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M. Sc. THESIS
GEOLOGY OF THE HIMALAYAS AND SOUTHERN TIBET

by

Ashok Kumar Duvadi

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 Geology
Carleton University
Ottawa, Ontario
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December, 1984.

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Submitted by Ashok Kumar Duvadi
in partial fulfilment of the requirements for
the degree of Master of Science.

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ABSTRACT

A 1:1,000,000 scale map has been compiled from the available geological data for the 2,500 kilometre, crescent-shaped Himalayan mountain belt and southern Tibet. The included lithostratigraphic legend adopts five longitudinal subdivisions, each of which reflects a particular geological environment. From the south they are: (i) Pleistocene-Recent Indo-Gangetic alluvial plain; (ii) sub-Himalayan Tertiary sediments, shale, limestone; (iii) lower Himalayan Precambrian-Cambrian phyllites, schists, quartzites; (iv) higher Himalayan Permo-Cretaceous crystalline rocks, granitic gneisses; and (iv) fossiliferous rocks of Tibetan/Tethys Himalayas. These subdivisions are separated by major northwest-trending, thrust faults and parallel the regional northward dip.

The plate tectonic model explains the evolution of the Himalayas as a result of the impingement of the Indian sub-continent on Asia. The forces were accommodated by imbricate thrust faults beneath the mountains, as well as strike-slip faults and grabens radiating behind them.

Data for 218 mineral occurrences are presented on maps- 1 and 2 in the pocket, and in tabular form. Discovery of small mineral and fossil-fuel deposits in many parts of the Himalayas indicates that additional significant mineral deposits may exist in the region.

A comprehensive bibliography of Himalayan geology is also included.

DEDICATION

To my parents

Shri Keshava Duvadi and
Shrimati Kunjalata Duvadi

whose support and encouragement have always been
a great inspiration to me.

With love,

Ashok Kumar Duvadi.

Unnamed peak, elevation approximately 7,800 metres, in higher Himalayas of Far-western Nepal. Recumbent "M" fold composed of granitic gneiss. (View looking north northeast).

TABLE OF CONTENTS

	Page
ABSTRACT.....	iii
DEDICATION.....	iv
FRONTISPIECE.....	v
TABLE OF CONTENTS.....	vi
List of Table and Appendices.....	vii
List of Figures.....	viii
 CHAPTER 1: INTRODUCTION.....	 1
CHAPTER 2: PHYSIOGRAPHY.....	4
CHAPTER 3: GENERAL GEOLOGY.....	8
Geological subdivisions.....	8
Stratigraphy.....	18
Structure.....	20
Metamorphism.....	23
Age determinations.....	25
Regional synthesis of the Himalayas....	27
CHAPTER 4: TECTONIC HISTORY.....	29
Tethys geosyncline and continental drift theory.....	29
The plate tectonic model.....	31
CHAPTER 5: MINERALIZATION.....	47
CHAPTER 6: CONCLUSIONS.....	51
ACKNOWLEDGEMENTS.....	53
BIBLIOGRAPHY AND REFERENCES.....	55
Appendix A.....	85
Appendix B.....	87
Map Sheets-1 and 2.....(in the pocket)	

List of Table and Appendices

Page

Table

Table 1. Some representative radiometric age determinations from the Himalayas.....	26
--	----

Appendices

Appendix A. Lithostratigraphic legend of the Himalayas and southern Tibet as used in maps- 1 and 2 (in pocket).....	85
Appendix B. Location of mineral deposits and fossil fuel occurrences in different parts of the Himalayas as plotted in maps- 1 and 2 (in pocket).....	87

