Journal of Nepal Geological Society
Vol. 4 No. 1 & 2., 1987, 1-19

THE GEOLOGY OF THE ROLWALING-LAPCHI KANG HIMALAYAS, EAST-CENTRAL NEPAL: PRELIMINARY FINDINGS

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ABSTRACT

Between the Tethyan sediments to the north and the Main Boundary Thrust to the south ten lithotectonic units have been identified in the Rolwaling-Lapchi Kang Himalayas and the Tamba Kosi region of east-central Nepal. These are (1) the Rolwaling Granites, (2) the Rolwaling Paragneisses, (3) the Rolwaling Migmatites, (4) the Alampu Schists, (5) the Khare Phyllites, (6) The Chagu-Chilangka Augen Gneisses; (7) The Laduk Phyllites, (8) the Suri Dhoban Augen Gneisses, (9) the Ramechap Group, and (10) the Mahabharat Crystallines. The Main Central Thrust (MCT) is a major lithologic, metamorphic and structural discontinuity separating the overthrust Higher Himalayan crystallines from the underthrust Lesser Himalayan metasediments. The Mahabharat Crystallines are an outlying klippe of Higher Himalayan rocks, underlain by the MCT, that has been thrust a minimum of 80 kilometers over the underlying Lesser Himalayan metasediments. Extending approximately 5 km below the MCT and 15 km above the MCT the Himalayas are a shear-thrust zone exhibiting ductile, brittle-ductile and brittle deformation as well as an inverted metamorphic sequence.

INTRODUCTION

Throughout their entire length the Himalayas can be divided into four tectonic zones (Gansser, 1964). These are, from north to south, the Tibetan or Tethys Himalayas, the Higher Himalayas, the Lesser Himalayas and the Sub-Himalayas. The Higher Himalayas, consisting of medium to high grade metamorphic and igneous rocks, have been thrust over the Lesser Himalayan sediments and metasediments along the controversial Main Central Thrust (MCT), which is considered by Le Fort (1975) to represent an intracontinental subduction zone. The Lesser Himalayas, in turn, have been thrust over the Siwalik sediments of the Sub-Himalayas by the presently active Main Boundary Thrust (MBT).

As part of a study on the structure and tectonics of Eastern Nepal I mapped the Rolwaling-Lapchi Kang Himalayas, including the Higher Himalayas, the MCT zone and a northern portion of the Lesser Himalayas, between September, 1984 and June, 1985 ,(figure 1). During the spring of 1986 I returned to Nepal to extend the study southwards, along the Tamba Kosi and Likhu Khola, to the MBT. Prior to the present study little geological research has been done in the Rolwaling-Lapchi Kang Himalayas and in the

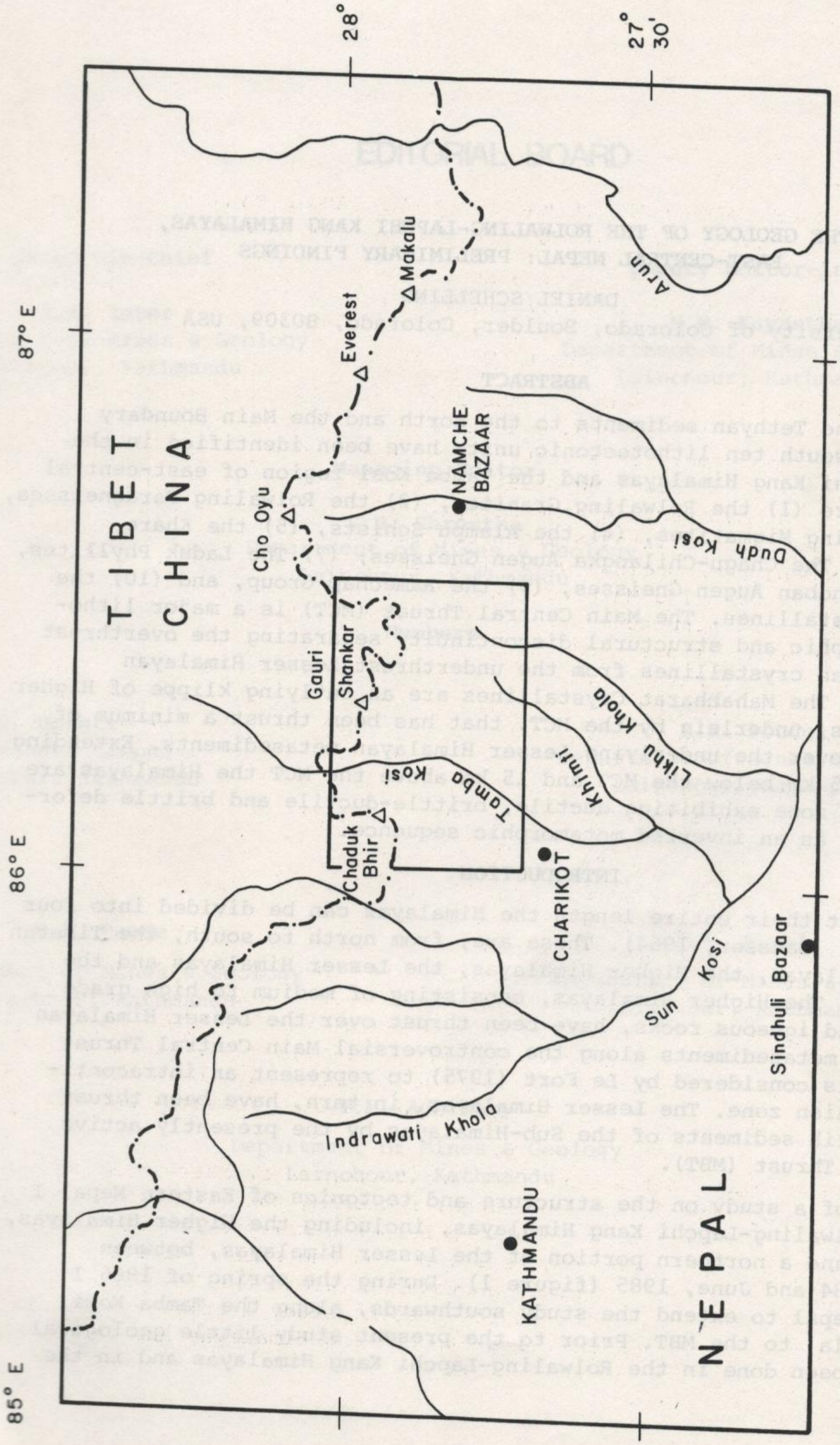
85° E
86° E
87° E
28°
27° 30'
TIBET
CHINA
NEPAL
Cho Oyu
Gauri Shankar
Everest
Makalu
Arun
NAMCHE BAZAAR
Dudh Kosi
Likhu Khola
Khimti Khola
Tamba Kosi
Chaduk Bhir
CHARIKOT
Sun Kosi
Sindhuli Bazaar
Indrawati Khola
KATHMANDU

Figure 1.

