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**EMPLACEMENT AND DEFORMATION OF THE LINGSHI
KLIPPE IN THE HIMALAYA OF NORTH-WESTERN BHUTAN**

By
Christopher N. A. Taylor, B.Sc.

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment
of the requirements for the degree of Master of Science,
Department of Earth Sciences

Carleton University
Ottawa, Ontario
September, 2003
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**EMPLACEMENT AND DEFORMATION OF THE LINGSHI
KLIPPE IN THE HIMALAYA OF NORTH-WESTERN BHUTAN**

Submitted by Christopher N. A. Taylor, B.Sc., in partial fulfilment of the requirements
for the degree of Master of Science

Richard L. Brown
Supervisor

✓ Claudia Schroder-Adams
Chair, Department of Earth Sciences

Carleton University
September, 2003

FRONTISPIECE

The south-east face of Chomolhari, with ruined Dzong (Bhutanese fortress) in the foreground. The Chomolhari Range is composed of an assemblage of metasediments that lie in the foot wall of an inactive segment of the South Tibetan Detachment System, and in the hanging wall of another detachment fault known called the Lingshi Detachment.

ABSTRACT

The Chomolhari Range and Lingshi Klippe in north-western Bhutan comprise unmetamorphosed to greenschist facies Tethyan Sequence and greenschist to amphibolite-facies Chekha Formation rocks. Tethyan Sequence rocks are in the hanging wall of the South Tibetan Detachment System (STDS) present between the Tethyan Sequence and Chekha Formation. The Lingshi Detachment is at the base of the Chekha Formation, and contains the Chekha Formation in its hanging wall. Greater Himalayan Sequence (GHS) gneisses in the footwall of the Lingshi Detachment comprise the surface lithologies surrounding the Lingshi Klippe. Deformation of the Tethyan Sequence predates, is contemporaneous with, and post-dates the STD. Two post-STD regional folding events affect the rocks of this area. The Lingshi Fault is a normal, steeply SE-dipping ductile to brittle structure in the eastern Chomolhari Range that displaced Tethyan Sequence rocks of the Lingshi Klippe in its hanging wall down to the south-east relative to the Chomolhari Range.

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I would like to warmly thank Dr. Richard Brown, whose input as my thesis supervisor has been stimulating, and who has shown me how to connect my ideas to the reality of a written thesis. I would also like to thank Dr. Brown for offering me the incredible opportunity of doing field research in the Himalaya of Bhutan, a place I never thought I'd have the opportunity to see.

I'd like to extend my thanks to Dr. Dan Gibson, who taught me the techniques of field geology over the course of the two summers I worked as his field assistant for in the Canadian Cordillera. My employment with Dan is the reason I undertook graduate level studies in structural geology, and his unparalleled work ethic and application of scientific methods have been an inspiration for my own research.

I'd also like to thank Mike Jackson, for all the technical instruction he's given me over the years, and also for allowing me the use of his lab's facilities.

I would also like to thank the people of Chebisa and Goyak, for their hospitality in taking me into their homes and providing me with food during my field work. Particularly I'd like to extend my thanks to my two companions Thinley and "Agae" (which means Grandfather), who kept me company during my field work and even taught me a few words of Bhutanese. Kanichaela (well, that's how it sounds like it's spelt)!

Funding for this research was provided through a Natural Science and Engineering Research Council of Canada grant to Dr. Richard Brown.

Finally, I'd like to thank my wife, Julie Privora, for her continual support and motivation towards the completion of this thesis. Your love, company (and constant feedings) have kept me going throughout my schooling. You are my greatest inspiration.

The King was a very strong, powerful ruler over his people. He built a Dzong in the valley of the sacred mountain, to protect himself and his people from the attacks of the Tibetans, as well as their Bhutanese neighbours, and ruled over all the lands thereabouts. There was nothing the King could ask for that he was not given, as his people respected and feared him. But one day, the King demanded too much. One morning, sitting outside of his fortress, he looked up and complained that the mountains of Nele La blocked the sun from warming his valley in the early morning. In the madness brought about by constant power, he then ordered his people to dig down the tops of the mountains themselves, so that he could sit in the morning sunlight. Angered by his impossible request, the Bhutanese cut off the King's head. His fortress now lies in ruins.

-The legend of the Headless King of the Chomolhari Dzong,
as it was told to the author by the local people.

This legend tells the outsider a lot about the strong, independent character of the Bhutanese, who in the author's experience can put up with incredible amounts of physical hardship without ever complaining, but have no patience for injustice or moral impropriety.

*To my grandparents, Lionel and Alice,
who led me to the road I walk today.*

ORIGINAL CONTRIBUTION

Four weeks of fieldwork were undertaken in the Lingshi area of north-western Bhutan in October of 2001. For one of these weeks, the author was in the company of Dr. Richard Brown, and for three weeks independently mapped and sampled a suite of rocks from areas that were accessible along the main trail through this region.

Observations and measurements were made of various structural features that were geologically prominent. Mapping and sampling included rocks of the Tethyan Sequence, Chekha Formation, and Lingshi Fault. Comparisons were made between the author's own observations and those of the sole previous worker in this area, Augusto Gansser (1967, 1983). Samples were taken in order to characterise mineralogy and structures.

Thin sections were made by the author at Carleton University of all collected samples. Petrographic analysis was subsequently carried out in the laboratory by the author.

A comparison of field observations with Landsat imagery suggested regional contexts for the observed structures. A review of the published body of literature was made in order to correlate structures observed in the study area to those which have been documented by other authors elsewhere in the Himalaya.

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1.0 INTRODUCTION

The Himalayas extend for over 2000 km and are the prime modern example of an inter-continental collisional orogen (**figure 1.1**). Development of the orogen began during the Eocene at ca. 50 Ma (Hodges, 2000), at which time the Tethyan ocean began closing as the Indian and Asian plates converged (**figure 1.2**). Indian continental material was subducted beneath Asia, and was also progressively imbricated by south-verging structures. The forced subduction of continental material beneath other continental crust resulted in the creation of the Tibetan plateau, which is the highest laterally extensive raised area on Earth, with an average elevation of over 5 km. The border range, known as the High Himalaya, that separates the Tibetan plateau from the southward propagating foreland thrust belt, contains the highest points of elevation on Earth, including peaks that exceed 8000 m along much of the range.

Several structural and stratigraphic features occur along strike over most of the Himalayan orogen. Structurally, the South Tibetan Detachment System (STDS) (Burchfiel et al., 1992) and Main Central Thrust (MCT)/Main Frontal Thrust (MFT) (e.g. Hodges et al., 2000) are primary structural influences on the overall lithological and metamorphic distribution (see Chapter 2). The highest structural levels of the Himalaya typically comprise greenschist facies to unmetamorphosed sedimentary rocks originally deposited in the Tethyan ocean that are referred to as the Tethyan Sequence. These are separated by the various local segments of the STDS from the underlying amphibolite facies crystalline units of the Greater Himalayan Sequence (GHS). The GHS units are of Indian continental affinity, and have been deformed and metamorphosed as a result of burial beneath Asia and subsequent tectonic extrusion (Hodges et al., 2000). The GHS is

Figure 1.1.1: Regional tectonic framework showing the Himalayan orogen, the location of Bhutan in the eastern Himalaya, and the location of the field study area.

Simplified after Sorkhabi and Stump, 1993

Figure 1.2: Representation of plate motion of the Indian continent over time relative to Asia. Source: United States Geological Survey, 2003.

Source: USGS, 2003.

separated by the MCT from the underlying greenschist to amphibolite facies units of the Lesser Himalayan Sequence (LHS), which are the upper levels of Indian crust being progressively involved in orogenesis as India continues to subduct northward beneath Asia.

Complicated structural histories characterize all of the lithologies. For example, evidence (Brown and Nazerchuk, 1993; Godin et al., 1999) from Nepal has suggested early (Middle Eocene to Late Oligocene) kilometre-scale tectonic fan-like fold structures are preserved in the Tethyan strata of the High Himalaya. These folds predate structures associated with normal-sense, down to the north shearing in the STDS. Within these same units, the presence of locally boudinaged horizons and faulted contacts (Gansser, 1983) are also suggestive of a complex strain history that is thus far undocumented in Bhutan. Although in theory the Tethyan strata are restorable to an undeformed configuration, the absence of laterally continuous, detailed palinspastic sections through the Tibetan plateau and High Himalaya attests not only to the inaccessibility of the terrain, but also to the structural complexity of these rocks.

The deformation history of the GHS is even less well constrained than that of the Tethyan. Complex infolding of mixed bodies of gneissic and other crystalline rock is apparent. The entire crystalline assemblage is interrupted by a number of ductile out-of-sequence thrusts (Godin, 1999), which have also been identified in Bhutan (Grujic et al., 2002). On the whole, shear sense indicators document top to the south shearing throughout the crystallines that penetrates past their base at the MCT, and which are overprinted in the upper structural levels by top to the north shearing as the STDS is approached.

The LHS is structurally complex, and in addition to being variably metamorphosed at low to medium grades, imbricates of high-grade crystalline gneisses, possibly from the GHS, are also present (Gansser, 1983). Like the GHS, the LHS are of Indian crustal affinity, but have a distinct structural history (see Chapter 6).

The eastern Himalaya, and Bhutan in particular, is an understudied area where geological work has been historically scarce and infrequent. The primary worker in this area was the inimitable Augusto Gansser, whose relevant publications include two editions (1964, 1983) that provide the framework for this study. Gansser's observations of stratigraphy and structure are excellent, but leave room for a significant volume of future work that will build on the details of sequence affinities, timing and mechanism of structural development, and overall tectonic processes as these relate to the evolution of the Himalayan orogen in Bhutan.

Since the 1990's, a number of researchers have studied the geology of Bhutan in greater detail, revealing the existence of a number of interesting features. Metasedimentary klippen, out-of-sequence thrusting, and Quaternary extension are three of the most interesting of these.

Among the metasedimentary klippen of Bhutan, the Lingshi Klippe in the north-west of the country is perhaps the largest and least studied (**figure 1.3**). Published information is largely confined to Gansser's observations in this area, and in Gansser's own words, "The Lingshi Basin is certainly an area where detailed studies are warranted." (p. 209, Gansser, 1964).

Out-of-sequence thrusting, first observed by Gansser (1983), was further constrained by Grujic et al. (1996, 2002) in eastern and central Bhutan. The "Kakhtang

Figure 1.3: Geology of the Bhutan Himalaya by Gansser (1983). Added lines are as follows. In black: The South Tibetan Detachment (STD) that has manifested the most recent phases of motion. In yellow: The Kakhtang Thrust, after Grujic et al. (1996). In red: The Main Central Thrust (MCT). In blue: The Main Frontal Thrust. Letters indicate locations discussed in the body of the text. A: The Lingshi Klippe. B: The Chomolhari Range. C: The Tang Chu Klippe. D: Area discussed in reference to Edwards et al. (1999).

GEOLOGICAL MAP
of the
BHUTAN HIMALAYA
by Augusto Gansser

1:500 000

50 Km

Based on fieldwork in 1963, 1965, 1967, 1969,
with some additions in 1977, on Landsat photos
and all other available informations.

Thrust” may be responsible for the preservation of metasedimentary klippen in southern Bhutan, where they are surrounded by GHS crystalline units. Out-of-sequence thrusting may also be responsible for the apparent division of the GHS in Bhutan into two units. These are the predominantly migmatitic augen gneisses of the northern and structurally higher GHS, and the predominantly non-migmatitic, schistose and gneissic rocks of the south, often referred to as the Paro Metasediments (Gansser, 1983; Grujic et al., 2002).

East-west, or orogen parallel extension has been documented throughout the northern High Himalaya and southern Tibetan plateau, where it is manifested as a series of graben and half-graben systems with north-south trends. The Yadong Cross Structure (YCS) is one of the largest of these systems (Cogan et al., 1998). Although it is mainly developed within southern Tibet, its close proximity to the Chomolhari Range, which defines the Bhutan-Tibet border, means that it affects portions of Bhutan as well.

With respect to the overall tectonic regime, the “channel flow” model of crustal flow has been developed to account for the distribution of metamorphic facies and structural characteristics within the High Himalaya (see Chapter 6). The recognition in the early 1990’s that the STDS and MCT were active contemporaneously between approximately 22 and 18 Ma (e.g. Burchfiel et al., 1992; Grujic et al., 1996) enabled Beaumont et al. (e.g. 2001) to model the GHS as extruding between these two faults under an erosionally and gravitationally induced pressure gradient. The material reservoir (i.e. the source of the GHS) in this model is a partially molten crust derived from Indian subducted material in residence beneath the Tibetan plateau. The channel flow mechanism has since become a popular hypothesis to explain orogenic evolution in many contexts. Many researchers have applied this model, or variants of it, to previous

periods of evolution within other orogenic belts (e.g. see Brown & Gibson, 2003, and Kuiper et al., 2002, in the Canadian Cordillera).

This thesis examines the Lingshi Klippe and Chomolhari Range (see **figure 1.4**) as these features are accessible from the main trail through the Lingshi area. The names of various study locations as referred to within this text are presented on **figure 1.4**. As can be seen on Gansser's 1983 map (see **figure 1.3**), the Lingshi Klippe, referred to by Gansser as the Lingshi Basin, is an erosionally isolated structural basin of metasedimentary rock, located in north-western Bhutan, of about 900 km² in area. The Chomolhari Range is an anomalously NE-SW trending spur of the High Himalaya that separates Bhutan from Tibet. As suggested by Gansser's observations (1964, 1983), the Chomolhari Range is in fact a large antiform, henceforth known in this study as the Chomolhari Range Antiform (CRA). The existence of the CRA has often been ignored in past publications concerning the study area, and hence the degree of connection between the Tethyan units of the Lingshi Klippe and those of Tibet was unclear.

The Lingshi Klippe occurs as a topographic high with peaks ranging from between 4500 to 6000 m (**figure 1.3**), and preserves two of the three main lithologic sequences. The first is the Tethyan Sequence, which comprises a series of greenschist facies marbles, calc-silicates, and phyllites, and unmetamorphosed shales, limestones and argillaceous limestones. These rocks occur in the core of the klippe, since it is a structural basin (see Chapter 4) at what are the structurally highest levels. The second of these is the Chekha Formation (Gansser, 1964, 1983), which comprises a series of greenschist to amphibolite facies marbles, quartzites, and calc-silicates, and occurs in the structurally lower levels, erosionally exposed surrounding the Tethyan units of the klippe

Figure 1.4: Tectonic assemblage map modified after Gansser (1983). Lettered localities are as follows. J: Jhari La. S: Shakshipasa. G: Goyak-Chebisa. N: Nele La. H: Harakim. T: Tando Gompa. C: Chomolhari. See text for discussion of faults and synformal and antiformal axes.

core. The Chekha Formation was intruded by multiple generations of Himalayan leucogranites.

For the purposes of this study, the Chomolhari Range will be considered to consist of the high peaks that comprise the Chomolhari Range ridge, which terminates in the low saddle that separates the Chomolhari Range from the more northerly Masang Kang Border Range ridge system. The Chomolhari Range is formed mainly from units of the Chekha Formation, but also contains some rock from the lowest structural levels of the Tethyan Sequence. Surrounding the Lingshi Klippe and Chomolhari Range are migmatitic augen gneiss units of the GHS, except on the north-western side of the Chomolhari Range, where Tethyan shales and limestones are present (see **figure 1.3**).

The main questions addressed during this study are:

- 1) What is the structure of the Chomolhari Range and Lingshi Klippe that accounts for the lithological distributions?
- 2) What is the structural relationship between the Tethyan Sequence units in this area and the Chekha Formation of Gansser (1964, 1983)?
- 3) What is the structural history and significance of the Lingshi Fault?

Three weeks of field work provided a small data set that allowed for the preliminary characterisation of the structures in the study area. Structures were related to structural features published by other researchers in the Himalaya, and a deformational history for the rocks of the Chomolhari Range and Lingshi Klippe was proposed.

2.0 LITHOLOGY AND STRUCTURAL BOUNDARIES

Throughout the Himalaya, the lithostratigraphic distribution of units is controlled by major faulted contacts that divide the rocks into three major lithological groups. These fault zones are the STDS and MCT. The three sequences thus produced are lithotectonic, and not primarily stratigraphic, in nature (**figure 2.1**). Accordingly, units that share the same structural position also share at least part of their total deformation and metamorphic histories. Although the Tethyan Sequence and LHS can in part be restored to an undeformed state through palinspastic reconstruction of cross sections (e.g. Corfield and Searle, 2000), this is certainly not the case for the Chekha Formation and GHS. In the case of the Chekha Formation, transposition of bedding and tectonic displacement of the sequence as a whole (see below) make it impossible to connect its units to those of the overlying Tethyan Sequence. The GHS is mostly gneissic, and deformation and metamorphism are polyphase, making associations with other lithotectonic sequences only possible through indirect evidence such as geochemistry and geochronology. These methods have yet to yield incontrovertible evidence regarding proper protolith assignments.

Work by other authors (e.g. Gansser, 1983; Burchfiel et al., 1992; Hodges, 2001; and Grujic et al., 1996, 2002) has shown that the following distribution of structures and fabrics is expected in the lithologic sequence centered on the Lingshi Klippe (**figure 1.3**). These are, beginning at the top of the orogenic sequence (see **Table 1**): The Tethyan Sequence, the Chekha Formation, the upper GHS, the lower GHS (i.e. the Paro Metasediments), and the LHS.

Figure 2.1: Lithologic column centred on the Lingshi Klippe. Thicknesses are maximum possible values based on Gansser (1983). Thicknesses of units are not expected to be equal across the Bhutan Himalaya, as regional folding before the initiation of the Kakhtang Thrust will cause local variations (Grujic et al., 2002). Red elongate shapes are concentrations of leucogranite.

Table 1: Lithostratigraphic units with structural boundaries, for a lithologic column centered on the Lingshi Klippe.
Sources: 1) Gansser, 1983, 2) Hodges, 2001, 3) Grujic et al., 1996 and 2002, 4) Burchfiel et al., 1992.

Feature	Metamorphism	Deformation	Distinguishing Features	Thickness
Tethyan Sequence^{1, 4}	Normal: very low to greenschist facies	Increasingly strained towards base	Fossils, lack of leucogranites	Maximum: 7 km Minimum: 4 km
South Tibetan Detachment (local folded segment)	Greenschist facies assemblages in both hanging wall and footwall	Highly sheared rocks: mylonites (annealed)	Outcrop: black phyllitic appearance Microscope: annealed quartz ribbons	Uncertain: unconstrained width of distributed strain, discrete planes of concentrated strain
Chekha Formation (CRMs locally)^{1, 3}	Normal (?): greenschist facies at top to amphibolite facies at base	Transposition of less competent units (schists, marbles, calc-silicates), preservation of original structures in quartzites	Large amounts of multiply intruded leucogranite, lack of abundant migmatite, lateral heterogeneity of lithologies	Maximum: 4 km Minimum: 2 km
Lingshi Detachment	Amphibolite facies assemblages in both hanging wall and footwall	Unknown: highly folded units observed at contact	Often hosts leucogranite sills	Uncertain
Upper Greater Himalayan Sequence^{1, 3}	Upper amphibolite facies	Polyphase, no primary features retained	Often consists of migmatitic augen gneisses	Maximum: 15 km Minimum: 7 km Variable thickness
Kakhtang Thrust³	Upper amphibolite facies assemblages in hanging wall, amphibolite facies assemblages in footwall	Highly ductily sheared rocks: protomylonites, sometimes host to leucogranites	Separates mostly migmatitic crystallines in hanging wall from mostly non-migmatitic crystallines in footwall, cuts across metamorphic isograds (i.e. out-of-sequence)	Uncertain: Hundreds of metres
Lower Greater Himalayan Sequence - Paro Metasediments^{1, 3}	Upper to lower amphibolite facies	Polyphase, no primary features retained	Migmatites less abundant than in upper GHS	Maximum: 15 km Minimum: 7 km Variable thickness
Main Central Thrust^{2, 3}	Metamorphic offset of amphibolite facies in hanging wall and greenschist to amphibolite grade in footwall	Highly sheared rocks: protomylonites	Difficult to isolate, often occurs as a zone of distributed shear; can be considered as a protolith boundary	Maximum: several km Minimum: hundreds of metres
LHS^{1, 2}	Greenschist to amphibolite facies	Polyphase, numerous slice-like imbricates of GHS and LHS units	Mixed character, structural complexity	Several km

2.1 Major Lithological Units

2.1.1 The Tethyan Sequence

The Tethyan Sequence outcrops across the Himalaya, and comprises most of the lithological units of the Tibetan Plateau. These greenschist facies to unmetamorphosed rocks are derived from sediments deposited in the Tethys Ocean on or outboard of the Indian continental margin, predominantly prior to the Miocene collision of India and Asia. The Sequence is greater than 10 km in thickness (e.g. Godin et al., 1999). Metamorphism is everywhere observed to increase with depth, yielding a “normal” (decreasing upwards) metamorphic gradient. The oldest, clearly Tethyan rocks thus far identified are Precambrian to Ordovician in age, with the uppermost units being Cretaceous or possibly even Tertiary in age (Hodges, 2000; Godin et al., 1999).

