1989), acting as the locus for at least 140 km of southward thrusting of the Higher Himalayan crystalline rocks in Eastern Nepal (Schelling and Arita 1991).

The MCT zone comprises intensely sheared and recrystallized mylonitc rocks, which can be lithologically divided into the lower and upper units (Paudel and Arita 1998). The lower unit consists of pelitic and psammitic schists, augen gneisses (Ulleri augen gneiss of Le Fort 1975), which are intruded by pegmatites. The upper unit is made up of calcareous and carbonaceous schists and marbles.

The Lesser Himalaya has experienced at least five deformation events (D_1-D_5), two of which (D_1 and D_2) are of the pre-Himalayan orogeny (Paudel and Arita 2000). The first deformation (D_1) produced bedding-parallel foliation (S_1=S_0). The S_1(=S_0) was deformed to produce west-vergent folds (F_2) with NNE-SSW trending axes due to west-vergent shearing during D_2. The S_1 foliation and F_2 folds are observed throughout the Lesser Himalaya to the south of the MCT zone. The foliation related to D_2 (i.e., S_2) has not been documented in the area. South-vergent bedding-parallel shearing (D_3) during the UMCT movement produced bedding-parallel shear foliation S_3(=S_1=S_0) [Fig. 4(B)] in the southern part of the Lesser Himalaya while it produced NE-dipping mylonitic S-C structures and NE-plunging stretching/mineral lineations (L_3) in the northern part of the Lesser Himalaya [Fig. 4(C)]. The L_3 stretching/mineral lineations are folded in the TS II by a later deformation, and plunge to the NE or SW. Shear-sense markers related to D_3 are observed throughout the TS II and the MCT zone [e.g., Figs. 5(B) and (C)], and they always show top-to-the-south sense of shearing in the Lesser Himalaya (Pêcher 1977; Brunel et al. 1979; Kaneko 1997). Post-UMCT imbricate thrusting along the LMCT and Phalebas Thrust (D_4) resulted in folding of all of the previous structures (S_0, S_1, S_3 and L_3) producing south-vergent major and minor folds (F_4) with WNW-ESE trending axes, and axial plane crenulation cleavages [Figs. 6(A), (B) and (C)]. Brittle faulting and jointing occurred at the final phase (D_5) during uplift and exhumation.

Higher Himalaya

The Higher Himalaya in the Pokhara area (about 10 km thick) is divided into the Formation I, II and III (from bottom to top) by Le Fort (1975). The Formation I, II and III are roughly equivalent to the lower argillo-arenaceous, middle calcareous and the upper calc-argillaceous units of Arita et al. (1982). The lower unit comprises coarse-grained, kyanite-bearing banded gneisses, augen gneisses and schists. The middle unit is made up of calcareous rocks such as hornblende schists, calc-silicate gneisses and marbles, and the upper unit consists of fine-grained mica schists and calcareous schists. The predominant foliation in the Higher Himalaya dip homoclinally to the NNE at angles ranging from 30-75° (Upreti 1999).

VARIOUS CRITERIA TO LOCATE THE UPPER MAIN CENTRAL THRUST IN THE POKHARA AREA

Lithology

The Upper Main Central Thrust (UMCT equivalent to the MCT) is both physiographically and lithologically well expressed in the field. Abrupt lithological changes can be observed in the field along the Seti River and Modi Khola valleys. Across the UMCT, the footwall rocks (the MCT zone) include fine- to medium-grained garnetiferous psammitic schists [Fig. 4(A)], pelitic schists and carbonaceous schists [Fig. 4(B)], quartzites and marbles. These rocks are similar to the metasediments of the lower and middle parts of the Nawakot Complex. Most probably the MCT zone rocks are the sheared and recrystallized equivalents of the Nawakot Complex rocks (Hashimoto et al. 1973; Colchen et al. 1980; Upreti 1999). Mylonitic and protomylonitic granitic augen gneiss layers and amphibolite sills are often found in the MCT zone. They are strongly sheared to form S-C fabric and stretching lineations [Fig. 4(C)]. Quartz grains in all the rock types have been strongly stretched to form quartz ribbons while feldspar clasts in metasediments and feldspar phenocrysts in granitic gneisses are sheared, fractured and granulated. The intensity of shearing increases from south to north in the MCT zone producing ultramylonites near the UMCT. The ultramylonites look like fine-grained sedimentary rocks with well-preserved laminations and beddings in the outcrops [Fig. 4(B)]. However, in thin sections, they show strong shearing parallel to bedding. Strongly stretched quartz ribbons can be also observed in the outcrops and handspecimens.

The above rock unit has been abruptly overlain by banded gneisses and schists at the village of Chhomrong along the Modi Khola and Karuwa along the Seti River valleys (Fig. 2). Those rocks belong to the Higher Himalaya and are different in all aspects (e.g., fabric, color, texture, mineralogy) compared to the underlying MCT zone rocks. The Higher Himalayan gneisses and schists look massive from distant view [Fig. 4(D)]. However they are well foliated and contain altenating leucocratic (quartz- and feldspar-rich) and melanocratic (biotite-rich) layers giving a banded appearance. Due to the higher amount (>40%) of coarse-grained (>0.1 mm) biotite and muscovite, the Higher Himalayan gneisses and schists are fragile and loose in handspecimens. Minerals are coarse enough to be identified with naked eyes. They contain very coarse-grained kyanite porphyroblasts (up to 7 cm long) [Fig. 4(D), in the inset], which are usually bent, fractured and broken. Garnet porphyroblasts are usually sheared and elongated parallel to foliation with well-developed pressure shadows [Fig. 5(F)]. The Higher Himalayan rocks have undergone strong plastic deformation forming ptygmatic and rootless folds.

The above-mentioned differences in lithology and texture between the Lesser and the Higher Himalayan rocks are very clear in the field along the Seti River and Modi Khola valleys. Therefore, the UMCT can be located without confusion in the study area. Although the UMCT coincides with the kyanite isograd in the Pokhara area, it should be emphasized that the locating UMCT based solely on the