List of Figures

	Page
Figure 1. Himalayas and adjacent mountain ranges (after Sharma, C.K., 1977).....	6
Figure 2. Regional geological subdivisions of the Himalayas (after Gansser, 1964).....	9
Figure 3. Tectonostratigraphy of the Himalayas and southern Tibet.....	19
Figure 4. Interaction of plates and microplates at the latest stage (after Sborshikov et al., 1981).....	32
Figure 5. Diagram (to scale) showing the continental subduction structure in the Himalayas (after Seeber et al., 1981).....	34
Figure 6. Sketch of rhombohedral block tectonics showing progressive deformation of part of the Tibetan plateau (from Rothery and Drury, 1984).....	37
Figure 7. Schematic diagram showing the "indentor model" (after Molnar and Tapponnier, 1975).....	38
Figure 8. Diagram showing the topography of the Himalayas and southern Tibet; and the Basement Thrust Front (BTF) (from Seeber and Armbruster, 1982).....	39
Figure 9. Map showing the tectonic activity in Asia (after Tapponnier and Molnar, 1976)..	41
Figure 10. Schematic diagram illustrating the (a) geometric styles of converging plates in the Himalayan-Tibetan plateau region; (b) possible exhumation of the Grenville province equivalent of Himalayan-Tibetan model (after Barazangi and Ni, 1982).....	43
Figure 11. Schematic diagram showing the evolution of the Himalayas and southern Tibet.....	44 to 45

INTRODUCTION:

The "Himalayas"- Sanskrit for "the house of the snow"-are the product of continental collision between India and Asia. Among the youngest mountains in the world, they are also the largest in both height and vastness; a spectacular, isolated lofty domain. Their snow covered slopes scraping on azure sky; while in the foreground, a lush green valley bright in the sun displays a magnificent and fascinating natural beauty.

The Himalayan chain extends for about 2,500 kilometres in a broad crescent from Afghanistan in the west, eastward through Pakistan, across northern India, southern Tibet, through Nepal, and Bhutan to Bangladesh and Burma in the east. This thesis documents the evolution of these mountains, and component rock types, which form relatively continuous belts through many of these countries.

Dr. J.D. Hooker, a geologist, visited the Tamor valley in the eastern part of Nepal in 1848. Geological mapping of the Himalayas began in 1864, under Dr. H.B. Medlicott of the British Geological Survey of India. Individual countries conducted general investigations of rocks within their (disputed) borders until recently, when projects sponsored by research groups of other nations (Austria, Britain, France, Germany, Japan, USSR, Switzerland, and USA) began to introduce "new ideas and tectonic theories" for the mountain belt, regarding it as a continuous geologic system, rather than discrete

political entities. Regional mapping of the Himalayas has progressed slowly, in part due to apparently low economic potential, and because the belt is divided by political boundaries which restricts the flow of scientific communication.

During the 1950's, T. Hagen conducted reconnaissance geological work in the Nepal Himalayas. His concept of nappe structures has remained highly controversial. The first attempt to bring together what was then known of the entire mountain chain was Dr. A. Gansser's (1964) "Geology of the Himalayas" which included a Geologic and Tectonic Map of the Himalayas (and Surrounding Areas) at 1:2,000,000 and 1:10,000,000 scales, respectively. A more recent compilation at 1:2,000,000 was published by G. Fuchs in 1982.

The present study has involved preparation by the author of a geological map of the Himalayas and southern Tibet at 1:1,000,000 scale, that is consistent with the current state of knowledge (maps- 1 and 2, in pocket). Accompanying the new map is (i) a modified litho-stratigraphic legend, (ii) a general geological description of the Himalayas and southern Tibet (this report) and (iii) an account of mineral occurrences and remarks concerning the mineral potential in the region.

This work is primarily a compilation from published and available unpublished maps and reports with interpretations by the author. Some unpublished data

have been made available by personal communication.

In addition, the author's field work from far-western, western, southcentral, and southeastern Nepal, completed during the 1981-1982 field seasons, are incorporated. The author pays tribute to the people who have devoted themselves to deducing the structure of this vast and magnificent land, and accepts full responsibility for the interpretations and possible errors in this report.

PHYSIOGRAPHY:

The world's mightiest mountain belt lies in the central part of Eurasia, north of the Indian Shield. These ranges (Himalayas) include fourteen peaks that rise over 8,000 metres, and hundreds over 7,000 metres high; when no other mountain chain on earth rises over 7,000 metres. They are unique in that their spectacular ruggedness is the recent product of rapid uplift.