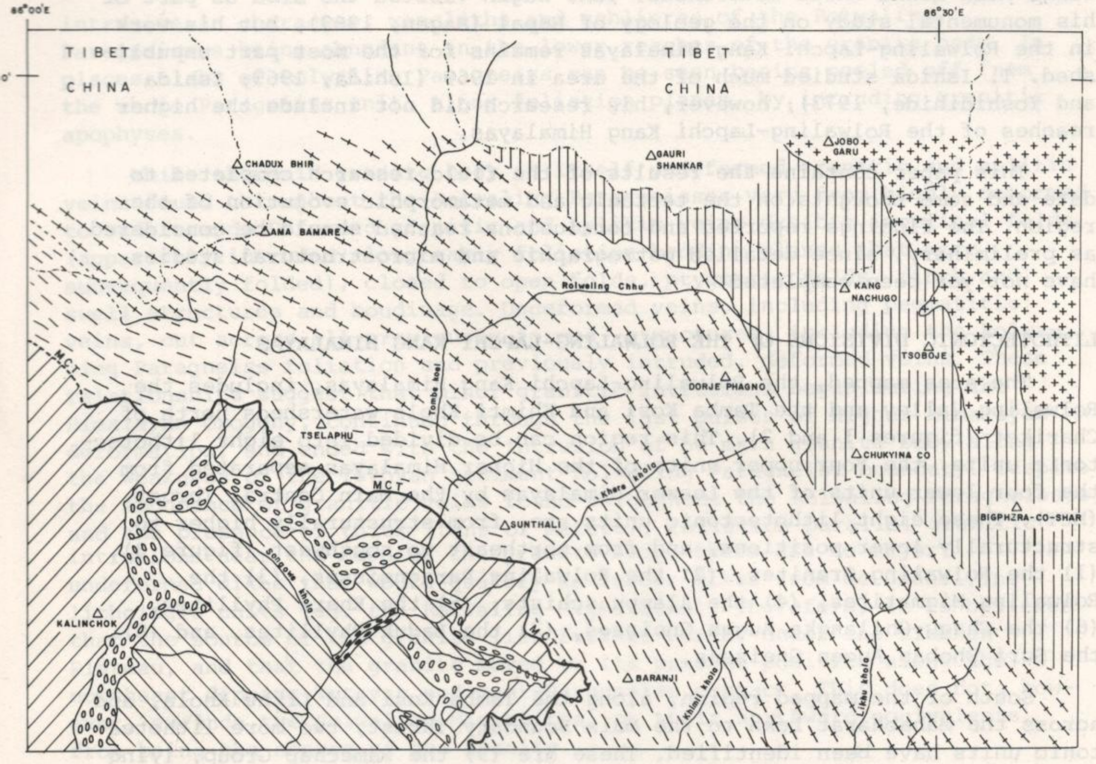

Fig. 2

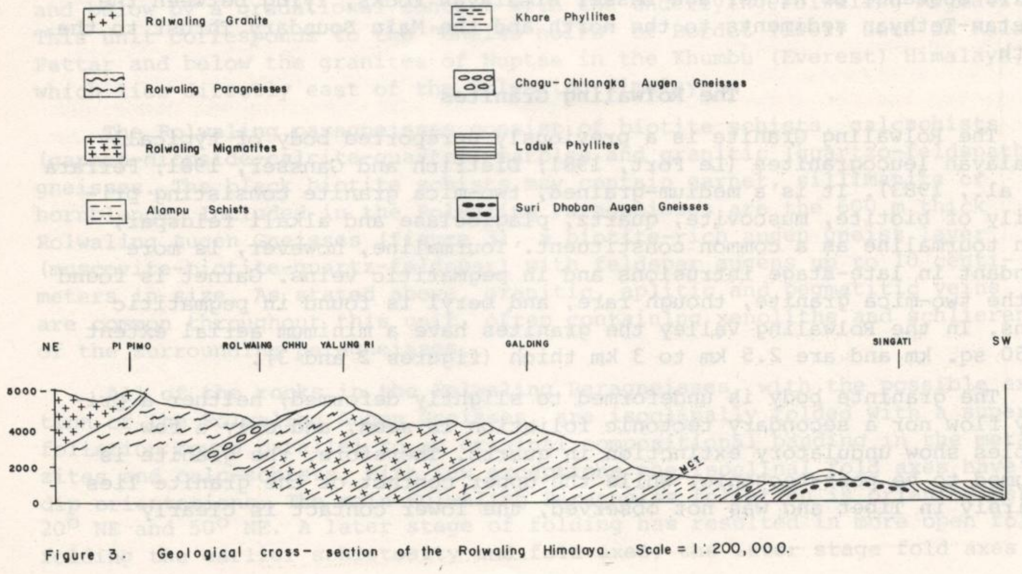

Figure 3. Geological cross-section of the Rolwaling Himalaya. Scale = 1:200,000.

No vertcal exaggeration.

Tamba Kosi-Likhu Khola watersheds. Toni Hagen visited the area as part o his monumental study on the geology of Nepal (Hagen, 1969), but his work in the Rolwaling-Lapchi Kang Himalayas remains for the most part unpublished. T. Ishida studied much of the area in 1969 (Ishida, 1969; Ishida and Yoshidihide, 1973); however, his research did not include the higher reaches of the Rolwaling-Lapchi Kang Himalayas.

This paper contains the results of the field research completed to date and some thoughts on the tectonic and metamorphic evolution of the region. The findings reported and conclusions reached should be considere as preliminary, since detailed petrographic and microstructural studies have not yet been completed.

LITHOTECTONIC DIVISIONS OF THE ROLWALING-LAPCHI KANG HIMALAYAS

The area mapped, the Rolwaling-Lapchi Kang Himalayas, includes the Rolwaling Valley and the Tamba Kosi and Khimti Khola watersheds north of Charikot (figures 1 and 2). This region can be divided into eight lithotectonic units, the four upper units of the Higher Himalayas separated from the four lower units of the Lesser Himalayas by the Main Central Thrust (MCT). These eight lithotectonic units are, from structurally higher to structurally lower positions, and from northeast to southwest (figure 3), (1) the Rolwaling Granites, (2) the Rolwaling Paragneisses, (3) the Rolwaling Migmatites, (4) the Alampu schists, (5) the Khare Phyllites, (6) the Chagu-Chilangka Augen Gneisses, (7) the Laduk Phyllites, and (8) the Suri Dhoban Augen Gneisses.

