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Geology, structure and metamorphism of the Lesser Himalayan metasedimentary sequence in Pokhara region, western Nepal

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ABSTRACT

The Lesser Himalaya in the Pokhara region, western Nepal, comprises low grade metamorphic rocks of the Nawakot Complex in the south and mylonitic rocks of the Main Central Thrust Zone in the north. It is delimited in the north by the Main Central Thrust (MCT), which brings the kyanite gneisses of the Higher Himalayan Crystallines over the Lesser Himalayan metasediments. Cross-cutting pegmatite veins injected prior and posterior to the main deformation event are reported for the first time from the MCT Zone. The Phalebas Thrust, Lumle Thrust and the MCT are the major structural discordances, which divide the area into various tectonic zones with different style and intensity of deformation. At least three deformation events are recognised in each tectonic zone. Sense of shearing is always top to the south in the MCT Zone.

The Higher Himalayan Crystallines and the Lesser Himalayan metasediments show marked differences both in history and grade of metamorphism. The gneisses of the Higher Himalayan Crystallines exhibit polyphase metamorphism. The older high grade (kyanite-grade) metamorphism formed pyrope-rich cores in garnets and plagioclase with An>20%. The younger retrograde metamorphism caused to recrystallise phengitic muscovite and to form retrograde chemical zoning in garnets. The Lesser Himalaya shows syn- to post-tectonic, garnet-grade, inverted prograde metamrophism. The grade of metamorphism increases from chlorite zone in the south to the biotite zone below the Lumle Thrust and the garnet zone in the MCT Zone. The garnets show prograde zoning pattern, muscovite gradually becomes poor in celadonite component, biotite becomes rich in Ti-content, and Ca-amphiboles become rich in Na and K from south towards the MCT. Both the Lesser Himalayan metasediments and the Higher Himalayan Crystallines have experienced the late-stage weak regression due to uplift and erosion.

INTRODUCTION

The western Nepal Lesser Himalaya in the Pokhara-Tansen area is devoid of any crystalline thrust sheets and exposes a thick sequence of metasediments. Regional geology of the area is studied by many geologists in the past (Hagen, 1969; Fuchs and Frank, 1970; Bordet et al., 1972; Hashimoto et al., 1973; Arita et al., 1982; Sakai, 1983 and 1985). Detailed geology of some parts of the area is found in published papers (Upreti et al., 1980; Sakai, 1985; Hirayama et al., 1988; Paudel and Dhital, 1996). Similarly, many geologists have taken traverses south of the Annapurna Range to study the metamorphic features of the Main Central Thrust (MCT) Zone (Le Fort, 1975; Pêcher, 1975; Arita, 1983; Le Fort et al., 1986; Vannay and Hodges, 1996). As a result, metamorphic patterns, mineral chemistry and P-T conditions of the MCT zone and the Higher Himalayan Crystallines are well constrained. Most outstanding feature of the area is the inverted metamorphic zonation, where the grade of metamorphism appears to increase northwards (structurally upwards) from the chlorite and biotite zones in the Lesser Himalaya through the garnet zone in the MCT Zone and to the kyanitesillimanite zones in the Higher Himalya (Le Fort, 1975; Arita, 1983). However, very little attention has been paid to the metamorphic patterns of the lower grade rocks of the Lesser Himalaya, which are believed to exhibit typical inverted metamorphism (Gansser, 1964).

Structural mapping of the Lesser Himalaya and the MCT Zone in the Pokhara-Syangja-Kusma area was carried out during the study. In order to investigate the metamorphic patterns in the area, samples were collected from various metamorphic zones (chlorite to kyanite zones) along the Pokhara-Syangja motor road and the Seti Khola valley and they were subjected to petrographic examination and microprobe analyses. This paper presents the defrormation features and metamorphic characteristics of the area based on the new data.

TECTONO-LITHOSTRATIGRAPHY

The Lesser Himalaya in the study area is divided into the Syangja, Pokhara and the MCT Zones by the Phalebas and the Lumle thrusts from south to north, respectively (Fig. 1 and 2). The Lesser Himalaya is overthrust by the kyanite gneisses of the Higher Himalayan Crystallines along the MCT. The Lesser Himalaya in central Nepal is made up of the late Pre-Cambrian to early Palaeozoic rocks of the Nawakot Complex and is divided into the Lower and Upper Nawakot groups (Stöcklin, 1980). Those lithostratigraphic units can be recognised also in the present area. The Pokhara Zone comprises the lower part of the Lower Nawakot Group and the Syangja Zone comprises the middle part of the Lower Nawakot Group.

Lower Nawakot Group

Kuncha Formation

The Kuncha Formation is widely distributed in the Pokhara area (Fig. 1). It is composed of very thick (>1500 m), rather monotonous alternating sequence of metasandstone and phyllite with occasional metaconglomerate bands and sill-like bodies of amphibolite. Arkosic metasandstone is a major component of the formation. It is often massive and very thick bedded (20 cm to 1 m) and forms steep cliffs in the area. It consists of ovoidal as well as angular clasts of quartz and feldspars (up to 5 mm) disseminated in phyllitic matrix. The clasts are stretched along the foliation. Graded bedding is often observed in them. The metaconglomerate bands encountered at various places consist of up to 3 cm long stretched quartz pebbles. The base of the Kuncha Formation is nowhere exposed and the upper limit with overlying the Fagfog Quartzite is sharp and conformable. It is abruptly overlain by the metamorphic crystalline rocks of the MCT zone in the north along the Lumle Thrust.

Fagfog Quartzite

The Fagfog Quartzite repeatedly occurs in the area due to folding and faulting. The lower part of the formation contains bedded (2-3 m), medium to coarse-grained white quartzite. In the middle and upper parts of the formation, bedded green quartzite (0.5-2 m) alternating with grey-green phyllite is predominant. The quartzite shows yellow, orange and pink color when weathered. The quartzite frequently contains current ripples and trough cross-laminae. Several metres thick sill-like bodies of metabasites of dioritic character are recorded. They are almost invariably associated with green chloritic phyllite. Some bodies enclose several patches of chloritic phyllite. Maximum thickness of this formation is about 1000 m at Naudanda.

Dandagaon Phyllite

The Fagfog Quartzite is gradationally overlain by a phyllitic sequence, which occupies the cores of major synclines in the area. It comprises mainly arkosic metasandstone, green phyllite and parallel laminated grey quartzite. In some parts it contains several metres thick massive, white quartzite and metaconglomerates. Calc-phyllite and schist is observed to the north of Birethanti along the Bhurungdi Khola. The formation is up to 600 m thick in the study area.