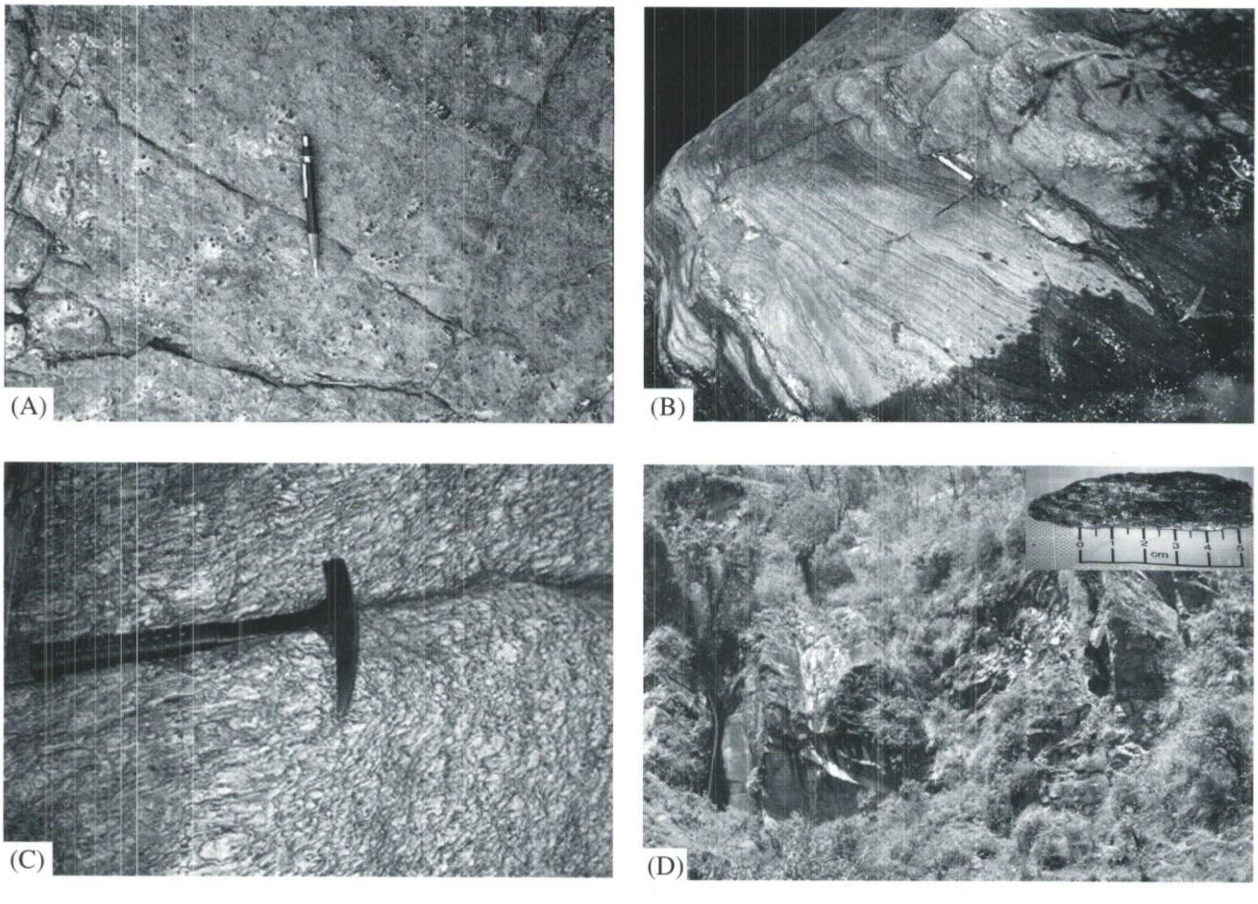

Fig. 4: Field photographs showing lithological differences between the MCT zone and the Higher Himalayan rocks along the Seti River valley, north of Pokhara. (A) Garnetiferous psammitic schist from the lower part of the MCT zone. (B) Graphitic schist of ultramylonitic character from the upper part of the MCT zone. (C) Granitic augen gneiss from the lower part of the MCT zone with penetrative stretching lineations. (D) Higher Himalayan gneiss just above the UMCT at Karuwa. The gneiss contains sheared and fractured kyanite blades (shown in the inset).

kyanite isograd is wrong. As the appearance of certain mineral is controlled by several factors like pressure, temperature and rock composition, isograds may not mark structural discontinuity. For example, the UMCT is believed to occur at the level of sillimanite isograd in the Gorkha area (Colchen et al. 1980) and garnet isograd in the Kathmandu area (Stöcklin 1980). Several other factors, as will be discussed in the following sections, should be considered when defining the UMCT.

Petrography

Mineral parageneses and texture of the Higher and Lesser Himalayan rocks in thin sections are very different and can be easily marked. The MCT zone rocks contain mainly the paragenesis 'Grt+Bt+Ms+Chl+Qtz±Ab' (mineral abbreviaiton after Kretz 1983) in metapelite and metapsammites. Remarkably the MCT zone rocks preserve abundant detrital minerals like tourmaline, feldspars and quartz. The detrital minerals are present either in the form of angular fragments of variable sizes (tourmaline and feldspar) or in the rounded form (quartz) under the microscope [(Fig. 7(B)]. Porphyroblastic minerals have grown mainly during and after the south-vergent shearing (D_3), and are probably associated with the UMCT movement. The porphyroblastic minerals like garnet, biotite and actinolite in metapelites, metapsammites and calc-schists contain s-shaped inclusions showing a top-to-south sense of shearing [Figs. 5(B) and (C)]. The garnet porphyroblast in the schists occur in different shapes (skeletal, elongated, tabular, s-shaped and eqidimensional) and sizes (0.1-5 mm). Many snowball garnets in the mica-rich layers display post-tectonic rim overgrowth across the main foliation [Fig. 5 (A)]. The feldspar augens in mylonitic gneisses and feldspar porphyroclasts in metapsammites show strong brittle fracturing, shearing and granulation [Fig. 5(D)]. It shows the enormity of shear strain in the MCT zone.

On the other hand, main mineral parageneses in the Higher Himalaya are 'Ky+Grt+Bt+Ms+Pl+Qtz' [Fig. 5(E)]. Different from the MCT zone rocks, chlorite occurs only as the secondary alteration product of garnet and biotite, and detrital feldspars and tourmaline are not observed in them. Similarly, garnets are equidimensional or elongated parallel to the foliation [Fig. 5(F)]. They are wrapped up by micaceous layers and accompanied by asymmetric pressure shadows showing a top-to-the-south sense of shearing [Fig. 5(F)]. The elongated garnets are fractured and altered to chlorite along the cracks and rims. They have inclusion-rich cores and inclusion-poor rims [Fig. 5(E)]. Kyanite blades are altered to phengitic and paragonitic muscovite. Biotite flakes commonly retrogressed to chlorite and phengitic muscovite. Feldspar grains in the Higher Himalayan rocks are plastically deformed to ellipsoidal form parallel to the foliation. In contrast to the feldspars in the Lesser Himalayan rocks, no brittle fracturing was observed in them. It indicates high temperature condition (>500°C) during deformation of the Higher Himalayan rocks (Passchier and Trouw 1996).

Style of Microfolding

The pelitic phyllites and schists of the Lesser Himalaya possess well-developed crenulation folds (F_4) and cleavages (S_4) developed during post-UMCT imbricate faulting (D_4) (Paudel and Arita 2000). The crenulation cleavage (S_4) becomes gradually intense from south to north and shows their maximum development in the upper part of the MCT zone. Crenulation cleavages are well delveloped in the chlorite zone of the TS II, in which the previous foliation (S_3) and crenulation cleavage (S_4) seem to be equally important [Fig. 6(A)]. In the biotite zone, the differentiated crenulation cleavage (S_4) clearly dominates over S_3 [Fig. 6(B)]. In the MCT zone, S_3 is preserved only as relict fold hinges defined by mica flakes oblique to the crenulation cleavages [Fig. 6(C)]. The gradual evolution of the crenulation cleavages in the Lesser Himalaya from south towards the UMCT shows that the intensity of deformation increased gradually from south to north during D_4 (Passchier and Trouw 1996). The high strain zone marked by the maximum development of crenulation cleavages and disappearance of the previous foliation and crenulation fold hinges coincides with the UMCT. In contrast to the Lesser Himalaya, the Higher Himalayan rocks show plastic flow structures with the development of rootless and ptygmatic folds. They are observable both in polished handspecimens and in thin sections [Figs. 5(F) and 6(D)]. These structures were formed at the deeper crustal levels before the UMCT thrusting.

Quartz Grain Microstructures

Quartz is very sensitive to deformation and displays various microstructures. The deformation process and resultant microstructures of quartz are widely dependent upon temperature, interstitial fluids, grain size and mineralogy of matrix phases (Passchier and Trouw 1996). However, if we consider rock types of similar grain size from the same tectonic environment, quartz microstructures may give important information as to the deformation mechanism, deformation history and temperature during deformation (Passchier and Trouw 1996; Kerrish et al. 1977).