Himalayan mountain ranges represent one of the roughest terrains in the world. Prominent peaks within the Himalayas are listed below:

<u>Peaks</u>	Elevation in metres above mean <u>sea level</u>
Nanga Parbat	8,126
Mount Dhaulagiri	8,172
Mount Annapurna	8,125
Mount Everest	8,848
Mount Kenchenjengha	8,586
Mount Chomolhari	7,314
Namche Barwa	7,449

Some of the world's major rivers have their sources in the Himalayan region. From the west to the east they include the Indus, Sutlej, Kali, Karnali, Narayani, Koshi, Manas, Brahmaputra, Chindwin, and Mali Hka Rivers (see map Sheets-1 and 2). More interesting is that the three major rivers of Nepal-

-the Karnali, Kali Gandaki, and Koshi all drain north to south cutting through the Himalayas, erosion having kept pace with uplift.

The Kali Gandaki river, at 1,200 metres elevation between Dhaulagiri and Annapurna mountains, lies 6,972 metres below the summit of Dhaulagiri and probably represents the greatest terrestrial relief on earth. In addition, the northern part of the Himalayas (southern Tibet) has an average elevation of 5,000 metres above mean sea level. Numerous large glacial lakes are located throughout the Tibetan region, with some minor ones in the Himalayas.

On a physical map of Asia, there are four striking physiographic features (Figure 1):

(a) several mountain ranges pass through the Pamir "knot" and branch towards the northeast, east, southeast (the Himalayas), southwest, west and northwest.

(b) a broad alluvial plain, covered by the Indus River to the west and the Ganges River on the east, which separates the Himalayas (to the north) from the Indian Shield.

(c) the Himalayas comprise three successive arcuate ranges which are convex towards the Indian Shield. These are the Arakan Yoma-Burma arc (east), the Sulaiman arc (west), and the Himalayan arc. These mountain arcs are separated by the "syntaxial bends" (Namche Barwa and Nanga Parbat, respectively), which are sharp bends in an orogenic belt accompanied by a fraying

Figure 1. Himalayas and adjacent mountain ranges
(after Sharma, C.K., 1977).

7
into several strands (terminology from Bates and Jackson, 1980).

(d) existence of the oval tableland (Tibetan plateau, average elevation 5,000 metres above mean sea level) between the Himalayas (to the south) and the Kun-Lun mountain chains (to the north).

GENERAL GEOLOGY:Geological subdivisions:

The Himalayas are divided into longitudinal geological subdivisions, and political and geographical regions (Gansser, 1964; Figure 2).

The pattern of the regional geographical subdivisions of the Himalayas shows a close relationship to the geological subdivisions. These subdivisions (see maps- 1 and 2, in pocket) from the west to the east are:

- (i) Punjab Himalayas (550 kilometres long)
- (ii) Kumaon Himalayas (320 kilometres long)
- (iii) Nepal Himalayas (about 800 kilometres long)
- (iv) Sikkim/Bhutan Himalayas (400 kilometres long) and
- (v) Arunachal Himalayas (about 400 kilometres long).

The longitudinal geological subdivisions of the Himalayas, from the south to the north are:

- (i) Northern part of the Indo-Gangetic plain
- (ii) Sub-Himalayas
- (iii) Lower Himalayas
- (iv) Higher Himalayas and
- (v) Tibetan/Tethys Himalayas.

Because the longitudinal subdivisions of the Himalayas show similar characteristics throughout their length (2,500 kilometres), a new litho-stratigraphic legend for the entire Himalayas and southern Tibet is proposed in this thesis (see maps- 1 and 2, in pocket;

Figure 2. Regional geological subdivisions of the Himalayas (after Gansser, 1964).

Appendix A). The legend combines the sedimentary formations of equivalent age, lithology, and tectonic environment within each subdivision of the Himalayan orogenic belt. Among them are minor volcanic horizons (of sedimentary origin) and dykes.