Nourpul Formation

The Nourpul Formation occupies the core of an anticline along the Andhi Khola. It is also exposed along the Kali Gandaki valley south of Phalebas. The exposed lower part consists of

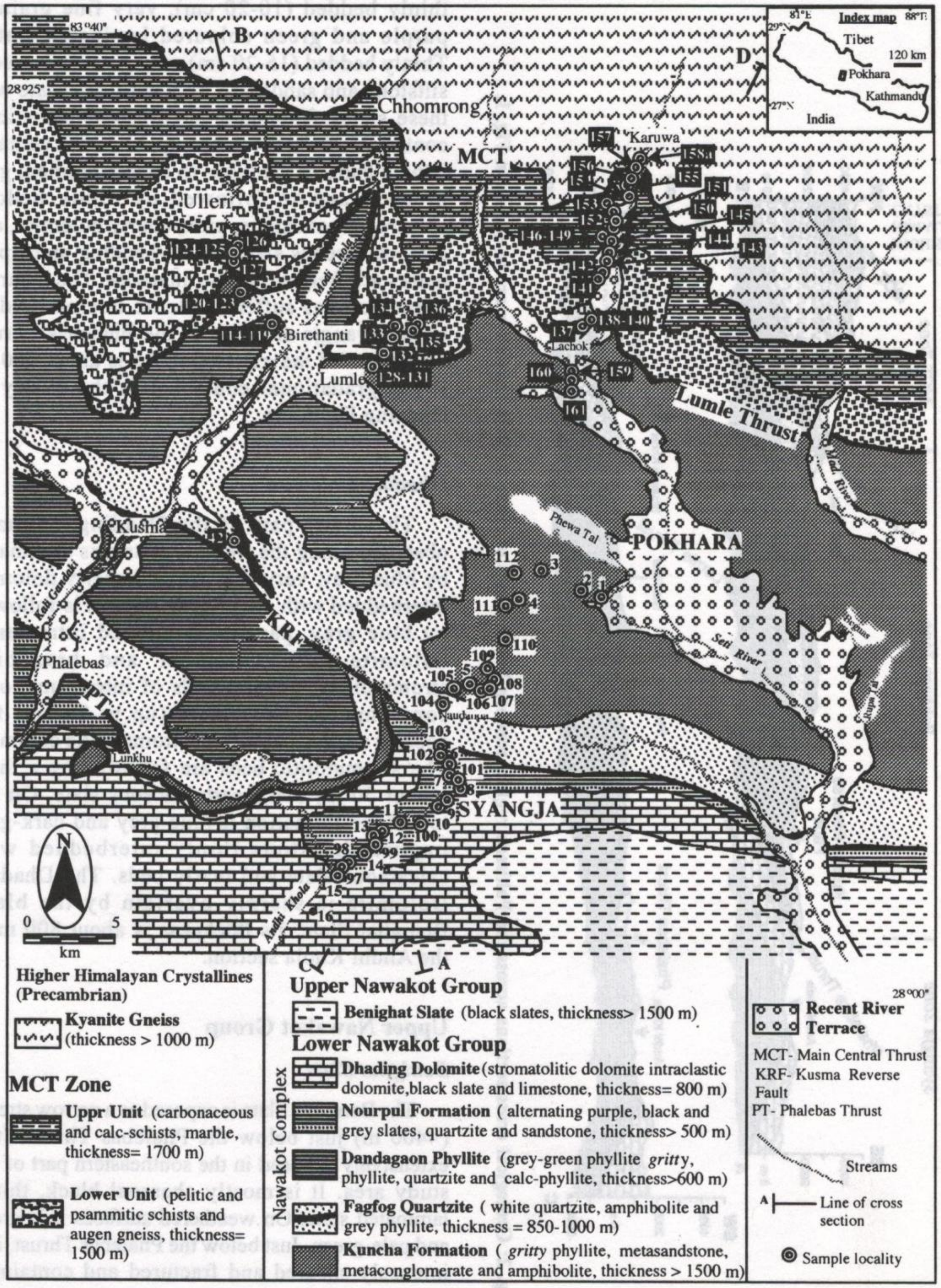

Fig. 1: Geological map of the Pokhara region, western Nepal Lesser Himalaya.

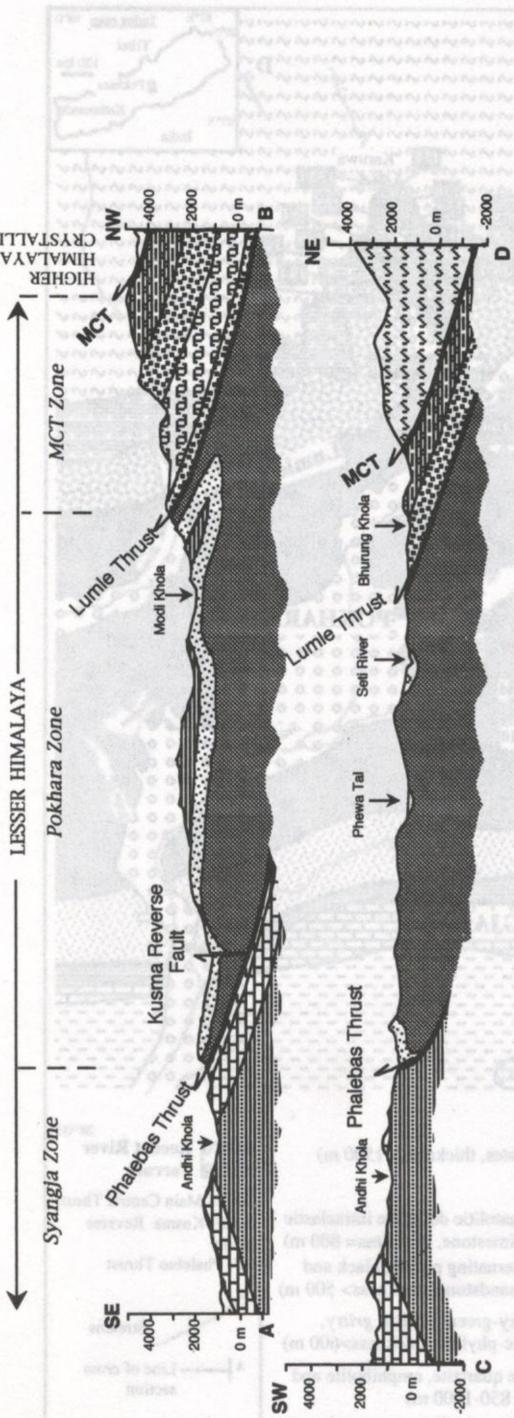

Fig. 2: Geological cross sections across the Pokhara region, western Nepal. Lines of cross sections and index are as shown in Fig. 1.

thinly bedded (10-20 cm), very fine grained, purple and green coloured laminated slates. Thinly bedded (15-20 cm) grey green calcareous siltstone and sandstone frequently alternate with these slates. The slate and siltstone sometimes contain mudcracks. In the upper part it contains a thick band of medium- to coarse-grained, grey green quartzite followed by thinly bedded calcareous sandstone, pink, cherty dolomite, and grey calcareous slate. Cross-bedding and ripple marks are frequent in the quartzite. The Nourpul Formation has suffered intense internal folding in the Syangja area due to the Phalebas Thrust. Thickness of the exposed rocks is about 500 m. It has gradational contact with the overlying Dhading Dolomite.