The Tethyan Sequence of Bhutan has been characterised by Gansser (1983). The deepest levels of the Tethyan Sequence exposed in the study area centred on the Lingshi Klippe are inferred to be Palaeozoic, while the upper units are clearly Cretaceous, based on fossil evidence (Gansser, 1983). It can thus be seen that a fairly complete, and several kilometre thick, stratigraphic succession is preserved within the Lingshi Klippe. Overall stratigraphic thickness of these sedimentary units is uncertain because of the numerous complications arising from multiple generations of folding and faulting (see Chapters 4 and 6), but can reasonably be estimated to be at least 5 km and at most 7 km, based on Gansser’s observations.

Interpreting Gansser’s detailed observations is confounded by four main factors, all of which are intimately related to the discovery of the STDS (Burchfiel et al., 1992) after Gansser’s work (1983) was completed:

- 1) local branches of the STDS that are present between the Chekha Formation and the overlying Tethyan Sequence are not considered in his work,
- 2) the numerous faults he observed have unknown displacements,
- 3) the division of Tethyan sediments from crystalline rocks of the Chekha Formation is not made, or is not clear, and
- 4) stratigraphic assignments are generally vague, and favour local “facies” attributions that are difficult to extrapolate from one area to another.

The lack of identification of a significant faulted boundary between the Tethyan Sequence and the Chekha Formation has enormous ramifications for the subsequent lithostratigraphic assignment of units. The STD was not identified by Gansser (1983) because its exposure within the Chomolhari Range makes the contact between the Tethyan Sequence and Chekha Formation relatively inaccessible, and therefore finding sheared rocks is only possible in the few locations like the Goyak-Chebisa cliff sections where erosion has not completely removed it. Other than the observed annealed mylonitic horizons (see below), most of the rocks across this contact from both sequences are variably metamorphosed limestones and impure limestones, and exhibit little identifiably different mineralogy across the boundary. Therefore, when working under a framework of upwardly decreasing, structurally uncontrolled metamorphism like Gansser, it is difficult to identify the where this boundary occurs.

Having failed to identify the local segment of the STDS, interpretations of upward decreases in metamorphism were not attributed by Gansser to structural or tectonic controls. As such, where he identified faulted boundaries between units, differences in folding style across faults were not considered. Estimates were not made of the total amount of displacement on these faults.

Perhaps the largest confound, which stems from the failure to identify the STD, is the inclusion of the Chekha Formation within the Tethyan Sequence of the Lingshi Klippe. Gansser explicitly identified the “main faulted contact” (the Lingshi Detachment of this study) between the metasedimentary units of the Chekha Formation and the migmatitic (i.e. GHS) augen gneisses below as being present within an intensely folded combination of marbles, calc-silicates and biotite psammite gneisses on the southern margin of the Lingshi Klippe. This contact is between his map units 12 (Chekha) and 15 (GHS migmatitic gneiss) (**figure 1.3**). Field observations confirm that this is the most obvious contact, since elsewhere it hosts thick (>0.5 km) leucogranite sills.

Since the Chekha Formation has a different deformation and metamorphic history than the Tethyan Sequence, it is presented in this work as a separate map unit (see Chapter 3). Calling these rocks the Chomolhari Range Metasediments (CRMs) clearly distinguishes them from the overlying Tethyan Sequence, and emphasises their distinct history. An examination of Gansser’s 1983 map reveals that different portions of the Chekha Formation are present beneath the Tethyan Sequence from area to area. For instance, the “limestone facies” of the Chekha Formation that is present in the study area and contains the Tando Gompa marbles does not appear to be present in the base of the Tang Chu Klippe (see **figure 1.3**). This observation of lateral lithological variation has led to the proposal in Chapter 7.1.2 of a tectonic mechanism responsible for the structure of the Chekha Formation that is based on modifications to the currently debated “channel flow” hypothesis of Beaumont et al. (2001).

2.1.2 The Chekha Formation

The Chekha Formation is part of a lithotectonic package that is only now being recognised in other areas of the Himalaya (Godin, pers. comm., 2003). In many areas such as Bhutan and Nepal, a distinctive, lithologically variable, amphibolite facies package of metasedimentary rock underlies the Tethyan Sequence. These rocks contain abundant intrusive leucogranite, sillimanite-bearing mineral assemblages, and occur between two discrete faulted boundaries. The lower boundary is a distinctive ductile detachment fault that commonly hosts leucogranite sills (up to a few kilometres in thickness and of variable lateral extent), while the upper boundary is a ductile detachment fault that marks the upper terminus of syn-deformational leucogranite intrusion. The lower fault has in the past been identified as the STD, but recent work has suggested that the upper faulted boundary is best considered as the “true” STD (see Chapter 6). These definitions will be applied to the observations made during this study, and in concert with direct observations, form the basis for dividing the clearly Tethyan units observed in the Lingshi Klippe and Chomolhari Range from the more highly metamorphic, doubly fault bound Chekha Formation units.

The continuity of the Chekha Formation within the Chomolhari Range and the lower levels of the Lingshi Klippe was suggested by Gansser (1983). This was based on the widespread extent of the characteristic, highly intruded marbles of the “Dando Gompa” (Tando Gompa in this study) facies of the Chekha Formation, which occur in both the Chomolhari Range and base of the klippe. However, though the suggestion of continuity was made, without a more constrained structural framework it was impossible for Gansser to definitively conclude that these rocks were in fact equivalent. This led

Gansser (1983) to divide the Chekha Formation into a number of local facies. The first of these was a “limestone” facies that included the Chomolhari marble and calc-silicate units, and the thick, highly intruded marbles of the “Dando Gompa” facies of the Chekha Formation. The second major facies contained the thick quartzites of the Chekha locality, along the southern margin of the Lingshi Klippe. The quartzites occur at structurally lower levels than the carbonate portions of the Chekha Formation. However, it should be noted that along the same structural level a variety of rocks are present. This is easily observed on **figure 1.3**, where the quartzites that outcrop at Chekha are discontinuous along the structural level of the Lingshi Detachment. The highly folded nature of the Chekha Formation (see Chapter 4), indicates this is not a lateral sedimentary facies change.

Metamorphic observations indicate that peak metamorphism was at amphibolite facies conditions, based on biotite and sillimanite bearing assemblages collected during this study (see Chapter 3). Metamorphism is confirmed to increase with depth, as observations from this study indicate the lowest structural levels achieved higher grade conditions during peak metamorphism than the uppermost units in contact with the basal Tethyan.

In light of these structural and metamorphic observations, it is simpler to assign all of these local facies to various segments of a lithologically and metamorphically variable whole.

2.1.3 The Greater Himalayan Sequence

The Greater Himalayan Sequence (GHS) is interpreted to be a highly deformed and metamorphosed part of the Indian Shield that has been subducted beneath Asia and then tectonically extruded (Davidson et al., 1997). The GHS occur along most of the length of the Himalaya (see **figure 1.1**), structurally between the STDS and MCT.

Mineralogically, the GHS consists of lower units of staurolite and kyanite grade crystalline schists and gneisses (Grujic et al., 2002; Hodges, 2000), representing maximally amphibolite facies metamorphism, and upper units of high grade metamorphic rocks that include abundant migmatite. These upper units contain sillimanite, K-feldspar and cordierite bearing assemblages that do not contain muscovite, and represent upper amphibolite facies peak metamorphism. This distribution of metamorphic facies indicates an inverted metamorphic field gradient is present.

The uppermost structural levels of the GHS were intruded by Tertiary age leucogranite plutons, which have been shown to be derived from partially melted crustal material (LeFort et al., 1987). These plutons are sill-like, and are often found emplaced within the highly strained units of the STD and other detachment faults at the top of the GHS.

In Bhutan, the lower GHS is referred to as the Paro Metasediments, and the predominantly migmatitic higher grade gneisses lie structurally above these, across a faulted boundary, between the Paro units and the Chekha Formation (Gansser, 1964, 1983). This boundary is an out-of-sequence ductile thrust fault, observed to cut across metamorphic isograds, and is referred to as the “Kakhtang Thrust” (Grujic et al., 2002). The Kakhtang Thrust has been inferred to cut across almost the entire length of Bhutan,

and is as such a major, laterally continuous feature with a significant effect on the lithological distributions of Bhutan.

2.1.4 Leucogranites

The GHS and CRMs both include significant amounts of intrusive leucogranite. These leucogranites tend to concentrate in the footwall of the STDS, where leucogranite bodies can form 20-70% of the rock by volume. Typically, Himalayan leucogranites are Qtz-Kfs-Plag-Ms-Bt-Tur-Grt-Sil (+/- Ky) (abbreviations after Kretz, 1983) in migmatitic horizons, and have similar assemblages that contain cordierite (as rims on garnet) where they outcrop as discrete bodies (e.g. Hodges et al., 2000). Granite bodies range in size from sills and dykes on metre scale to huge sills that are hundreds of square kilometres in extent. The prime example of one of the latter bodies in Bhutan is the Khula Kangri pluton and the Monlakarchung-Pasalum intrusion in the north of the country (see **figure 1.3**). These sit structurally in the footwall of the STDS, within non-migmatitic crystalline rocks that may be distant equivalents of the Chekha Formation.

In the field area, leucogranites were consistent with the above descriptions, but were not studied in detail with respect to rock types. The structural contexts of the observed leucogranites were integrated into this research, and have numerous kinematic and structural implications. Large sills dividing the Chekha Formation and Tethyan Sequence from the underlying GHS gneisses occur along the northern and southern boundaries of the Lingshi Klippe and Chomolhari Range. Leucogranite was also observed in poorly exposed outcrops below the Chekha Formation on the eastern flank of Jhari La, and several kilometres south of Chomolhari in the inferred footwall of the

Lingshi Fault along the Paro Chu (see **figures 1.3 and 1.4**). Locally variable mineralogy is a common feature of Himalayan leucogranites across the orogen, and does not change the interpretation that all of these leucogranitic bodies are derived entirely from the partial melting of continental crustal material (e.g. see Searle et al., 1999 for the origin and structural context of various Himalayan leucogranites).

In Bhutan, Grujic et al. (1996) have indicated additional exposures of leucogranitic migmatite in the hanging wall of the Khaktang Thrust. Leucogranite bodies are particularly common in the west of the field study area in the Chomolhari range, where these are significant enough to contain large (hundreds of metre sized) enclaves of the surrounding country rock (Gansser, 1983).

2.2 The South Tibetan Detachment System

The South Tibetan Detachment System is a major top to the north plastic to brittle deformation zone up to 4 km thick, running along the northern High Himalaya, and is believed to have extended much further south in Bhutan than it currently exposed (Grujic et al., 2002). Its erosive removal has left synformal metasedimentary klippen in place that show what is arguably the STD at their bases.

The STD is a very extensive geological feature that places Palaeozoic to Mesozoic Tethyan Sequence hanging wall rocks onto the Cambrian to Precambrian footwall units of the GHS. Hanging wall units exhibit normal metamorphic gradients that contain greenschist facies metamorphic assemblages at their base. North vergent S-C mylonitic fabrics are well developed in the footwall, with the greatest mylonitization

occurring within the STD between the GHS and the Tethyan Sequence (Burchfiel et al., 1992).

Three distinct phases of motion are understood to have occurred on the STDS. The first is ductile top to the south shearing, the second is ductile top to the north shearing, and the third is top to the north brittle normal faulting (Brown & Nazarchuk, 1993; Godin, 1999). Although the STD may have begun as a compressional structure, it has since demonstrated greater than 30 km of normal sense hanging wall to the north extensional motion since having become an extensional fault system. Displacement is difficult to quantify, however, since as of yet no piercing points have been observed on both sides of the STD, limiting displacement estimates to minimum values. Seismic profiling has shown the STDS to extend northward over 100 km beneath the Tibetan Plateau with an average dip of several degrees (Makovsky et al., 1996), and it is thought that normal bounding faults of the large north-south aligned Tibetan graben systems may be exploiting the STD as a deep-rooted weak plane along which they can accommodate orogen-parallel extension (Hurtado Jr. et al., 2001, 2001).

Since the STD is often accepted to include all of the ductile and brittle detachment faults near the top of the GHS and in the base of the Tethyan Sequence (e.g. Edwards et al., 1996; Wu et al., 1998), it is difficult to determine in many publications what faults are being described. This is complicated by the referral to lithological units that occupy the same structural level as the Chekha Formation as low-grade Tethyan sedimentary strata (Wu et al., 1998), even though these units are intruded by leucogranites and exist in the footwall of the structurally higher STD (which is often unidentified). Using these definitions, it is not uncommon (e.g. Edwards et al., 1996) to see later segments of the

STD cutting across earlier segments of the STD. This imprecise terminology generally interferes with the interpretation of the relative ages of the diachronous segments of the STDS. A sensible, though as of yet not universally adopted terminology referring to the STDS, which accepts its polyphase evolutionary character, would refer to the early ductile extensional phases of activity on the STDS, which are often folded by later structural events, as the “paleo-STDS” in order to distinguish these from the most recent, and unfolded segments of the STDS. This clarifies what generation of extensional faulting is being referred to, and is the terminology that will be applied during this study. Early phases of shearing commensurate with compressional, top to the south displacement of hanging wall units were not observed during this study, but could be referred to as “precursors” to the STD.

In northern Bhutan the STD has been observed to be folded in kilometre scale low amplitude warps (e.g. Edwards & Harrison, 1997). The warping was accompanied by steep, north and south dipping brittle normal faults, which in conjunction with the warping somewhat obscures the overall shallowly north dipping nature of the STD and serves to complicate local lithostratigraphic distributions.

2.3 The Main Central Thrust

The Main Central Thrust (MCT), like the STDS, is a shallowly north-dipping plastic to brittle thrust fault that is present along the Himalaya, separating the GHS to the north in its hanging wall from the LHS to the south in its footwall, and is characterised by top to the south shearing and a wide zone of deformation (e.g. Hodges et al., 2000). Strained fabrics associated with top to the south thrusting exhibit plastic to brittle style

shearing (Godin et al., 1999) and range from hundreds of metres to tens of kilometres in thickness, comprising highly deformed schists and gneisses of both GHS and LHS affinity, with well developed north plunging mineral lineations (Grujic et al., 1996). The MCT has been dated by U-Pb monazite dating as having been active as early as ca. 22.5 Ma in the Annapurna region of Nepal, while more recent low temperature brittle deformation has been dated at ca. 7 Ma (Godin, 1999). Commonly, the main period of motion on the MCT is currently understood as having occurred around 20-15 Ma. This is similar to the timing of motion on the STDS (25-18 Ma). These structures were contemporaneously active for several million years (the STDS having been active as a compressional structure prior to the formation of the MCT). The MCT can be understood as a protolith boundary (Davidson et al., 1997) across which amphibolite facies rocks of Indian shield origin of the GHS are separated from greenschist to amphibolite facies rocks of north Indian passive margin origin of the Lesser Himalayan Sequence (Gansser, 1983).

2.4 The Kakhtang Thrust:

Gansser identified the Kakhtang Thrust on his 1983 map of Bhutan (Gansser, 1983), but located it in the central portion of Bhutan near the town of Kakhtang. More recently, Grujic et al. (2002) have drawn the Kakhtang thrust as continuing well into western Bhutan. They have indicated that the Kakhtang Thrust is an out-of-sequence ductile thrust that results from transferral of the locus of deformation to the interior of the GHS as shearing within the GHS was beginning to wane. Inverted isograds observed below the Kakhtang thrust are primarily due to the presence of increased heat along the

fault plane of the thrust due to the intrusion of significant quantities of leucogranite along it (Grujic et al., 1996). The Kakhtang Thrust has been suggested to involve some 10-20 km of vertical displacement, based on observations that it cuts across metamorphic isograds (Grujic et al., 1996). Stretching lineations within the fault indicate top to the south shearing similar to that observed within the MCT. Migmatite becomes more common in the hanging wall of the Kakhtang Thrust, and petrography indicates that hanging wall rocks have been heated past the second sillimanite isograd, with inferred peak metamorphic temperatures of up to 750°C (Davidson et al., 1997). In contrast to this, in the footwall rocks were not heated past 600-650°C (Grujic et al., 1996). The progressive replacement of staurolite by sillimanite along the fault trace at the same structural level forms the basis of the out-of-sequence argument proposed by Grujic et al. (1996), since the fault must thus cut across metamorphic isograds, and is later than metamorphism.

There may be a connection between the occurrence of the Kakhtang Thrust in Bhutan, and the presence of metasedimentary klippen containing Tethyan Sequence rocks in southern Bhutan. Grujic et al. (1996, 2002) indicate that stratigraphic duplication and thickening by the Kakhtang thrust created a thicker package of the GHS in Bhutan, that subsequently took longer to erode than the thinner crystalline packages elsewhere in the Himalaya, explaining the observed Bhutanese klippen. Regional folding predates the Kakhtang Thrust, preserving them in their folded state (**figure 2.2**) (Grujic et al., 2002). Given the relatively small amount of vertical displacement on the Kakhtang Thrust (10-20 km after Grujic et al., 2002), the significance of regional folding may actually be greater for klippen preservation than out-of-sequence thrusting.

Figure 2.2: Schematic cross-section through the Bhutan Himalaya modified after Grujic et al. (2002). The erosion surface in this cross section, drawn through central Bhutan, exposes deeper structural levels than are exposed in the study area centred on the Lingshi Klippe. The Kakhtang Thrust is inferred by Grujic et al. (1996, 2002) to have 10-20 kilometres of vertical displacement. Vertical scale is approximately three times horizontal scale.

It should be emphasised that the Lingshi Klippe (**figure 1.3**), where field observations were made during this study, is entirely within the proposed hanging wall of the Kakhtang Thrust (**figure 2.2**), and is thus not preserved by the same mechanism of out-of-sequence thrusting combined with regional folding as the other metasedimentary klippen of Bhutan.

2.5 The Yadong Cross Structure, Chomolhari Fault System, and Lingshi Fault

Immediately west of the Chomolhari range the largest non-syntaxial across strike discontinuity of geology and topography within the Himalaya is found, called the Yadong Cross Structure (YCS) (Burchfiel et al., 1992). Two studies, by Wu et al. (1998) and Cogan et al. (1998) examined the YCS as part of the INDEPTH project. They produced cross sections based on field observations and seismic profiles that partially include western Bhutan. The data presented in this study compliments the published data set of Wu et al. (1998) and Cogan et al., (1998) with observations from the eastern flank of the northern Chomolhari range.

The YCS was described by Burchfiel et al. (1992) as the surface manifestation of a deep-seated structural variation in the Himalayan range. Seismic data indicate (Wu et al., 1998, and references therein) that recent earthquake activity associated with the YCS originates at roughly 42 km depth, indicating that the ongoing contemporary evolution of this structure is deep-seated. At surface, the YCS comprises a series of grabens and half grabens that are the expression of Neogene to Quaternary east-west extension, and which

extend from the Sikkim-Bhutan border west of the Chomolhari range over a distance of roughly 500 km to the interior of Tibet (Cogan et al., 1998).

Near Bhutan, in the southern Yadong-Gulu rift, several kilometres of down to the west-north-west normal motion has created a half graben system containing a thick sequence of clastic sedimentary fill. Seismic profiles reveal several distinctive reflection surfaces. These have been interpreted to represent (with increasing depth):

- 1) A shallowly east-dipping and up to 1.5 km thick package of sedimentary graben fill
- 2) An approximately 10 km thick and steepening to the east package of Tethyan sedimentary strata
- 3) An approximately 20 km thick package of Greater Himalayan Sequence, within which no distinction is made between the Chomolhari Range metasediments and the migmatitic augen gneisses more characteristic of the GHS, as the crystalline nature of these sequences gives them similar seismic reflective properties
- 4) A basal package of Indian Lower Himalayan Sequence, of unspecified thickness (Wu et al., 1998)

Wu et al. (1998) refer to the Chomolhari range as the geomorphological expression of the YCS. They also mark the presence of a series of roughly parallel sets of normal faults that accommodate the normal sense motion on the western flank of the Chomolhari range. These normal faults are currently active, as evidenced by geomorphological terrain disruptions, and are collectively called the Chomolhari Fault system (CFS). The CFS is clearly visible in Landsat imagery of the area (see Chapter 5).

In addition to the CFS which is currently active, a non-active parallel fault set also exists along the eastern flank of the Chomolhari Range. This is the Lingshi Fault identified by Gansser (1983) that extends from the Goyak and Chebisa areas in the north as far south as the southern edge of the Chomolhari range.

The Lingshi Fault has been firmly identified in one locality in the Goyak-Chebisa area. Gansser's observations and a variety of structural characteristics strongly suggest this fault continues a significant distance along the eastern flank of the Chomolhari range.

The apparent sense of motion on the Lingshi Fault is down to the south-east, based on the juxtaposition of units of high-grade Chomolhari Range non-migmatitic metasediments to the west of the fault and low-grade Tethyan shales and limestones to the east. Although this is confirmed, down to the north-west motion on the Lingshi Fault is also observed (see Chapter 5).

2.7 Geochronology

It is important to note that all of the geochronology done in the Bhutan Himalaya has come from high precision ion microprobe dating of the U-Pb systematics of monazite crystals. Omnipresent xenocrystic zircon has proven to be an insurmountable complication for dating with this mineral (Hodges, 2000), and hence age conclusions are instead drawn from monazite analysis, because this mineral is present in many rock types and can form by metamorphic and igneous processes.

The published geochronological data pertaining to Bhutan is limited in scope. Segments of the STD that ductily deform leucogranite bodies have been dated in northern Bhutan (Edwards & Harrison, 1997; Wu et al., 1998). Timing of motion on the MCT has been partially constrained using the same methods and through dating on sheared metamorphic mineral assemblages within the LHS and GHS (Davidson et al., 1997; Grujic et al., 2002). Timing of motion on the Kakhtang Thrust has also been presented through the dating of deformed leucogranite within this fault (Grujic et al., 2002).