Quartz microstructures were compared in psammitic phyllites and schists from the Lesser and Higher Himalaya along the Seti River valley. Quartz microstructures in the Lesser Himalaya show a gradual increase of deformation and dynamic recrystallization from south to north and reaches a maxima near the UMCT (for location see cross-section in Fig. 7(E)). The quartz grains in psammitic phyllites from the TS II (chlorite zone) show dominantly pressure solution and subordinate dynamic recrystallization and rare plastic deformation [Fig. 7(A)]. Pressure solution features are shown by strongly indented, curved and sutured contacts of adjacent quartz grains. Recrystallized quartz grains occur as polygonal aggregated in the matrix and along the pressure shadows of sheared porphyroclasts. Quartz clasts show core-and-mantle structure with relict clast surrounded by the polygonal aggregates. Strong undulatory extinction and development of deformation lamellae in quartz grains are indicative of intracrystalline creep.

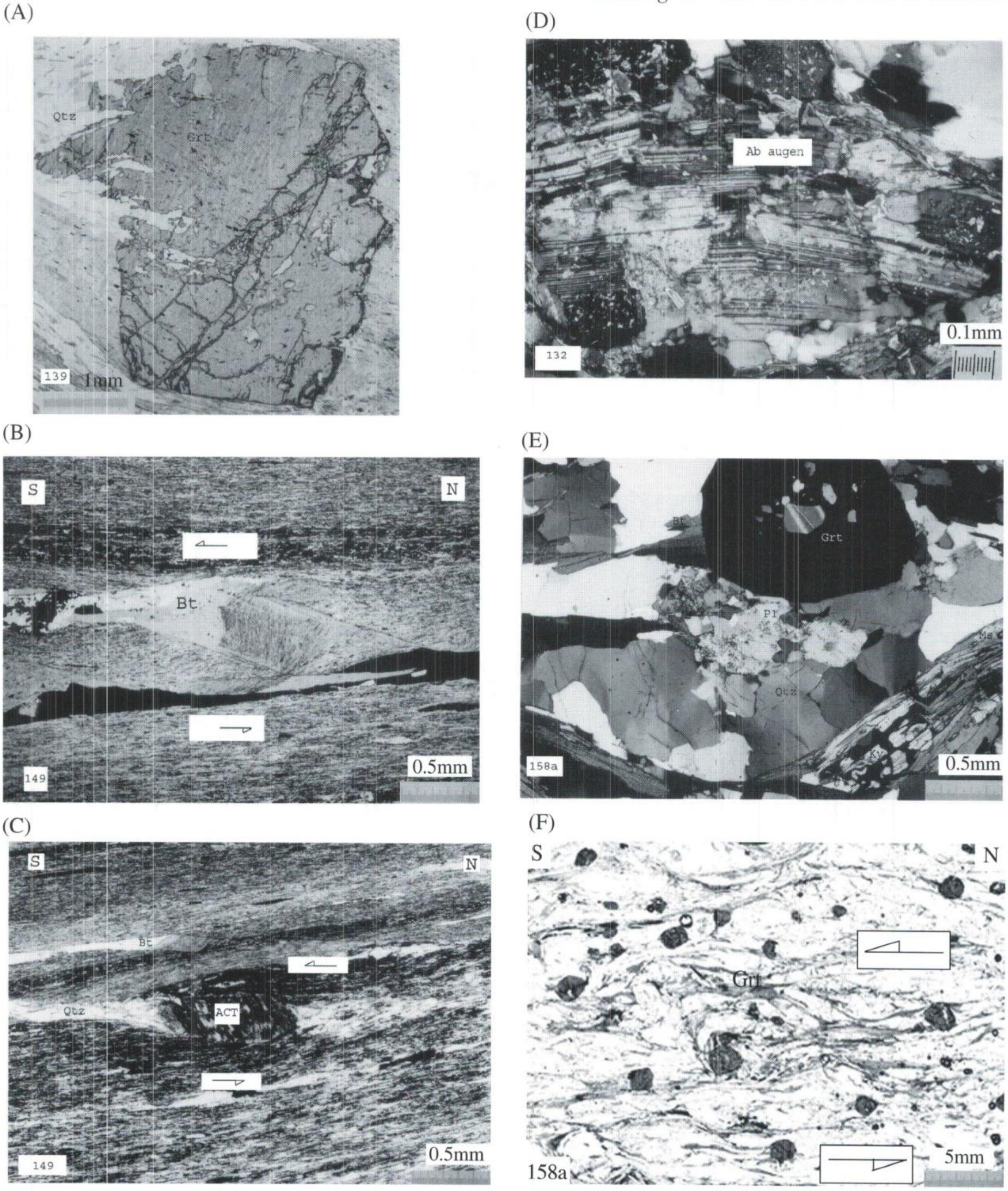

Fig. 5: Photomicrographs showing the difference in petrographic characters between the MCT zone and Higher Himalayan rocks along the Seti River valley. Sample numbers are shown at the bottom left corners. (A) Garnet porphyroblast in the pelitic schist of the MCT zone with syn-tectonic core and post-tectonic rim. (B) and (C) Syn-tectonic biotite and actinolite porphyroblast with s-shaped inclusions showing top-to-the-south sense of shearing in the MCT zone. (D) Intensely sheared and fractured plagioclase phenocryst in granitic augen gneiss from the MCT zone. (E) 'Ky+Grt+Bt+Pl+Ms+Qtz' mineral assemblages in the Higher Himalayan gneiss. Kyanite is highly fractured and altered to phengite (lower right corner). Garnet shows inclusion-rich core and inclusion free-rim. (F) Elongated garnet porphyroblasts accompanied by asymmetric pressure shadows with top-to-the-south sense of shearing observed on the polished surfaces of the Higher Himalayan gneiss. Rootless intrafolial fold is observed at the middle part of the photograph. Ky-Kyanite, Grt-Garnet, Bt-Biotite, Pl-Plagioclase, Ms-Muscovite, Qtz-Quartz, Ab-Albite, Act-Actinolite.