Dhading Dolomite

The lower part of the Dhading Dolomite observed along the ridge of Satam is dominated by blue grey, very fine grained cherty dolomite interbedded with silver grey slate. It is followed by blue grey, parallel laminated intraclastic dolomite with columnar and branching stromatolites. Several beds of intraformational conglometates with large (up to 15 cm) flat cobbles occupy the base of stromatolitic dolomite. The stromatolitic beds are followed by a thick (about 50 m) black carbonaceous slate. On the top of the formation is blue-grey and dark-grey impure limestone thinly interbedded with calcareous slate and marly beds. The Dhading Dolomite is sharply overlain by the black Benighat Slate. Its thickness is about 800 m in the Andhi Khola section.

Upper Nawakot Group

Benighat Slate

The Benighat Slate is exposed as a narrow stretch (<400 m) just below the Phalebas Thrust. It is extensively exposed in the southeastern part of the study area. It is mostly charcoal black, thinly laminated slate. On weathered surfaces it is green and pale-green. Just below the Phalebas Thrust, it is intensely sheared and fractured and contains a number of folded quartz veins. Slaty cleavage developed oblique to the bedding is a prominent feature of this slate.

MCT Zone

A more than 3 km thick, intensely sheared and recrystallised rock sequence of the MCT Zone is lithologically divided into the Lower Unit with psammitic and pelitic schist and the Upper Unit with carbonaceous and calcareous schists.

Lower Unit

The Lower Unit comprises a thick sequence of interbanded, coarse grained garnetiferous pelitic and psammitic schists with few bands of green chloritic schist and quartzite. Garnetiferous psammitic and pelitic schist with snowball garnet porphyroblasts up to 5 mm in diameter appear abruptly north of the Lumle Thrust. A very thick (about 100 m) yellow foliated quartzite band within the garnetiferous schist is exposed at several places. Coarse grained amphibolite lenses are observed at various level interbanded with the schist. Mylonitic augen gneiss (Ulleri augen gneiss of Le Fort, 1975) is an important component of this unit. Lenticular bodies of augen gneisses are intercalated with the garnetiferous schist at the lower part of the unit. They contain rotated and fractured quartz and feldspar augens up to 6 cm in diameter. Stretched quartz ribbons and feldspar augens define a very strong lineation. Mineral lineations possessed by the preferred orientation of mica flakes are well observed on the foliation planes. Pegmatitic veins discordantly cutting the country rock are found in the lower part of the MCT Zone. They are described in detail in seperate section.

Upper Unit

The upper part of the MCT Zone is dominated by black graphitic schist, calc-schist and marble. A few bands of quartzite and pelitic and psammitic schist are found in the uppermost part. Graphitic schist interbanded with parallel laminated black schist is exposed along the Seti valley. It is with or without snowball garnets. The graphitic schist is followed by calc-schists and yellowish white saccharoidal marble. The marble bands can be traced uninterruptedly in the study area. In the upper part of the unit, a band of cream coloured quartzite and pelitic and psammitic schist interbanded with the calc-schist occurs.

Higher Himalayan Crystallines

Present study covers only the lower part of the HHC. Kyanite gneisses of the lower part of the Higher Himalayan Crystallines start at the Karuwa village in the Seti valley and north of Chhomrong in the Modi valley. They abruptly override graphitic and calcareous schists of the MCT Zone. They are composed of grey and dark grey, very coarse grained mylonitic gneiss and banded gneiss containing blue green kyanite and almandine garnet porphyroblasts. Kyanite porphyroblasts are as large as 7 cm in length.

PEGMATITES IN THE MCT ZONE

Two cross cutting granitic pegmatite veins injected in the garnetiferous schist occur in the MCT zone of the Modi Kohla area (Fig. 3). They are exposed at Sudame (28° 20' 18'' N, 83° 44' 35'' E) and occupy the basal part of the MCT Zone in the proximity of the Ulleri augen gneiss. The older vein, about 15 cm thick, is strongly sheared, boudinaged, and foliated with the surrounding rocks. It contains up to 0.5 cm thick books of muscovite as large as 2 cm in length. They are sheared, bent and sometimes deformed by kinking. The pegmatite contains many xenoliths of the pelitic schist in the form of thin layers to irregular patches. They are completely embedded in the pegmatite. Besides this, the pegmatite contains many irregular dark spots which are made of spessartine rich skeletal garnet. Probably they were preferably grown along the included xenoliths.

Sharp, wavy and chilled contact of the pegmatite with the host schist is clearly visible on the polished surfaces (B and C in Fig. 3). In thin section, the contact is very sharp. Large plagioclase phenocrysts in the pegmatite are sheared along the contact of the host rock and the contact is deflected around the grains. The pelitic xenoliths contain randomly grown, zoned tourmaline crystals. It may be the result of boron metasomatism. Microprobe analysis shows that the garnet is rich in spessartine component (up to 14% MnO), muscovite is close to the idealised muscovite and plagioclase is albitic (<3% An) (Fig. 5 and 7; Table 1 and 2). The above evidence shows that the pegmatite