South of the mapped region, along the Tamba Kosi and Likhu Khola, and across the Mahabharat Lekh to the Main Boundary Thrust, two more lithotectonic units have been identified. These are (9) the Ramechap Group, lying north of the Sun Kosi, and (10) the Mahabharat Crystallines, making up most of the Mahabharat Lekh south of the Sun Kosi (figures 1 and 4).

In east-central Nepal these ten lithotectonic units make up the entire sequence of Higher and Lesser Himalayan rocks, lying between the Tibetan-Tethyan sediments to the north and the Main Boundary Thrust to the south.

The Rolwaling Granites

The Rolwaling Granite is a previously unreported body of typically Himalayan leucogranites (Le Fort, 1981; Dietrich and Gansser, 1981; Ferrara et. al., 1983). It is a medium-grained, two-mica granite consisting primarily of biotite, muscovite, quartz, plagioclase and alkali feldspar, with tourmaline as a common constituent. Tourmaline, however, is more abundant in late-stage intrusions and in pegmatitic veins. Garnet is found in the two-mica granite, though rare, and beryl is found in pegmatitic veins. In the Rolwaling Valley the granites have a minimum aerial extent of 50 sq. km and are 2.5 km to 3 km thich (figures 2 and 3).

The graninte body is undeformed to slightly deformed; neither a primary flow nor a secondary tectonic foliation is seen, and only a few samples show undulatory extinction in quartz. Therefore, the granite is assumed to be post-tectonic. While the upper contact of the granite lies entirely in Tibet and was not observed, the lower contact is clearly intrusive in character, xenoliths and schlieren of the Rolwaling Paragneisses being abundant in the lower reaches of the granite body. In places slabs of Rolwaling Paragneiss can be seen beeing peeled off from the whole Paragneiss unit, along foliation planes, by intruding granitic apophyses.

While the main granite body is itself undeformed granitic and aplitic veins found throughout the Rolwaling Paragneisses vary from highly deformed to undeformed. Deformed granitic and aplitic veins exhibit isoclinal folds (apparently intruded along early foliation-bedding planes that were subsequently folded), closed to open folds, ptygmatic folds, pinch and swell structures and boudinage. Undeformed veins, including pegmatitic veins, cut across all previously formed structures, including the Rolwaling Paragneiss foliation and previously intruded, deformed veins. These relationships suggest that minor granitic intrusions began during the Himalayan Orogeny, continued through the last pulses of Higher Himalayan deformation, and ended with the intrusion of he main granite body along the weakness of the Tethyan sediment-Rolwaling Paragneiss boundary. Despite the abundance of granitic veins found throughout the Rolwaling Paragneisses, and the presence of thick (tens of meters), foliation-parallel granitic intrusions near the base of the granite body, there are no major undeforned dikes that would qualify as feeder dikes from he underlying lithologic units (eg. the Rolwaling Migmatites). Therefore, it is believed that the source of the granite lies further north, under the Tibetan Plateau, and that the granite moved to its present position along the northeast dipping Tethyan sediment-Paragneiss contact. This does not, however, exclude the Rolwaling Migmatites, or their northward equivalents, from being the source of the granite.

The Rolwaling Paragneisses

The Rolwaling Paragneisses are approximately 6,000 m thick and are delimited above by a sharp contact with the intrusive Rolwaling Granites and below by a gradational contact with the underlying rolwaling Migmatites. This unit corresponds to the "Gneiss noirs" of Bordet (1961) seen on Kala Pattar and below the granites of Nuptse in the Khumbu (Everest) Himalaya, which lies directly east of the Rolwaling Himalaya.

The Rolwaling paragneisses consist of biotite schists, calcschists (garnet-diopside-calcite-quartz), marbles and granitic (quartzo-feldspathic) gneisses. The black biotite schists may contain garnet, sillimanite or hornblende. Included in the Rolwaling Paragneisses are the 600 m thick Rolwaling Augen Gneisses (figure 3), a biotite-rich augen gneiss layer (muscovite-biotite-quartz-feldspar) with feldspar augens up to 10 centimeters in size. As stated above, granitic, aplitic and pegmatitic veins are common throughout this unit, often containing xenoliths and schlieren of the surrounding paragneisses.

All of the rocks in the Rolwaling Paragneisses, with the possible exception of the Rolwaling Augen Gneisses, are isoclinally folded with a superposed foliation found parallel to an original compositional banding in the metaquartzites and calc-schists. With few exceptions the isoclinal fold axes have downdip orientations. The main Rolwaling Paragneiss foliation is oriented between 20° NE and 50° NE. A later stage of folding has resulted in more open folds, folding the earlier schistosity and fold axes; the later stage fold axes trend northwest-southeast, approximately parallel to the general structural trend of the Higher Himalayas. It is probable that these two different stages of folding are the result of progressive deformation during the Himalayan Orogeny, and not the result of polyphase deformation. The fact that the main Rolwaling Paragneiss foliation is parallel to foliations throughout the Higher Himalayan sequences, which are in turn parallel to the MCT and related shear zones, suggests that the foliation, shear zones and the MCT are all genetically related, in which case the earlier stage of isoclinal folding would be Himalayan in age. The more open, northwest-southeast trending folds, then, are probably the result of late stage deformation during the Himalayan Orogeny.

The Rolwaling Migmatites

The Rolwaling Migmatites are a 5,000 m to 6,000 m thick unit of predominantly sillimanite-bearing migmatites containing muscovite, biotite, garnet, quartz and feldspar. Tourmaline is a common constituent throughout the unit. Granitic and pegmatitic veins are abundant and usually cross-cut migmatitic structures. Unlike the Rolwaling Paragneisses, which are clearly intruded by granitic veins, field relations suggest that most of the "leucosomes" in the Rolwaling Migmatites have been formed in situ, derived from the migmatites by local melting and the sweating out of granitic material from the more melanocratic layers. The presence of sillimanite in the Rolwaling Migmatites suggests that metamorphic temperatures have been reached which are capable of melting the tourmaline-rich rock (Dietrich and Gansser, 1981).