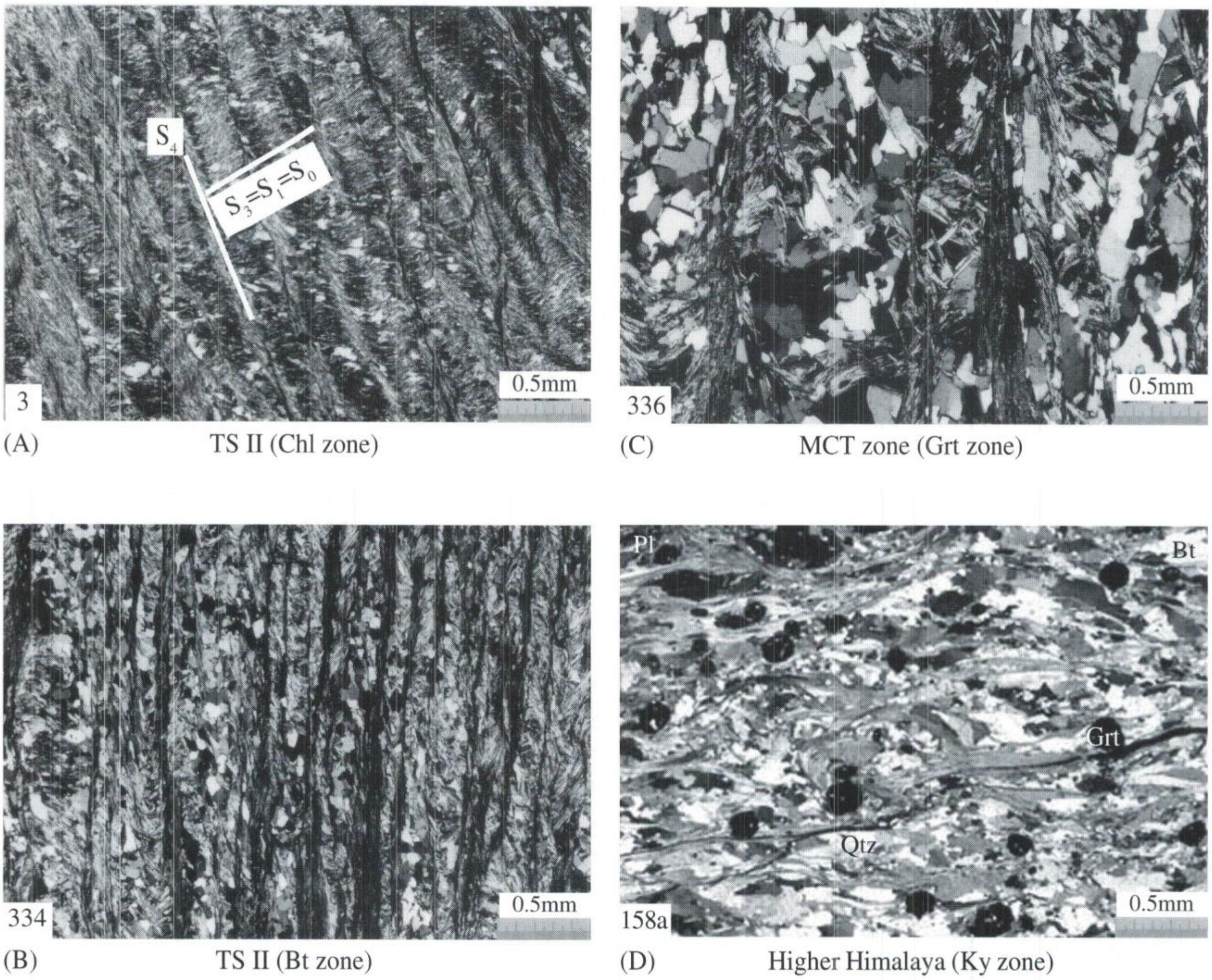

Fig. 6: (A), (B) and (C) Photomicrographs showing gradual development of the crenulation cleavages in the Lesser Himalaya from south to north. (D) Photomicrograph of the Higher Himalayan gneiss showing rootless folds. TS II-Thrust Sheet II, Chl- Chlorite, Grt-Garnet, Bt-Biotite, Ky-Kyanite, Qtz-Quartz, Pl-Plagioclase. Sample numbers are shown at the bottom left corners (see Fig.3 for sample locations).

In the biotite and garnet zones, the rocks have been deformed almost entirely by crystal plasticity, and no pressure solution features are observed. The quartz clasts have been strongly flattened and recrystallized in the biotite zone. The clasts are almost entirely transformed to polygonal sub-grains in continuity with the aggregates crystallized in the pressure shadows. However, the original grain shape can still be recognized [Fig. 7 (B)]. In the lower part of the MCT zone, original grains of quartz are not recognizable. The quartz is in the form of elongated, polygonal mosaics, generally flattened parallel to the foliation [Fig. 7(C)]. The contact between the quartz grains is either polygonal or interlobate or amoeboid. In the upper part of the MCT zone, quartz shows ribbon texture. The quartz grains look like needles arranged parallel to the foliation [Fig. 7(D)]. The ribbons are made up of strongly flattened polygonal quartz. The crystals show faint deformation lamellae and well-developed undulose extinction.

In contrast to the intense deformation, shearing and dynamic recrystallization in the Lesser Himalaya, the Higher Himalayan rocks show quartz microstructures characteristics of static recrystallization. Most of the rocks from the Higher Himalaya show exaggerated grain-growth microstructures [Fig. 8]. The elongated and platy minerals like biotite and muscovite. The quartz grains have straight or smoothly curved boundaries. Randomly orented muscovite and biotite grains have been partially or completely embedded in them. It is, however, important to note that the recrystallized polygonal quartz grains also show undulose extinction and sometimes subgrain development around the boundaries indicating a new cycle of deformation after static recrystallization. The above microstructures show that the Higher Himalayan rocks were recrystallized under static conditions (or it may be early high temperature deformation followed by annealing), most probably before the UMCT activity, and they experienced a shearing event related to the UMCT movement.

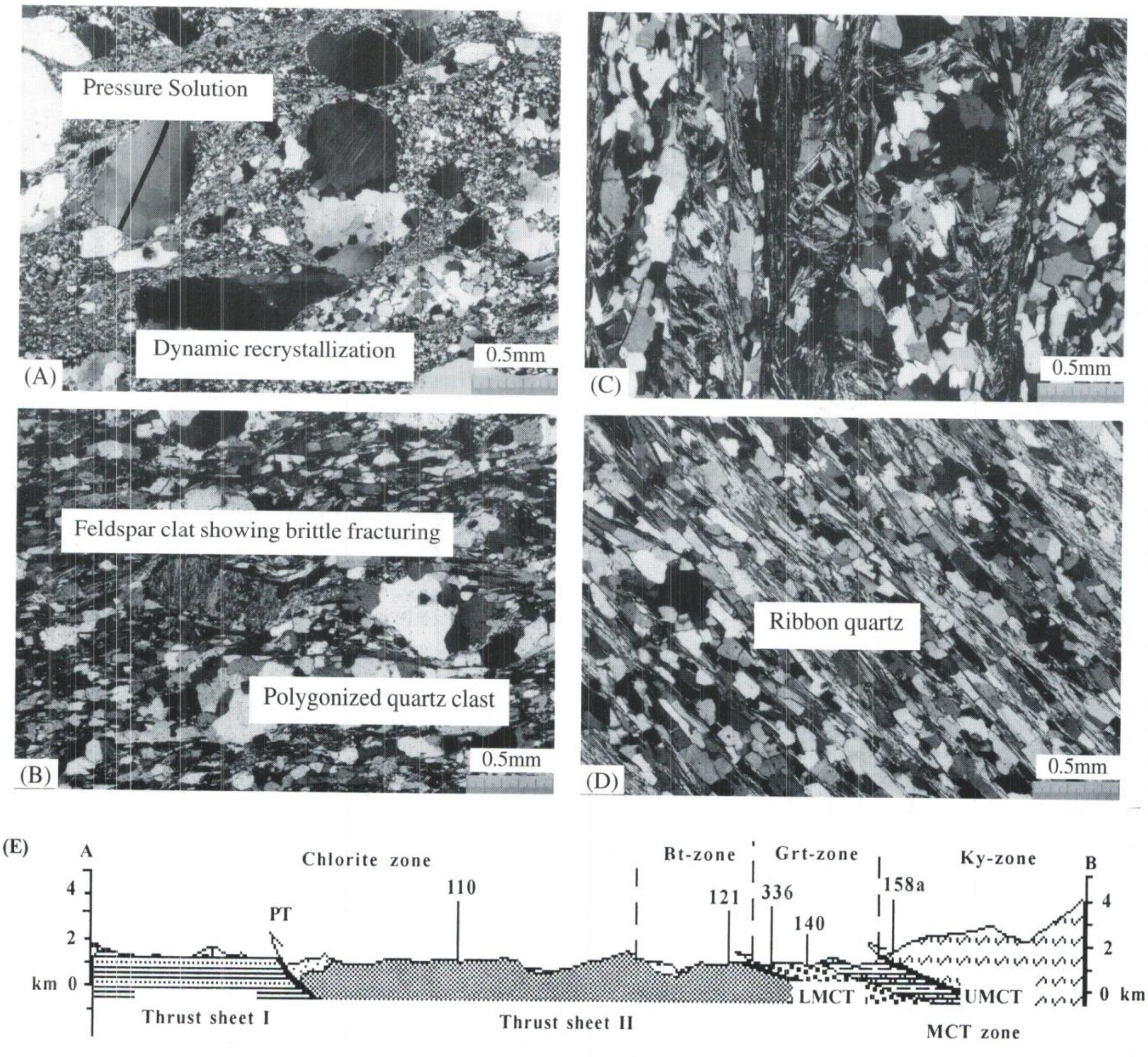

Fig. 7: Photomicrographs showing gradual evolution of the quartz grain microstructures with northward increasing deformation intensity in the Lesser Himalaya, and sharp discontinuity in quartz grain microstructures across the UMCT. (A) Pressure solution and dynamic recrystallization of quartz in metasandstone (sample no. 110). (B) Elongated and polygonized quartz (sample no. 121). (C) Quartz show plastic flow structure with strong elongation along the foliaiton in the MCT zone (sample no. 336). (D) Ribbon quartz seen near the UMCT (sample no. 141). (E) Simplified cross-section showing the positions of the samples. Bt-Biotite, Grt-Garnet, Ky-Kyanite, PT-Phalebas Thrust, LMCT-Lower Main Central Thrust, UMCT-Upper Main Central Thrust.