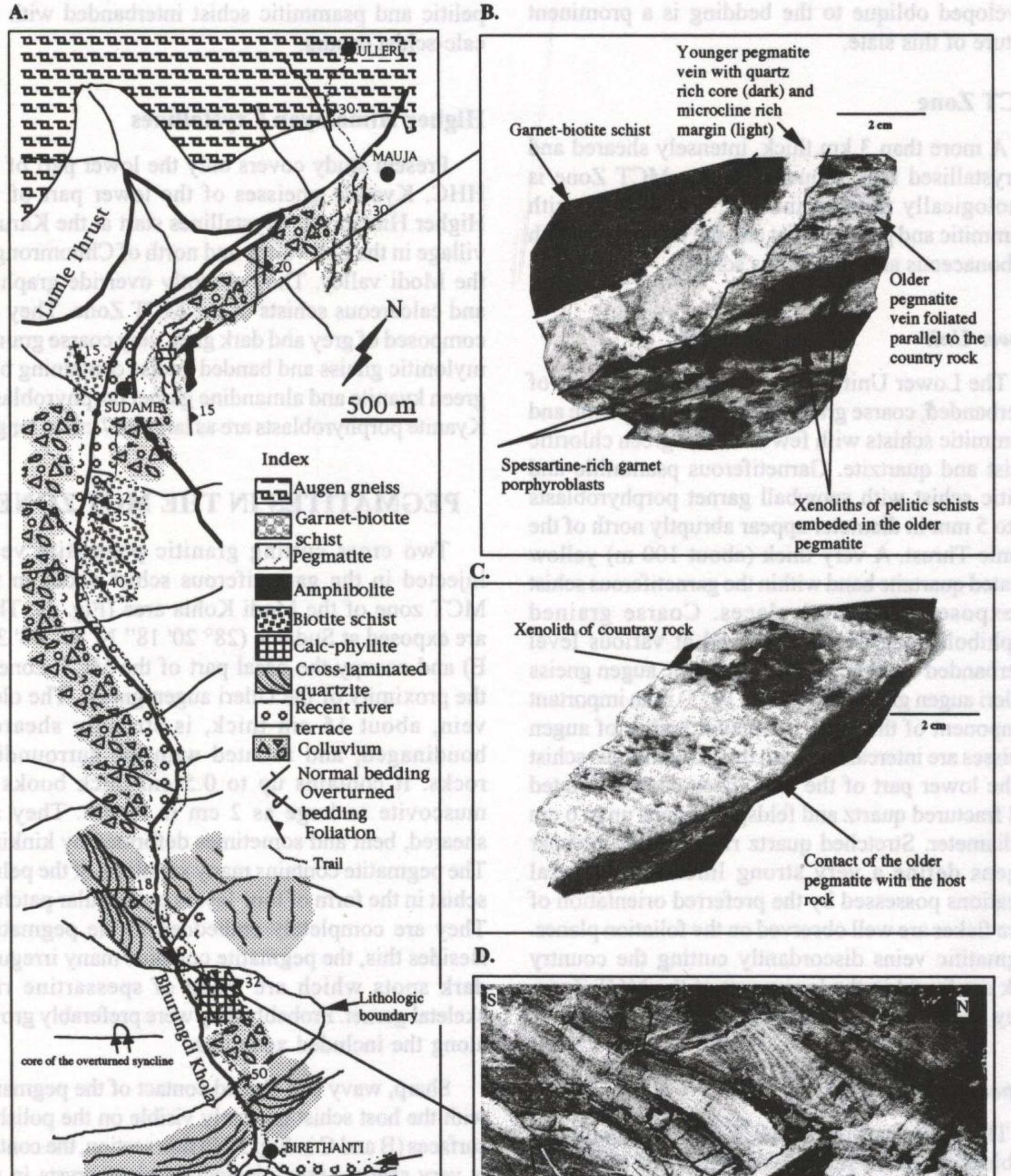

Fig. 3: A. Route map along the Bhurungdi Khola showing the location of the pegmatite veins, B. Contact of the younger pegmatite vein with the country rock seen on the polished surface, C. Contact of older pegmatite vein with the country rock, D. Overturned cross-laminae in quartzite beds just below the Lumle Thrust.

Table 1: Representative garnet analyses.

Rock	Higher Himalayan Crystallines				MCT Zone						
Type	Kyanite gneiss (158a)				Spiral garnet in schist (155)				Skeletal garnet in pegmatite		
Wt. % Oxides	A-core	A-rim	B-core	B-rim	F-core	F-rim	G-core	G-rim	L-1	L-2	L-3
SiO_2	38.42	38.88	38.39	37.94	37.57	37.92	37.37	37.56	36.65	36.25	35.95
Al_2O_3	21.44	21.86	21.45	21.15	21.09	21.26	20.76	21.03	20.91	20.74	20.86
FeO*	30.35	30.81	30.43	30.85	26.35	29.36	24.46	29.46	28.46	27.84	27.55
MnO	1.82	2.48	1.75	2.42	5.04	1.44	7.30	2.79	14.00	14.60	14.32
MgO	5.35	4.49	5.46	4.39	0.70	1.07	0.61	1.11	0.40	0.37	0.34
CaO	3.54	3.21	3.20	3.36	9.09	9.45	8.84	7.64	0.14	0.10	0.12
Total	**100.92**	**101.73**	**100.68**	**100.11**	**99.84**	**100.50**	**99.34**	**99.64**	**100.61**	**99.89**	**99.17**
	Number of atoms per 12 Oxygen										
Si	3.02	3.00	3.01	3.01	2.59	2.59	2.58	2.59	2.57	2.56	2.56
Al	2.00	1.98	1.98	1.98	1.71	1.71	1.69	1.71	1.73	1.73	1.75
Fe*	2.00	1.98	1.99	2.04	1.52	1.67	1.41	1.70	1.67	1.65	1.64
Mn	0.16	0.12	0.12	0.16	0.29	0.08	0.43	0.16	0.83	0.87	0.86
Mg	0.52	0.62	0.64	0.52	0.07	0.11	0.06	0.11	0.04	0.04	0.04
Ca	0.27	0.30	0.27	0.29	0.67	0.69	0.65	0.57	0.01	0.01	0.01
Alm%	65.6	67.8	66.1	68.9	59.4	65.5	55.3	66.9	65.4	64.1	64.4
Pyr%	20.6	17.6	21.1	16.5	2.8	4.3	2.5	4.5	1.6	1.5	1.4
Sps%	4.0	5.5	3.9	5.7	11.5	3.2	16.7	6.4	32.6	34.1	33.9
Gro%	9.8	9.1	8.9	9.0	26.3	27.0	25.6	22.2	0.4	0.3	0.4

Fe*= Total Fe as FeO

Table 2: Representative plagioclase analyses.

	Higher Himalayan Crystallines		MCT Zone				Pokhara Zone	
Rock type	Kyanite gneiss(158a)		Augen gneiss (132)		Pegmatite (127)		Amphibolite (126)	
Wt. % Oxides	F1-core	F1-rim	F17-core	F17-rim	F3-core	F3-rim	F21-core	F21-rim
SiO_2	63.12	61.31	68.23	68.39	68.87	68.61	68.28	69.88
Al_2O_3	22.73	23.08	19.89	20.49	19.15	19.83	19.35	19.65
CaO	4.28	4.30	0.10	0.35	0.27	0.51	0.22	0.45
Na_2O	9.43	8.40	11.29	10.15	11.81	11.30	11.00	11.56
K_2O	0.07	0.11	0.10	0.17	0.05	0.08	0.16	0.07
Total	**99.61**	**97.09**	**99.61**	**99.53**	**100.15**	**100.34**	**99.01**	**101.60**
	Number of atoms per 32 Oxygen							
Si	11.208	11.125	11.870	11.935	12.018	11.942	12.009	11.989
Al	4.756	4.936	4.079	4.214	3.938	4.067	4.008	3.974
Ca	0.814	0.835	0.019	0.066	0.051	0.096	0.041	0.082
Na	3.248	2.955	3.808	3.433	3.996	3.813	3.752	3.846
K	0.015	0.025	0.023	0.037	0.011	0.018	0.036	0.015
Kf%	0.3	0.7	0.6	1.0	0.2	0.5	0.9	0.4
Ab%	79.7	77.4	98.9	97.1	98.5	97.1	98.0	97.5
An%	**20.0**	**21.9**	**0.5**	**1.9**	**1.3**	**2.4**	**1.1**	**2.1**

Fe*= Total Fe as FeO

was discordantly injected in the country rock and later on, it was deformed and foliated along with the country rock.