The Rolwaling Migmatites are, in general, foliated, the foliation being formed by both the alignment of biotite and muscovite flakes and a compositional banding of biotite-rich and biotite-poor zones. The main Rolwaling Migmatite foliation is parallel to the overall Higher Himalayan structural trend, strikes lying between N30°W and N80°W and dips lying between 25°NE and 60° NE. An initial stage of isoclinal folding has been refolded both parallel and perpendicular to the early isoclinal fold axes. Like the overlying Rolwaling paragneisses and the underlying Alampu Schists the Rolwaling Migmatites are frequently cut by foliation-parallel layers of augen gneisses, implying foliation parallel shear zones. As was suggested for the Rolwaling Paragneisses, the presence of shear zones and a main foliation plane sub-parallel to the MCT implies a genetic relationship; the main foliation of the Rolwaling Migmatites and the shear zones are believed to be Himalayan in age. Since many of the pods and veins of granitic material found in the Rolwaling Migmatites are practically undeformed, partial melting is believed to have occurred during and after the period of Himalayan shear deformation related to movement along the MCT.

The Rolwaling Migmatites are probably representative of the type of mid-crustal rocks which, through melting, have given rise to the Higher Himalayan leucogranites, such as the Rolwaling Granites (Le Fort, 1981). However, as stated above, there is no field evidence to indicate that the presently exposed Rolwaling Migmatites are the source for the Rolwaling Granites. Rather, the source rocks for the Rolwaling Granites, though perhaps a northward extension of the Rolwaling Migmatite unit, lie further north and below the Tibetan Plateau.

The Alampu Schists

The Alampu Schists are approximately 6,000 m thick and consist of well-foliated, interlayered biotite-garnet schists, calc-schists, metquartzites, feldspathic gneisses, augen gneisses and hornblende-bearing schists. The presence of blue and green kyanite in aluminous rocks is a distinguishing characteristic of the Alampu Schists, as are centimeter-scale garnet porphyroblasts in the biotite-rich schists. In a few localitie directly above the MCT, kyanite-hornblende schists have been found, implying a high-pressure metamorphic environment (J. Selverstone, personal communication). The Alampu Schists grade upwards into the Rolwaling Migmatites, the boundary corresponding to a kyanite-sillimanite isograd. The lower boundary of the alampu Schists is the MCT, along which the Higher Himalayan crystallines have been thrust over the Leser Himalayan metasediments and which corresponds, in the Rolwaling-Lapchi Kang Himalayas, to a kyanite isograd.

The well developed foliation in the Alampu Schists is seen to be superposed on an original sedimentary compositional banding. This early foliation has been refolded by isoclinal to open folds with widely varying fold axes. As with the Rolwaling Paragneisses the early and late stage folds are believed to be the result of deformation during the Himalayan Orogeny, a deformation related to thrusting along the MCT. Evidence of simple shear deformation in the Alampu Schists includes the presence of feldspathic augen gneisses and helicitic almandine garnets with quartz trails stretched out along foliation planes in the biotite-rich schists. Foliations in the lower Alampu Schists are parallel to the underlying MCT.

The Khare Phyllites

The Khare Phyllites are an approximately 2,500 m thick unit of intercalated sequences of graphite-schists, talc-schists, chlorite-biotite phyllites, slates, quartzites, limestones and magnesites. Garnet is locally common and in areas is almost entirely altered to chloritoid. Down-dip mineral lineations formed by the alignment of millimeter-scale actinolite-tremolite laths are characteristic of the phyllites and schists. Quartz veins are abundant throughout the unit. The black slates found on Kalinchok are an easily identified formation that can be traced eastwards across the Tamba Kosi and Khimti Khola to the Likhu Khola.

The talc-schists, graphite-schists and chlorite-phyllites have all been intensely sheared along their foliation planes. Thin sections show that the main foliation plane is often a glide-plane cutting across a previous mica-alignment foliation, bending mica flakes into "S" shapes. It is these phyllonites which show the strongest development of the actinolite tremolite down-dip mineral lineations.

Isoclinal folds are commonly seen in the Khare Phyllites, as are large and small-scale, open to closed, southwest-vergent assymetric folds. The schists and Phyllites are cut by two crenulation cleavages or "pucker" folds, one approximately parallel and the other approximately perpendicular to the northwest-southeast structural trend, the latter being parallel to the actinolite-tremolite mineral lineation. In thin-section the along-strike crenulation cleavage is seen to consist of millimeter-scale, assymetric, often overturned, southwest-vergent folds.

Orientations of foliation and bedding planes in the Khare Phyllites, Chagu-Chilangka Augen Gneisses, Laduk Phyllites and Suri Dhoban Augen Gneisses define a late stage, elongate dome along the Tamba Kosi (figure 2 and 3). The dome may be related to the recent orogenic activity associated with movement on the Main Boundary Thrust.

The Chagu-Chilangka Augen Gneisses

The Chagu-Chilangka Augen Gneisses are between 400 m and 700 m thick and consist of tourmaline-bearing muscovite-biotite-quartz-alkali feldspar augen gneisses, the quartz often having a bluish tint. Feldspar "augens" reach up to 10 centimeters in size and are usually rotated and fractured with trails of polygonized quartz stretched out along the main foliation plane. Along the Likhu Khola sequences of quartz-rich mylonites are present within the augen gneisses.

The Chagu-Chilangka Augen Gneiss is a classic "S-C" mylonite, similar to that described by Pecher (1977) for Central Nepal. The main foliation, which is sub-parallel to the foliations of the overlying Khare Phyllites and the underlying Laduk Phyllites, defines a "C" (cissaillement) glide horizon. A previously formed "S" foliation is cut by this later "C" glide foliation, micas being bent and rotated into a characteristic "S" shape. Geometrical relationships between the "S" and "C" foliations, as well as rotated feldspar porphyroclasts (augens) and mica "fish", suggest southwestward movement of the higher sequences relative to the lower sequences of the unit, a movement direction consistent with that of thrusting along the MCT. Stretched quartz ribbons and feldspar augens define a very strong augen gneiss lineation, which is parallel to the actinolite-tremolite lineations in the overlying and underlying phyllites, defines a kinematic "a" axis or movement direction.

While the feldspar augens are porphyroclasts that have undergone brittle deformation, quartz has deformed ductily. Deformation has taken place in a brittle-ductile transition zone corresponding to the biotite zone of the greenschist facies.

The lack of baked contacts in the surrounding Khare Phyllites and Laduk Phyllites proves that the augen gneiss was not intruded into these units as a mobile granite body. Rather, as has been suggested by Pecher and Le Fort (1977) for the Lesser Himalayan augen gneisses of Central Nepal, the Chagu-Chilangka Augen Gneisses, with their pods of metasedimentary mylonitic rocks, are interpreted here as being volcano-sedimentary in origin.