Thus the quartz grain microstructures indicate a sharp textural discontinuity and difference in recrystallization history across the UMCT. The UMCT is located where the MCT zone rocks show maximum shearing and elongation of quartz grains. It also coincides with maximum asymmetry in quartz c-axes patterns (Bouchez and Pêcher 1976).

Mineral Compositions

Garnet, muscovite and plagioclase compositional study was carried out in samples along the Seti valley to investigate whether they show any compositional differences, and hence the different metamorphic histories, between the Lesser and Higher Himalayan rocks. Compositional study was carried out by means of point analysis, profiling and X-ray compositional map analysis using the Electron Probe Microanalyzer (EPMA). Point analysis and profiling were done by the JEOL Superprobe 733 (specimen current 200 mA, accelerating voltage 15 kV, natural and synthetic silicates and oxides as standards) at Hokkaido University, Japan. All the raw data were corrected using conventional

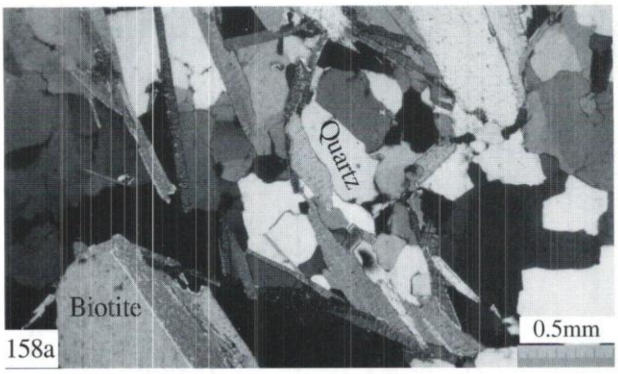

Fig. 8: Photomierograph showing exaggerate quartz-grain microstructure in the Higher Himalaya (sample no. 158a) (see Fig.7(E) for sample location).

ZAF correction procedures. The X-ray compositional map analysis was performed on the JEOL Superprobe JXA-8900M (specimen current 200 mA, accelerating voltage 15 kV) at the same university.

Garnet

Garnets from the MCT zone and the Higher Himalaya were analysed at cores and rims, and the data are projected on the Fe*-Mg-(Mn+Ca) triangle (Fig. 9). Compositional profiling and X-ray compositional map analysis for Mn-, Ca- and Mg-contents were done for the large porphyroblasts. Garnets in the MCT zone are spessartine rich (Mn 25-45% core, 15-35% rim) (Fig. 9). Individual garnets show bell-shaped Mn-profiles which is characteristic of prograde metamorphism (Spear 1993), with Fe gradually increasing and Mn decreasing towards the rims [Fig. 10(A)]. The profiles are reversed at the outermost rim, probably due to late-stage retrogression (Barker 1990). Particularly informative are the compositional X-ray maps of garnet porphyroblast from the MCT zone. The garnet porphyroblast in thin section seems as a post-tectonic grain grown across the foliation [Fig. 5(A)]. X-ray compositional map of the same garnet porphyroblast shows asymmetric zoning with core lying in the upper left corner [Fig. 11(A)]. It gives an impression that the upper left portion of the garnet was broken and removed by shearing. However, in fact, the core of the garnet grew synchronous with shearing, and rim overgrowth took place under relatively static conditions after the shear movement terminated.

Garnets from the Higher Himalaya are different from the Lesser Himalayan garnets in composition and zoning patterns. The Higher Himalayan garnets are rich in pyrope (Mg 20-25% core, 15-20% rim) and almandine (Fe 65-70% core, 70-75% rim) content. Compositional profiles of garnets from the Higher Himalaya [Fig. 10(B)] show plateau in the cores. However, the margins of garnets from the Higher Himalaya show different zoning patterns. Mostly they have retrograde zoning, with Fe and Mn increasing and Mg decreasing towards the rim [Fig. 10(B)]. Some grains show prograde mantle and retrograde zoning in the outermost part [Fig. 11(B)].

The above-mentioned compositional patterns of garnets are very consistent along several sections of central Nepal

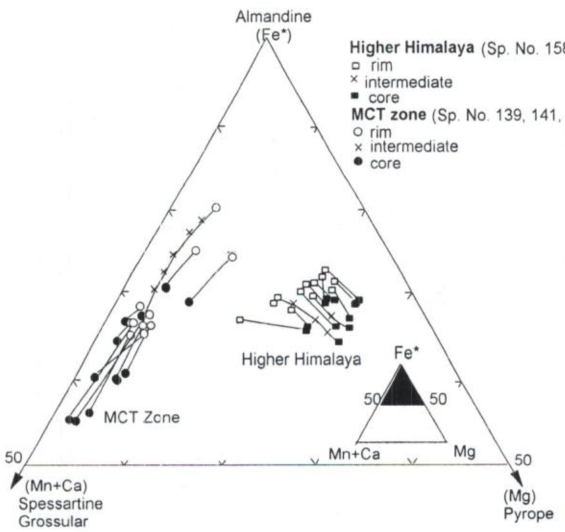

Fig. 9: Chemical composition of garnets from the Higher Himalaya and the Main Central Thrust zone. Fe* means total Fe as Fe^{+2} (see Fig. 3 for the location of the samples).

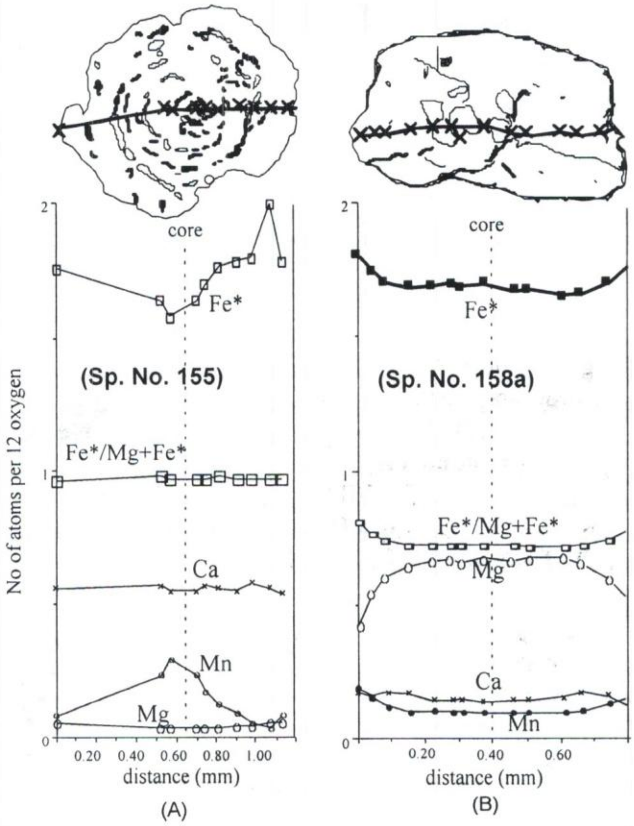

Fig. 10: Compositional profiles of garnets from the MCT zone (A) and the Higher Himalaya (B) along the Seti River valley (see Fig. 3 for location of the samples).