Timing of motion on the Lingshi Detachment and similar intra-GHS detachment faults at the base of the Chekha Formation has also been partially constrained by dating deformed and cross-cutting granites on these faults (Wu et al., 1998; Grujic et al., 2002). A summary of these results is presented in Table 2.

The STDS throughout the Himalaya was primarily active between 25-18 Ma (Edwards & Harrison, 1997), but local segments of the fault system have been active as recently as the last several Ma as brittle detachments, often associated with activity in orogen-parallel graben systems. Dating in the Khula Kangri area (north central Bhutan) indicate the STD was active here at ca. 12 Ma (Edwards and Harrison, 1997). Similar dating in the Wagye La area (to the west of Khula Kangri) yielded dates centred near 12 Ma (Wu et al., 1998). A younging to the east trend is apparent in these ages, indicating more recent activity in Bhutan relative to the western Himalaya (also see Hodges, 2000).

Ages such as the 100 Ma date from LHS schists presented in Table 2 are undoubtedly related to pre-Himalayan (Himalayan orogenesis having begun during the Eocene or Oligocene) thermo tectonic processes and represent ages of the rocks before Himalayan deformation. Ages of 16-18 Ma for migmatites and deformed leucogranites within the lower GHS (below the Kakhtang thrust), indicate that these rocks were being exhumed at this time. Monazite ages of 12-14 Ma from deformed leucogranites within higher structural levels of the lower GHS indicate shearing was still in action at this time. Leucogranites that have been deformed by the Kakhtang thrust are also dated at about 14-15 Ma. The Kakhtang thrust was therefore shearing rocks that were still hot enough to have later crystallised monazites within bodies of leucogranite after this time. Published dates for upper GHS gneisses are not yet available for Bhutan, although the

Table 2: Summary of geochronological data available from the Bhutan Himalaya.
Sources:
1) Grujic et al., 2002, 2) Wu et al., 1998, 3) Edwards & Harrison, 1997.

Structure Dated	Structural Framework	Approximate Monazite U-Pb age (to nearest 0.5 Ma)	Event dated	Implication
LHS biotite schist ¹	Footwall MCT	100 Ma	Pre-Himalayan metamorphism	minimum age of Indian continental cover sequence
LHS biotite schist ¹	Footwall MCT	6-11 Ma	Himalayan metamorphism	minimum age of peak Himalayan metamorphism
lower GHS garnet staurolite schist ¹	Hanging wall MCT	22 Ma	Himalayan metamorphism	minimum age peak Himalayan metamorphism in lower GHS
deformed leucogranite within lower GHS ¹	Hanging wall MCT	17-18 Ma	Crystallisation age of leucogranite	maximum age of top to the south shearing within GHS
deformed migmatite within lower GHS ¹	Hanging wall MCT	16-17 Ma	Crystallisation age of leucogranite	age pre-to syn-top to south shearing
deformed leucogranite within lower GHS ¹	Hanging wall MCT, Footwall KT	13.5 Ma	Crystallisation age of leucogranite	maximum age of top to the south shearing lower GHS
deformed leucogranite within the KT ¹	Footwall KT, high strain zone of KT	14 Ma	Crystallisation age of leucogranite	maximum age of top to south shearing on KT
deformed leucogranites cross-cutting basal shear zones of Sakteng Klippe ¹	Hanging wall of faults equivalent to the Lingshi Detachment	17-22 Ma	Crystallisation age of leucogranite	maximum age north-directed shearing on Lingshi Detachment
Gaowu granites (undeformed?) ²	Footwall and Hanging wall of Lingshi Detachment	23 Ma	Crystallisation age of leucogranite	Possible minimum age of activity on Lingshi Detachment
Khula Kangri pluton (deformed) ³	Footwall of STD	12.5 Ma	Crystallisation age of leucogranite	maximum age of north-directed shearing on STD
Wagye La pluton (deformed) ²	Footwall of STD	12 Ma	Crystallisation age of leucogranite	maximum age of north-directed shearing on STD

younging of deformation toward the top of the GHS is well documented in that deformed granite bodies at the top of the GHS in the footwall of the STD have recent crystallisation ages, and are often syn-deformational with respect to the dominant foliation (Edwards & Harrison, 1997).

The overall consensus derived from these dates is that at higher structural levels within the GHS, rocks have seen more recent exhumation, indicating more rapid exhumation towards the top of the GHS (Grujic et al., 2002). This is inferred because the time between granite emplacement, deformation and crystallisation is typically very short (Wu et al., 1998), which in conjunction with tectonic models of GHS extrusion (see Chapter 6), indicate that rocks at the upper structural levels of the GHS have been extruded more rapidly than those at lower structural levels. Conversely, the LHS rocks demonstrate a much more recent exhumation. Young dates from the out-of-sequence Kakhtang Thrust indicate that towards the close of active shearing within the GHS, deformation was transferred towards the centre of the orogen (Grujic et al., 2002). Conflicting maximum and minimum dates for motion on the Lingshi Detachment and similar detachment faults at the base of the Chekha Formation (older than 22 Ma in Wu et al., 1998, versus younger than 17 Ma in Grujic et al., 2002) mean that the question of whether the Lingshi Detachment truly predates the most recent ductile activity on the STD is still debatable until a more complete data set is revealed. The integration of these observations into tectonic models is discussed in Chapter 6.

3.0 STRUCTURE AND METAMORPHISM

Field observations were combined with petrographic analysis in order to characterise the structural histories of the units examined. Observations of mineral assemblages formed during the various deformation generations allowed estimation of metamorphic facies.

Results demonstrate that the various units of the Lingshi Klippe have experienced a more complex structural history than can be inferred from the works of Gansser (1964, 1983). Deformation events that apparently predate, are contemporaneous with, and post-date activity on the paleo-STD are preserved in the Tethyan Sequence and Chekha Formation of the study area.

3.1 Tethyan units of the Lingshi Klippe

Deformation of the Tethyan Sequence is variably complex. Kilometre-scale warping was observed throughout these rocks (Gansser, 1983). The SW-NE trending synformal axis Gansser identifies on his 1983 map (see **figure 1.3**) is a primary example of obvious large scale folding. Field observations in this study confirm the existence of at least three previously undocumented generations of deformation affecting these rocks.

The structural and deformation history of the Tethyan units of the Lingshi Klippe can be tentatively divided into five generations based on observations made in this study.

3.1.1 D_1 : F_1 : S_1 : microscopic rotation fabrics, transposition of bedding

Petrographic observations of samples from the lower to middle structural levels of the Tethyan Sequence reveal microscopic isoclinally folded compositional bands (**figure**

3.1a) and possible kinematic indicators of a rotational component to the main foliation (**figure 3.1b**), in greenschist facies marbles. Apparent top to the north ductile shearing (**D₁**) is responsible for the development of a foliation defined by the preferred orientation of calcite (**S₁**) that transposes primary bedding (**S₀**). Since transposition is accomplished through isoclinal folding, it is obvious that geometrically unconstrained episodes of isoclinal folding associated with **D₁** affect the lower to middle structural levels of the Tethyan Sequence of the Lingshi Klippe. Apparently isoclinal folding of bedding is also observed in siliceous lithologies at these structural levels (**figures 3.2a and 3.2b**). In these rocks quartz clasts and microfossils in a sericite matrix have asymmetric pressure shadows formed from the bending of **S₁** around the quartz clasts.

Sericitic muscovite is observed as a syn-deformational phase (**figure 3.3**), but mineral assemblages more representative of specific metamorphic facies (e.g. muscovite is stable at greenschist and amphibolite facies) were not observed. Microstructural evidence of **D₁** was not observed in thin sections of the upper structural levels of the Tethyan Sequence.

Folding of the Tethyan rocks by later events (i.e. **D₂**-see below) may have led to stratigraphic inversions that render kinematic interpretations concerning **D₁** highly suspect. As such, isoclinal folding (**D₁**), as the **S₁** forming event, may have occurred during either regional compression or extension.

3.1.2 D₂: F₂: S₂: isoclinal folding

The presence of geometrically unconstrained, macroscopic folds in the Tethyan Sequence is suggested by some of Gansser's observations (e.g. figure 36 of Gansser,

Figure 3.1a: Small isoclinal fold hinge (F_1) refolding primary bedding (S_0) in limestone from lower to middle structural levels of the Tethyan Sequence at Nele La. Hinge closes to right of photomicrograph. 4x magnification, plane polarised light.

Figure 3.1b: Possible kinematic indicator (of S_1) within limestones from the lower to middle structural levels of the Tethyan Sequence at Nele La. 4x magnification, plane polarised light.

Figure 3.2: Fine sericite defines **S1**, and is refolded by **D2** into an axial planar cleavage (**S1**) to **F2**. Sample of phyllite from the middle to lower structural levels of the Tethyan Sequence at Nele La. Pyrites are syn- to post-**S2**, as the pyrites truncate **S1** but **S2** is partially bent around them. 4x magnification, cross-polarised light.

Figure 3.3a: S_1 is folded into S_2 . Quartz clasts are primary sedimentary features, but S_0 has been transposed into S_1 and is not apparent. Asymmetric pressure shadows flanking quartz clasts indicate S_1 is a shear fabric. 4x magnification, plane polarised light.

Figure 3.3b: Incomplete bedding preservation (S_0) transposed into strong S_{1-2} schistosity from the lowest structural levels of the Tethyan Sequence at Jhari La. 4x magnification, plane polarised light.

1983), but Gansser did not identify folding within these rocks that predated the folding of the Chomolhari Range.

The hinge of a macroscopic fold that refolds S_1 was observed (**figure 3.4**) in the lower to middle structural levels of the Tethyan Sequence at Nele La (see **figure 1.4** for various named locations), making this a second generation, or F_2 fold. Only one limb of this fold is exposed, which is continuous for several hundred metres away from the hinge. S_1 is folded into an orientation that is parallel to the axial planes of these F_2 folds, suggesting these folds may be large isoclinal or near-isoclinal. No thickening of units was apparent towards the hinge of the fold, suggesting that the hinges have undergone parallel folding (after Ramsay and Huber, 1987). The axial plane of the observed fold appears to dip steeply to the NE. The hinge plunges to the ENE at a moderate angle ($\sim 40^\circ$). The observed limb of this fold is refolded by the regional folding that produced the CRA (F_3 ; see below), thus providing the relative timing for the formation of these structures, as D_2 .

Quartz is precipitated as veinlettes within microscopic dilations sub-parallel to the axial planes, and sericite is ductily bent by crenulations that are sub-parallel to the fold hinge, indicating metamorphic conditions favoured its stability during D_2 . The quartz veinlettes cross-cut the crenulation cleavage and therefore post-date it. However, since the precise orientation of the F_2 axes is unknown, it is not known whether the quartz veinlettes or the axial planar cleavages are more closely aligned with the F_2 axial planes. Senses of shear are similar for both microstructural features (**figure 3.5**).

Figure 3.4: Hinge of large F_2 in the lower to middle structural levels of the Tethyan Sequence at Nele La. Axial plane dips steeply to the north-east, hinge plunges moderately to the east. This fold is isoclinal in its limbs and is pre- S_8 . Lower photograph shows folded S_1 and F_2 without tracing.

Figure 3.5: S_1 composed of sericite is bent into the axial planar cleavage (S_2) of F_2 .
Quartz-filled fractures are interpreted to be late syn- to post- D_2 , as they cross-cut S_2 . Both the quartz-filled fractures and S_2 are sub-parallel to the axial planes of F_2 . 4x magnification, cross-polarised light.

One example of an isoclinal fold that may be either an F_1 or F_2 was observed in the very lowest structural levels of the Tethyan Sequence of the Goyak-Chebisa area (**figure 3.6a and b**). This fold was present high in a cliff section in the immediate footwall of the Lingshi Fault and could not be sampled. Since it was present in the distributed fracture zone that occurs in close proximity to the Lingshi Fault (see Chapter 5), and was partially obscured by aragonite, the continuity of its limbs at a distance from the hinge is uncertain. The macroscopic nature of this fold, and its presence in the lower structural levels of the Tethyan Sequence, lead to its tentative classification as an F_2 fold. If this is accurate, the horizontal axial plane of this fold, and the NE-SW trend of its hinge do not correspond to that of the F_2 fold observed at Nele La (**figure 3.4**). F_2 geometries are observed to be more upright at higher structural levels of the Tethyan Sequence (**figure 3.7**). These observations are compatible with better documented data sets in Nepal, which indicate that F_2 structures can be expected to assume a more horizontal character closer to the STD near the base of the Tethyan Sequence (e.g. Godin, in press., and Brown and Nazarchuk, 1993). This is inferred to occur due to the transposition into parallelism of D_1 and D_2 structures by penetrative deformation within the Tethyan Sequence associated with shearing on the STD (Godin, in press).

Shales in the upper structural levels of the Tethyan Sequence display brittle cleavages that are sub-parallel to S_{0-1} (it is not known whether D_1 affects the upper structural levels) (**figure 3.8**). Since foliation is approximately parallel to the F_2 axial planes, outcrops such as that depicted in **figure 3.8** provide evidence that unobserved fold closures associated with F_2 are present at all structural levels of the Tethyan Sequence. This is the case because axial planar cleavage associated with F_2 will occur at an angle to

Figure 3.6a: Possible (F_2) in the lowest structural levels of the Tethyan Sequence in the immediate hanging wall of the paleo-STD (S_5), immediate footwall of D_{3-4} motion on the Lingshi Fault, and in the hanging wall of D_5 brittle fractures (S_5) and hanging wall of D_5 motion on the Lingshi Fault. See text for descriptions of these structures. The nearly horizontal orientation of the axial plane of this fold does not correspond to the upright orientation of F_2 in higher structural levels of the Tethyan Sequence, and may be a result of unconstrained straining associated with the STD.

Figure 3.6b: The cliff section at Chebisa where the above photograph was taken. Notice steeply SE-dipping (S_{3-4}) in the Lingshi Fault zone, and the truncation of S_5 against the Lingshi Fault zone or within its western margins.

Figure 3.7: The main synformal axis of Gansser (1983) centred on the Nele La pass. S_{0-2} to the north of the pass dip gently SE, while S_{0-2} south of the pass dip gently to the NE. This suggests a synform with a gently east plunging hinge. A F_2 fold hinge may be visible in the south-western portion of this photograph. Vergence of F_2 is unconstrained, although the example in this photograph may be northerly-vergent. The upright geometry of the F_2 visible in this photograph, which is at structurally higher levels than the STD, is apparent. F_3 and F_4 refold S_{0-2} . It is the interference pattern between F_3 and F_4 , superimposed on S_{0-2} , that is responsible for the orientation of units in the Lingshi Klippe.

Figure 3.8: Microscopic and outcrop scale observations of brittle cleavage (S_2) at an angle to bedding (S_0). An older planar fabric that may be primary bedding (S_0) or cryptic S_1 is cross-cut by S_2 . In most units of the upper structural levels of the Tethyan Sequence, S_2 is sub-parallel to bedding. It is only near F2 hinges, to which S_2 is sub-parallel, that this angle becomes as high as in this outcrop. Microscopic view is at 10x magnification in plain polarised light. Pen aligned with S_0 is provided for scale in outcrop photograph.

the F_2 axial planes only at or near a fold hinge (as in **figure 3.4**). Based on these observations, the dominant planar fabric within the lower to middle structural levels of the Tethyan Sequence is S_1 . The dominant brittle cleavage of the upper structural levels of the Tethyan Sequence is S_2 .

3.1.3 D_3 : F_3 : S_3 : folding during CRA formation

At Nele La, an asymmetric NNE-SSW trending, WNW verging antiform with an interlimb width of several metres marks the westernmost extent of the Tethyan Sequence rocks (**figure 3.9**). This antiform is parallel to the Chomolhari Range Antiform (CRA) and is obviously a related structure. It refolds S_1 and F_2 and thus constitutes a third generation of deformation (D_3). The style of folding is Type 1B or 1C (Twiss and Moores, 1992). Examinations along the Paro Chu valley between the Chomolhari Range and Lingshi Klippe indicate this structure is laterally continuous over a distance of at least a few kilometres to the south of Nele La.

The CRA and its paired synform within the Lingshi Klippe constitute this third generation of deformation affecting the Tethyan Sequence (D_3). F_3 is one of the two largest, and regionally recognised (Gansser, 1983) folding events that affects the rocks of the study area. The CRA is examined in detail in Chapter 4.

Elsewhere along the eastern flank of the Chomolhari Range, the folding of the Tethyan strata over the CRA does not display the same antiformal structure observed in **figure 3.9** at the contact with the Lingshi Klippe. To the north, as suggested by cross-sections in Gansser (see figure 133 of Gansser, 1964), the contact when interrupted by the Lingshi Fault is a south- eastward-verging synformal warp with a NE-SW trending axis

Figure 3.9: Antiform within Tethyan Sequence rocks of Nele La. Folding is **F3** because it refolds the limb of an **F2**. NE-SW strike of the axial plane is parallel to that of the CRA. This fold is continuous for several kilometres parallel to the CRA within the Tethyan Sequence of the Lingshi Klippe.

(see **figure 1.4**). This is consistent with down-to-the-south-east normal displacement of the Tethyan Sequence strata by the Lingshi Fault, and an apparent draping combined with normal faulting relationship over the CRA as suggested by Wu et al. (1998) from observations on the western flank of the Chomolhari Range.

A pervasive crenulation cleavage (S_3) was observed at Jhari La and at Goyak-Chebisa (**figure 3.10**) and affects the lowermost and middle structural levels of the Tethyan Sequence. At Goyak-Chebisa, within the eastern limb of the CRA, S_3 crenulated the phyllitic foliation surfaces (S_1 - S_2) of the samples in an intersection lineation that is parallel ($17^\circ/221^\circ$, i.e. SW-NE trending) to the trend of the CRA's axis (SW-NE trending).

At Goyak-Chebisa, S_3 comprises a C-S fabric within which the nearly horizontal S fabrics dip 11° to the SE. Sericitic muscovite is syn to post- S_3 , having been bent by this cleavage and having overgrown it.

The Lingshi Fault, for reasons explained in Chapter 5, can be considered as an initially D_3 - D_5 structure, and thus constitutes an additional deformational event affecting the Tethyan Sequence. The Lingshi Fault's effects on the Tethyan Sequence are described in Chapter 5, but can be summarised as consisting of a major down to the south-east sense brittle disruption of these units that is spatially and genetically associated with the development of the CRA.

Apart from S_3 , most of the influence of D_3 on Tethyan Sequence structures is confined to the macroscopic warping (F_3). This is pervasive (**figure 3.11**) throughout the observed portions of the Lingshi Klippe. Since the examined areas were near the klippe's

Figure 3.10: S_3 brittle cleavage in muscovite phyllites from the lowest structural levels of the Tethyan Sequence at Jhari La. S_3 comprises a macroscopic crenulation at outcrop scale. Intersection lineation of S_{0-2} and S_3 trends NE-SW, aligned with the fold axes of F_3 . 4x magnification, plain polarized light.

Figure 3.11: Warps (F_3 and F_4) of S_{0-2} in shales of the upper structural levels of the Tethyan Sequence near Shakshipasa.

boundary, it is possible warping and related crenulations are more obvious in these areas than in the core of the klippe.

3.1.4 D₄: F₄: S₄: NW-SE trending regional folding

Long wavelength folding (F₄) of the Tethyan units about NW-SE trending axial planes is responsible for isolating the Lingshi Klippe along its northern and southern boundaries from the surrounding higher grade units of the GHS and CRMs (see **figure 1.4**). This warping is evident at Jhari La, where a series of south-verging warps refold S₁₋₂ and F₃ (see **figures 3.12a and 3.12b**). The south to south-westward dip of S₁₋₂ at Jhari La is present because the northern Lingshi Klippe is folded into a south-dipping limb of F₄, which contains the entire Lingshi Klippe within one half of its wavelength (see Chapter 4). The long wavelength of F₄ means that the effects of this fourth generation of deformation (D₄) are not obvious in more central areas of the klippe, and are difficult to distinguish from F₃ at the outcrop scale because both generations merely warp the S₀-S₁.

Gansser reports folding of this style in the eastern klippe at Kang Bum (see figure 42 in Gansser, 1983), in addition to at Jhari La (figure 43 in Gansser, 1983) where observations were made in this study.

3.1.5 D₅: S₅: brittle faulting

The final major structural event is the disruption of the Tethyan Sequence by brittle normal faults. This deformation is related to the formation of the Yadong Cross Structure (see Chapter 5). The full extent of this disruption within the Tethyan Sequence

Figure 3.12a: View of south dipping S_{0-2} of the lowest structural levels of the Tethyan Sequence and the CRMs at Jhari La. F_3 and F_4 fold S_{0-2} into a series of basins and domes that account for the overall basin structure of the Lingshi Klippe. F_4 is evident in this photograph due to the obvious, southward dip of S_{0-2} .

Figure 3.12b: Alternate view to SW along Jhari La showing the moderate south-dip of S_{0-2} caused by F_4 . Harakim is in the background. This view is approximately parallel to the axis of the CRA, which culminates to the right at Shakshipasa.

is limited to its westernmost portions that are close to or a part of the Chomolhari Range. Late, brittle down to the north-west sense displacement of the Chomolhari Range rocks is accomplished by a series of SW striking faults.