The Laduk Phyllites

The Laduk Phyllites vary from approximately 1,000 m thick on the north side of the Tamba Kosi Dome to more than 2,000 m thick on the south side of the dome. The unit consists of phyllites, sandy-phyllites, chlorite-schists and occasional graphite-schists. Garnets and millimeter-scale actinolite laths, defining a down-dip lineation, are common in the upper sequences of chlorite and graphite-schists near the Chagu-Chilangka Augen Gneiss contact. A single doleritic dike has been observed near Ratto Matto that has been intruded into the surrounding metasediments. However, the doleritic dike was intruded prior to the development of the main Laduk Phyllite foliation, the foliation being well-developed in the dike itself and continuous with that of the surrounding metasediments.

As in the Khare Phyllites, isoclinal folding of an original sedimentary compositional banding has created a superposed foliation; actinolite lath, down-dip lineations are common; along strike and down-dip crenulation cleavages are seen; and quartz veins are locally abundant.

The Suri Dhoban Augen Gneisses

The Suri Dhoban Augen Gneisses outcrop in the core of the Tamba Kosi Dome (figure 2 and 3) and have a minimum thickness of 200 m. The lower contact can not be seen in the study area. The augen gneiss consists primarily of muscovite, biotite, quartz and alkali feldspar. Fractured and rotated feldspar augens, up to several centimeters in size, all attest to the high degree of brittleductile shearing the unit has undergone. In the vicinity of Suri Dhoban an approximately 10 m thick sequence of quartz-mylonites and sericite-schists are found within the augen gneiss unit. As with the Chagu-Chilangka Augen Gneisses, the lack of baked contacts and the presence of metasedimentary mylonites and phyllonites within the augen gneiss unit suggests a volcano-sedimentary origin for the Suri Dhoban Augen Gneisses.

The Ramechap Group

The Ramechap Group lies south of the mapped region and, therefore, does not appear in figures 2 and 3. This unit is found south of the Tamba Kosi - Khimti Khola confluence (figure 1), and lies structurally beneath the southern extension of the Chagu-Chilangka Augen Gneisses. The southern boundary of the Ramechap group lies along the Sun Kosi where there is a major fault, the Sun Kosi Fault, separating the Ramechap Group to the north from the Mahabharat Crystallines to the south. The Ramechap Group, along the Tamba Kosi, is approximately 8,000 m thick.

The Ramechap Group consists of sandstones, graywackes, shales, pebble-cobble conglomerates, limestones and occasional doleritic sills. Graphite-schists, sericite-phyllites and chlorite-phyllites occur directly below the Chagu-Chilangka Augen Gneisses. The main bedding-foliation plane dips uniformly to the northeast between 20° and 40°, with a strike varying from N60°W to N80°W. An approximately down-dip crenulation cleavage, along with a down-dip actinolite-lath mineral lineation in the upper sequences of phyllitic rocks, is cut by a later, along-strike crenulation cleavage. Metamorphism within the Ramechap Group increases upwards from unmetamorposed to slightly metamorphosed in the lowest shale sequences to lower greenshist facies in the phyllites directly under the Chagu-Chilangka Augen Gneisses.

On the southern slope of the Mahabharat Lekh, north of Sindhuli Bazaar, a small sliver of Ramechap Group-type sediments outcrops between the Mahabharat Crystallines to the north and the Main Boundary Thrust to the south (figure 4). Here the Ramechap sediments appear to be sandwiched between the underlying Main Boundary Thrust and the overlying Mahabharat Crystallines.

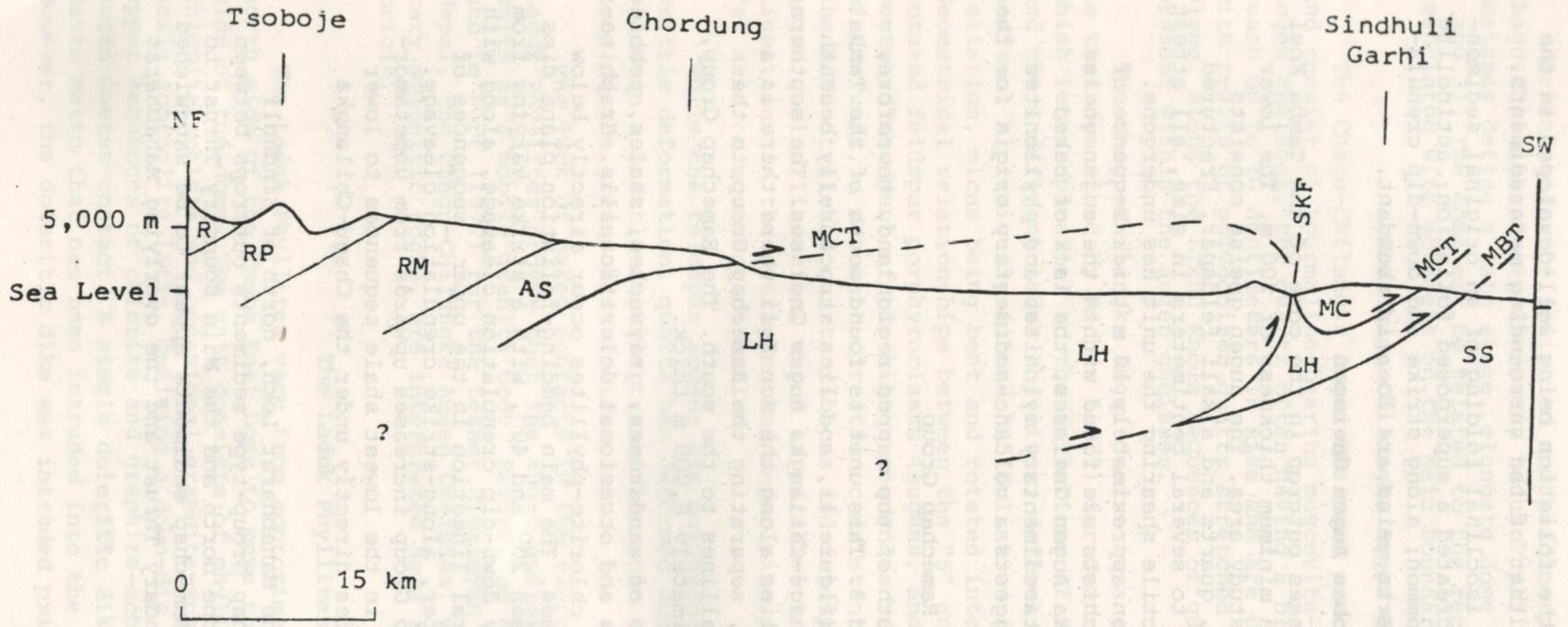

Figure 4. Geological cross-section through the east-central Nepal Himalayas. R=Rolwaling Granites: RP=Rolwaling Paragneisses: RM=Rolwaling Migmatites: AS=Alampu Schists: LH=Lesser Himalayan sediments and metasediments: SS=Siwalik sediments: MCT=Main Central Thrust: MBT= Main Boundary Thrust: SKF= Sun Kosi Fault. Scale=1:500,000. No vertical exaggeration.