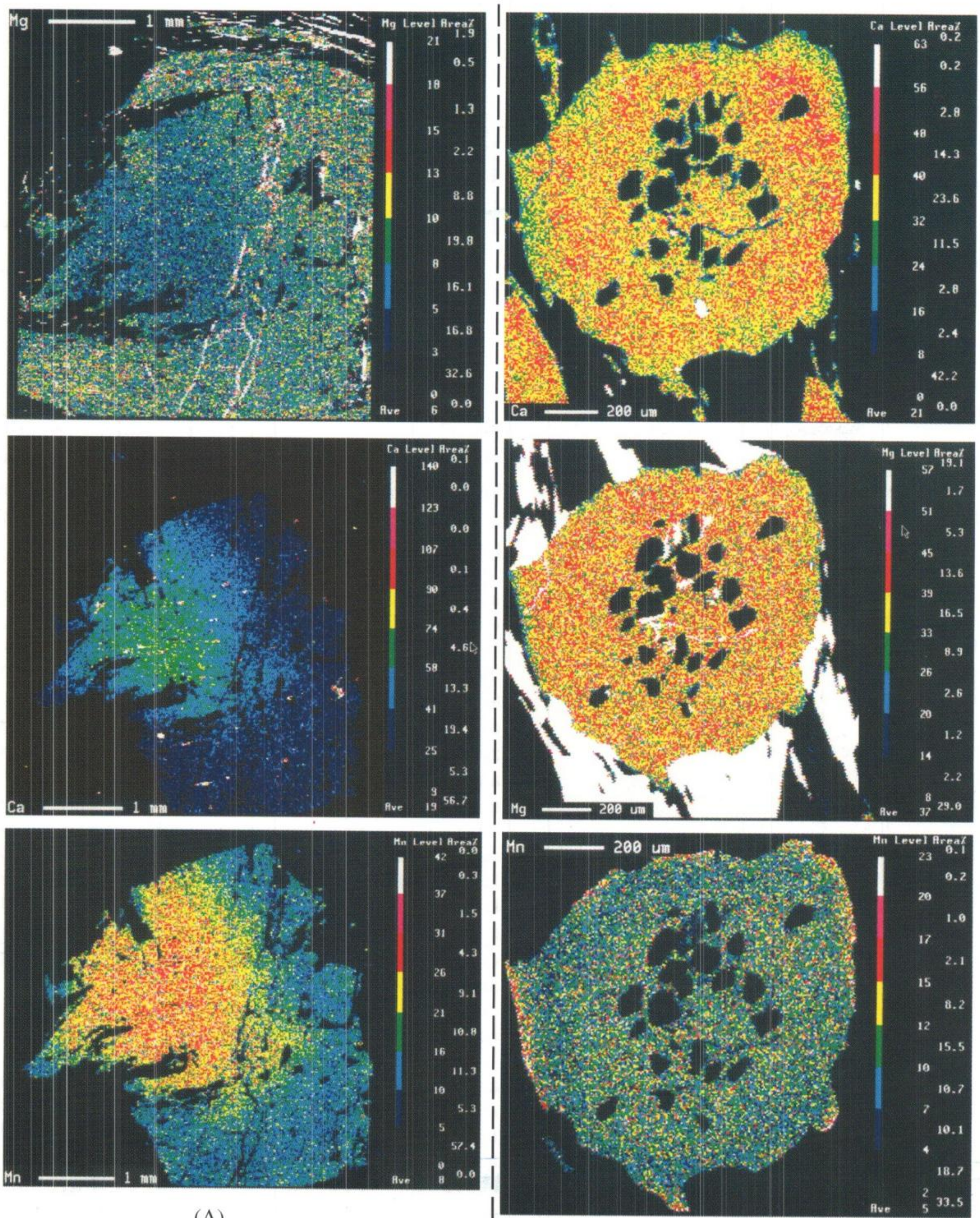

Fig. 11: Compositional X-ray maps of garnets. (A) Garnet from the MCT zone, sample no. 139. (B) Garnet from the Higher Himalaya, sample no. 158a (See Fig. 3 for sample locations).

e.g., Kali Gandaki valley (Le Fort et al. 1986; Vannay and Hodges 1996), Modi valley (Arita 1983; Kaneko 1997), Trisuli valley (Macfarlane 1995), and Kathmandu area (Rai et al. 1998) and point to different grades and histories of metamorphism between the Lesser and Higher Himalayas. The garnet compositions and zoning patterns from the Lesser Himalaya show a simple prograde growth during and after thrusting and subsequent retrogression under steady state during exhumation. They reflect a simple history depicted in Fig. 12 (E). However, the Higher Himalayan garnets show a complex history of growth, diffusion and retrogression (Spear 1993). Most probably, the Higher Himalaya experienced kyanite-grade prograde metamorphism before thrusting along the UMCT, which grew pyrope-rich garnets. Preservation of relict growth zoning in large porphyroblastic garnets [Fig. 11(B)] indicates that initially the Higher Himalayan garnets had growth zoning patterns. Partial diffusion and rehomogenization at the cores and retrograde reequilibration at the rims [Fig. 12(C)] took place due to thrusting along the UMCT and subsequent exhumation. Complete rehomogenization of the cores and retrogression of the rims [Fig. 12(D)] produced the zoning patterns as in Fig. 10(B). The UMCT marks the garnet composition changes from dominantly spessartine-rich varieties to pyrope-rich varieties, garnet zoning pattern changes from dominantly growth-type to retrograde-type.

Muscovite

Variations in white mica compositions can be adequately shown in a simple plot of Al_2O_3 against FeO* (Butler 1967). Generally, FeO* decreases and Al_2O_3 increases with higher metamorphic grades (Velde 1965; Butler 1967; Miyashiro 1973). All the recrystallized muscovites in the MCT zone and Higher Himalayan rocks of the present study are shown on a Miyashiro diagram (Fig. 13). A notable feature of the diagram is that most of the muscovites from the kyanite-grade rocks of the Higher Himalaya have lower Al_2O_3 (higher FeO*) content than those from the garnet-grade rocks of the MCT zone. Miyashiro (1973) pointed that muscovite from the staurolite and sillimanite zones and those from chlorite, biotite and garnet zones plot in distinctly different fields on the compositional diagrams as shown in Fig. 13. However, in the present case, muscovite from the MCT zone plot in both the fields, while muscovite from the Higher Himalayan rocks bearing pyrope-rich garnet and kyanite do not plot in the field of staurolite and sillimanite zones but plot in the field of chlorite, biotite and almandine zones. It indicates that most of the muscovites of the Higher Himalayan rocks were recrystallized or reequilibrated at metamorphic conditions lower than the kyanite grade as suggested by Arita (1983)