Pre-deformational sericitic muscovite (of S_1) is bent into these faults and associated microfractures, and quartz and calcite are precipitated in these microfractures and cut across S_{1-2} . Additionally, some deposition of chlorite is apparent adjacent to these sealed microfractures in the lowest structural levels of the Tethyan Sequence of the Goyak-Chebisa area (figure 3.13).

3.2 The Chomolhari Range Metasediments

Due to the basin structure of the Lingshi Klippe (see figure 1.4), its deepest structural levels are exposed along its edge. As such, the metasedimentary units that lie below the Tethyan Sequence of the Lingshi Klippe were examined in several locations representative of different structural levels.

The deepest level was explored in the Jhari La pass on the klippe's northern margin, where biotite-sillimanite schist, marble and calc-silicate lithologies were observed. As indicated by Gansser (1983), metamorphic grade within the Chekha Formation generally increases with depth, from apparently greenschist facies at the top to amphibolite facies at the base.

The identification of highly strained horizons at Goyak-Chebisa between what Gansser considers to be the upper Tethyan and the lower Tethyan (i.e. between the Tethyan Sequence and the Chekha Formation), in combination with differences in lithology, metamorphism and deformation history, suggests that in fact the Tethyan

Figure 3.13: Chlorite growth along **D**₅ fractures at Goyak-Chebisa. Calcite and quartz have grown in all of the **D**₅ fractures and faults. Abundant circulation of fluids within **S**₅ is suggested by this mineralization..

Sequence and the Chekha Formation are distinct lithotectonic units. As outlined in Chapter 2, the local portion of the Chekha Formation examined during this study is referred to as the Chomolhari Range Metasediments (CRMs).

Metamorphism within the CRMs is a combination of regional heating due to depth of burial, and contact heating due to intrusion (e.g. after Grujic et al., 2002 with respect to other Chekha Formation rocks). Anomolously, mapping by Gansser (1983) has identified second sillimanite grade (upper amphibolite facies) migmatitic gneisses towards the top of the Chomolhari Range within the CRMs. The upper CRMs have otherwise been shown (Gansser, 1983) to be below upper amphibolite grade even in the most highly intruded localities within Chomolhari itself.

Metamorphism has been characterised in rocks at equivalent structural levels to the CRMs within Nepal (i.e. in the footwall of the STD and hanging wall of a deeper detachment fault) (Searle & Godin, in press.). Tremolite and calcite bearing metamorphic assemblages at the upper structural levels of these rocks indicate peak metamorphic condition did not exceed 530°C at 3 kbar (Searle & Godin, in press.). Diopside and potassic feldspar-bearing marbles at the structural base of these rocks did not experience metamorphic conditions that exceeded 580°C at 4-5 kbar (Searle & Godin, in press.).

Deformation has not been characterised throughout the CRMs. However, limited observations in this study and by Gansser (1983) indicate that the intensity of shearing is closely linked to unit composition and proximity to the local early segment of the STD and the Lingshi Detachment that occur respectively at the top of and at the base of the CRMs. For example, the thick biotite-bearing quartzites that occur at Chekha (see **figure**

1.3) were observed by Gansser (1983) to preserve cross-beds, indicating a lack of fabric transposition. However, observations in this study of isoclinal fold hinges and duplicated stratigraphy from the lowest northern level of the CRMs at Jhari La and Shakshipasa (see below) indicate a complex polygenerational deformation history that includes transposition. The difference between these two localities, which lie at the same structural level, is likely due to the competent behaviour of the thick quartzites at Chekha relative to the marbles and schists at Jhari La.

Five phases of deformation have been observed within the CRMs:

3.2.1 D_{1-2} : F_{1-2} : S_{1-2} isoclinal folding

The CRMs are different than the Tethyan Sequence in that higher maximum temperatures have created more complex mineral assemblages, and intrusive leucogranite is abundant. Lithologies are also more variable over smaller areas than is observed in the overlying Tethyan Sequence, and exhibit repetitions characteristic of transposed, polydeformed rocks.

The dominant foliation in the CRMs is a combination of primary bedding (S_0) and transposed bedding (S_1). S_0 is preserved in competent quartzites (Gansser, 1983), but is transposed (S_{1-2}) in calc-silicate, marble, and schistose lithologies such as those at Shakshipasa and Jhari La (**figure 1.4**). The first phase of deformation (D_1) experienced by these rocks is thus an isoclinal folding event.

Observations of deformed leucogranites within the marble, calc-silicate and schistose lithologies of the lower to upper structural levels of the CRMs indicate that at least two generations of isoclinal folding (F_1 and F_2) relating to at least two generations

of deformation (D_1 - D_2) are possible. Some leucogranite bodies are early syn- D_{1-2} (see **figures 3.14a, 3.14b and 3.14c**), since extensive boudinage that is concordant with the transposition foliation (S_{1-2}) is apparent. In two outcrops (**figures 3.15a and 3.15b**) outcrop scale kinematic indicators (i.e. boudin asymmetries) do not agree, and discrete injections throughout D_{1-2} are suggested. Elsewhere, even within the same location, leucogranites do not appear to be deformed at all (**figure 3.16a**), occurring in completely cross-cutting (**post- D_{1-2}**) bodies, or as locally discordant sills (**figure 3.16b**). This last form is the most volumetrically significant, as supported by observations made by Gansser (e.g. figure 29 of Gansser, 1983) and during this study. These observations indicate leucogranite intrusion, which is both concordant with and discordant to the dominant foliation (S_{1-2}), is thus pre- to post- D_{1-2} . Leucogranites have not been observed cutting across the Lingshi Fault (a D_{3-5} structure), but are present as deformed bodies within the eastern limb of the CRA (F_3) (**figure 3.17**) because CRM's rocks folded into the CRA were previously intruded by leucogranites during and possibly after D_{1-2} , but prior to D_3 .

Although kinematic interpretations made using deformed leucogranite bodies (**figure 3.15a**) appear to suggest as many as three phases of ductile shearing, this can be simplified to two (D_{1-2}) using incremental strain arguments (e.g. Ramsay & Huber, 1983). In brief, a deforming body such as that of **figure 3.15a** can, if rotated within a consistent strain system, first be extended and then compressed, depending on its orientation in space with respect to the major strain axes. Since the original spatial orientation of the observed deformed leucogranites is unknown, it cannot be determined based on outcrop geometries whether progressive straining within one strain system or

Figure 3.14a: Syn- to late syn-**D**₁₋₂ granite bodies recording various amounts of straining within the Tando Gompa marbles of the CRMs.

Figure 3.14b: A syn-**D**₁₋₂ leucosome boudin in the upper structural levels of the CRMs at Goyak-Chebisa, demonstrating these granites are present at all structural levels of the CRMs.

Figure 3.14c: Semiconcordant sills of leucogranite in the lower structural levels of the CRMs at Shakshipasa. These semiconcordant bodies are the most volumetrically significant, and commonly account for over 40% of rock volumes. These intruded during late syn-**D**₂, and may be related to peak metamorphism at this time.

Figure 3.15a: Syn $\mathbf{D}_{1-2}$ leucosome within the lower structural levels of the CRMs at Shakshipasa. Last recorded shearing is top to the south.

Figure 3.15b: Late syn- $\mathbf{D}_{1-2}$ leucosome within the middle structural levels of the CRMs at Tando Gompa. Last recorded shearing is top to the south.

Figure 3.16a: Post- D_{1-2} leucogranite in the middle structural levels of the CRMs at Tando Gompa. Hammer for scale. Gansser's observations (1983) indicate that either late syn- D_{1-2} or post- D_{1-2} leucogranites are the most volumetrically significant.

Figure 3.16b: View of late syn- D_{1-2} leucogranite in the lower structural levels of the CRMs with outline of body relative to S_{1-2} . Although predominantly concordant with foliation, these granites do cut between strata and form interconnected networks.

Figure 3.17: Late syn- to post **D**₁₋₂ leucogranite body (marked by white x's) within the eastern limb of the CRA (**F**₃). This is most likely a semiconcordant sill similar to those shown in figure 3.16b, as clear evidence of post-**F**₃ leucogranite intrusion has not been identified.

straining within two strain systems with opposing senses of shear has caused the boudin asymmetries.

Macroscopic folds within the CRMs have been identified by Gansser (e.g. see figure 22 of Gansser, 1983), and during this study (**figure 3.18a**) in marbles. These (F_{1-2}) folds refold S_{0-1} and mylonitic horizons (**figure 3.18b**). These large folds are axial planar to S_{1-2} . Since S_{1-2} was formed from D_{1-2} , these folds are F_{1-2} . Only one example of F_{1-2} was observed in this study.

Highly strained rocks were identified between the lowest Tethyan Sequence and the CRMs that have profound structural and tectonic ramifications which are discussed in Chapter 6. Although these rocks have been subsequently altered by regional metamorphism after D_{1-2} , annealed quartz ribbons preserve evidence of high strain typical of mylonitic rocks (**figure 3.19a and b**), and kinematic indications of top to the north ductile extension. The presence of these units at the boundary between the Tethyan and CRMs is consistent with units reported by other authors that have been interpreted as pre-brittle segments of the STDS (Burchfiel et al., 1992; Wu et al., 1998; Godin et al., 1999), referred to as the paleo-STD in this study.

Penetrative deformation (S_S) associated with the paleo-STD (D_S) has not yet been characterised within the CRMs and Tethyan Sequence of Bhutan. Observations from Nepal have shown the paleo-STD should transpose primary stratigraphy and D_{1-2} structures into a planar foliation (S_S) within a distributed zone of shearing that penetrates over 1500 m into the Tethyan Sequence of the hanging wall of the paleo-STD, and for an unspecified distance into the footwall lithologies that in the study area are the CRMs (Godin, in press.).

Figure 3.18a: F_2 isocline in CRMs marbles at Goyak, in immediate footwall of paleo-STD. S_5 displaces this hinge from its limbs. Isoclinal folding of this kind is common in the CRMs (e.g. Gansser, 1983).

Figure 3.18b: Geological context of the fold shown in 3.18a. S_5 forms large blocks of the Tethyan Sequence and CRMs. Aragonite growth on the cliff surface obscures structures, and hence the location of the paleo-STD is uncertain. A ruined fortress is present for scale beneath the drawn F_3 hinge.

Figure 3.19a: Annealed quartz ribbon from the paleo-STD at Goyak-Chebisa. Top to the north shearing is suggested by the available kinematic indicators. 4x magnification, cross-polarised light.

Figure 3.19b: Annealed floating fold hinge from a shear plane of the paleo-STD that was folded into the CRMs. Some suggestion of a quartz-rich ribbon is preserved. S_s is so heavily annealed that only a microscopic lineation defined by the microscopic hinges indicate these rocks were highly strained. 20x magnification, cross-polarised light. This is not an oriented thin section.

The upper levels of the CRMs were not sampled during this study, but highly strained units of the paleo-STD that appear to be folded into the CRMs (**figures 3.20a and 3.20b**) yield metamorphic information. Biotite is inter-grown with minor muscovite as a syn- S_S phase within the hinges of the earliest isoclinal folds (see **figure 3.20a**, and **figure 3.20b**). Both biotite and muscovite are bent into the pervasive C-S crenulation fabrics defined by S_S (**figure 3.20b**). Since biotite and muscovite were stable phases after folding into F_{1-2} in the CRMs, D_{1-2} in the upper CRMs occurred at biotite grade. Sericitic muscovite overgrows all other minerals as a post- D_S phase. At this upper level of the CRMs, metamorphism during all phases of deformation does not appear to have exceeded greenschist to lower amphibolite facies conditions.

In the lower structural levels of the CRMs at Jhari La and Shakshipasa, (S_{1-2}) occurred at greenschist to amphibolite facies conditions, since biotite and muscovite (with quartz) define the S_{1-2} . Sillimanite and minor additional biotite (**figure 3.21**) overgrow the matrix minerals as syn to post- S_{1-2} phases, indicating that the maximum metamorphic conditions were amphibolite facies. Muscovite, and to a lesser extent biotite growth occurred as post- S_{1-2} phases, with biotite growth at the expense of sillimanite (**figure 3.21**). This suggests the transition into lower temperature conditions was made during the final episodes of mineral growth (post- D_2).

In the calcareous members of the lower structural levels of the CRMs, amphibolite facies metamorphism is also suggested by mineral assemblages. Clinopyroxene and tremolite bearing calc-silicates were observed (**figure 3.22**). Tremolite, where present, has irregular grain forms that indicate it was incompletely

Figure 3.20a: Intergrown muscovite and biotite in hinge of microscopic fold within annealed shear plane of paleo-STD sampled at Goyak. Although recrystallized, folded remnants of syn- S_S muscovite and biotite are present throughout the rock. 40x magnification, cross-polarized light.

Figure 3.20b: Syn- S_S hinges within annealed shear plane of paleo-STD. These define a lineation (L_S) in cross-section. 10x magnification, plane polarized light.

Figure 3.21: Mineral generations from the lower CRMs at Shakshipasa. The dominant planar fabric is S_{1-2} . 1) Syn D_{1-2} biotite, incompletely replaced by, 2) late syn- to post- D_{1-2} sillimanite. Sillimanite is concordant with but also 3) overgrows S_{1-2} , and 4) is overgrown by post- D_2 biotite (and muscovite, which was not shown). Some chlorite is present in association with late microfractures (and is thus D_3 - D_5).

Figure 3.22: Calc-silicate CRM units near the eastern limb of the CRA at Jhari La. Tremolite and clinopyroxene are the dominant mineral phases, with minor clinozoisite and orthopyroxene present locally. These minerals indicate amphibolite facies peak metamorphic conditions. 10x magnification, cross-polarized light.

consumed at peak metamorphic conditions. Marbles contain both calcite and dolomite in thin section. Dolomitic units are distinguishable by their higher degree of iron staining relative to the calcite horizons. Information concerning specific metamorphic grade is difficult to extract from these calcareous rocks since the numerous leucogranite intrusions have chemically altered their hosts (**figure 3.23**). Immediately at the calc-silicate-granite contact, mineralogy is simplified to quartz, plagioclase, clinopyroxene, and minor orthopyroxene, which indicates upper amphibolite facies contact metamorphic conditions in the metasomatic margins of these intrusions (Yardley, 1989).

The sillimanite and biotite bearing mineral assemblages at the base of the CRMs define higher peak metamorphic temperatures than the muscovite and biotite bearing mineral assemblages contained within the mylonitic horizons that have been folded into the upper CRMs. As such, Gansser's observations of a normal metamorphic gradient appear to be substantiated.

3.2.2 D₃: F₃: S₃: folding into the CRA and Lingshi Fault 1

The most obvious folding of the CRMs is into the antiformal structure of the Chomolhari Range (**D₃**). Only the steeply south-west dipping eastern limb of the CRA (**F₃**) was observed in this study. This folding is apparent from Jhari La on the northern klippe boundary, to south of Chomolhari itself, all along the eastern flank of the Chomolhari Range. At Jhari La, the absence of the Lingshi Fault reveals the south-east sense of vergence of **F₃**. Folding has attenuated the units of the CRA's eastern limb. This is observed in the reduction to less than 10 cm of units that are over 1 m thick only hundreds of metres away towards the core of the CRA (**figure 3.24**). Refolded

Figure 3.23: Metasomatic margin of a leucogranite sill within calc-silicates of the CRMs. Simplification of mineralogy at these contacts to ortho and clinopyroxene (plus quartz) is indicative of amphibolite facies (contact) metamorphism. 4x magnification, plane polarised light.

Figure 3.24: Attenuated units of the CRMs within the eastern limb of the CRA. Units in the limb at less than 10 cm in thickness, while those in other lower structural levels of the CRMs are minimally half a metre in thickness.

isoclines (F_3) form small parasitic folds within the eastern limb of the CRA in marbles from the lower structural levels of the CRMs.

The Lingshi Fault disrupts the eastern limb of the CRA at Goyak-Chebisa (**figures 3.25, 3.26a, 3.26b**). Ductile folding (F_3) of the CRMs predates the penetration of the Lingshi Fault (S_{3-5}) through these rocks and the overlying Tethyan units. This is evident because the Lingshi Fault is not present in the eastern limb of the CRA at Jhari La. However, the Lingshi Fault has been determined to be a late- D_3 to early D_5 structure (see Chapter 5), and so the Lingshi Fault is also an initially D_3 structure.

Sillimanite is observed to be a degraded, pre- D_3 phase that is overgrown by chlorite in the vicinity of cleavages (S_3) attributed to D_3 within the eastern limb of the CRA (**figure 3.27a**). Chlorite and quartz are observed to be late syn and post- D_3 phases within the Lingshi Fault (see **figures 3.27b and 3.27c**), and eastern limb of the CRA, indicating greenschist facies metamorphic conditions existed during D_3 .

3.2.3 D_4 : F_4 : NW-SE trending fold axis

The NW-SE trending regional fold axis that together with the CRA isolates the Lingshi Klippe and Chomolhari Range from the surrounding, structurally deeper rocks of the GHS, affects the CRMs by folding S_{0-2} . Foliations dip to the south within the northern Lingshi Klippe and Chomolhari Range, and were observed by Gansser (1983) to dip to the north in the southern regions of these features (**figure 1.3**). Observed

Figure 3.25: The CRA as seen from the village of Chebisa, with interruption by the Lingshi Fault in the foreground. Lingshi Fault trace is provided. The lowest structural levels of the Tethyan Sequence comprise the relatively leucocratic units visible above the village. White arrow represents sense of hanging wall displacement on the Lingshi Fault (i.e. down to the south-east).

Figure 3.26a: Erosive removal of the steeply dipping eastern limb of the CRA and Lingshi Fault zone at Tando Gompa. Harakim in the background. The same shoulder of land is present in the left of this photograph and the right of the photograph shown below. The obscured presence of the CRA's eastern limb makes it an easy feature to overlook, despite its large size.

Figure 3.26b: The NE-SW trending trace of the Lingshi Fault. The fault has truncated the gently east-dipping eastern limb of the CRA south of the town of Lingshi. CRMs in background, Tethyan Sequence shales in the foreground.

Figure 3.27a: Syn- D_{1-2} biotite and sillimanite being overgrown by chlorite near S_3 axial planar cleavage to F_3 in the CRMs within the eastern limb of the CRA. 4x magnification, cross polarized light.

Figure 3.27b: Chlorite deposition surrounding and within S_5 fractures, lowest structural levels of the Tethyan Sequence at Goyak-Chebisa. 4x magnification, cross-polarized light.

Figure 3.41: Quartz precipitation in S_5 fractures in the lowest structural levels of the Tethyan Sequence at Goyak-Chebisa. S_5 are related to the formation of the YCS during (D_5)

microscopic scale fabric elements could not be correlated to **D₄** based on the current data set.

3.2.4 D₅: S₅: The Yadong Cross Structure, Chomolhari Fault System and Lingshi Fault 2

The final deformation event that affected the CRMs was the development of a south-west striking, north-west dipping brittle fracture system (**D₅**) that is parallel to the axial surface trace of the CRA. These faults (**S₅**) are extensional in nature and exhibit down to the north-west sense motion. They are concentrated in a multiply fractured zone in close proximity (within a few hundred metres) to the Lingshi Fault, and were observed to increase in magnitude and decrease in frequency towards the interior of the Chomolhari Range.

These fractures cut across all the previous deformation fabrics, and petrographic evidence of syn-**D₅** growth of muscovite over **S₀₋₂** fabric elements, and of chlorite and quartz in fracture-hosted veins during this deformation indicate it occurred at greenschist facies (refer back to **figure 3.13**). Both the CRMs and the Tethyan Sequence are cross-cut by **S₅** at Goyak-Chebisa.

A more detailed account of this fracturing is provided in Chapter 5.

3.3 Deformation and metamorphism within the GHS of Bhutan

The GHS was not extensively sampled during this study, but has been examined in detail by other authors. Deformation and metamorphism within the GHS of Bhutan has been well documented by Grujic et al. (1996, 2002) and Davidson et al. (1997). It

must be noted, however, that these authors do not consider the Chekha Formation to have ever been part of the GHS, and hence care must be taken when interpreting their work to consider the Chekha Formation to be in the footwall of the STD, and therefore reinterpret the structural framework of their arguments accordingly.

GHS rocks experienced top to the south shear during the main foliation forming event (D_1) (Davidson et al., 1997). This shearing penetrated at least a few kilometres beneath the MCT itself, into rocks of the LHS (Grujic et al., 2002). This top to the south shearing was overprinted in the upper portions of the GHS by top to the north shear fabrics (S_s) associated with the STD (Burchfiel et al., 1992, Edwards et al., 1996). All of these kinematic interpretations are based on S-C fabrics defined by preferred orientations of micas, shear band relationships, and quartz microtextures (Davidson et al., 1997).

Overthrusting of the high temperature units of the GHS over the cooler, subducting Indian continent, and “underthrusting” of the GHS beneath the cooler, overlying cap of the Tethyan Sequence rocks accounts for the apparently inverted metamorphic field gradient observed across the GHS (Hodges, 2000). Heat for metamorphism was provided and distributed by the interaction of heat advection by leucogranite intrusion before, during and after south directed shearing (Davidson et al., 1997), metamorphic heating due to burial, and partial melting during nearly isothermal decompression (Grujic et al., 2002). The pervasive, top to the south shear fabrics within the GHS indicate it has not been emplaced as a rigid, previously cooled “slab”, but rather as a more highly ductile, hotter, and internally deforming package between the two confining and relatively rigid packages of the subducting Indian continent and the Tethyan Sequence (Grujic et al., 1996).