The younger vein about 3 cm in thickness, sharply cuts the older vein, country rock and the main foliation (B in Fig. 3) and has escaped from any deformation. It has chilled contact with the host rocks. It shows strong mineralogical zonation, the margins rich in microcline and the core almost entirely of quartz. This vein was injected after the main deformation event in the area.

GEOLOGICAL STRUCTURE

Major Faults

The Phalebas Thrust, Kusma Reverse Fault, Lumle Thrust and the MCT are the major surfaces of structural discordance observed in the area (Fig. 4). The Phalebas Thrust, extending from Phalebas to Naudanda, truncates many rock units at the footwall. The Kusma Reverse Fault extends from Kusma in the west to Naudanda in the east lying approximately parallel to the Phalebas Thrust. In most places it is either vertical or steeply south

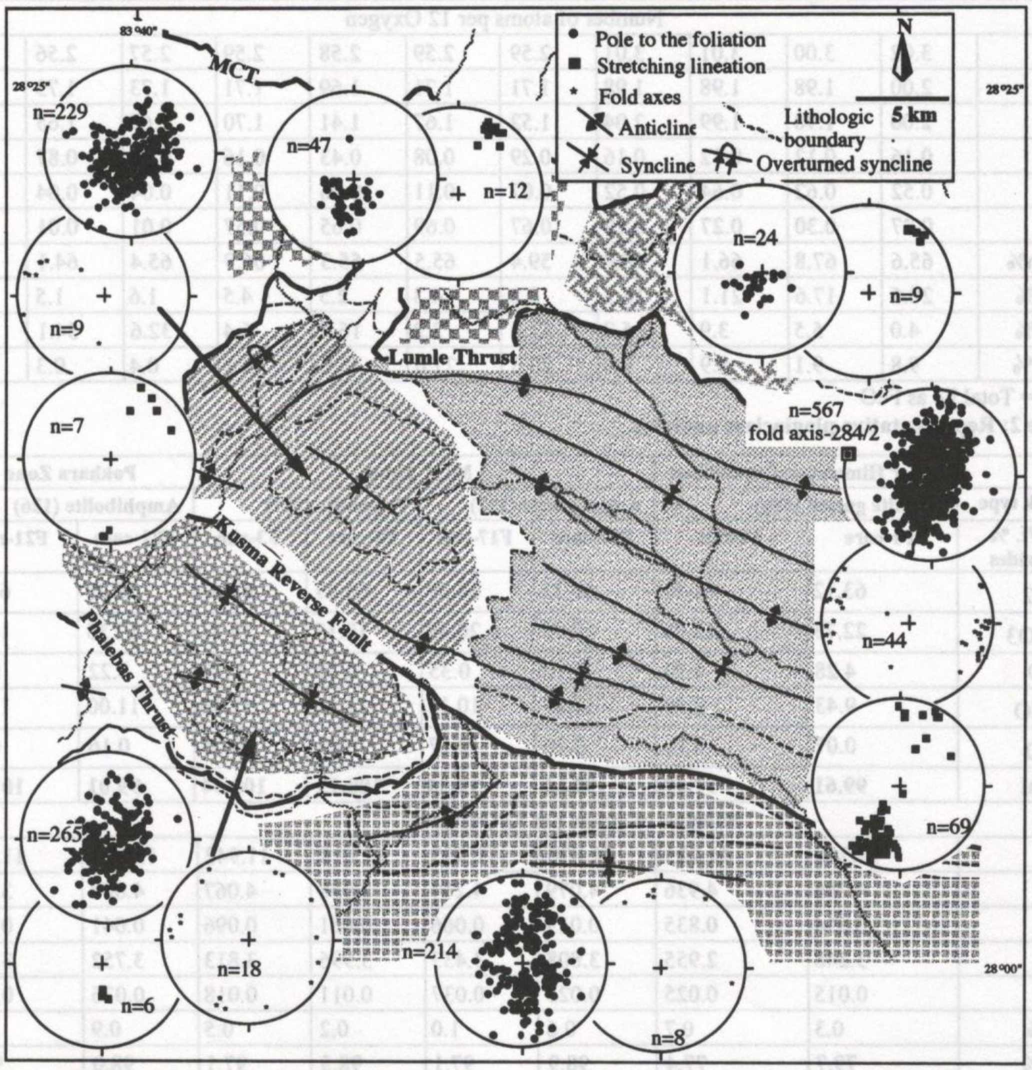

Fig. 4: Structural map of the Pokhara region. Foliation and Lineation measured from the shaded area are projected on the Schmidt's lower hemisphere.

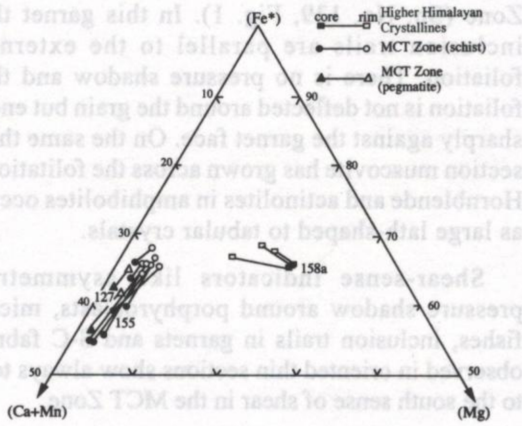

Fig. 5: Composition of garnet in Fe*+Mg+(Ca+Mn) triangle. Tie line connects the core and rim composition of the same grain.

dipping and cuts many folds on the hangingwall of the Phalebas Thrust.

The Lumle Thrust (Lower MCT) separates the relatively high grade metamorphic rocks of the MCT zone from the low grade metamorphic rocks of the Nawakot Complex. Discordant nature of the boundary is revealed from the fact that the rocks of the footwall are intricately folded near the thrust, and in contrast, those of the hangingwall show a homoclinal structure gently dipping northward. Many formation boundaries on the footwall are truncated by the fault. Besides this, the hangingwall rocks show flat cleavage parallel to the bedding, pronounced penetrative lineation, and strong mylonitisation, which is lacking in the rocks of the Nawakot Complex.

In the area, the Main Central Thrust is placed where very coarse-grained kyanite bearing gneisses and schist of the Higher Himalayan Crystalline abruptly ride over the fine grained, highly sheared schists of the MCT zone. It is observed at the Karuwa village in the Seti valley and north of Chhomrong in the Modi valley.

Folds, Foliation and Lineation

Axial traces of the large scale folds observed in the area are shown in Fig. 4. Foliations in the area are mostly parallel to the bedding. Poles to the foliation planes, folding axes and stretching lineations measured in the area are projected on the lower hemisphere of Schmidt-net (Fig. 4). The MCT zone shows homoclinal structure with gently (10-30°) NE-dipping foliation and gently (5-25°) NE plunging stretching and mineral lineations. WNW-ESE trending kink folds are also observed at many places in the pelitic schists of the MCT zone.