Regional metamorphism has affected most of the belt making it difficult to identify the protolith and early history of many formations. Generalized cross-sections constructed across one part of the belt are normally applicable to formations to the west or east.

(i) Northern part of the Indo-Gangetic plain:

This is the southernmost longitudinal subdivision of the Himalayas, lying between the Sub-Himalayas to the north and the Indian Shield to the south (see maps- 1 and 2, in pocket, Figure 2). The plain (average elevation 118 metres above mean sea level), of Pleistocene and Recent alluvium deposits, alluvial fans, sand, clay, and gravel is thought to be underlain by the Sub-Himalayas.

(ii) Sub-Himalayas:

This is the first mountain range (foothills) to the north of the Indo-Gangetic plain and there is no well defined boundary between them. However, in places rocks of the sub-Himalayas are thrust southward over the Indo-Gangetic plain along the Main Frontal Thrust fault (Duvadi, 1982, unpublished data). The ranges are also called the "Siwaliks", and rise sharply 1,500 metres above mean sea level. For the most part, they consist of

Tertiary sediments, including well-bedded sandstone (calcareous graywacke), shale, mudstone, siltstone, conglomerate, and some limy beds (argillaceous limestones). Minor marly shales and mudstones are also present. Clasts are chiefly quartz, with muscovite universally present in loosely cemented, commonly limy strata. The Siwaliks are divided into lower and upper Formations, primarily on basis of the grain sizes of their clastic components: they are composed of fine and coarse clastics respectively. Siwalik sediments are mainly the erosional detritus (or molasse) derived from the rising Himalayas and deposited in a basin. The strata have been tilted to the north.

Palaeontological studies have confirmed an Oligocene to Pleistocene age for the Siwaliks (West et al., 1978). On the basis of vertebrate and plant remains, as well as similar lithology, the Murree Formation (named after the type locality Murree, about 45 kilometres north-northeast of Islamabad) of the Salt Range region in the southwestern Punjab Himalayas is correlated with the lower Siwaliks (Gansser, 1964; Fuchs, 1982).

(iii) Lower Himalayas:

The Lower Himalayas occur to the north of the Siwaliks and rise as high as 4,000 metres above mean sea level. Rocks within this longitudinal belt are also known as the Midland Metasedimentary group, and the belt

is sometimes termed the Middle mountain range or Mahabharat range (in Nepal).

The boundaries of the lower Himalayas with the Siwaliks (in the south) and the higher Himalayas (in the north) are tectonic, and are defined by the Main Boundary Thrust and Main Central Thrust, respectively.

Most formations in the lower Himalayas lack abundant index fossils and their age is in dispute. Environments of sedimentation, conditions unfavourable to the development and preservation of life, and later complex metamorphism and tectonics are the causes for this (Le Fort, 1975). However, a few fossils, such as the stromatolite "Plicatina" from the Kapkot Formation (Calc zone of Tejam) of Kumaon lower Himalayas (Bhattacharya, 1983); some microbiota and algae of the late Precambrian and the base of the lower Cambrian; trace fossils from Kashmir (Kumar et al., 1984); and stromatolites from Dhading Dolomite, Nepal (Stocklin, 1980) are noted. Stocklin (1980) mentioned the fossiliferous (crinoids, trilobites) lower to middle Palaeozoic sequence of Phulchauki-Chandragiri, southeast of Kathmandu in central Nepal. He also referred to the work of Termier and Gansser for the similar (counterpart) sequence in Tangchu basin, Bhutan.

The Eocene belt between the Siwaliks in the south and the lower Himalayas in the north, and intermittently in Punjab, Kumaon, Nepal, and the Arunachal Himalayas is the normal cover of the autochthonous unit (for example

the Simla slates in the Kumaon Himalayas, (see maps - 1 and 2, in pocket) and is preserved below the various thrusts. The Subathu Formation (Kumaon Himalayas), Jarbutta Formation (Nepal Himalayas), and the Dzongbuk shale (in Tibet) are the type localities. Eocene rock types are mainly limestones (nummulitic), calcite-veined olive shale, green and white sandstones, shelly (broken oysters) limestones, white quartzite, purple shale, pink to green slate and phyllite.