These studies provide detailed information regarding the metamorphic conditions during various deformation events within the GHS. Although most authors agree that equilibrium conditions were not achieved due to the rapidity of the tectonic processes involved (e.g. Davidson et al., 1997; Hodges, 2000, and references therein), the consensus is that peak metamorphism occurred during decompression at temperatures between 600°C and 800°C (Davidson et al., 1997; Grujic et al., 2002).

High peak metamorphic temperatures are based on the conditions required to produce the abundant leucosomes of the GHS. Discrete leucogranite bodies are inferred to have been produced in a source region (beneath the Tibetan Plateau) with temperatures of 700-770°C, and within the GHS rocks themselves as partial melts. Two competing hypotheses exist as to what conditions are necessary for production of these leucogranites. The first of these is fluid present melting at the base of the GHS, where fluid is derived from the dehydration during subduction of the subducting Indian continent. This model requires temperatures near 700°C, and a small amount of water (Scaillet et al., 1995 *in* Davidson et al., 1997). Conversely, dry higher temperature melting with water sourced from muscovite breakdown (i.e. *in situ* partial melting to produce migmatites and provide material for the larger leucogranite bodies) could have allowed for the segregation of granitic melt. This could have occurred at temperatures towards 770°C, and has some support in the petrographic evidence, where the highest temperature migmatites are poor in muscovite and contain a large amount of sillimanite and K-feldspar (Davidson et al., 1997).

Examinations of mineral assemblages within migmatitic augen gneisses of the upper GHS show evidence of the breakdown of biotite and sillimanite (with quartz) to

cordierite, potassic feldspar and a melt component (Davidson et al., 1997). Also observed is the breakdown of garnet with sillimanite and quartz to cordierite, biotite and quartz, accounting for cordierite rims observed on garnets in the upper GHS (Davidson et al., 1997). These reactions are inferred to have occurred under temperatures of approximately 750°C and pressures of approximately 4.5 kbar. Kyanite is not observed as a stable phase during top to the south shearing anywhere in the upper structural levels of the GHS. Muscovite is also observed to react with quartz to form sillimanite, potassic feldspar and a melt component (i.e. the sillimanite-out isograd). These reactions describe nearly isothermal decompression, or minor heating during decompression (Davidson et al., 2002).

Within the lower GHS (i.e. the Paro Metasediments), kyanite is present and reacts to form sillimanite to an increasing degree of completion structurally up section in these rocks. Mineral assemblages are indicative of lower temperature, higher pressure metamorphism (Davidson et al., 1997) than in the upper GHS. Staurolite and quartz are observed to react to sillimanite and garnet. Garnet is observed to react with muscovite to produce biotite and sillimanite (Davidson et al., 1997). These reactions indicate peak temperatures of 600-710°C (increasing upwards with structural level) at 7-9 kbar. The same pattern of minor heating during decompression that is observed in the upper GHS rocks is also observed in the lower structural levels of the GHS.

4.0 REGIONAL FOLDING

One of the main questions to be answered is that of the structural mechanisms responsible for the distributions of map units in the Chomolhari Range and Lingshi Klippe. Observations made during this study indicate that two generations of relatively open, many kilometre-scale folds (F_3 and F_4 of both the Tethyan Sequence and CRMs) are present in north-western Bhutan that refold the entire exposed lithological sequence. These folds generate an approximately Type 1 interference pattern (after Ramsay and Huber, 1987) that is responsible for a series of basinal and domal culminations. These account for the regional structures and distribution of lithologies in the study area.

Since Gansser (1983) and Grujic et al. (2002) have also observed F_3 and F_4 in other areas of Bhutan (e.g. in the northern border range, and in the other metasedimentary klippen of Bhutan), these are the first two generations of folding that are identifiably regional in occurrence. Folding of the Tethyan Sequence and Chekha Formation together into F_3 and F_4 constitutes the third and fourth deformational events (D_3 and D_4) experienced by these units. D_{1-2} structures as identified within the Tethyan Sequence and CRMs may also occur regionally, but have not yet been identified by other authors in Bhutan. D_{1-2} of the Tethyan Sequence therefore cannot yet be described as regional events.

Gansser identified the antiformal nature of the Chomolhari Range in both of his publications that dealt with Bhutan (1964, 1983, e.g. see figure 133, Gansser, 1983). The antiformal nature of the entire Border Range between Bhutan and Tibet has been affirmed by numerous authors (e.g. Edwards et al., 1997, and Grujic et al., 2002), and the Chomolhari Range is no exception. However, the antiformal nature of the Chomolhari

Range is often ignored, primarily as a result of ambiguities in facies assignments within Gansser's 1983 volume (see below), which make the nature of the Chekha Formation unclear. Additionally, because Gansser did not map with an active tectonic model in mind, features like in-folded local segments of the STD were not sought out during his mapping. Accordingly, interpretations of gradual upwards decreases in metamorphism are made, where in fact, highly strained horizons are identified in this study that separate rocks with different metamorphic and structural histories.

Neglecting to consider the Chomolhari Range as a major antiformal structure has led authors such as Wu et al. (1998) to infer the presence of a large basement ramp beneath the Chomolhari Range. Other authors (such as Stuwe and Foster, 2001), have presented geological maps of Bhutan that consider the entire Lingshi Klippe to be merely a preserved, attached erosional outlier, or "flap" of the Tethyan Sequence of Tibet. These assumptions naturally include the Chekha Formation in the lowest members of the Tethyan Sequence, largely after Gansser (1983), and serve to de-emphasise the importance of the large antiform within the Chomolhari Range.

4.1 The Chomolhari Range Antiform

Field observations made during this study confirm that a large antiform exists within the Chomolhari Range (the CRA). The axial surface trace of this steeply SE-verging antiform (F_3) trends NE-SW, parallel to the margins of the Chomolhari Range itself, and has a parallel synformal couple within the Lingshi Klippe (**figure 4.1**). This NE-SW trending regional folding (F_3) constitutes D_3 . At all study localities, some attenuation of units is apparent towards the steeply dipping eastern limb of the CRA.

Figure 4.1: Equal angle stereonet projection of poles to foliations within the CRA.
Dotted line is a great circle average of these values, and indicates the CRA has an axis that trends NE-SW.

This is corroborated by microtextural studies of the units in this area, all of which indicate these rocks preserve strain related to the development of the CRA.

Parasitic folds from the CRA's eastern limb are axial planar to refolded S_{0-2} in the Jhari La area (see **figure 1.4**), forming a new planar fabric (S_3) that defines the dominant foliation within this limb of the CRA. S_3 dips very steeply to the west ($72-86^\circ$) with an associated strikes that is NW-SE ($220-240^\circ$) (**figure 4.2**), parallel to the main axial planar trace of the CRA. As such, it can be seen that the eastern limb of the CRA is at least locally overturned.

Fold hinges of the same parasitic folds (F_3) at Jhari La plunge shallowly ($\sim 15^\circ$) to the north-east, though this direction of plunge is not indicative of the overall structural trend of the Chomolhari Range. Later NW-SE directed folding (D_4) and faulting have modified the orientation of these units. Late-stage rotation of pre-existing fabrics is a common phenomenon throughout the entire border range, as indicated by several authors (e.g. Edwards & Harrison, 1997), and complicates structural restorations.

The CRA is observed from the northern terminus of the Lingshi Klippe at Jhari La, south past the Chomolhari area (**figure 1.3**). However, in addition to misidentification problems caused by the ambiguous facies attributions of Gansser's work, the Lingshi Fault is also a major structurally disruptive factor that masks the presence of the CRA (see Chapter 5). Observations of the CRA from the Goyak-Chebisa area include disruptions by the Lingshi Fault (refer back to **figures 3.25, 3.26a and 3.26b**). In these areas, the Lingshi Fault has locally removed part or all of the steepened fabrics of the CRA's eastern limb (**figure 4.3**), which in conjunction with erosion has obscured the CRA's presence.

Figure 4.2: Overturned eastern limb of the CRA at Jhari La. S3 (axial planar cleavage to F3) is steeply NW dipping, and indicate that the CRA has a steep, SE verging character.

Figure 4.3: Disruption of the Tethyan Sequence in the eastern limb of the CRA by the Lingshi Fault. The fault runs sub-parallel to the CRA, and so differently dipping fabrics are intersected along strike. For instance, south of the location shown here, nearly vertical (S3) foliations are preserved. Photograph taken at Chebisa. See figure 3.6 for the wider geological context.

Evidence that D_3 has also produced a synform adjacent to the CRA within the Lingshi Klippe is less obvious because the half-wavelength of the synform within the Lingshi Klippe is on the order of 40 km. However, large warps (F_3) within the Tethyan Sequence at Jhari La that correspond to this synform were observed, where a definite “stepping down” to the south-east pattern of F_3 was observed. On the larger scale, Gansser (1983) reported this style of regional folding in the eastern Lingshi Klippe (e.g. figures 41 and 43 of Gansser, 1983).

Wu et al. (1998) and Cogan et al. (1998) observed the CRA from the NW in Tibet. They attributed the presence of the crystalline units of the Chekha Formation at high elevation in the Chomolhari Range to the draping of the strata over a large amplitude (>10 km) monoclinial flexure of the middle crust beneath Bhutan (Wu et al., 1998). Though this explanation fits the observations from the western flank of the Chomolhari Range, it does not explain the south-easterly vergent character of F_3 within the Chomolhari Range. However, since observations reveal that the lowest horizons of the Tethyan strata east of Chomolhari are still several kilometres higher than their western counterparts in Tibet, some mechanism of crustal thickening must have affected the area, of which a basement ramp as proposed by Wu et al. (1998) is one possibility.

A combination of these author's observations with observations from this study and by Gansser (1983) produce the NW-SE cross-sectional extrapolation through the Chomolhari Range presented in **figure 4.4a**. This clearly shows the CRA and Lingshi Klippe as large amplitude, asymmetric long-wavelength fold structures. A cross-section in this orientation demonstrates the effects of D_3 without the complications of the second, NW-SE trending regional folding event (D_4). South-east vergence for the CRA is

Figure 4.4a: NW-SE cross-section through the Chomolhari Range and Lingshi Klippe showing the effects of **D₃** and **D₅**. Information from the NW flank of the Chomolhari Range is modified after Wu et al., 1998.

Figure 4.4b: N-S cross-section extrapolated after Grujic et al. (2002). Yellow box indicates location of the Lingshi Klippe relative to **F₄**, which is the long-wavelength folding that is obvious in this view. The cross-section demonstrates the hypothetical link between **D₄** and out of sequence thrusting on the Kakhtang Thrust (see text for discussion).

STD: South Tibetan Detachment, LD: Lingshi Detachment
 CFS: Chomolhari Fault System, LF: Lingshi Fault

Modified after Grujic et al., 2002.

suggested by the lack of reported overturned fabrics by Wu et al. (1998) on the western flank of the CRA. Since fabrics are observed to be overturned on its eastern flank (**figure 4.2**), SE vergence is possible. However, since overturned fabrics have not yet been observed further to the south than Jhari La, continuity of sense of vergence and even tightness of the CRA cannot be extrapolated with any degree of certainty down the entire length of the Chomolhari Range at this point.

Since ductile folding of the CRMs is observed during **D₃**, and the paleo-STD (**S_S**) is folded by **F₃** and was hence not active during **D₃**, the Tethyan Sequence and underlying CRMs must have been folded together to form the CRA. This was accomplished through ductile shearing within the CRMs, but the structurally higher Tethyan Sequence lithologies at shallower crustal levels would have deformed brittely. Shallow crustal brittle faults typically root into middle crustal ductile shear zones in this situation (Twiss & Moores, 1992). The Lingshi Fault can thus be understood to have initiated as a syn-**D₃** structure.

4.2 The NW-SE trending **F₄ Folds**

F₄ is poorly constrained by both Gansser (1983) and the field observations made during this study. **D₄** folds the Tethyan Sequence and CRMs together into a series of many kilometre long folds with NW-SE trending axial surfaces, and in conjunction with erosion isolates these lithologies in map view from the high grade GHS within Bhutan (**figure 4.4b**). However, due to its long wavelength (> 50 km) **F₄** is only obvious along the outside margins of the Lingshi Klippe and Chomolhari Range, where large-scale warping is apparent (e.g. see **figure 3.12a** and **b**). Within most of the studied units, **D₄**

serves only to rotate existing fabrics and is preserved as F_3 warping at the outcrop scale (**figure 4.5**).

Within the large leucogranite sill that separates the Chekha Formation from the underlying GHS augen gneisses at Jhari La (see **figure 1.4**), foliations defined by feldspars, biotite and tourmaline dip steeply ($>70^\circ$) to the south-south-west beneath the Chekha Formation units. An approximately NW-SE trend is proposed for F_4 . However, since structural observations were not collected within the GHS north of the Klippe, the exact orientation of the fold axes of F_4 are unknown. Evidence for the overall trend of the axial surface traces of these folds must be amalgamated from information presented in different sources.

The first line of evidence derives from the field observations taken in this study. The overall south-south-west dip of the foliations within the sub-Chekha leucogranites that occur in the southern limb of an inferred F_3 antiform present to the north of Jhari La suggest a WNW to ESE axial planar orientation for F_3 . However, as only one locality was measured, and it is the interference between F_3 and F_4 (overprinted on the earlier primary stratigraphies and D_{1-2} structures) that accounts for the current orientation of the rocks, these measurements cannot be taken by themselves to indicate the overall regional trend of the F_4 axes.

The second line of evidence arises from Gansser's observations. In the body of his 1983 text, Gansser's observations are suggestive of a synformal axis through the Khan Bum massif within the Chekha Formation of the eastern Lingshi Klippe (see **figure 1.3**). The asymmetry of the Lingshi Klippe, which is a large structural basin arising from the interference between F_3 and F_4 (see **figure 1.3**), strongly suggests that a non-linear

Figure 4.5: Plot of poles to foliations (**S0-2**) in the Jhari La area east of the CRA. Great circle is an average of the poles, and indicates that **F₄** have NW-SE trending axes.

(curving gently to the east) antiform and synformal couple exists within the Chomolhari Range and Lingshi Klippe (F_3), and that another antiformal-synformal pairing must be present trending approximately NW-SE through the Lingshi Klippe. This would produce the greater apparent thicknesses of the Tethyan and Chekha units in the south-eastern areas of the Lingshi Klippe. In this case, the first order F_4 antiformal culmination occurs with a NW-SE trend just to the north of the Lingshi Klippe and Chomolhari Range, and the first order synformal culmination (F_4) runs parallel to this with its western culmination in the Chomolhari area and its eastern culmination in the area of Khan Bum. Currently, insufficient data exists to accurately describe the vergence of F_4 .

Representative of the current ambiguities in the structural data set is that no information exists elucidating the relative timing of F_3 and F_4 (see Chapter 7.5). This is a major omission in the current data that cannot be firmly resolved based on the field observations amassed during this study, and a more extensive sampling suite would be required for a thorough microstructural study. Field observations that better constrain boundary conditions are a necessity for better determinations of relative timing.

5.0 THE LINGSHI FAULT

The Lingshi fault is a NE-SW trending strike with a sub-vertical dip that separates the lowest structural levels of the Tethyan Sequence and Chekha Formation in its footwall from upper Tethyan Sequence rocks in its hanging wall. The boundary is a brittle to ductile shear zone with the following structural features:

- 1) A completely annealed cataclastic zone up to 200 metres wide that affects both high grade and low grade metasediments of the hanging wall and footwall
- 2) A highly strained zone is present in the centre of the annealed cataclastic zone that represents the latest, ductile, central shearing planes of the Lingshi Fault
- 3) A zone of distributed brittle fracturing (**D₅**) is present in the higher grade metasediments and lowest Tethyan units to the north-west of the fault, which decrease in magnitude of apparent displacement but increase in frequency towards the fault

See **figure 5.1** for a detailed cross section west to east of the Lingshi Fault.

As has been demonstrated in Chapter 3, the identification within the Goyak-Chebisa cliff section of a discrete fault (i.e. the paleo-STD) between the lowest structural levels of the Tethyan Sequence and the uppermost structural levels of the CRMs has confirmed that both Tethyan Sequence and CRMs are found to the north-west of the Lingshi Fault, within the Chomolhari Range. As such, the Lingshi Fault separates CRMs and Tethyan Sequence rocks in its footwall from Tethyan Sequence rocks from upper structural levels in its hanging wall.

5.1 Annealed Cataclastic Zone

The dominant rock type within the Lingshi Fault zone is an approximately 100 meter wide “quartzite” unit. These rocks are extremely fine grained, siliceous, virtually devoid of observable structures on outcrop scale, and weather positively relative to the

Figure 5.1: The Lingshi Fault at Goyak-Chebisa. Depth of penetration of structures is unconstrained. The approximately 100 m wide zone of annealed cataclasites (AC) that comprise the Lingshi Fault occurs near the eastern limb of the CRA, which it partially removed. Central shear planes (S_{3-4}) preserve C-S fabrics that are commensurate with down to the south-east displacement of the Tethyan Sequence relative to the Chomolhari Range. These shear planes are kinked (F_5), and indicate the Lingshi Fault was also affected by a minor component of down to the north-west displacement (D_5) of the Chomolhari Range relative to the Tethyan Sequence of the Lingshi Klippe. A lower detachment boundary is speculated to exist to accommodate D_5 . Other than these minor kinked fabrics, the Lingshi Fault acts as the eastern boundary of S_5 , which otherwise do not occur further to the east than the Lingshi Fault zone. The darker grey units of the westernmost Lingshi Fault Zone are partially annealed cataclasites (PAC). The Lingshi Fault is probably listric to the south-east at depth (see text for discussion).

Tethyan Sequence shales in the Lingshi Fault's footwall, forming a unit that is harder and more cohesive than rocks of the upper Tethyan Sequence. In fact, only three pieces of information indicate these rocks are not, in fact, quartzites (i.e. metamorphosed quartz arenites). The first of these is the abrupt vertical contact of this unit with the Tethyan Sequence rocks of the Lingshi Fault's hanging wall, which precludes a real stratigraphic variation. The second is the quartz-filled fractures that criss-cross these rocks, and indicate fluid-mediated diagenesis is a component of their structural evolution (**figure 5.2**). The third is the abrupt interface of this unit with the footwall CRMs and lowest Tethyan Sequence units of the Lingshi Fault. Although erosion has removed the complete transition between these "quartzites" and the footwall rocks, an abrupt boundary is still present that contains, within the fault zone, fractured and rotated remnants of the footwall units (**figure 4.3**). These points indicate that these rocks are in fact fault units.

These rocks have been interpreted as annealed cataclasites. Although the north-western (cataclasite against lower Tethyan/CRMs) boundary is visible (**figure 4.3**), weathered material obscures the actual cataclasite-upper Tethyan boundary. This south-eastern boundary was obvious because the cohesive nature of the silicified cataclasite makes it a buttress-forming unit that cliffs-out above the neighbouring shales. Additionally, the shales near the contact have roughly horizontal (dipping gently to the east-south-east) (S_{0-1}) planar fabrics that do not match the steeply dipping foliations of the CRA units on the other side of the fault. This indicates an abrupt boundary exists between the Tethyan shales and the Lingshi Fault units, similar in nature to the north-western contact.

Figure 5.2: Main quartzite unit of the Lingshi Fault zone, interpreted as fully annealed cataclasite. Quartz-rich mineralogy is obvious in this section. Note the lack of preserved strain in these units, the late sericite and chlorite present interstitially, and the late prominent quartz vein. Quartz-forming fluids solidified the Lingshi Fault zone over a thickness of approximately 100 m. 4x magnification, cross polarized light.

There is a gradational interface between the fine grained siliceous units and the more schistose highly strained shear planes at the centre of the Lingshi Fault (see below). As such, featureless aphanitic annealed cataclasites become more schistose as the centre of the fault zone is approached.

The Lingshi Fault does not strike exactly parallel to the CRA. As such, while between the villages of Chebisa and Goyak the cataclastic zone disrupts only the slightly south-east-dipping Chekha rocks of the fault's hanging wall, in the cliff section near Goyak nearly vertical fabrics are preserved relatively undisrupted by the Lingshi fault. An estimate for the regional strike of the CRA is about 37° (or 217°), whereas a first approximation for the strike of the Lingshi Fault in this area is about 30° . The exact extent of the cataclastic zone is unknown, as the study area only intersected it in two places.

A great deal of excess quartz and calcite-precipitating fluid was present within the annealed cataclastic zone. The present, completely cemented nature of these rocks attests to this. Photomicrographs reveal that both calcite and quartz were grown in shear planes and fractures during the structural evolution (S_{3-5}) of these rocks (**figures 3.27b, 3.27c and 5.2**). Silica was the final phase crystallised in the annealed cataclasites of the Lingshi Fault.

5.2 Discrete Central Shear Planes

Highly foliated schistose rocks occur over a distance of a few dozen metres in the centre of the cataclastic zone (**figure 5.3**), grading into the cataclastics towards the edge of this zone. A more accurate understanding of the width of this zone of shearing was

Figure 5.3: Outcrop of the central shear planes of the Lingshi Fault at Goyak-Chebisa. F_5 kinking is visible in outcrop. Mafic character is a result of grain size reduction during shearing and graphite mineralisation as an interstitial phase. Hammer for scale.

obscured by the modern sediments that covered much of this area. The planar fabrics of these shear planes dip steeply to the north-west ($\sim 85^\circ$), and in outcrop are noticeably crenulated by sub-parallel multiple crenulation sets. Distinguishing between the predominantly siliceous, vein-ridden cataclasites and the relatively mafic highly foliated schists of the Lingshi Fault shear planes is easy in outcrop. The lateral extent of these shear planes within the Lingshi Fault is questionable, as this was the only locality where they were observed in this study. However, given their close association with the cataclastic zone, these two features undoubtedly occur together.