Rocks in the Pokhara and Syangja zone are intricately folded giving rise to a number of WNW-ESE trending, non-cylindrical, doubly plunging, en-echelon type folds. An overturned syncline is observed just below the Lumle Thrust along the Bhurungdi Khola (Fig. 2 and 3). Stretching lineations trend NNE-SSW and gently plunge on either side according to the dip direction of the foliation. Trend and plunge of minor folds and crenulation axes in the area roughly coincide with the major fold axes. Minor folds from the area south of the Kusma Reverse Fault and the Syangja zone trend also to the NNE and SSW. The Syangja Zone comprises steep to overturned folds. Stretching lineation is rarely observed in this zone.

PETROGRAPHY

Petrographic study was carried out in thin sections cut parallel to the stretching lineation and perpendicular to the foliation. Mineral paragenesis observed in various rock types is described. For this, mineral abbreviations are used after Kretz (1983).

Higher Himalayan Crystallines

The gneisses of the Higher Himalayan Crystallines exhibit the following mineral assemblages:

Ky-Grt-Bt-Ms-Pl-Qtz
Grt-Bt-Ms-Pl-Qtz

Ilmenite, and zircon occur as accessories. Quartz occurs as coarse grained polygonal aggregate in the matrix. Kyanite blades are elongated parallel to the foliation. Kyanite is generally rimmed by fine grained, phengitic muscovite. Poikiloblastic euhedral garnets are up to 5 mm in size. They have inclusion rich core and inclusion free rim and are often fractured and altered to chlorite. Coarse grained (2-4 mm long) biotite and muscovite flakes are the predominant matrix phases defining the foliation. Biotite shows strong pleochroism from pale yellow to dark brown. It is usually masked by phengitic muscovite. Biotite also occurs as inclusions in kyanite.

MCT Zone

The MCT zone comprises various kinds of schists with augen gneiss, quartzite, amphibolite and marble. Main mineral assemblages in them are as follows:

Augen gneiss:	Grt-Bt-Ms-Chl-Mc-Pl-Qtz
Psammitic schist:	Grt-Bt-Ms-Chl-Pl-Qtz
Pelitic schist:	Grt-Bt-Ms-Chl-Qtz
	Bt-Ms-Chl-Qtz
	Cld-Bt-Ms-Chl-Qtz
Calc-schist:	Bt-Ms-Cal-Qtz
Amphibolite:	Hbl-Act-Bt-Chl-Plag-Qtz

Altered sphene (leucoxene), magnetite, tourmaline and zircon occur as accessories. Muscovite and biotite are predominant matrix phases in all rocks defining foliation. Quartz occurs as granoblastic, polygonal aggregate in the schist and gneiss of the lower part of the MCT Zone. In the upper part, it is storngly sheared and shows ribbon texture.

Augen gneisses are mylonitic to protomylonitic. Augens are made of quartz, perthitic microcline and plagioclase up to 1 cm in diameter. Feldspar is oftern granulated along the margin and rimmed by myrmekite. The microcline augens are poikiloblastic and contain mainly euhedral plagioclase laths. Included plagioclase laths show zonal texture with highly altered core and unaltered rim. Muscovite and biotite flakes make up the foliation in the rock. Biotite is strongly pleochroic from pale yellow to dark brown. Muscovite flakes are sheared, bent and kinked and show wavy extinction. Garnet is occasionally found as fine-grained porphyroblasts in the micaceous layers.

Poikiloblastic garnet in the schists is found in different shape (skeletal, elongated, s-shaped and eqidimensional) and size (0.1mm to 5 mm). Syn-tectonic garnets with spiral shaped inclusions of quartz and opaque minerals is common in the MCT zone. Many snowball garnets show post-tectonic overgrowth of rim into the mica-rich layers. Large post-tectonic garnet was observed in pelitic schist from the lower part of the MCT Zone (Sp. No. 139, Fig. 1). In this garnet the inclusion trails are parallel to the external foliation. There is no pressure shadow and the foliation is not deflected around the grain but ends sharply against the garnet face. On the same thin section muscovite has grown across the folitation. Hornblende and actinolites in amphibolites occur as large lath-shaped to tabular crystals.

Shear-sense indicators like asymmetric pressure shadow around porphyroclasts, mica-fishes, inclusion trails in garnets and S-C fabric observed in oriented thin sections show always top to the south sense of shear in the MCT Zone.

Pokhara Zone

The Pokhara Zone belongs to the chlorite and biotite zones of the greenschist facies. "Ms-Chl-Pl-Qtz" is an unique mineral assemblage found in the phyllite and metasandstone in the southern part. The rocks are usually fine grained (<0.1 mm). Phyllitic cleavage with micro-folds and crenulation is common in pelitic rocks. Metasandstone contains large ovoidal clasts of quartz arranged parallel to the foliation. They are accompanied by pressure shadow and mortar structure.

Biotite apperars to the north of Pokhara near the Lumle Thrust. The rocks are highly sheared and mylonitised. Quartz clasts are elongated parallel to the foliation and polygonised. Matrix contains coarse grained aggregate of polygonal quartz.

The following assemblages are found in the rocks:

Psammitic schist:	Bt-Ms-Chl-Ab-Qtz
Pelitic schist:	Bt-Ms-Chl-Qtz
Amphibolite:	Hbl-Act-Bt-Chl-Pl-Qtz (Calcite)

Tourmaline, epidote, calcite, sphene and magnetite occur as accessories. Amphibolite contains large plagioclase laths. Original igneous texture is still preserved in amphibolite.

Syangja Zone

The rocks in the Syangja Zone still preserve the sedimentary features like parallel laminae, cross-laminae, graded-bedding, mud-cracks and stromatolitic structures. Phyllitic and slaty cleavages are developed in fine grained pelitic rocks. Metasandstones and siltstone contain large clasts of quartz, plagioclase, K-feldspar and muscovite. Quartz and feldspar clasts are slightly sheared and the matrix is deflected around the clasts showing fluxion texture. Quartz clasts show wavy extinction. In sandstones and siltstones, the matrix is slightly recrystallised. "Chl-Ms-Qtz" is the mineral assemblage found in them. Besides this, tourmaline, apatite, zircon and magnetite is found in the matrix.

MINERAL CHEMISTRY

Minerals in selected rock specimens from different metamorphic grade were analysed by EPMA (JEOL Superprobe 733, specimen current 200 mA, accelerating voltage 15 Kv, natural and synthetic silicates and oxides as standards).

Garnet

Garnets from the Higher Himalayan Crystallines and the MCT zone were probed at core and rim and the data are projected on the Fe*-Mg-(Mn+Ca) triangle (Fig. 5). Some representative analyses are shown in Table 1. Garnets in the Higher Himalayan Crystallines are rich in pyrope and almandine content and show a retrograde zoning pattern with Mg and Fe rich core and Mn rich rim.