Lower Himalayan rock types include phyllites, schists, quartzites, and carbonates. The Muth quartzites and Salkhala schists (Punjab Himalayas) are the type examples. Salkhala schists are correlated with the Jutogh limestone of Simla (Kumaon Himalayas) on the basis of their stratigraphic positions. The Krol Formation (cherty limestone, red shale) and the Tal Formation (arkosic quartzite, limy sandstone with trace fossils) in the Kumaon Himalayas in Simla, are the best studied sections of the lower Himalayas.

The Gondwana rock series, in the Pir Punjal range of the Punjab Himalayas is characterized by the *Glossopteris* flora. Widespread volcanic rocks in the Pir Punjal range formed at this time (Permo-Carboniferous) now called the "Panjal Traps", have been stratigraphically correlated with glaciogenic deposits, such as the Talchir boulder beds of the Salt Range region, tillite-type (diamictite) conglomerate and the Tal/Krol Formation of Simla (Kumaon

Himalayas), Sallyan Series of Nepal Himalayas, and the Abor volcanics of Bhutan (Le Fort, 1975; Remy, 1975 a and 1975 b). Similarly, the Baxa Formation (dolomites, limestones, calcareous shales, and local gypsum and quartzite beds) of the Bhutan Himalayas are correlated with the Deoban and Shali Formations of Simla (Kumaon Himalayas) (Gansser, 1983; Jangpangi, 1978). Also, Miri quartzites and Bomdila group rocks (quartzites, schists) can be taken as the typical examples from the Arunachal Himalayas (Sinha, 1981 a).

(iv) Higher Himalayas:

The higher Himalayas are located to the north of the lower Himalayas and have an average elevation of 6,000 metres above mean sea level. The boundary between them is called the Main Central Thrust. This feature is not present to the east, so that there the distinction between the higher Himalayas (Central Crystalline zone) and the lower Himalayas (crystalline masses) is not clear. Granitic gneisses with occasional augen structures are the main rock type of the higher Himalayas, with subordinate marble lenses and minor amphibolites, paragneisses, and calc-mica schists. The Darjeeling gneiss of the Sikkim/Bhutan Himalayas is the type example. The lithologically similar Se Le group is an example from Arunachal Himalayas. The higher Himalayas consist of thick crystalline thrust sheets that form the base of the Tibetan/Tethys Himalayas (thick sedimentary sequences) to the north.

The lower part of the higher Himalayas is characterized by banded kyanite- and sillimanite-bearing garnet-mica gneisses with associated metasediments, while the upper part consists of augen gneisses, migmatitic gneisses, migmatites, and granitic gneisses. Within the gneisses are sills, dykes, and larger intrusions of tourmaline-bearing leucogranites. Examples include: Nanga Parbat in Punjab Himalayas; Badrinath and Kedarnath in Kumaon Himalayas; Api and Mustang, Makalu, Barun gneisses, Manaslu (Le Fort, 1981) (and its continuation into the Shisha Pangma in northern Nepal and southern Tibet), Everest, and Makalu region in Nepal Himalayas; Kenchenjengha and Chomolhari in Sikkim/Bhutan Himalayas; and Namche Barwa in the Arunachal Himalayas. These leucogranitic bodies generally occur in the uppermost part of the higher Himalayas.

One exception to the "lofty leucogranite phenomenon" is Mount Everest whose summit is formed of limestone, an erosional relic underlain by pelitic rocks. The famous yellow band in the Everest limestone consists of schistose limestone and is capped by the schistose to dolomitic limestones which contain poorly preserved crinoid fragments that indicate a Carboniferous to lower Permian age.