Petrographic microtextural observations indicate that the S-C fabrics (S_{3-4}) of this central zone are of a protomylonitic nature (**figure 5.4a**). These shear bands display down to the south-east relative senses of shearing, placing the upper Tethyan units in the hanging wall south-east of the fault next to the lowest Tethyan and CRMs units in the footwall north-west of the fault. Deformation may have occurred under greenschist facies conditions, as muscovite and quartz appear as syn- D_{3-5} phases within the S_{3-5} . A later pervasive kinking of these rocks is present (F_5), visible in outcrop (**figure 5.3**) and thin section (**figure 5.4b**), that indicate down to the north-west motion of the lowest Tethyan and CRMs relative to the upper Tethyan Sequence was the last phase of deformation (D_5) recorded by the Lingshi Fault. This event may also occurred at greenschist facies conditions, as syn- D_5 quartz is precipitated in extensional fractures related to this event (**figure 5.4b**).

Figure 5.4a: C-S fabrics of central shear planes of Lingshi Fault. Down to the south-east shearing ($\mathbf{D}_{3-4}$) is apparent. 10x magnification, plane polarized light.

Figure 5.4b: $\mathbf{F}_5$ kinking of $\mathbf{S}_{3-4}$. Sense of rotation on kink bands is compatible with down to the north-west shearing. This is correlated to $\mathbf{D}_5$, inferred to be E-W extension associated with the opening of the YCS (of Wu et al., 1998). 10x magnification, plane polarized light.

5.3 Distributed Fracture Zone

A distributed fracture zone (S_5 of the Tethyan Sequence and CRMs) abuts the cataclastic zone, and extends into the CRMs and lowest Tethyan Sequence rocks, with fractures concentrated nearest to the cataclastic rocks. At the interface with the cataclastic rocks, as one travels north-west into the fractured units, an abrupt but somewhat listric (dipping very steeply to the north-west) and irregular boundary is crossed, after which point regular columnar fracture sets are encountered (**figures 5.5a and b**). Down-faulting of more north-westerly rock relative to more south-easterly rock across these fracture sets indicate down-to-the-north-west senses of displacement (**figure 5.5a**). The slight warping of fault-bound rocks into S_5 indicates that deformation occurred near the brittle-ductile transition (e.g. Ramsay and Huber, 1987). This is corroborated by quartz precipitation within these small faults, which is also indicative of greenschist or lower metamorphic facies conditions and fluid-assisted brittle fracturing (Davidson et al., 1997). Faulting is closest to vertical nearest to the cataclastics, and begins to display listric tendencies and shallower dips to the north-west within dozens of metres of the boundary with the cataclastics. More distal to this boundary, fault-bound rock packages tend to be larger (e.g. see **figure 3.18b**), and before the fracture sets disappear, at about a half kilometre from the Lingshi Fault, faults are now more significant, and are separated from one another by several metres of unfaulted rock, forming more substantial fault blocks. Faults are also even more listric here, with lower planes that dip only shallowly to the north-west.

Figure 5.5a: Concentration of S_5 faults with down to the north-west senses of displacement adjacent to the Lingshi Fault zone.

Figure 5.5b: Perpendicular view of these same fractures, demonstrating their columnar nature. Notice that the fractures have a component of NW-SE trending, steeply SE dipping oblique-normal motion. This may correspond to the larger geological context as presented in figure 5.9.

Pervasive fracturing of the upper Tethyan Sequence to the south-east of the Lingshi Fault at Goyak-Chebisa was not observed, indicating that the annealed cataclastic zone, of the Lingshi Fault represent the effective south-eastern boundary of the influence of late brittle down to the north-west fracturing.

Examinations of satellite imagery reveal a unique vertical planar fabric in the rocks of this area that is not observed elsewhere in the study area. These lineaments (as they appear from above) are continuous across ridges and have a geomorphological gully-like signature similar to that observed on the western flank of the Chomolhari range, and have been shown by Wu et al. (1998) to be the Chomolhari Fault System locality of the Yadong Cross Structure (**figure 5.6a**). As such, these lineaments are inferred to be late brittle faults that were active recently enough to leave a prominent geomorphological signature, and are probably related to the YCS and the formation of the graben system west of the Chomolhari Range.

It should be noted that while the linear trend of the Lingshi Fault can be determined in satellite images, the main areas where the fault was examined, such as the Goyak-Chebisa area, do not exhibit the same pronounced preferential erosion of fault units, forming linear gullies in mountainsides, as are observed elsewhere. As such, many of the linear gullies that are present throughout the northern Chomolhari Range, and are concentrated in (and are probably responsible for) the low saddle between the Chomolhari Range Ridge and the ridge to the north, appear to correspond more closely to the more recently active YCS faults, which are easy to trace west of the Chomolhari Range and are confirmed by the observations of Wu et al. (1998) in these areas.

Figure 5.6a: Photograph of the western flank of the Chomolhari Range taken from Wu et al. (1998), showing the characteristic planar geomorphological disruptions caused by the Chomolhari Fault System (the local portion of the YCS). Interpretations of Landsat imagery (see figure 5.7) have identified similar planar geomorphological signatures in the low saddle between the Chomolhari Range and Masang Kang Range (i.e. between Goyak and Shakshipasa).

Figure 5.6b: Trace of the Lingshi Fault in the Shakshipasa and Jhari La areas. Motion of the Tethyan Sequence is down to the SE, forming a local transcurrent jog in the fault. The listric nature of the fault plane is suggested by the bending of the fault to the east at Jhari La, where it deviates from its previous NE-SW trend.

Source: Wu et al., 1998.

5.4 Extent of the Lingshi Fault

The existence of the Lingshi Fault across much of the eastern margin of the Chomolhari Range is uncertain. Its presence at Goyak-Chebisa and near Shakshipasa (see above and **figure 5.6b**) is clear from observations made during this study. Gansser drew the Lingshi Fault on some of his cross sections (e.g. figure 133 of Gansser, 1964), but field observations in the illustrated areas indicate that erosion has removed or buried the Lingshi Fault in most of the study area, such that relationships as expressed by Gansser are seldom apparent.

Satellite data provide some clues as to the Lingshi Fault's extent. **Figures 5.7 (a and b)** are composed from the panchromatic band of a Landsat 7 scene that contains the study area. This multispectral band has a 15 m per side pixel size that sufficiently resolves some of the geological features, like the Lingshi Fault, allowing for their extrapolation outside of the study area. As shown on **figures 5.7a and b**, the Lingshi Fault has a characteristic linear trace that corresponds to observations of faulted boundaries made during field observations. Near the Shakshipasa area, observed NW-SE trending brittle fault zones assume a linear trend consistent with south-east motion of the Tethyan units at this point. These "Z" bends in the linear trend of the Lingshi Fault suggest these are local areas of transcurrent motion on the fault (**figure 5.7b**).

The E-W trend of the Lingshi Fault in the Jhari La area is interesting because its tendency to follow F_3 (which is NE-SW trending) is superseded by its diversion at Shakshipasa to the east. This diversion indicates that F_4 was also in place during the evolution of the Lingshi Fault (i.e. D_4 is syn-Lingshi Fault), because if this had not been

Figure 5.7a: Interpretation of D_3 - D_5 faulting and geology based on field observations made during this study, interpretations of satellite imagery, and observations by Wu et al. (1998) and Gansser (1983). The axial surface trace of the CRA is also included, based on structural observations. The paleo-STD is not drawn but is present at the contact between the CRMs and the lowest structural levels of the Tethyan Sequence. The Lingshi Detachment is also not drawn but is present at the contact between the GHS and the CRMs. Stereonets are provided showing poles to foliations and associated averages of these values defining great circles. See text for discussion of fabric generations.

Stereonets display poles to foliations (S_{0-2}) as follows:

- A: Tethyan Sequence east of eastern limb of CRA at Jhari La
- B: CRMs within CRA at Jhari La
- C: CRMs within CRA at Shakshipasa
- D: Tethyan Sequence east of eastern limb of CRA between Shakshipasa and Tando Gompa
- E: CRMs within CRA at Goyak-Chebisa
- F: CRMs within CRA at Tando Gompa
- G: Tethyan Sequence east of eastern limb of CRA at Nele La

Figure 5.7b: Landsat scene with station numbers and **D₃-D₅** brittle structures superimposed. Some of the structural features, like the CFS, Lingshi Fault and **D₅** fracture system to the north-west of Goyak are visible in this image.

LEGEND

89.3

- Graben Fill (Quaternary)
- Leucogranite (various ages)
- Middle to upper structural levels of Tethyan Sequence (Mesozoic) *Unmetamorphosed to greenschist facies*
- Lower structural levels of Tethyan Sequence (Mesozoic) *Greenschist facies*
- Chekha formation/CRMS (Paleozoic?) *Greenschist to amphibolite facies*
- Mixed Schists and granites (Paleozoic of Chekha formation?) *Amphibolite facies*
- GHS (Precambrian?) *Amphibolite facies*

- Chomolhari Fault System
- Trace of Chomolhari Range Antiform
- Proposed Brittle Faults
- Primary bedding
- Third generation planar fabric
- Lingshi Fault
- Second generation planar fabric

27.9

27.8

the structural situation, the Lingshi Fault would have retained its NW-SE trend.

Although this is inferred from the data that indicate the Lingshi Fault has a D5 structural component at Goyak-Chebisa (see above), these satellite observations comprise an additional, supporting line of evidence for the conclusion that the Lingshi Fault is S_{3-5} .

Further evidence of fluid phases in the faults of Bhutan is especially abundant in the E-W striking fractures observed in the Jhari La area in the lowest Tethyan Sequence in the hanging wall of the Lingshi Fault (**figure 5.8a**). These fractures were misidentified during field research as leucogranite dykes, and are observable in the Jhari La area as positively eroding sheets with an approximately E-W trend (105°) and nearly vertical orientation (dipping 85° to the south) that cut across all pre-existing structural elements (S_{0-5}). The amount of vertical displacement across these fractures is uncertain, and hence although identified as fractures these may in fact be faults with some component of hanging wall to the south senses of displacement (commensurate with motion on the Lingshi Fault). They are roughly parallel to the Lingshi Fault's inferred trace in this area, and are composed exclusively of hydrothermally textured quartz (**figure 5.8b**). These features may best be described as silicified hydrothermal fluid conduits. Since a great deal of fluid migration is apparent within the various units of the Lingshi Fault, these fractures, now completely filled with quartz, may have sourced hydrothermal springs above this area similar to those now active across the Himalaya of Bhutan. Contentions by Grujic et al. (1996) that brittle fracturing during deformation of many of the observed units was fluid mediated, appear to be supported by the various observations of quartz-filled fractures made in this study.

Figure 5.8a: Large fracture with questionable offset in the immediate hanging wall of the Lingshi Fault as inferred from Landsat imagery. Poor exposure of outcrop in this area concealed the location of the fault, which fortunately has a geomorphologically traceable signature. Possible smaller splays off of the Lingshi Fault are present in this area.

Figure 5.8b: Photomicrograph of the quartz-filled fracture outlined above. The brecciated character of this rock is clear in thin section, as is the variably brittely deformed nature of some of the quartz clasts (Q). Black material present in areas of the rock demonstrated more evidence of brittle shearing (as in this photomicrograph) is interpreted as pseudotachylite (P). 4x magnification; cross-polarized light.

The inferred trace of the Lingshi Fault on **figure 5.8** also implies that at depth it is listric (i.e. it becomes less steeply dipping) to the south or south-east. If this were not the case, the NE-SW and E-W trends of the Lingshi Fault as observed at Goyak-Chebisa and Jhari La, respectively, could not have developed within the same fault. No data exists to constrain the structural level at which the Lingshi Fault is rooted.

5.5 Relationship Between the Lingshi Fault and D₅

Fluids played an important role in the history of the Lingshi Fault by solidly cementing the main cataclastic zone. The cohesive nature of these rocks is apparent in their buttress-forming character in the Goyak-Chebisa area. Satellite imagery suggests that the Lingshi Fault units may not be as resistant to erosion elsewhere along the trace of the fault (see above), but this is not a major concern in the Goyak-Chebisa area, where D₅ is concentrated as a series of fault blocks that terminate against the Lingshi Fault zone. In fact, as brittle faulting does not penetrate into the Tethyan Sequence to the south-east of the fault at Goyak-Chebisa (the footwall of the second phase of motion), or noticeable on satellite image elsewhere along the Lingshi Fault, the Lingshi Fault units can be said to act as an effective deformation barrier to the D₅, insulating the upper Tethyan units from the effects of the late E-W extensional brittle faulting.

It is likely that the system of down to the north-west brittle fractures (S₅) that comprise the distributed fracture zone could not begin to form before graben formation to the west of the Chomolhari Range was sufficiently developed to allow for the component of motion required by the highly listric normal faults to form, transferring material to the north-west. The well-cemented cataclastic zone of the Lingshi Fault apparently acted as

a near-vertical boundary along which the CRMs and lowest Tethyan units could slide downward (see **figures 5.1 and 5.9**). This hypothesis accounts for the concentration of fractures closer to the Lingshi Fault, while also accounting for the observations that the Lingshi Fault itself only records minor down to the north-west (**D₅**) motion, demonstrating that it is not highly influenced by late down to the north-west faulting. Additionally, the observation that the cataclasites were cohesive before (**D₅**) places the development of these two structures in separate timeframes, where enough time must elapse between termination of the first phase of motion and initiation of the last phase to completely solidify the cataclastic zone.

That far field stresses rotated from favouring down to the south-east motion to favouring down to the north-west motion during the development of the Lingshi Fault is apparent because the deformation style is similar for both the earlier main fabrics and the later kinked fabrics. Both senses of motion occurred under arguably greenschist facies conditions, while fluids that precipitated quartz were present. This indicates a progressive evolution of the fault structure during and after the formation of the CRA, and indicates the Lingshi Fault is a **D₃-D₅** structure.

Figure 5.9: Cross-section through the Chomolhari Range showing the influence of the YCS in the low saddle between Goyak and Shakshipasa. The Lingshi Fault is also indicated on the south-east flank of the CRA. Not shown is the CFS, of which the proposed fault blocks may be a part. Side bounding faults would be dip-slip to strike-slip, depending on the dip of the basal detachment. One boundary fault may be present in the valley between Shakshipasa and Chebisa, while the other may be centered on the valley adjacent to Goyak. The box-like diagram is a simplification; the boundary faults could dip towards the center.

6.0 TECTONICS

6.1 Tectonic Models

A currently debated model for the evolution of the Himalayan orogen is the channel flow model of Beaumont et al. (e.g. 2001). The channel flow model was developed as structural and geochronological data sets provided a more complete image of the orogen as a whole.

The existence and sense of displacement on the MCT has been known for many years (e.g. Heim and Gansser, 1939 *in* Gansser, 1983). It was apparent that a laterally continuous series of thrust faults (i.e. the MCT) were present along the orogen that placed the more highly metamorphic units of the GHS over the less metamorphic units of the LHS, and that in turn an additional series of thrusts (the Main Frontal Thrust) placed the LHS over rocks that were clearly Indian. The MCT and MFT both demonstrate top to the south thrust senses of displacement. Field observations also indicated that metamorphism apparently increased with structural level up to the base of the Tethyan, in what was an inverted metamorphic (field) gradient (e.g. England & Molnar, 1993).

In 1992, Burchfiel et al. published observations building on their earlier observations (Burchfiel & Royden, 1985) of the series of laterally continuous top to the north normal faults that occurred in the High Himalaya between the mountains and the plateau of Tibet. More than one phase of motion was apparent on these faults, with both earlier plastic shearing and later brittle faulting preserved. They identified motion on these faults as being contemporary with motion on the southern thrust faults, thus isolating the GHS from the overlying Tethyan units and underlying LHS units by simultaneously active fault surfaces.

Contemporary activity on the STDS and MCT led to hypotheses accounting for the presence of an apparently extruding package of high-grade metamorphic rock between the two levels of lower-grade material of the Tethyan Sequence and the LHS. The first of these models was presented by Burchfiel et al. (1992) and suggested that the GHS had a wedge-shape, and was extruded between the confining layers as a result of topographic collapse of the southern Tibetan plateau (**figure 6.1a**). This was facilitated by leucogranite production within the mid-crust, which made the crystallines more amenable to flow, and was driven by the affects of gravity on the topographically elevated plateau.

Hypotheses containing wedges of extruding material have since made their way into much of the literature (e.g. Grujic et al., 1996; Davidson et al., 1997). However, seismic profiling beneath the High Himalaya and Tibetan Plateau by INDEPTH teams suggested that the large Himalayan faults rooted into a large partially molten zone beneath the Plateau, and hence were more extensive than a “stubby” wedge-model suggested. With a source for the same type of partially molten rock observed in the GHS identified beneath Tibet, Beaumont et al. (e.g. 1996, 2001) applied orogenic evolution models they had been using to explain other orogens than the Himalaya.

The ‘channel flow’ model accounts for the inverted metamorphic gradient observed across the GHS, and takes into consideration the apparently contemporaneous activity of the STDS and MCT. The channel flow mechanism, whereby the GHS is extruded as a flowing semicoherent package between the underlying MCT and overlying STDS, appears to satisfactorily account for the gross details of metamorphic assemblages and structural relationships observed in the Himalaya, especially on an orogen-wide scale

Figure 6.1a: A wedge-shaped extrusive channel after Grujic et al. (1996). Vertical scale is exaggerated.

Figure 6.1b: The channel flow model of Beaumont et al. (2001), showing the GHS extruding between two parallel faults that root beneath the Tibetan Plateau. See text for discussion.

A

Source: Grujic et al., 1996.

B

Source: Beaumont et al., 2001.

and when uncomplicated by subsequent (out-of-sequence) thrusting and brittle normal faulting related to extension.

The channel flow model (e.g. Beaumont et al., 2001) involves the subduction of Indian crustal material to a 'turn around point' (as defined by P-T-t pathways) approximately 200 km north of the current MCT beneath the Tibetan Plateau. After a residence period of several Ma under pressure and temperature conditions of greater than 8.5 kbar and 750 °C, upper amphibolite to granulite facies, kyanite bearing metamorphic assemblages are produced, with an accompanying shift of rheological properties towards the ductile regime. Some mobilisation of volatile components leads to enhanced ductility through the introduction of a melt component resulting primarily from muscovite breakdown. The thickened crustal rocks become capable of flowing under a sufficient pressure gradient. This gradient is established by the erosive removal of the brittle cover at the orogenic front, and the establishment of a laterally continuous aneuritic mechanism (see Zeitler et al., 2001), whereby a feedback loop replaces material eroded at the orogenic front through mobilisation between the parallel STDS and MCT, both of which are ultimately rooted beneath the Tibetan plateau (**figure 6.1b**).

The primary driving force for this extrusion is gravity (Beaumont et al., 2001), and various boundary conditions can produce various end member models. These include situations where flowing material channels underneath the incoming continental material (if erosion is insufficient), asymmetric extrusion of the flowing material occurs with and without underthrusting by the incoming material (under low to high erosion rates, depending on the strength of the upper layers that represent the Tethyan Sequence), and situations that closely match the Himalayan orogen and include a detached foreland

thrust belt representative of the LHS between the MCT and MFT (where the upper crust representative of the Tethyan is weak, and erosion rates are low). Other models that include the formation and movement of domes (representative of the north-Himalayan gneiss domes; see Hodges, 2000) and combinations of all of the above behaviours can be produced by changing boundary conditions. Enhanced mobility of the GHS is ensured by decompression melting during exhumation, and emplacement of leucogranite melts along the primary zones of motion further enhances mobility by reducing frictional drag within the STD and MCT (**figure 6.1b**).

Mechanisms of granite ascent and emplacement within the Himalayan orogen can be explained using models developed by Brown and Solar (1998a, 1998b), Lister and Kerr (1991), and Hutton (1988, with Ingram, 1994).

It has been shown by Brown and Solar (1998a) that granitic magma is capable of migration through shear zones within orogens. This occurs through a process of localised microscopic dilations within the anisotropic fabrics of asymmetrically stressed rocks. Functionally, asymmetric far field stresses cause asymmetric strain within the lithologic package that is localised in shear zones through a “self-organisation” process of entropic dissipation. Asymmetric stresses cause the development of foliated and lineated fabrics within the shearing rocks that influence percolative melt of leucogranitic melt flow by creating lithological strength differentials parallel and perpendicular to rock fabrics. These strength differences cause micropores to open parallel to elongated mineral fabrics (e.g. initially forming within grooves on elongate mineral surfaces), or in areas of low relative pressure in the pressure shadows of larger mineral grains.

These dilations create microporosities that operate synergistically with melt-induced high pore fluid pressure to create micropermeability through a process of melt-induced (microscopic) brittle fracturing. These networks of interconnected, opening and closing pore spaces allow melt to migrate through the shear zone. Since silicate minerals readily anneal under high pressure and temperature conditions (commensurate with partial melting), migration of melt out of one area will quickly lead to healing of microfractures, and maintenance of the required low effective stresses within the rocks required for melt migration. Increased partial melting and focused melt collection within shear zones enhances the process through lithological strength reduction, and large volumes of melt are ultimately transferred through the crust by this mechanism (Brown and Solar, 1998a and b).