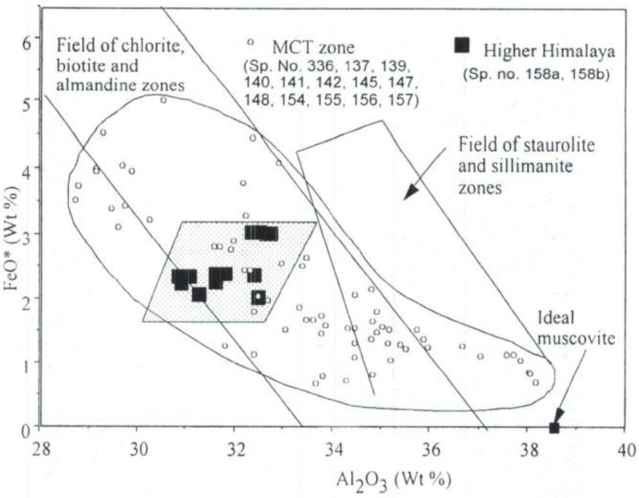

Fig. 13: FeO*-Al_2O_3 plot of the white mica compositions from the central Nepal Himalaya. FeO* means total FeO+Fe_2O_3 as FeO. Fields of chlorite, biotite, and almandine zones and staurolite and sillimanite zones after Miyashiro (1973) (see Fig. 3 for sample locations).

and Paudel and Arita (1998). Most probably, the retrograde reaction of the type 'Ms+Bt+Kfs+Qtz+H_2O=Phengites' (Velde 1965) occurred at the base of the Higher Himalaya in the presence of high pH_2O prevailed during the UMCT activity (Le Fort 1975). Retrograde metamorphism at the base of the Higher Himalaya is also shown by the retrograde zoning patterns of garnet, alteration of kyanite into muscovite and paragonite and frequent intergrowth of biotite with muscovite (Arita 1983; Caby et al. 1983; Paudel and Arita 1998). Therefore, muscovite compositions also mark a sharp metamorphic discontinuity between the Lesser and the Higher Himalayan rocks and provide a basis for locating the UMCT. The UMCT is located where the white mica compositions change from pure muscovite (having compositions close to ideal muscovite) to phengitic muscovite.

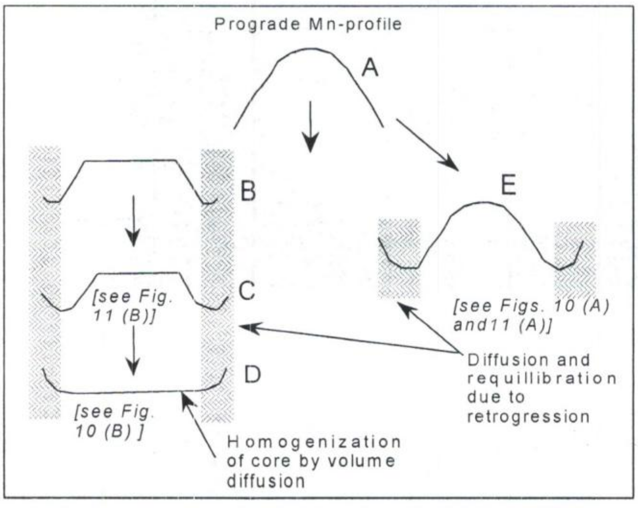

Fig. 12: Schematic diagrams showing possible evolution of Mn-profile shape of garnet during prograde growth and later modification by diffusion.

Plagioclase

Representative plagioclase compositions from the area are given in Table 1. Plagioclase from the Lesser Himalaya are almost entirely albitic (≤6% An). The An-content sharply increases to ≥20% in the Higher Himalaya. This also shows a marked difference in the metamorphic grade below and above the UMCT as shown by the other evidences explained above.

CONCLUSIONS

Several criteria demonstrate that the MCT is a sharp and discordant tectono-metamorphic boundary separating the Higher Himalaya from the Lesser Himalaya in central Nepal. In the Pokhara area, the MCT lies where

1. the lithology changes from interlayered psammitic, calcareous and carbonaceous phyllites and schists,

Table 1: Representative plagioclase analyses from the Pokhara area, central Nepal.

	Higher Himalaya				MCT zone										
Sample No.	158b	158b	158a	158a	156	156	152a	132	132	132	132	159	331	107	107
Rock type	Gneiss	Gneiss	Gneiss	Gneiss	Schist	Schist	Schist	Gneiss	Gneiss	Gneiss	Gneiss	Phyllite	Phyllite	Phyllite	Phyllite
Analysed Position	Core	Rim	Core	Rim	Core	Core	Core	Core	Rim	Core	Rim	Core	Core	Core	Core
SiO_2	65.48	65.10	63.12	63.31	67.79	68.11	68.13	69.49	69.39	68.85	69.34	68.93	69.08	71.78	71.74
Al_2O_3	22.00	22.01	22.73	23.08	19.63	20.48	19.97	19.80	20.37	19.72	19.49	19.37	20.08	19.51	19.07
CaO	3.32	3.29	4.28	4.30	0.66	1.29	0.55	0.36	0.69	0.51	0.33	0.10	0.80	0.22	0.03
Na2O	10.32	10.44	9.43	9.40	11.99	11.32	11.94	11.38	10.84	11.09	11.45	12.20	11.42	8.47	8.53
K2O	0.04	0.05	0.07	0.11	0.00	0.06	0.02	0.08	0.28	0.11	0.07	0.12	0.08	0.13	0.05
Total	101.16	100.88	99.62	100.20	100.07	101.25	100.61	101.11	101.57	100.27	100.69	100.72	101.47	100.11	99.42
Cations for 32 oxygens															
Si	11.423	11.397	11.208	11.173	11.879	11.793	11.865	11.987	11.921	11.974	12.011	11.974	11.900	12.302	12.329
Al	4.523	4.542	4.756	4.801	4.055	4.179	4.099	4.025	4.125	4.042	3.980	3.965	4.076	3.940	3.918
Ca	0.621	0.618	0.814	0.812	0.124	0.239	0.102	0.067	0.127	0.094	0.062	0.019	0.148	0.040	0.006
Na	3.490	3.542	3.248	3.216	4.072	3.799	4.032	3.805	3.612	3.739	3.846	4.110	3.815	2.815	2.884
K	0.009	0.010	0.015	0.025	0.000	0.014	0.005	0.018	0.061	0.025	0.015	0.025	0.018	0.028	0.010
Total	20.07	20.11	20.05	20.04	20.13	20.02	20.10	19.91	19.85	19.88	19.93	20.11	19.98	19.15	19.16
Ab (%)	85	85	80	79	97	94	97	98	95	97	98	99	96	98	99
An (%)	15	15	20	20	3	6	2	2	3	2	2	0	4	1	0
Or (%)	0	0	0	1	0	0	0	0	2	1	0	1	0	1	0

metacarbonates and quartzites of the Lesser Himalaya to coarse-grained banded gneisses and schists of the Higher Himalaya,

2. detrital minerals like feldspar and tourmaline completely disappear in the metasediments,
3. the deformation style in feldspar changes from dominantly brittle fracturing to plastic flow,
4. the highly differentiated crenulation cleavage show their maximum development,
5. the plastic flow textures with rootless and ptygmatic folds appear for the first time,
6. quartz microstructures change from ribbon structure to exaggerate grain growth microstructures,
7. pre-tectonic garnets accompanied by asymmetric pressure shadows appear for the first time,
8. garnet composition changes from dominantly spessartine-rich varieties to pyrope-rich varieties, and garnet zoning pattern changes from dominantly growth-type to retrograde-type,
9. white-mica composition changes from muscovite to phengite, and
10. plagioclase composition changes from albite to oligoclase.

Some or all of the above features should be recognized across the MCT in other sections of the Himalaya and provide important criteria to locate the MCT.

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REFERENCES

Arita, K., 1983, Origin of the inverted metamorphism of the lower Himalayas, central Nepal. Tectonophysics, v. 95, pp. 43-60.