(v) Tibetan/Tethys Himalayas:

This represents the northernmost geological subdivision of the Himalayas and has an average elevation

of more than 6,000 metres above mean sea level. The lower boundary of the Tibetan/Tethys Himalayas with the Central Crystalline zone of the higher Himalayas is transitional. This region chiefly consists of a continuous, remarkably concordant succession of gneisses and sedimentary rocks ranging in age from late Precambrian to Cretaceous. At the base are gneisses, some of which are calcareous. The augen gneisses, with pegmatites and aplites, are overlain by mica schists, limestone, sandstone and fossiliferous shale. Further north in the upper Indus and Tsang po valleys of Tibet, ophiolites-dunites, harzburgites, garnet-bearing amphibolites, serpentinites, andesitic lavas and pillow lavas are found (Girardeau et al., 1984; Nicolas and Prinzhofer, 1983). Regional metamorphism has reached various levels in different parts of the region and the effects are noted in the Precambrian to Cambrian rocks in the Spiti basin (Punjab Himalayas), in Cambrian strata in Kumaon Himalayas, in Ordovician strata in Nepal Himalayas, and north of Everest in the Kampa Dzong basin (southern Tibet). In general, the Tibetan/Tethys Himalayas represent a 15,000 metre-thick section of fossiliferous sedimentary cover resting on the crystalline rocks (Precambrian basement) of the Higher Himalayas. The Spiti region in the Punjab Himalayas contains a continuous stratigraphic section from Precambrian to Cretaceous in which the Giumal sandstone and Chikkim limestone, named for type localities, represent the Cretaceous sediments.

deposits occur in the Kumaon Himalayas, but recently interest in these formations has extended into the western and eastern Nepal Himalayas. Magnesite and talc in these areas are irregularly produced in small amounts. Gems such as world-famous sapphires (Sumcham), rubies and emeralds are found in Kashmir (Punjab Himalayas), while aquamarine and tourmaline (both zoned and transparent), and amber and jade come from the Nepal Himalayas (Hyakule) and Burma, respectively.

Several gas seeps and oil occurrences are present in Kashmir. Some unusual gas seeps in the contorted phyllite of Far-western Nepal are thought to rise from Eocene strata which lie below the Ranimatta and north of the Main Boundary Thrusts (Nepal Himalayas) but are not considered indicative of a large reservoir. Taking into consideration the structural complexity, a reservoir of economic size is unlikely to be present in this environment. Lower to middle Tertiary rocks, however, occur in the Brahmaputra valley (east to southeast of the Sikkim/Bhutan Himalayas), and if they continue beneath the Indo-Gangetic plain and below the Siwaliks, they constitute a favourable site for possible oil and gas occurrences.

A second place with petroleum potential lies beneath the northern part of the Indo-Gangetic plain. There the base of the Ganga plain is considered to be a major unconformity which is partly subducted beneath

represent the oldest rocks of the Transhimalayas. Larger areas are occupied by Carboniferous and Permian-Carboniferous sedimentary rocks which in the south are intruded by granodioritic plutons (Mitchell, 1979). A major discontinuous belt of plutons, including the Ladakh batholith, is the main geological feature of the Transhimalayas. Unlike the leucocratic rocks in the higher Himalayas, these plutons are predominantly granodioritic in composition (with a predominance of hornblende).

Stratigraphy:

A regional tectonostratigraphic framework for the Himalayas and southern Tibet is shown in Figure 3. It attempts to portray the major stratigraphy in a simple, general way. These are the units depicted on maps- 1 and 2.

This tectonostratigraphy is based mainly on stratigraphic position, lithological similarity, and depositional environment. Where available, information in palaeontology, metamorphic grade and structural style has also been taken into consideration. For details of individual stratigraphic units, reports and compilations by the following workers are recommended: Frank and Fuchs, 1970; Gansser, 1964 and 1983; Kumar, 1980 a; Kumar and Gupta, 1981; Mitchell, 1979; Nakajima and Pradhan, 1979; Ohta and Akiba, 1973; Searle, 1983.

a; Srikantia and Bhargava, 1983; Stocklin, 1980; Stocklin and Bhattarai, 1977; and Wadia, 1975.