Examples of sill-like granite body emplacement in shear zones have been presented in many lithotectonic contexts. Ingram and Hutton (1994) have demonstrated the emplacement of the Great Tonalite Sill within a contractional shear zone in the North American Cordillera, through a process that combines the above mechanism of related shear zone creation and melt migration with a component of hydrostatic wedging. Since magma is incompressible, once it has intruded into a space it will tend to maintain the volume of that space (hence the driving mechanism of low effective stresses/high pore fluid pressures outlined above). Coupled with crystallisation and multiple magma pulses, the construction of composite sill structures or plutonic complexes within the crust can maintain activity on fault zones and make these structures persist over geologic time.

Other workers (e.g. Brown and Solar, 1998b, Paterson and Fowler, 1993) have modelled that the type of shear zone (i.e. transpressive versus extensional versus

compressive) is not related to that shear zone's ability to percolatively conduct melt, although the type of shear zone will modify the direction of melt migration through it.

A component of many of these granite emplacement models is the significance of fault bends and other non-linear departures from shear zones. Generally, these bends provide space (under very shallow crustal conditions) or low-pressure areas (deeper in the crust than the upper few kilometres) that allow melt to accumulate, commonly as sill-like injections (Karlstrom et al., 1993, Ingram and Hutton, 1994).

These models have interesting implications for melt migration through the Himalayan orogen. Specifically, the presence of large sills of leucogranite within the footwall of the STD and to a lesser degree in the hanging wall of the MCT, together with additional sill like bodies in the footwall of the Lingshi Detachment, migmatites throughout the GHS, and numerous sills and dykes within the Chekha Formation, all may have acted as the modelling of Brown and Solar (1998) suggests. That is, these discrete faulted boundaries may be both the cause and the effect of having a partially molten lithological package beneath the Tibetan plateau. This assertion forms the basis of the numerous tectonic models, such as channel flow (Beaumont et al., 2001).

The tectonic channel within the Himalaya is commonly understood as having been actively extruding between roughly 23 and 12 Ma, with numerous local perturbations (e.g. out-of-sequence thrusts like the Kakhtang in Bhutan), with extrusion being dated as more recent towards the east (Hodges, 2000). Why the channel flow process shut down is unknown. This is likely due to a change in the boundary conditions, such as climate (as this affects erosion), rate of continental convergence or redirection of material to syntaxial removal points (Zeitler et al., 2001). In the last scenario, trans-

orogenic channel flow may have been replaced by more highly focused “plug” flow.

Conversely, a combination of all of the discussed factors may be responsible for the shut-down of the extrusive channel.

Fabrics expected within the extrusive channel vary depending on the boundary conditions. However, in the Himalayan case the kinematic sense at the base of the channel should indicate top to the south shearing commensurate with thrusting, while shear sense indicators at the top of the channel should have formed in response to top to the north shearing commensurate with extension. These fabrics can be explained as “drag” at the margins of the channel due to the viscosity of the extruding medium. At both the upper and lower boundary of the channel, highly focused strain will lead to the development of discrete faults. Discrete faults at the edge of the channel are what led researchers to refer to the GHS as a crystalline “slab”. Grujic et al. (1996) propose the idea of a Main Central Thrust Zone (MCTZ) based on their observations in Bhutan. This is a zone of *distributed* shear that affects the Greater Himalayan Sequence. The MCT itself, as a poorly defined horizon within the MCTZ, is by their definition a protolith boundary between the GHS and the LHS (see also Searle et al., 2002). Top to the south thrusting within the MCTZ is the dominant fabric throughout all but the upper few kilometres of the channel (Grujic et al., 2002, also reported by Burchfiel et al., 1992, & Edwards et al., 1996), where it is overprinted by top to the north extensional fabrics. It is thus apparent that the GHS did not act as a solid slab during extrusion, but rather as a plastic solid.

The Tethyan Sequence and Chekha Formation examined during this study occur respectively above and within the upper layers of the extrusive channel.

Recent studies have shown that the Himalayas are more structurally complex than is currently accounted for by modelling. More than one upper detachment boundary is present in some areas (Searle & Godin, 2002), indicating a multi-layered channel was present. A laminated channel is also suggested by the apparently continuous “stratigraphy” of the GHS, which is obvious in the Everest and Annapurna regions, and to a great extent across the entire orogen (see Hodges, 2000, and references therein). This stratigraphy also applies to Bhutan, where the lower GHS (i.e. the Paro Metasediments) corresponds to Formations I and II of Nepal, and is overlain by the upper GHS migmatitic orthogneisses that correspond to Formation III of Nepal. The trans-orogenic applicability of “out-of-sequence” thrusting, which is proposed as the contact between these units in Bhutan (the Kakhtang Thrust) is discussed below in Chapter 7.2.

6.2 Structural and Tectonic History

The data presented in the previous chapters has led to the following conclusions regarding the deformational and tectonic histories of the studied units. These conclusions are drawn in the framework of the channel flow hypothesis of Beaumont et al. (2001).

The Tethyan Sequence units now exposed in the Lingshi Klippe and as a partially preserved cap on the Chomolhari Range were folded by **D₁** and **D₂** prior to initiation of the extrusive crystalline channel (**figure 6.2a**). **D₁** and **D₂** may be related to early phases of compressional (i.e. top-to-the south) motion on what would later become the STD, accompanied by the formation of a composite structural fan, based on studies of the Tethyan Sequence in Nepal (Godin, 1999 and in press; Searle & Godin, in press.). The extrusive channel was subsequently established beneath these units, accompanied by

Figure 6.2 is based partially on the tentative correlation of Tethyan Sequence structures as observed by Godin (e.g. 1999) and Brown and Nazarchuk (1993) in Nepal and those observed within the Tethyan Sequence of the Lingshi Klippe during this study (see text for elaboration of this chronology).

Figure 6.2a: Top to the south shearing created F_1 of the Tethyan Sequence chronology within the lower structural levels of the Tethyan Sequence.

Figure 6.2b: A composite fan (F_{1-2}) was formed that affected all structural levels of the Tethyan Sequence. This is represented diagrammatically as NW-verging (F_2) folds that refold the SE-verging (F_1) folds.

Figure 6.2c: Top to the north ductile shearing was active on the paleo-STD. The CRMs was emplaced (D_{1-2} of the CRMs chronology) between the paleo-STD and the Lingshi Detachment.

Figure 6.2d: The orogenic channel was folded (F_3) (F_4 not shown). The Lingshi Fault was active from D_3 - D_5 , and brittle faulting (D_5) occurred along the western flank of the CRA with accompanying graben formation in the YCS.

development of the extensional STD (S_s). With initiation of the extrusive channel, the Chekha Formation was emplaced below the Tethyan Sequence (**figure 6.2b**). The Lingshi Detachment (S_L) was formed between the Chekha Formation and the central, largely migmatitic augen gneiss units of the GHS. S_L may predate S_s , based on limited geochronological studies in Bhutan (e.g. Wu et al., 1998; Grujic et al., 2002), but the data is far from conclusive. D_1 - D_2 within the CRMs are pre- to syn-peak metamorphic. If peak metamorphism occurred while the CRMs was part of the extrusive channel (i.e. syn- S_s), then it is possible that D_{1-2} had formed before incorporation of the CRMs into the channel. D_3 then created the CRA and neighbouring synform to the east (both F_3). The Lingshi Fault (S_{3-5}) was initiated along the eastern flank of the CRA. D_4 also folded the rocks about a series of NW-SE trending axes (F_4) (**figure 6.2c**). There are indications that D_3 and D_4 affected most of the orogen in Bhutan (Gansser, 1983; Edwards & Harrison, 1997; Grujic et al., 2002). Finally, brittle deformation (D_5) relating to the formation of the YCS affected the Tethyan Sequence and Chekha Formation of the Chomolhari Range (**figure 6.2d**).

In the simplest terms, and without referencing any particular tectonic theory, the emplacement of the Lingshi Klippe is therefore caused by the emplacement of the Tethyan Sequence and CRMs above higher grade crystallines by detachment faults. The Tethyan Sequence of Bhutan are then separated by folding of the Chomolhari Range and Lingshi Klippe and erosion from those of Tibet. Finally, regional E-W extension that is largely manifested in the YCS down-faulted some portions of the Chomolhari Range to the north-west.

7.0 INTERPRETATION AND DISCUSSION

7.1 Deformation and Metamorphism

The temporal relationship between episodes of deformation within the Tethyan Sequence and CRMs is summarised in **Table 3**.

One of the main drawbacks of the small data set collected during this field study is the uncertainty regarding the width and structure of the paleo-STD (S_S) as this was observed in the Goyak-Chebisa area. In particular, studies elsewhere in the Himalaya (e.g. Burchfiel et al., 1992; Godin, in press., and et al., 1999; Corfield & Searle, 2000) have demonstrated that the STD will be manifested as a wide zone of plastic to brittle deformation that will strongly overprint earlier deformation fabrics. Since accurate structural measurements could not be made from within the paleo-STD during the timeframe of this study, the degree to which earlier fabrics are transposed or otherwise altered by it is not known.

The Lingshi Detachment was not examined during this study, and therefore deformation fabrics associated with it (S_L) cannot be described.

7.1.1 Deformation of the Tethyan Sequence

Two main observations involving the interpretation of lithostratigraphy within the Tethyan Sequence that comprises the core of the Lingshi Klippe are made from this study. These are:

- 1) Deformation of the Tethyan Sequence is shown to be polyphase and to contain structures that pre-date the development of the STD, and
- 2) At least one of the numerous and structurally unconstrained faults identified by Gansser (1983) within the Lingshi Klippe must be a folded local segment of the STDs.

Table 3: Relationship Between Tethyan and CRMs deformation events. Sources for relationship to structural events as follows: 1) Godin, in press., 2) Brown & Nazarchuk, 1993, 3) Wu et al., 1998, 4) Gansser, 1983, 5) Grujic et al., 2002.

Tethyan Event	Cause of Tethyan Event	Metamorphic Grade of Tethyan Event	Relative Timing of Tethyan Sequence Event	Where Event Documented
S₀: bedding	sedimentary deposition	NA	1	Nele La, Lingshi S ₀
D₁: isoclinal folding	early compression ¹	greenschist	2	Nele La S ₁ , F ₁
D₂: isoclinal folding	tectonic fan formation (?) ²	greenschist	3: Pre-STD	Nele La, Lingshi S ₂ , F ₂
D_S: deformation within STD	top to north shearing on STD ¹	greenschist	(?) Post-D ₂ Pre-D ₃	Strained rocks at Tethyan Sequence-CRM boundary at Goyak-Chebisa (S _S)
D₃: Regional folding 1	unknown	greenschist	4: Post-STD	All areas F ₃
D₃-D₅ Lingshi Fault	D₃ to D₅	greenschist	4-6: protracted evolution	Goyak-Chebisa D ₃₋₅
D₄: Regional folding 2	unknown	greenschist	5: Post-D ₃	Jhari La F ₄
D₅: brittle faulting	E-W extension in YCS ³	greenschist	6: Post-D ₄	Goyak-Chebisa, Shakshipasa D ₅

CRMs Event	Cause of CRMs Event	Metamorphic Grade of CRMs Event	Relative Timing of CRMs Event	Where Event Documented
S₀: bedding and other fabrics pre-dating incorporation of CRMs into GHS	sedimentary deposition ^{4,5}	NA	1: Pre-STD	not seen in this study, was seen by Gansser (1983), (S ₀)
S_S: deformation within STD	top to north shearing on STD	greenschist	(?) Pre- to syn-D ₁₋₂	Strained rocks at Tethyan Sequence-CRM boundary at Goyak-Chebisa (S _S)
S_L: deformation within the Lingshi Detachment	top to north shearing on Lingshi Detachment ^{4,5}	amphibolite	(?) Pre- to syn-D ₁₋₂	Observed by Gansser (1983)
D₁₋₂: isoclinal folding	shearing within upper structural levels of GHS?	amphibolite, caused by heat advection by leucogranite (syn to late D ₂)	3: Syn-S _S (?)	Shakshipasa in micaceous schists, Goyak in marble folds S ₂ , D ₂
D₃, D₄, D₅	Same as Tethyan	Same as Tethyan	4-6: Same as Tethyan	Same as Tethyan

Since F_1 and F_2 developed prior to initiation of the STD, and these folds partially transpose primary bedding (indicating isoclinal, or nearly isoclinal folding occurred), some amount of stratigraphic repetition will be present within the Tethyan Sequence. This is not mentioned in Gansser's (1983) work and should be considered by future workers in the Lingshi area. A lack of constraining data from Bhutan make it necessary to look at areas of the Himalaya outside of Bhutan in an attempt to characterise pre-STD folding.

The Tethyan Sequence of Nepal (Godin, 1999, and in press.) contains large nappes (F_1) related to the Eocene southward thrusting of the Tethyan Sequence over the Indian continent (D_1). These folds define an early foliation (S_1) that transposes bedding, but is overprinted by megascopic, isoclinal folds (F_2) with axial planar schistosity that define the dominant foliation (S_2). In Nepal, F_2 are north-verging. Deformation is characterised by an increasing strain with depth. F_1 and F_2 define a composite tectonic fan-like structure that developed between the compressional formation of nappe-like bodies during initial south-directed thrusting and later, ductile top to the north extension related to the initiation of the South Tibetan Detachment (Brown and Nazarchuk, 1993).

These speculations may be applicable to the Tethyan of the Lingshi Klippe. As indicated in Chapter 4, the rotation of D_1 and D_2 within the Lingshi Klippe by F_3 and F_4 (i.e. the CRA and NW-SE trending folds) renders kinematic interpretations inaccurate, and therefore the present lack of data makes comparison of sense of vergence difficult between Nepali and Bhutanese Tethyan fold structures. Firm correlations cannot therefore be made. This is further complicated by the complexly faulted nature of the Tethyan units of the Lingshi Klippe (see below). That being said, it is important to note

that five apparent generations of deformation and similar folding styles are observed in both areas, and suggest a similar structural evolution.

The complex faults identified by Gansser (see Chapter 2.1.1) throughout the Lingshi Klippe are also important modifiers of stratigraphic interpretations. Based on the deformation history, these faults have undoubtedly formed at different times during the structural evolution of the Lingshi Klippe, as some appear to be associated with major ductile straining, and others appear to be brittle (e.g. see figure 27 of Gansser, 1983).

Without better constraints, the faults reported by Gansser within the Tethyan Sequence of the Lingshi Klippe may be pre-STD compressional, syn- (paleo-) STD-extensional, or syn-**D**₃ or **D**₄ extensional or compressional structures. The most recent, brittle extensional activity on the STD has not been observed south of the northern border range, and so is not likely to be present within the Tethyan Sequence of the Lingshi Klippe. However, Grujic et al. (2002) do maintain that folding identified as **D**₄ (see **figure 4.4b**) during this study is associated with the latest, brittle phases of motion on the STD. If **D**₄ is a component of the structural history of the Lingshi Fault (as is suggested by the available data in Chapter 5), it may correspond in time to the last brittle shearing on the STD. Depending on which structural level the Lingshi Fault ultimately roots into (which cannot currently be constrained), and whether or not it is also present within the eastern Lingshi Klippe, will determine whether it can be viewed as a contemporaneous structure to the late STD.

Future workers in the study area should be aware of the complex folding and faulting of the Tethyan Sequence.

7.1.2 Deformation of the CRMs and Chekha Formation

The main observations concerning the CRMs that have been made during this study are:

- 1) The CRMs are bound at their top and base by discrete faults, the upper of which is considered to be the folded STD and the lower of which shall be called the Lingshi Detachment, and because of this
- 2) The CRMs, and hence the entire Chekha Formation, should be included in the GHS because by definition the GHS comprises the footwall lithologies of the STD

Recent suggested changes to the definitions of what constitutes the STD and MCT (Searle et al., 2002, Searle & Godin, in press.) must be considered in order to reconcile some debates that exist concerning the nature of the Chekha Formation. In the case of the STD, recent work in Nepal has shown (Searle and Godin, in press.) that highly strained horizons that are cross-cut by Himalayan leucogranites have been identified as segments of the STDS, when in fact structurally higher faults above which syn-deformational (i.e. syn-S_s) leucogranites are not found are better considered as the 'true' STDS. Since the STD was active in different, discrete phases, and at different structural levels (e.g. Godin, 1999), many sections of the lower Tethyan Sequence and upper Chekha Formation are in fact in the hanging wall of structurally lower detachment faults (like the Lingshi Detachment) and in the footwall of the STD.

Based on these considerations, it is expedient to place the 'true' STD structurally above the highest level of rocks that contain volumetrically significant leucogranite intrusions (i.e. above the Chekha Formation). During ductile shearing, leucogranites would have been present in the footwall of the STD and would have been prevented from being emplaced at structural levels above the STD by the rheological contrasts across this fault. These would favour granite migration through the ductily shearing GHS after the

modelling of Brown and Solar (1998) rather than across the STD into the more cohesive Tethyan Sequence rocks of the hanging wall. The Lingshi Detachment, which separates the CRMs rocks from the GHS units below, hosts a large number of significant leucogranite bodies such as the one recorded at Jhari La (**figure 5.7a**), but is not the structurally highest level of leucogranite emplacement. This lies below the heavily annealed units of the pre **D**₃₋₅ (i.e. paleo-) STD that is observed in the study area.

In addition to the MCTZ arguments of Grujic et al. (1996) and Davidson et al. (1997) outlined above (in section 7.1.1), Kohn et al. (2002) have indicated that discrete, thin packages of rocks were probably scraped off the Indian plate (e.g. LHS units) and attached to the hanging wall of the MCT. Extending this argument to also include the top of the extrusive channel (i.e. the Chekha Formation), it is possible to incorporate slivers of the Tethyan Sequence and LHS strata that surround the GHS, into the GHS, and vice versa.

These delaminations would occur primarily as a function of the expansion and contraction of the extruding channel over time. Although actual vertical contraction and expansion of the channel may occur, field observations that appear to require expansion may be the result of folding of the entire stratigraphic package during extrusion of the orogenic channel. Initiation of new planar shear zones (i.e. more recently active segments of the STD and MCT) that cut through synformal depressions at the top of the channel or antiformal prominences at the base of the channel could delaminate slices of material from the cap or base of the channel and incorporate these into it. This would give the impression of channel expansion in outcrop, if the long-wavelength folding of the rocks prior to the initiation of the more recent shear zones was not recognised.

These delaminated “tectonic slices” would range in thickness and width, which would be controlled by the combination of the pre-delamination fold amplitudes and wavelengths, and the planarity of the fault paths through the synformal and antiformal “bulges” at the top and base of the channel (**figure 7.1**). This is one method of constructing, over time, lithologically variable, fault-bound packages of rock like the CRMs. These tectonic slices would be bound by faults along all sides; earlier faults would be present along the sides facing the interior of the channel, and younger faults on the sides facing away from the channel. At the top of the orogenic channel these would be detachment faults, and at the base of the channel these would be thrust faults. This distribution of faults and ages matches that observed around the CRMs (see Table 2).

Future workers should bear in mind that discrimination between the lowest Tethyan and uppermost CRMs can be difficult, especially if the local segments of the paleo-STD are not identifiable in outcrop. Subsequent regional metamorphism of early segments of the STDS may obliterate kinematic indicators, and otherwise alter rocks through recrystallization processes that make their original identity unclear. This has been shown to be the case at Goyak-Chebisa, and must also be true elsewhere.

Although the Chekha Formation is structurally, metamorphically and lithologically variable, it has more in common with the GHS through leucogranite intrusion and structural position in the footwall of a segment of the STD than it has with the Tethyan Sequence, and hence must be considered the uppermost unit of the GHS. This is a valid assertion regardless of its origin and its debatable total residence time in the GHS. In this, the Chekha Formation may have a great deal in common with the Paro

Figure 7.1 is a method of constructing mixed assemblages of units equivalent to the CRMs, LHS and possibly the Paro Metasediments.

Figure 7.1a: An orogenic channel wherein the central layer is extruding (in this case to the left) is folded.

Figure 7.1b: Boundary faults of the central channel are reinitiated in a planar fashion.

Figure 7.1c: Material that is bisected by the reinitiated faults is either accreted to the top or base of the channel, or delaminated into it, depending on its structural level relative to the new faults.

Figure 7.1d: The channel is then folded a second time.

Figure 7.1e: The delamination process occurs again, but since this is not the first time this has occurred, in addition to new exotic material (i.e. from structurally above and below the channel), material is being incorporated into the channel that was once already in the channel, but had been accreted into the boundary packages.

Figure 7.1f: Straining (and subsequent folding together), heating due to leucogranite intrusion, and annealing of previous highly strained fabrics, act in concert to obscure the mixed origins of the rocks that have been delaminated.

Figure 7.1g: After repetition of this process, distinct tectonic assemblages are developed that are bound by more recently active faults on their flanks that face away from the centre of the channel, and older inactive faults on their boundaries that face into the channel (see text for discussion).

Metasediments, forming a mirror-image equivalent to these units at higher structural levels (**figure 7.2**).