Arita, K., Hayashi, D., and Yoshida, M., 1982, Geology and structure of the Pokhara-Piuthan area, central Nepal. J. Nepal Geol. Soc., Sp. Issue, v. 2, pp. 5-29.

Barker, A. J., 1990, Introduction to Metamorphic Textures and Microstructures: Blackie, New York, 162 p.

Bouchez, J. L., and Pêcher, A., 1976, Microstructures and quartz preferred orientations in quartzites of the Annapurna area (central Nepal), in the proximity of the Main Central Thrust. Him. Geol., v. 6, pp. 118-132.

Brunel, M, and Kienast, J. R., 1986, Étude pétro-structurale des chevauchements ductile Himalayens sur la transversale de l'Everest-Makalu (Nepal oriental). Canadian Jour. Earth Sci., v. 23, pp. 1117-1137.

Brunel, M., Colchen, M., Le Fort, P., Mascle, G., and Pêcher, A., 1979, Structural analysis and tectonic evolution of the central Himalaya of Nepal, *in* Saklani, P. S., ed., Structural Geology of Himalaya, pp. 247-264.

Butler, B. C. M., 1967, Chemical studies of minerals from the Moine schists of the Ardnamurchan area, Argyllshire. Scot. Jour. Petrol., v. 8, pp. 233-267.

Caby, R., Pêcher, A., and Le Fort, P., 1983, Le grand Chevauchement central himalayen: nouvelles données su le métamorphisme inverse à la base de la Dalle du Tibet: Revue de Géographie physique et de Géologie Dynamique, Paris, v. 24, pp. 89-100.

Colchen, M., Le Fort, P., and Pêcher, A., 1980, Carte géologique Annapurnas-Manaslu-Ganesh Himalaya du Népal au 1/200 000è. Centre National de la Recherche Scientifique, Paris.

Frank, W., and Fuchs, G., 1970, Geological investigations in western Nepal and their significance for the geology of the Himalayas. Geologischen Rundschau, v. 59, pp. 552-580.

Fuchs, G., and Frank, W., 1970, The geology of west Nepal between the rivers Kali Gandaki and Thulo Bheri. Jahrb. Geol. Bund., v. 18, pp. 1-103.

Gansser, A., 1964, Geology of the Himalayas: Interscience Publisher, London, 289 p.

Hashimoto, S., Ohta, Y., and Akiba, C., 1973, Geology of the Nepal Himalayas. Saikon, Tokyo, 286 p.

Heim, A., and Gansser, A., 1939, Central Himalaya, geological observations of the Swiss expedition 1936. Mémoires de la Société Helvétique des Sciences Naturelles, Zürich, v. 73, 245 p.

Hubbard, M. S., 1996, Ductile shear as a cause of inverted metamorphism. example from the Nepal Himalaya: Jour. Geol., v. 104, pp. 493-499.

Hubbard, M. S., Harrison, T. M., 1989, $^{40}Ar/^{39}Ar$ age constraints on deformation and metamorphism in the Main Central Thrust zone and Tibetan Slab, eastern Nepal Himalaya. Tectonics, v. 8, pp. 865-880.

Kaneko, Y., 1997, Two-step exhumation model of the Himalayan metamorphic belt, central Nepal: Jour. Geol. Soc. Japan, v. 103, pp. 203-226.

Kerrish, R., Beckinsale, R. D., and Durham, J. J., 1977, The transition between deformation regimes dominated by intercrystalline diffusion and intracrystalline creep evaluated by oxygen isotope thermometry. Tectonophysics, v. 38, pp. 241-257.

Kretz, R., 1983, Symbols for rock-forming minerals. Amer. Miner., v. 68, pp. 277-279.

Le Fort, P., 1975, Himalayas: the collided range, present knowledge of the continental arc. Amer. Jour. Sci., v. 275A, pp. 1-44.

Le Fort, P., Pêcher, A., and Upreti, B. N., 1986, A section through the Tibetan Slab in central Nepal (Kali Gandaki Valley): mineral chemistry and thermobarometry of the Main Central Thrust zone. Sciences de la Terre, Nancay, Mémoire 47, pp. 211-228.

Macfarlane, A. M., 1995, An evaluation of the inverted metamorphic gradient at Langtang National Park, central Nepal Himalaya. Jour. Metamor. Geol., v. 13, pp. 595-612.

Miyashiro, A., 1973, Metamorphism and Metamorphic Belts. Allen and Unwin, London, 492 p.

Passchier, C. W., and Trouw, R. A. J., 1996, Microtectonics: Springer-Verlag, Berlin, 289 p.

Paudel, L. P., and Arita, K., 2000, Tectonic and polymetamorphic history of the Lesser Himalaya in central Nepal. Jour. Asian Earth Sci., v. 18, pp. 561-584.

Paudel, L. P., and Arita, K., 1998, Geology, structure and metamorphism of the Lesser Himalayan metasedimentary sequence in Pokhara region, western Nepal. J. Nepal Geol. Soc., Sp. Issue, v. 18, pp. 97-112.

Pêcher, A., 1975, The Main Central Thrust of the Nepal Himalaya and the related metamorphism in the Modi-Khola cross-section (Annapurna Range). Him. Geol., v. 5, pp. 115-131.

Pêcher, A., 1977, Geology of the Nepal Himalaya: deformation and petrography in the Main Central Thrust Zone, *in* Ecologie et Géologie de l'Himalaya: Colloques Internationaux du Centre National de la Recherche Scientifique, Paris, v. 268, pp. 301-318.

Rai, S. M., Guillot, S., Le Fort, P., and Upreti, B. N., 1998, Pressure-temperature evolution in the Kathmandu and Gosainkund regions, central Nepal. Jour. Asian Earth Sci., v. 16, pp. 283-298.

Sakai, H., 1985, Geology of the Kali Gandaki supergroup of the Lesser Himalaya in Nepal. Memoirs Fac. Sci., Kyushu Univ. (Japan), Series D, Geology, v. 25, pp. 337-397.

Schelling, D., Arita, K., 1991. Thrust tectonics, crustal shortening, and the structure of the far-eastern Nepal Himalaya. Tectonics v. 10, pp. 851-862.

Sorkhabi, R. B., Valdiya, K. S., and Arita, K., 1999, Cenozoic uplift of the Himalayan Orogen: chronologic and kinematic patterns. Gond. Res. Group Memoir, v. 6, pp. 189-206.

Spear, F. S., 1993, Metamorphic phase equilibria and pressure-temperature-time paths. Miner. Soc. Amer. Monograph, Washington, 799 p.

Spencer, D. A., 1995, Where is (is there a?) Main Central Thrust in the NW Himalayas of Pakistan? J. Nepal Geol. Soc., Sp. Issue, v. 11, pp. 63-72.

Stöcklin, J., 1980, Geology of Nepal and its regional frame. Jour. Geol. Soc. Lond., v. 137, pp. 1-34.

Upreti, B. N., 1999, An overview of the stratigraphy and tectonics of the Nepal Himalaya. J. Asian Earth Sci., v. 17, pp. 577-606.

Valdiya, K. S., 1980, Two intracrustal boundary thrusts of the Himalaya. Tectonophysics, v. 66, pp. 323-348.

Valdiya, K. S., 1983, Lesser Himalayan Geology: crucial problems and controversies: Curr. Sci., v. 52, pp. 839-857.

Vannay, J. C., and Hodges, K. V., 1996, Tectonothermal evolution of the metamorphic core between the Annapurna and Dhaulagiri, central Nepal. Jour. Metamor. Geol., v. 14, pp. 635-656.

Velde, B., 1965, Phengite micas: synthesis, stability and natural occurrence. Amer. Jour. Sci., v. 263, pp. 886-913.