Structure:

Rock units in the Himalayas generally dip northward, but younger rocks of the Siwaliks lie at the bottom of the structural pile as expected in an upturned, thrust-repeated structural style with right-side-up stratigraphic position (Figure 3). Middle to late Tertiary Siwalik strata are overlain by the early Tertiary Mahabharat formations (lower Himalayas) which are overthrust by older and more highly metamorphosed phyllites, quartzites, and carbonate rocks. The high Himalaya core consists of high grade schists, gneisses, and granites, flanked to the north by the younger Tibetan sedimentary rocks.

Faulting has played a dominant role in Himalayan geology. Two major thrust faults, the more southerly and presently more active Main Boundary Thrust (Pliocene-Pleistocene) at the top of the Siwaliks belt, and the Main Central Thrust (late Oligocene-Miocene) at or near the base of the Tibetan/Tethys Himalayas trend nearly parallel to the mountain belt.

These thrusts and other related minor faults generally dip to the north with the regional dip of the formations. However, the Main Boundary Thrust displays a steep dip which flattens out at depth,

whereas the Main Central Thrust has a moderate dip 30° to 40° northwards (Gansser, 1964; Valdiya, 1976 and 1980). The northernmost tectonic element, the Indus-Tsang po suture zone is almost vertical and is seismically inactive. All these northwest-southeast and east-west trending thrust faults with their successive branches represent a broad schuppen zone (en echelon) in the Himalayas. Molnar and Tapponnier (1975) estimated some 300 to 700 kilometres of shortening and underthrusting of India beneath the Himalayas and Tibet along these thrust faults. These bedding plane faults tend to occur within a particular stratigraphic horizon for tens, even hundreds of kilometres. The Main Central Thrust was active during the climax of the deformation, metamorphism, and granitization (Bordet et al., 1981), whereas the Main Boundary Thrust corresponds in timing to late Alpine large scale folding. Several cross-cutting structural features that trend more or less perpendicular (or at a high angle) to the regional Himalayan trend are followed by the major river gorges in Nepal and Sikkim. Some reflect or match the reactivated old northeast-southwest directed structural features of the Indian Shield.

Alternation of wide synclines with steep narrow anticlines are commonly observed in the Siwaliks, with their axial planes dipping to the north (see maps- 1 and 2, in pocket). Several north-south directed rivers such as Arun in the Nepal Himalayas, and Tista and

Manas in the Sikkim/Bhutan Himalayas follow the anticlines.

Lineations developed in the foliation planes of some of the phyllites and quartzites in the lower Himalayas plunge north-northeast at moderate angles. They indicate the direction of gliding along these planes, and presumably record the direction of the thrusting.

Linear features (lineaments) in the Indo-Gangetic plain have important significance in the structure of the Himalayas. They are interpreted as the possible upward continuation of the structural planes of weakness in the bedrock below (Geol.Rept., 1982). Their principal directions are:

- (i) more or less normal to the mountain front. These north-south to northeast-southwest directed structures are commonly occupied by rivers that flow along steep fractures or faults.
- (ii) parallel to the mountain front. These east-west trending structures are considered as indicative of buried Siwaliks ridges and some are probably hidden thrust faults in the foreland basin.
- (iii) at an angle (45° or approximately so) to (i) and (ii). These may be conjugate shears, also related to the thrusting in the Himalayas.

Regional metamorphism is widespread throughout the Himalayas. Grade and type of metamorphism are generally constant along strike. Secondary mica in shales and mudstones in the south is the first indication of regional metamorphism. Associated changes include silica cementing along concordant zones in quartz sandstones thereby hardening the rocks, and the presence of crystalline and secondary calcite stringers in carbonates interbedded with dark shales. Higher grades of metamorphism are best observed in slate where mica is ubiquitous, and in gneisses and schists where garnet, amphibole, and kyanite become abundant (Ghose and Singh, 1977). In the higher Himalayas, granitization is common and pegmatites and aplites cut the gneissic structure of the rocks.