The preliminary hypothesis is therefore made that the CRMs are an assemblage of one or more allochthonous tectonic slices of Indian platform origin that have been incorporated into the extrusive crystalline channel of the GHS, and emplaced at shallower structural levels. The CRMs could have originated at the base of the Tethyan Sequence or from another, unconstrained source, or could contain rocks from a number of sources. As such, folds and other structural features within the CRMs (i.e. D_{1-2}) may be associated with shearing of these rocks before or during incorporation into the extrusive channel. In future, the positive identification of second sillimanite grade migmatitic gneisses (delaminations after Kohn et al., 2002) within the CRMs may confirm the tectonic slice model presented above. Tantalisingly, Gansser's 1983 map (see **figure 1.3**) does include GHS units at high elevation in the Chomolhari Range that may lie in the upper structural levels of the CRMs. These gneisses should be examined by future workers to further constrain the tectonic emplacement of the CRMs.

One final point can also be raised concerning the Chekha Formation. This concerns the use of the term "Formation" for the description of these units. Recognition of a complicated deformational and metamorphic history precludes the understanding of these rocks as a simple stratigraphic sequence that can be described as a sedimentary formation, as presented by Gansser (1983). Although the general cartographic term "formation" does apply to these units in that collectively they are bound by easily mappable boundaries (i.e. the paleo-STD and Lingshi Detachment) (Jackson, 1997), these units are clearly not a sedimentary formation, and are perhaps better referred to as an

Figure 7.2: A speculative reinterpretation of the orogenic channel in Bhutan, based on observation that: 1) the CRMs have faulted contacts at their upper and lower boundaries, 2) Gansser suggests the CRMs contains GHS gneisses, 3) recent observations in Nepal (Godin, in press.) have shown that the Chekha Formation has distant equivalents that are metamorphically and structurally similar to the Chekha of Bhutan, and 4) the suggestion by Kohn et al. (2002) that tectonic slices of LHS material have been incorporated into the GHS channel by delamination processes. Unit thicknesses are not representative.

“assemblage” of lithologically variable units, of uncertain affinity. The nomenclature of “Chekha Formation” has been used throughout this work because this is the accepted terminology in Bhutan. However, in future, referring to these rocks as the Chekha Assemblage is a possible alternative to the use of the term “Formation”, and may serve to highlight the differences between these rocks and the overlying units of the Tethyan Sequence.

7.1.3 Deformation of the GHS

Observations made during this study imply the following with respect to understanding the structural history and metamorphism of the GHS:

- 1) The Chekha Formation should be considered as the upper unit of the GHS, and kinematic data should be interpreted accordingly

Deformation and metamorphism within the GHS of Bhutan has been well documented by Grujic et al. (1996, 2002) and Davidson et al. (1997) (see above). Although shear planes of the paleo-STD (S_S) between the lowest Tethyan Sequence and the Chekha Formation rocks in the Lingshi Klippe were difficult to identify during field observations, additional burial of similar rocks as a result of out-of-sequence thrusting on the Kakhtang Thrust (Grujic et al., 1996, 2002) (see **figure 2.2** in Chapter 2) would have further enhanced retrogressive metamorphic alteration and the annealing of strain indicators in these rocks. This would overprint pre-existing fabric elements associated with active shearing on the paleo-STD (S_S) and local equivalents to the Lingshi Detachment (S_L) to a greater extent than observed in the Chomolhari Range, which has not been buried by out-of-sequence thrusting. This additional burial would further obscure the allochthonous nature of the Chekha Formation relative to the Tethyan Sequence. The large leucogranite bodies that are commonly found within the Lingshi

Detachment would make this structure easy to identify. The effect of retrogressive metamorphism and crystal annealing within the paleo-STD would more effectively obscure evidence of shearing within these rocks, making them much more difficult to identify after burial by out of sequence thrusting in southern Bhutan than equivalent structures in the Lingshi Klippe.

The presence of limestones, instead of marbles, in the Chekha Formation rocks in the bases of other metasedimentary klippen in Bhutan (Grujic et al., 2002) indicates these rocks were not as highly metamorphosed as the CRMs. However, Grujic et al. (2002) also indicate that garnet staurolite schists are present in the lower structural levels of the Chekha Formation, and that at the lowest structural levels leucogranite intruded sillimanite-bearing lithologies are present, which correspond to observations in the Lingshi Klippe.

Grujic et al. (2002) observe that final top to the north shearing (D_{1-2} of the CRMs) occurred under conditions at which sillimanite was stable (i.e. amphibolite facies). This matches the syn- to post- D_{1-2} pattern of sillimanite growth in the CRMs. It is also indicated that deformation during the main fabric forming event (possibly corresponding to D_1 of the CRMs) occurred during top to the south shearing under greenschist facies conditions, based on the precipitation of quartz instead of polyminerally leucosome in syn- D_1 structures such as boudin necks (Grujic et al., 2002). This may correspond to the muscovite-biotite assemblages that were present syn- D_{1-2} in the CRMs (see **figure 3.21** of Chapter 3), which can thus be tentatively concluded to also have developed under greenschist facies metamorphic conditions during top to the south shearing.

It is obvious that the CRMs and the Chekha Formation units in the base of the other Bhutanese klippen are mineralogically different. This may relate to differences in bulk chemistry of the protoliths of these rocks. For example, less aluminium and more magnesium in the CRMs relative to the Chekha Formation elsewhere in Bhutan would preclude the growth of staurolite or garnet under identical greenschist facies metamorphic conditions that have grown these minerals in rocks with more aluminium and iron-rich bulk compositions. Conversely, these differences in mineralogy and metamorphism may relate to different structural histories for different portions of the Chekha Formation.

7.2 F₃ and F₄

The minimum amplitude of the CRA (F₃) can be inferred to be 2-3 kilometres from examinations at Jhari La, where the Lingshi Fault (S₃₋₅) is not present as a complicating factor (**figure 5.7a**). Since the sillimanite bearing CRMs units observed at Jhari La occur only at the base of the Chekha Formation (e.g. see Grujic et al., 2002), and the greenschist facies marbles observed east of the CRA at Jhari La occur only at the base of the Tethyan Sequence (see Chapter 3), the juxtaposition of these two units across the eastern limb of the CRA at Jhari La indicates that almost the full thickness of the CRMs is absent in this area. Since the Lingshi Fault is absent in this area, the CRA is the structural mechanism that (together with erosion) accounts for the surface distribution of lithologies. As Gansser's (1983) observations in the Chomolhari area indicate a maximum thickness of the CRMs of 2-3 kilometres, the distribution of lithologies across the CRA's eastern limb at Jhari La indicate that the minimum amplitude of the CRA must also be 2-3 kilometres.

It is important that future workers in the Bhutan Himalaya be aware of the two apparent generations of regional folding (F_3 and F_4) that have been observed in the Lingshi area during this study and north of the Lingshi area by Gansser (1983) (see **figure 1.3**, where the synform paired to the CRA is continuous into the Laya area). An excellent example from elsewhere in Bhutan of the likely interference between F_3 and F_4 occurs in the Khula Kangri area, as examined by Edwards et al. (1999). A large synform is present that folds the Tethyan Sequence and underlying GHS here that, like the Lingshi Klippe, is separated from the Tethyan of Tibet by the GHS. Although data concerning the eastern terminus of this synform is unpublished, it should be noted that if this body has a “lozenge” shape (i.e. elongate ovoid) and is a structural basin as has been published by Edwards et al. (1999), then F_3 and F_4 may account for the structural distributions (**figure 7.3**). In the western portion of this synform, Tethyan Sequence rocks are isolated from surrounding crystallines by a bifurcation of the Border Range that preserves GHS rocks as topographic prominences around the Tethyan Sequence. The similarities to the proposed structural situation in the Lingshi Klippe and Chomolhari Range are obvious and likely highly significant.

7.3 History of the Lingshi Fault

In order to estimate the amount of vertical displacement on the Lingshi Fault, the lithological juxtapositions across the fault and across the eastern limb of the CRA must be compared, along with estimates of unit thicknesses of the CRMs and Tethyan Sequence.

Figure 7.3: Cross section through the northern border range near Khula Kangri, northern Bhutan, modified after Edwards et al. (1999). A basin similar to the Lingshi Basin is present here. Two generations of post ductile STD folding (i.e. F_3 and F_4) were identified during this study, of which F_3 is along the entire border range (after Gansser, 1983). If F_4 is also present in this area (after Grujic et al., 2002), then this basin must have an elongate ovoid shape, because F_3 and F_4 may be at a small angle to each other along much of the northern border range. Therefore, the Tethyan Sequence rocks of this structural basin's core may be separated from the Tethyan Sequence of Tibet, as is the case in the Lingshi Klippe.

Modified after Edwards et al. (1999).

The CRA has an amplitude of at least 2-3 kilometres (see above), which is sufficient to place lowest CRMs rocks against lowest Tethyan Sequence rocks at Jhari La. Gansser's (1983) observations of unit thicknesses within the Lingshi Klippe indicate that the Tethyan rocks in the Klippe's core at most 5-7 km thick (see **figure 4.4a**). Shales in the hanging wall of the Lingshi Fault at Goyak-Chebisa are inferred from Gansser's (1983) work to be from the upper structural levels of the Tethyan Sequence (see **figure 1.4**). Since the footwall lithologies at Goyak-Chebisa consist of the lowest structural levels of the Tethyan Sequence, most of the Tethyan Sequence must be removed across the Lingshi Fault here. This is approximately 4-6 kilometres of rock, because several hundred metres thickness of lowest Tethyan Sequence rock is still present within the CRA in the footwall of the Lingshi Fault. With the CRA accounting for at least 2-3 kilometres of this lithological offset, 4 kilometres of vertical displacement is the maximum possible thickness of rock that could be missing across the eastern flank of the CRA that cannot be accounted for by F_3 (the CRA). Hence, only 1 to 4 kilometres of added vertical displacement on the Lingshi Fault are required to account for all of the observed lithological distributions.

The Lingshi Fault cuts across all structures except the D_5 late brittle faults that are components of the Chomolhari Fault System. However, since brittle faults like the Lingshi Fault often root into ductile shear zones at depth (e.g. Ramsay & Huber, 1983), and the Lingshi Fault is spatially associated with the eastern limb of the CRA, which itself contains ductile syn- D_3 structures, the fault may have begun forming during late D_3 . Furthermore, the fault is also observed to be influenced by D_4 , (see **figure 5.8**) and D_5 was initiated close enough in time to D_4 so that the Lingshi Fault was still experiencing

its waning phases of activity (e.g., quartz was grown in F_5 kink folds within the central shear planes of the fault) during D_5 . These observations suggest the Lingshi Fault is a late D_3 to early D_5 structure, that was mainly active during D_4 . The possible correlation between D_4 and out of sequence thrusting on the Kakhtang Thrust as presented by Grujic et al. (2002), would indicate that D_5 did not significantly post-date the last phases of motion on the STD, because the Lingshi Fault experienced its final phases of motion in early D_5 .

7.4 Isolation of the Tethyan Sequence of the Lingshi Klippe

Gansser's (1983) map is ambiguous about whether the Tethyan Sequence of the Lingshi Klippe's core is truly isolated from the Tethyan Sequence rocks of Tibet. Separation of these rocks from one another other by the CRA appears, in fact, to be complete. Photographs taken of the valley north-west of Goyak show the presence of lowest Tethyan Sequence rocks closer to the village (and Lingshi Fault) and Chekha rocks (Tando Gompa thick marble units) at the border ridge that separates Bhutan from Tibet (**figure 7.4**). This is corroborated, in part, by the assertion by Gansser that leucogranite horizons were observed in the Jam La pass that occurs at the head of this valley, indicating these are Chekha Formation rocks. Although Gansser has sometimes mistaken distantly identified marbles as leucogranites (e.g. Grujic et al., 1996), Gansser illustrates the border rocks as being leucogranite bearing (e.g. figure 40 of Gansser, 1983). However, on the same diagram he also illustrates late faults (apparently NW-SE trending as those proposed in Chapter 5 to run south of Shakshipasa and Northwest of Goyak) juxtaposing clearly Tethyan rocks against leucogranite-bearing units. Based on

Figure 7.4a: NW view along the valley north of Goyak. Lowest Tethyan Sequence lithologies comprise the upper structural levels close to the village of Goyak.

Figure 7.4b: WNW view of same valley, showing a more distant ridge that forms the border with Tibet. Less well foliated, evenly weathering CRMs marble units are visible in the distance. This suggests that the Tethyan Sequence of the Lingshi Klippe and Chomolhari Range are completely separated from the Tethyan Sequence of Tibet, indicating the Lingshi Basin is in fact a Klippe. The Tethyan Sequence rocks of the foreground of figure 7.7a may be preserved as a large rotated block within the proposed fault system in this area.

observations made during this study, and based on the photographic and satellite evidence, a complete separation of the Tethyan units of the Lingshi Klippe and Tibet must be assumed until additional observations can be made in the border passes to clarify Gansser's observations.

Regardless of whether separation is complete or not, the Lingshi Basin is justifiably referred to as a klippe in order to highlight the antiformal nature of the Chomolhari Range, which intervenes as a major structure between the Tethyan units of the Klippe and those of Tibet, and should not be ignored by workers in this area.

7.5 Unresolved Observations

One of the main problems remaining in this work is the uncertainty regarding the relative timing of the two regional folding events. The data set collected was not large enough to allow discriminations to be made between the timing of **D₃** and **D₄**, and field observations of these events was confounded by the impossibility of following many of the lithological contacts into areas that would resolve these questions. This was not merely a question of topographic accessibility, but also of the short time period available for field research, and the political realities that made work near the Tibetan border impossible.

Relative timing of **D₃** and **D₄** was provided based on the hypothesis of Grujic et al. (2002) that the Kakhtang Thrust is a reactivation of the STD that formed as a result of **D₄** of this study. The approximately NW-SE or more generally E-W trend of the axes of a the large amplitude, long wavelength folding present in **figure 2.2** (which is modified after Grujic et al., 2002) correspond to **F₄** of this study. Relative timing can be

determined because F_3 is apparently present in the Tang Chu klippe of southern Bhutan, (see **figure 1.3**) which is in the footwall of the Kakhtang Thrust, and thus predates D_4 . If subsequent investigations establish that D_4 is also present in the other metasedimentary klippen of Bhutan, the Kakhtang thrust will have to be understood as a syn-to post- D_4 structure.

The second unresolved observation that presents itself concerns the north-dipping leucogranites sampled at Jhari La (see **figure 5.7a**). The contact between these leucogranites and the steeply south-dipping leucogranite suite that clearly underlies the CRMs and Tethyan Sequence at the northern Klippe boundary was obscured by unconsolidated sediment in the examined localities. As such, it is not known whether or not these granites are part of the same body. It is clear that the main foliation of these north-dipping leucogranites forms a high angle with the northernmost (lower) Tethyan Sequence rocks, but the contact is covered by unconsolidated sediment. Both of the obscured contacts must be exposed somewhere along this boundary, and would help resolve the origin of these granites.

The third unresolved observation is also from the Jhari La area and is closely related to the above question of the north-dipping leucogranites. This involves the apparent truncation of the paleo-STD by the Lingshi Detachment, as depicted in **figures 4.4b** and **5.7**. This relationship would have dramatic consequences for the interpretation of the tectonic emplacement of the CRMs and Lingshi Klippe, by indicating that the Lingshi Detachment post-dates the paleo-STD, and as such that the CRMs, and by extension the Chekha Formation as a whole, is only discontinuously present beneath the Tethyan Sequence. It should be indicated briefly that this is reconcilable with the

tectonic assemblage (delamination and incorporation) model presented in **figure 7.1**.

That being said, without more extensive field observations to identify the nature of the north-dipping leucogranites at this boundary, this may only be the effect of local, unconstrained faulting that itself post-dates the Lingshi Detachment, and cannot at this point be extrapolated beyond the Jhari La area.

The fourth unresolved point involves the causative mechanism behind **D₃** and **D₄**. Arguments involving southward propagating domal structures (e.g. Beaumont et al., 2001) can be invoked to account for gneiss domes exposed in Tibet, and their equivalents in the Border Range Antiform of the High Himalaya. It is the formation of these gneiss domes that Grujic et al. (2002) speculate is responsible for the initiation of out of sequence thrusting on the Kakhtang thrust. However, these arguments do not as easily explain **D₃**, which cannot be as easily modelled in a southward propagating orogen. This is an interesting question for future modellers to examine.

The final unresolved observation is the thickness and structure of the paleo-STD (**S_s**). Although this can be partially inferred from other areas of the Himalaya (e.g. Burchfiel et al., 1992; Godin, in press.), detailed observations should be undertaken in the Goyak-Chebisa area in order to clarify what fabric effects this high strain zone has on the lowest structural levels of the Tethyan Sequence and upper structural levels of the CRMs.

8.0 SUMMARY OF CONCLUSIONS

The geology of Bhutan, though complex, is being revealed to be similar to many other areas of the Himalaya. All of the geological features present in the Chomolhari Range and Lingshi Klippe have parallels elsewhere in the Himalaya.

Deformation within the Tethyan Sequence of the Lingshi Klippe is recognised to consist of five phases (D_{1-5}). Near-isoclinal folding (F_1) of uncertain vergence is observed on a microstructural level through the transposition (S_1) of primary bedding (S_0) and is recognised as the first phase of deformation (D_1). The axial planes of a second generation of folding (F_2) are parallel to the dominant foliation (S_2) within the structurally middle to lower Tethyan Sequence, and a brittle cleavage (S_2) at upper structural levels. D_1 and D_2 predate the establishment of the paleo-STD as observed at the base of the Tethyan units. The third generation of deformation (D_3) corresponds to folding which formed the CRA (F_3) and adjacent synform within the Lingshi Klippe. The fourth generation of folding (F_4) corresponds to the NW-SE refolding of F_3 . All studied lithologies are ductily to brittely deformed (S_{3-5}) within the Lingshi Fault. This fracturing has a protracted history (D_{3-5}), and is observed to continue into the development of the YCS (D_5). The final generation of deformation experienced by the Tethyan Sequence (D_5) is brittle fracturing associated with E-W extension associated with the YCS. All generations of deformation within the Tethyan Sequence occur at greenschist facies or lower metamorphic conditions.

Deformation within the CRMs is recognised to occur in five phases (D_{1-5}). In all but the thickest quartzite units, bedding (S_0) is transposed. Isoclinal folding and transposition of bedding occurred in at least two phases (D_{1-2}). Kilometre-scale isoclinal

folds (F_{1-2}) are observed to refold the previous foliations (S_{0-1}). The dominant foliation (S_{1-2}) is inferred to be parallel to the axial planes of F_2 . Leucogranite intrusion occurred throughout D_{1-2} . D_3 - D_5 correspond to those events experienced by the overlying Tethyan Sequence, as D_3 - D_5 affect the CRMs and Tethyan Sequence simultaneously.

Deformation during D_{1-2} occurred at greenschist to amphibolite facies conditions, but advection of heat by numerous leucogranite sills and dykes may be the cause of the early D_2 peak of temperatures, when sillimanite bearing assemblages became temporarily stable. Sillimanite is observed to break down to biotite in late-syn to post- D_2 .

Greenschist facies conditions persist during D_{3-5} .

D_3 - D_4 are recognised regionally, and affect the Lingshi Klippe and Chomolhari Range. D_3 is responsible for the CRA (F_3) and the synform adjacent to this structure (also F_3) in the Lingshi Klippe. This axes of F_3 are NE-SW trending, and corresponds to the antiform-synform couple that occurs in the entire Border Range that separates Bhutan from Tibet. The F_4 trends approximately NW-SE, and interacts in an approximately Type 1 interference pattern to create a domal culmination to the north of the Chomolhari Range, and a basin within the Lingshi Klippe.

F_3 is responsible for complete separation of the Tethyan Sequence of the Lingshi Klippe's core from the Tethyan Sequence of Tibet by having folded these rocks into the CRA and having the Tethyan Sequence units at the top of the CRA subsequently removed through faulting (during D_{3-5} in the Lingshi Fault and D_5 in the Chomolhari Fault System) and erosion. This is tentatively supported by satellite image interpretations that suggest separation of units is complete. However, geological observations of the area in question are required to resolve this debate.

The Lingshi Fault (D_{3-5}) is a steeply dipping normal structure that occurs in spatial proximity to the eastern limb of the CRA and is genetically related to F_3 . It manifests down to the south-east motion of the hanging wall Tethyan units relative to the footwall CRMs and lowest Tethyan Sequence rocks that persisted into D_4 , but also displaces upper structural level Tethyan Sequence rocks in its hanging wall down to the south or south-east relative to lower structural level Tethyan Sequence rocks of its footwall in the northern Lingshi Klippe. This was followed by a small amount of down to the north-west motion of the CRMs and lowest Tethyan Sequence relative to the upper Tethyan Sequence rocks during D_5 . As such, down faulting of the Tethyan relative to the CRMs on the Lingshi Fault, and formation of the CRA, predates opening of the YCS graben structure to the west of the Chomolhari Range. Excess fluids were present during D_{3-5} within the Lingshi Fault. Fluid-mediated static annealing of the Lingshi Fault zone was extensive, and cemented the main fault sequence. This made the Lingshi Fault a discrete solid barrier across which east-west extension related to the YCS could not propagate.

The CRMs is identified to be separated from the lowest structural levels of the Tethyan Sequence by highly strained (S_S), though subsequently annealed, rocks that correspond to a folded local segment of the (paleo-) STDS. The presence of numerous generations of intrusive leucogranite within the CRMs, and the much higher maximum metamorphic conditions achieved by these units relative to the structurally overlying Tethyan Sequence, indicates these rocks have different structural histories. Based on the above observations, the CRMs, which lie in the footwall of a segment of the paleo-STD,

are more properly considered to be the uppermost units of the GHS than the lowermost units of the Tethyan Sequence.

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