Garnets in the MCT zone show prograde zoning pattern with Mn rich core and Fe rich rim (Fig. 5). Compositional profile in a spiral garnet from the MCT Zone shows bell-shaped Mn-profile characteristic of prograde metamorphism (Fig. 6). Fe gradually increases and Mn decreases towards the rim. But at the outermost part, the profile is reversed probably caused by late-stage retrogression (Barker, 1990). Garnets in the schists from the MCT Zone shows comparatively high grossular content. It may be the effect of bulk chemical composition. The sample analysed was from the upper part of the MCT Zone where the rocks are usually calcareous.

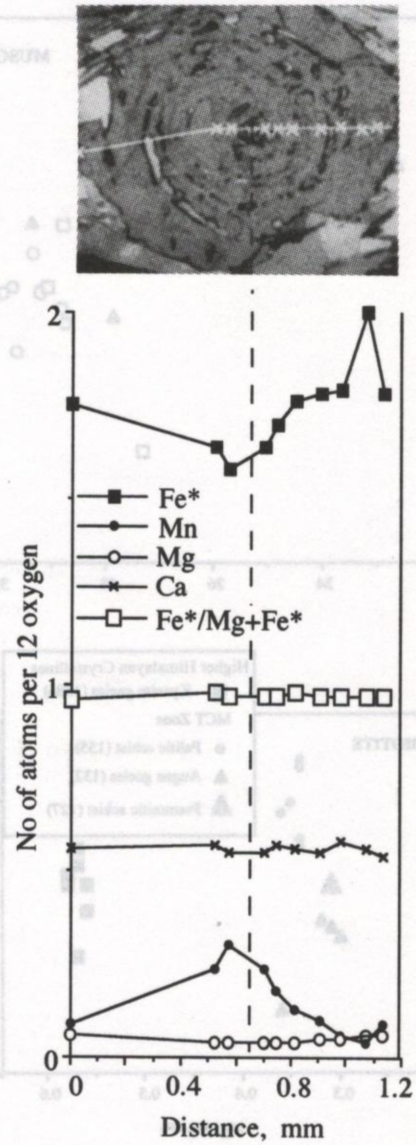

Fig. 6: Compositional profile of a spiral garnet from the upper part of the MCT Zone (sp. no.155). Fe* means total Fe as Fe^{2+}. Cross marks indicate the probed points.

Garnets in the pegmatites are rich in spessartine and poor in grossular content. MnO and CaO rich garnets form at low temperature in the presence of aqueous fluids (Miyashiro, 1973). So it is likely to form spessartine rich garnet in pegmatites. The lower CaO content (Table 1) may be due to the effect of bulk chemical composition.

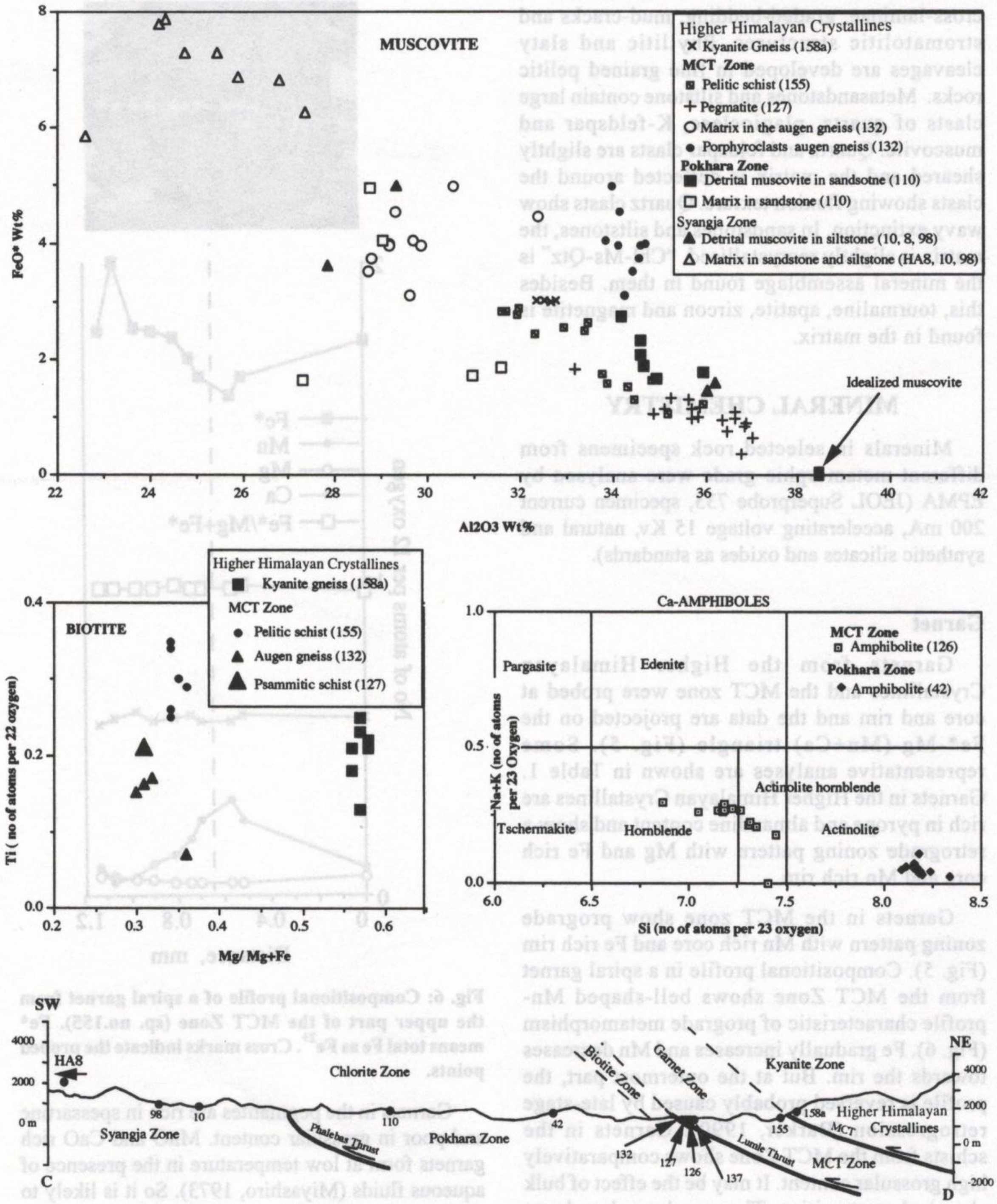

Fig. 7: Composition of muscovite, biotite and Ca-amphiboles in rocks of different metamorphic grade from the Pokhara region. Number in brackets indicates the specimen number and approximate structural position of the sample analyzed is shown in the cross-section.