The Mahabharat Crystallines

The Mahabharat Crystallines are composed entirely of medium to high grade metamorphic rocks and igneous rocks. The unit includes biotite-garnet schists, metaquartzites, amphibolites, calc-schists, augen gneisses and granites. There are two different phases of granitic intrusions in the Mahabharat Crystallines, an earlier, biotite rich granite and a later, more leucoratice and tourmaline - rich granite containing stretched xenoliths of biotite schists. The tourmaline - rich granite intrudes both the surrounding metasediments & the earlier biotite - granite. Both granites are cut by late stage, quartz-tourmaline veins.

The northern boundary of the Mahabharat Crystallines coincides roughly with the Sun Kosi Fault, running northwest-southeast along the Sun Kosi (figure 4). A thin sequence of chlorite-garnet schists, with a vertical foliation, is present along the southern bank of the Sun Kosi north of the Mahabharat Crystallines. The southern boundary of the Mahabharat Crystallines is a thrust fault along which the unit has been thrust southwestwards over sediments of the Ramechap Group (figure 4). A 300 m thick zone of chlorite-garnet schists lies between the southern thrust fault boundary of the Mahabharat Crystallines and the underlying Ramechap Group sediments. Foliations in the Mahabharat Lekh define a synform (Stoecklin, 1981), the core of which consists of granitic augen gneisses.

SHEARING, THRUSTING, METAMORPHISM AND THE MAIN CENTRAL THRUST ZONE

The Main Central Thrust

In the Rolwaling-Lapchi Kang Himalayas the Main Central Thrust is a major lithologic, metamorphic and structural discontinuity separating the underlying Lesser Himalayan rocks from the overlying Higher Himalayan sequences. It is the only indisputable thrust fault present throughout the 20 km to 25 km thick pile of rocks making up the Lesser and Higher Himalayas. The zone across which this break occurs is usually less than 30 m wide. The MCT, as here defined, can be traced for over 60 km between the Sun Kosi in the west to the Likhu Khola in the east.

Below the MCT argillaceous and calcareous metasediments belong to the upper greenschist facies, and include limestones, talc-schists, graphite-schists, slates and chlorite phyllites. Above the MCT the more arenaceous metasediments belong to the epidote-amphibolite and amphibolite facies, and include kyanite-bearing schists and gneisses, hornblende-bearing schists, granitic gneisses, augen gneisses, biotite-schists with abundant almandine garnet, and calc-schists. Several samples collected from directly above the MCT contain both kyanite and amphibole. The transition between the Lesser and Higher Himalayan rock sequences is sharp. While in the Annapurna Himalayas of Central Nepal kyanite has been reported in the Lesser Himalayan metasediments below the MCT (Bordet et. al., 1981), kyanite is not found below the MCT in the Rolwaling-Lapchi Kang Himalaya, where the MCT corresponds to a kyanite isograd.

The MCT can apparently be traced from the Tibetan Border, just west of the study area, southwest to the Indrawati Khola east of Kathmandu, and then southeast to where it joins the Sun Kosi Fault, along which flows the Sun Kosi north of the Mahabharat Lekh (Stoecklin and Bhattarai, 1981). The Mahabharat Crystallines can thus be shown to lie south of, and structurally above, the MCT at the Sun Kosi. The MCT, where it coincides with the high angle Sun Kosi Fault, separates unmetamorphosed shales of the Ramechap Group to the north from the medium-grade metamorphics and igneous rocks of the Mahabharat Crystallines to the south. The same metamorphic discontinuity is seen where the MCT reappears south of the Mahabharat Lekh, the overthrust Mahabharat Crystallines being separated from the underthrust sediments.

The Mahabharat Crystallines have thus been thrust a minimum of 80 km southwestwards over the Lesser Himalayan sediments and metasediments to their present position. The chlorite-schists structurally underlying the Mahabharat Crystallines are here interpreted as being a zone of Ramechap-type sediments which have been heated and deformed (sheared and perhaps dragged out along the MCT) by the overthrusting of the relatively hot, mid-crustal slab of Higher Himalayan crystalline rocks.

The Sun Kosi Fault, which coincides approximately with the location of the MCT between the Tamba Kosi and Likhu Khola, is believed to be a high-angle reverse fault, the Ramechap sediments to the north being lifted upwards relative to the Mahabharat Crystallines to the south. Movement along the Sun Kosi Fault is probably related to the presently active tectonic deformation associated with the MBT, the fault may flatten at depth & could be a splay fault coming off of the MBT, which is also believed by the author to flatten at depth (figure 4).

The Higher Himalayas

Throughout most of the 18 km thick Higher Himalayan thrust sheet there is evidence of intense shear deformation. Mylonitic augen gneisses are observed in all the Higher Himalayan lithotectonic units except the post-tectonic Rolwaling Granite; helicitic garnets with quartz trails are common in the biotite schists of the Alampu Schists, which lie directly over the MCT. Since the main foliation of all the Higher Himalayan augen gneisses (which would be sub-parallel to a simple shear direction) is parallel to the general Higher Himalayan foliation, and since these foliations are parallel to the MCT, it is here suggested that there is genetic relationship between the formation of all three. Accordingly, the MCT is considered to be a late stage brittle deformation preceeded by, and perhaps coeval with, the ductile shear deformation seen throughout the Higher Himalayan rocks.

The inverse metamorphic gradient of the Higher Himalayas is defined by the presence of sillimanite-bearing migmatites, the Rolwaling Migmatites overlying kyanite-bearing schists and paragneisses of the Alampu Schists. Under normal geothermal gradients, and in a normal crustal sequence, kyanite-bearing schists and paragneisses would not be found underlying sillimanite-bearing migmatites. Three pressure-temperature-time tectonometamorphic scenarios may be used to explain the Higher Himalayan inverse metamorphism (Thompson, 1976):

(1) The initial geothermal gradient was high enough to produce a medium pressure metamorphic sequence (Miyashiro, 1978) in the Higher Himalayan crustal unit. Initially, sillimanite was the equilibrium aluminosilicate present in these mid-crustal rocks. Increased lithostatic

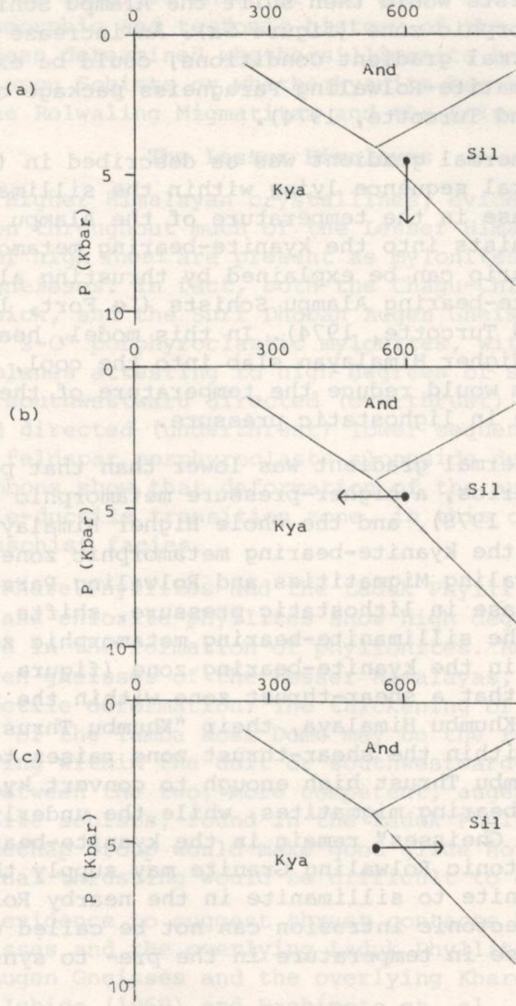

Figure 5. Pressure-temperature diagrams showing change in aluminosilicates within the Higher Himalayan crystallines for three different tectonic models:

(a) Alteration of sillimanite to kyanite as a result of underthrusting of the Alampu Schists;

(b) Alteration of sillimanite to kyanite as a result of overthrusting on the MCT;

(c) Alteration of kyanite to sillimanite as a result of shear-stress heating within the Rolwaling Migmatites.

pressure in the Alampu Schists would then shift the Alampu Schists into the kyanite-bearing metamorphic zone (figure 5a). An increase in temperature, under static geothermal gradient conditions, could be explained by thrusting a Rolwaling Migmatite-Rolwaling Paragneiss package over the Alampu Schists (Oxburgh and Turcotte, 1974).

(2) The initial geothermal gradient was as described in (1), the whole Higher Himalayan mid-crustal sequence lying within the sillimanite-bearing metamorphic zone. A decrease in the temperature of the Alampu Schists would shift the Alampu Schists into the kyanite-bearing metamorphic zone (figure 5 b). Such a scenario can be explained by thrusting along the MCT which underlies the kyanite-bearing Alampu Schists (Le Fort, 1975; Bordet et. al., 1981; Oxburgh and Turcotte, 1974). In this model, heat transfer from the hot, overthrust Higher Himalayan slab into the cool, underthrust Lesser Himalayan sediments would reduce the temperature of the Alampu Schists without any change in lighostatic pressure.

(3) The initial geothermal gradient was lower than that postulated for the previous two scenarios, a higher-pressure metamorphic sequence being produced (Miyashiro, 1978), and the whole Higher Himalayan mid-crustal unit lying within the kyanite-bearing metamorphic zone. An increase in temperature in the Rolwaling Migmatities and Rolwaling Paragneisses, with no accompanying increase in lithostatic pressure, shifts these two lithotectonic units into the sillimanite-bearing metamorphic zone, while the Alampu Schists remain in the kyanite-bearing zone (figure 5c). Maruo and Kizaki (1983) suggest that a shear-thrust zone within the sillimanite-bearing migmatites of the Khumbu Himalaya, their "Khumbu Thrust", does just this; shear heating within the shear-thrust zone raises temperatures in the vicinity of the Khumbu Thrust high enough to convert kyanite-bearing gneisses into sillimanite-bearing migmatites, while the underlying kyanite-bearing "Himalayan Gheisses" remain in the kyanite-bearing zone. Instrusion of the post-tectonic Rolwaling Granite may supply the necessary heat source to convert kyanite to sillimanite in the nearby Rolwaling Paragneisses, but a post-tectonic intrusion can not be called upon to cause the necessary increase in temperature in the pre- to syn-tectonic migmatites.

It should be pointed out, however, that scenarios (1) and (2) are not mutually exclusive. Thrusting along a ductile shear zone between the Rolwaling Migmatites and the Alampu Schists, followed by thrusting along the MCT, would result in a combination of increased lithostatic pressures and decreased temperatures in the Alampu Schists, altering sillimanite to kyanite.

Alternatively, if we consider the whole Higher Himalayan thrust sheet above the MCT to be a shear zone (Mattauer, 1975), as is suggested by the abundance of augen gneiss units and the sub-parallel, pervasive Higher Himalayan foliation, then simple shear along a northeast-dipping shear zone, 15 km thick, will also result in increased lithostatic pressure in the lower sequences. Combined with a brittle-ductile or brittle overthrusting along the MCT, this would result in both increased pressures and decreased temperatures in the Alampu Schists, likewise altering sillimanite to kyanite.

It is yet to be resolved which of the above models most accurately reflects the metamorphic and tectonic history of the Higher Himalayas; to date it has not been determined whether sillimanite has been altered to kyanite in the Alampu Schists or whether kyanite has been altered to sillimanite in the Rolwaling Migmatites and the Rolwaling Paragneisses.

The Lesser Himalayas

As with the Higher Himalayan crystallines, evidence of intense shearing is common throughout much of the Lesser Himalayan metasedimentary sequence. Zones of high shear are present as mylonites, phyllonites and mylonitic augen gneisses. In fact, both the Chagu-Chilangka Augen Gneisses, 400 m to 700 m thick, and the Suri Dhoban Augen Gneisses, a minimum of 200 m thick, are "S-C" porphyroclastic mylonites, with characteristic "S-C" foliation planes attesting to high degrees of simple-shear deformation between the southwestward directed (overthrust) higher sequences and the northeastward directed (underthrust) lower sequences. Fractured, brittly-deformed feldspar porphyroclasts alongside ductily-deformed mosaic-quartz ribbons show that deformation of the augen gneisses took place in a brittle-ductile transition zone, in this case, in the biotite zone of the greenschist facies.

In both the Khare Phyllites and the Laduk Phyllites talc-schists, graphite-schists and chlorite-phyllites show high degrees of simple shear which has resulted in the formation of phyllonites. However, unlike the feldspar-rich augen gneisses of the Lesser Himalayas, these rock types show primarily ductile deformation. The thickening of the Laduk Phyllites on the south side of the Tamba Kosi Dome may be the result of either undetected thrusting within the unit or southwestward-directed ductile "squeezing out" between the two, more competent, augen gneiss units. Talc schists and graphite schists, found in the Laduk Phyllites, Khare Phullites and the upper Ramechap Group would make good glide horizons for thrust sheets, and internal thrusting would be difficult to detect.