Mica

The chemical composition of muscovite and biotite are shown in Fig 7. Muscovites analysed included the detrital grains in metasandstones, recrystallized grains in metasandstones and schists and porphyroclats and recrystallised grains in gneiss and pegmatites. In general celadonite component in muscovite decreases with increasing metamorphic grade (Miyashiro, 1973). Chemical composition of recrystallised muscovite from the Lesser Himalaya in FeO-Al_2O_3 diagram shows continuous decrease of celadonite component from south to the MCT. Recrystallised muscovite in sandstone from the Syangja Zone contains up to 8% FeO. This value decreases to 3-6% in the Pokhara Zone and 1-3% in the MCT Zone. But the muscovites from the kyanite grade rocks of the Higher Himalayan Crystallines (HHC) are higher in celadonite component than those from the garnet grade rocks of the MCT Zone. Muscovite in the pegmatite has composition close to the pure muscovite. Detrital muscovite from the Pokhara and Syangja zones vary in celadonite content. The detrital muscovites plotted closed to the pure muscovite are probably derived from older high grade metamorphic rocks.

Increase of Mg/Mg+Fe and Ti content in biotite with increasing metamorphic grade is widely observed phenomenon (Miyashiro, 1973). In the MCT Zone, Ti content in biotite increases from the basal part to the upper part. But Ti content in biotite from the upper part of the MCT Zone is higher than in the gneisses of the Higher Himalayan Crystallines. It may be the effect of bulk rock compostion.

Amphiboles and Plagioclase

Ca-amphiboles were analysed in two specimens from the MCT Zone and the Pokhara Zone. Ca-amphiboles in the study area show increase in Na and K and decrease in Si content with increasing metamorphic grade as in the other metamorphic terrains (Fig. 7). Amphiboles in the Pokhara Zone are mainly actinolite whereas those in the MCT Zone are hornblende and hornblende-actinolite.

Representative plagioclase compositions from the area is given in Table 2. Plagioclase from the Lesser Himalaya is albite (<4% An) whereas the plagioclase from the HHC contains more than 20% anorthite. In all cases, anorthite content in the rim is slightly higher than in the core.

DEFORMATION AND METAMORPHISM

The present study shows that each tectonic zones in the area experienced at least three deformation events. The first event in the MCT Zone produced the foliation preserved as inclusion trails in garnets, the second event produced dominant penetrative foliation, S-C fabric and mineral stretching lineations and the third event is attributed by the crenulation and kink folds in pelitic schist layers. In the Pokhara and Syangja zones, first deformation produced dominant bedding-parallel foliation. Stretching lineations in these zones trend perpendicular to the fold-axes and plunge steeply on either side of the folds according to dip and dip direction of the foliation. It shows that these were formed earlier than the folds and it is supposed to be the result of second event of defromation. The last event in the area produced various major and minor folds. Consistently NW-SE trend of faults and folds, NNE-SSW orientation of stretching lineation and top to the south sense of shearing along the fault zones is the expression of extensive N-S compression and shearing and south-vergent thrusting in the Himalaya.

The gneisses of the Higher Himalayan Crystallines belong to the kyanite zone of amphibolite facies. Garnet core is rich in pyrope component and shows retrograde chemical zoning pattern. Plagioclase has higher anorthite component than in the MCT Zone. The muscovite in the kyanite grade rocks is remarkably higher in celadonite component than that in the garnet grade rocks of the MCT Zone. This shows that there is a marked difference in the mineral composition above and below the MCT as noted also in the Modi Khola valley (Arita, 1983) and in the Kali Gandaki valley (Le Fort et al., 1986). Probably the gneisses suffered polyphase metamorphism, that is, the older metamorphism was of relatively high grade (kyanite grade) which formed the pyrope rich cores of garnets and plagioclase with An>20% (Fig. 8). The younger metamorphism is retrograde metamorphism (Caby et al., 1983), which caused to recrystallise phengitic

Fig. 8: Photomicrographs showing progressive increase in deformation and recrystallization of quartz towards the MCT. A) Metasandstone from the Syangja Zone is weakly deformed and sheared resulting undulosed extinction in quartz and fluxion texture. B) Matrix in the metasandstones from the southern part of the Pokhara Zone contains polygonal aggregate of qurtz. Quartz clasts show mortar texture and deformation bands. C) Quartz clasts in the metasandstones in the northern part of the Pokhara Zone are polygonized and the matrix contains coarse grained polygonal aggregate of quartz. D) Quartz occurs as elongated polygonal aggregate in the psammitic schists of the lower part of the MCT Zone. Quatz clasts in metasandstones no more exist in this zone. D) Rocks are extremely sheared just below the MCT. Quartz in metapsammites shows ribbon texture.

muscovite and produced retrograde chemical zoning in garnet.

In the Lesser Himalaya, the grade of metamorphism incereases from south to the Main Central Thrust. The Syangja and the Pokhara zones belong to the chlorite and biotite zones of the greenschist facies. Biotite appears only below the Lumle Thrust. The MCT Zone belongs to the garnet zone of the epidote-amphibolite facies. Muscovite becomes gradually poor in celadonite component, biotite becomes rich Ti-content and Ca-amphiboles become rich in Na and K from south to the MCT. Garnets in the MCT Zone show snowball texture and prograde chemical zoning pattern. Schists in the MCT Zone also contain post-tectonic garnet and muscovite porphyroblasts as well as post-tectonic overgrowth of snowball garnet rims into the micaceous matrix. It shows that the MCT Zone suffered syn- to post-tectonic garnet grade metamorphism. The rocks finally suffered very weak late-stage retrogression which is attributed in the garnet zoning profile and chloritisation of garnet along the fractures and rim.

In the Syangja Zone, the rocks are very fine grained and very weakly deformed. Quartz clasts in sandstones are weakly deformed and show undulose extinction. Matrix is sheared and shows fluxion texture. Sedimentary features like laminae and graded-bedding are still preserved. In the southern part of the Pokhara Zone, rocks are relatively coarse grained and phyllitic cleavage is well-developed. Ovoidal quartz clasts are arranged parallel to the foliation. They show mortar texture and deformation bands. Matrix contains polygonal aggregate of quartz. In front of the Lumle Thrust, the rocks are more sheared and mylonitized. Quartz clasts are elongated and polygonised. Matrix contains coarse-grained aggregate of polygonal quartz. In the MCT Zone, the rocks are extensively mylonitised and show penetrative foliation and lineation. Quatz is extremely sheared and changed into polygonal aggregate arranged parallel to the foliation. Compositional layering, asymmetric pressure shadows and S-C fabric are well developed in gneiss and schist. In the upper part of the MCT Zone, the rocks are more sheared and quartz show ribbon texture. The above evidences shows that the intensity of deformation and recrystallisation also increases nowrthwards within each tectonic units and as a whole in general.

In conclusion, there is a marked difference between the history and grade of metamorphism between the Higher Himalayan Crystallines and the Lesser Himalayan sequence. The Higher Himalayan Crystallines show polyphase metmophism: the older high grade (kyanite grade) metamorphism has been overprinted by the younger retrograde metamorphism. The Lesser Himalayan rocks show syn- to post-tectonic, garnet grade, inverted prograde metamorphism. Both the Lesser Himalayan metasediments and the Higher Himalayan Crystallines have experienced late-stage weak retrogression due to uplift and erosion.

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