There is no evidence to suggest thrust contacts between the Suri Dhoban Augen Gneisses and the overlying Laduk Phyllites, and between the Chagu-Chilangka Augen Gneisses and the overlying Khare Phyllites, as have been reported by Ishida (1969) and Hashimoto et. al. (1973). Differing rheological properties between the units, however, has resulted in disharmonic deformation. It is possible, though, that the Chagu-Chilangka Augen Gneisses are underlain by a thrust fault. Elsewhere in Nepal (Bordet, 1981; Pecher and Le Fort, 1977; Maruo and Kizaki, 1981) only one sequence of augen gneisses is reported in the Lesser Himalayan metasediments, whereas in the Tamba Kosi two units, the Suri Dhoban Augen Gneisses and the Chagu-Chilangka Augen Gneisses, are seen. This may be the result of overthrusting, the Chagu-Chilangka Augen Gneisses and the Suri Dhoban Augen Gneisses actually being the same unit. If a thrust fault is accepted as underlying the Chagu-Chilangka Augen Gneisses then it would represent 40 km of shortening within the Lesser Himalayas.

Inverted metamorphism in the Lesser Himalayas has been explained by Le Fort (1975) as being the result of heat-transfer from the hot, overthrust Higher Himalayan crystallines to the previously unmetamorphosed Lesser Himalayan sediments. Lithostatic pressures also would increase in the Lesser Himalayan sediments if a 15 km to 20 km thick slab were thrust on to them. Therefore, it is not surprising that given appropriate chemical compositions kyanite would form beneath the MCT; lithostatic pressures would initially be very high, on the order of 5-6 kilobars, as the Lesser Himalayan sediments were heated up.

Between the outcropping of the MCT along the Tamba Kosi and the outcropping of the MCT south of the Mahabharat Lekh there are major changes in both the thermal gradients of the Lesser Himalayan sediments and the depth to which shear deformation is seen below the MCT. Extending to more than 4 km below the MCT on the Tamba Kosi, the Lesser Himalayan sequences have been metamorphosed up to the biotite zone of the greenschist facies and have undergone extreme ductile and brittle-ductile shear deformation. Yet, south of the Mahabharat Lekh a comparable metamorphic-deformation zone extends only 300 m below the MCT. This is best explained by postulating that the frontal portions of the Higher Himalayan thrust sheet cooled progressively as it moved forward, and perhaps upward, through heat transfer to the underlying cooler sediments; thus the depth to which underlying sediments would be heated up to the biotite isograd would be progressively reduced. Furthermore, as the MCT cut up section in the footwall, and the Higher Himalayan crystallines cooled, deformation became increasingly brittle in the vicinity of the MCT. This would explain both the abundance of mylonitic augen gneisses in the Mahabharat Crystallines and the fact that the MCT is a much sharper metamorphic and structural discontinuity under the Mahabharat Crystallines than it is along the Tamba Kosi and the Likhu Khola.

In fact, differences in the appearance of, and therefore definitions of, the Main Central Thrust throughout the Himalayas are easily explained by thrust geometry. This includes (a) lateral changes in the lithologies of the hanging wall and footwall of the MCT, (b) frontal and lateral ramping in the footwall and hangingwall of the MCT, and (c) changing temperatures (relative and absolute) in the hangingwall and footwall rocks of the MCT, both along-strike and in the transport direction. As a result of these the MCT will separate rocks of different lithologies and different metamorphic grades in different areas, and the degree to which an inverted metamorphic sequence will be produced, as well as the relative importance of brittle versus ductile deformation in the vicinity of the MCT, will also vary.

CONCLUSIONS

Between the Tethyan sediments to the north and the Main Boundary Thrust to the south the Rolwaling-Lapchi Kang Himalayas can be divided into ten lithotectonic units. These are (1) the Rolwaling Granites, (2) the Rolwaling Paragneisses, (3) the Rolwaling Migmatites, (4) the Alampu Schists, (5) the Khare Phyllites, (6) the Chagu-Chilangka Augen Gneisses, (7) the Laduk Phyllites, (8) the Suri Dhoban Augen Gneisses, (9) the Ramechap Sediment Group, and (10) the Mahabharat Crystallines.

The Main Central Thrust is a major lithologic, metamorphic and structural discontinuity dividing the Lesser Himalayan metasediments from the higher Himalayan crystallines. In the Rolwaling-Lapchi Kang Himalayas the MCT corresponds to a kyanite isograd. The Mahabharat Crystallines making up the Mahabharat Lekh are underlain by the Main Central Thrust, and are an outlying klippe that has been thrust southwestwards for approximately 80 km over the underlying Lesser Himalayan metasediments.

The Himalayan shear-thrust zone extends approximately 5 km below and 15 km above the Main Central Thrust. This shear-thrust zone contains abundant mylonites, phyllonites and mylonitic augen gneisses, and including the Main Central Thrust, the Himalayan shear-thrust zone shows evidence of ductile, brittle-ductile and brittle deformation. The presence of an inverted metamorphic sequence, ranging from unmetamorphosed to slightly metamorphosed sediments in the lower Ramechap Group to sillimanite-bearing migmatites in the Rolwaling Migmatites, is explained by thrusting along faults or shear zones with subsequent heat transfer from hotter, overthrust units to cooler, underthrust units, and subsequent changes in lithostatic pressure.

The Rolwaling Granite is a Higher Himalayan leucogranite that has been intruded along the Tethyan Sediment-Higher Himalayan crystalline contact. The main granite-body is undeformed, and thus post-tectonic. The source of the granite lies below the erosion surface to the north, under the Tibetan Plateau, and may consist of rocks similar to the Rolwaling Migmatites.

ACKNOWLEDGMENTS

Financial support for the field work upon which this paper is based has come from a National Science Foundation Graduate Fellowship and an AMOCO Masters Fellowship. I have had invaluable discussions on my research and Himalayan geology with Prof. R. Kligfield, Prof. C. Stern, Prof. J. Selverstone, Dr. P. Le Fort, Dr. Y. Maruo and Daniel Vuichard. In the field, Krishna Bahadur Gurung's help has enabled me to accomplish my work with a minimum of difficulties. I am particularly indebted to my wife, Hilary Jacobs, who has been a patient and hard-working aide-de-camp on all the field excursions, who has given me her generous and invaluable support both in Nepal and at home, and without whom this work would not have been possible.

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