Constant increase in regional metamorphism in the lower Himalayas from the bottom upwards is common so that the low grade metamorphic rocks are found in the deepest outcrops. Whether the reversed metamorphism affect the normal rock sequences or the sections are equally reversed is not clear. Large scale recumbent folding could explain overturned formations in many places within the Himalayas. Also, some sections that are structurally normal in eastern Kumaon Himalayas show an increase in metamorphism upwards (Gansser, 1964). Strata north of the Main Boundary Thrust should be in normal sequence, with the older strata thrust upon

them along north dipping thrust faults. Regional metamorphism decreases upwards within the crystalline rocks of the higher Himalayas; and the top part of the Main Thrust sheets (Main Crystalline Thrust sheet) is covered by fossiliferous sediments (beginning with the Cambrian). These sedimentary cover rocks within the higher Himalayas are either unmetamorphosed or were only affected by the low grade metamorphism.

Knowledge about metamorphism throughout the Himalayan range is very limited. Generally the metamorphism is restricted to previously metamorphosed rocks. Thrusting has transported already metamorphosed Precambrian rocks, which, later have undergone subsequent metamorphism. These sheets of metamorphosed rocks then lie above the thrust contacts in the lower Himalayas, whereas the underlying younger rocks remain unaffected by the metamorphism. Most of the thrust faults have been overprinted by the metamorphism that took place during and/or after faulting. Thus putting a major thrust zone like the Main Central Thrust at the base of the rocks with higher grade of metamorphism than that below (Sinha-Roy, 1982 a) is geologically reasonable. A systematic radiometric age determination study would help to establish the validity of major proposed thrust faults along poorly established portions of their strike length. At present, the suggested thrust faults explain the anomalies in metamorphic grades. Banerji et al., (1980), Honegger

et al., (1982), Virdi (1981 a), and Windley (1983) have investigated the problem. Windley (1983) mentioned two stages of metamorphism (separated by an inactive period of 20 to 30 million years), of crustal growth and of crustal deformation (shortening) for the formation of the Himalayan belt.

Age determinations:

Fossils useful for dating are known only in a few formations in the Himalayan region. They include microbiota (late Precambrian) from Kashmir (Punjab Himalayas; Kumar et al., 1984), stromatolites (lower Riphean) from the Kumaon lower Himalayas (Bhattacharya, 1983), and a Neogene vertebrate fauna from the Siwalik group in the Dang valley of the Nepal Himalayas (West et al., 1978).

Some of the relevant age determinations that have been made in different parts of the Himalayan region are shown in Table 1 (also see maps- 1 and 2, in pocket). Resetting of the isotopic "clock" during high temperature metamorphism has affected most of the potassium-argon age determinations, which reflect the cooling age rather than the age of the original deposition or crystallization (Geol.Rept., 1982).

Table 1: Some representative radiometric age determinations from the Himalayas.

Region	Rock type	Age (in million years)	Method	Source
Punjab Himalayas	Migmatitic gneiss	500 $\pm$ 8	Rb-Sr; whole rock	Mehta, 1977
	Mandi granite	545 $\pm$ 12	"	"
Kumaon Himalayas	Munsiari gneiss	1983 $\pm$ 80	Rb-Sr; whole rock	Bhanot et al., 1981
	Biotite-chlorite schist, Simla area	23	K-Ar; whole rock	Crawford, 1981
Nepal Himalayas	Biotite schist	1195 $\pm$ 33	K-Ar; biotite	Khan and Tater, 1970
	Slate	540 $\pm$ 17	K-Ar; whole rock	" "
	Manaslu granite	29 $\pm$ 1	Rb-Sr; whole rock	Hamet and Allegre, 1978
	Lhotse granite	52	"	Pisa et al., 1983
Sikkim/Bhutan Himalayas	Schists (low grade, Daling)	180-190	Rb-Sr; whole rock	Crawford, 1981
	Augen gneiss (Paro Formation)	178-213	K-Ar; whole rock	"
Arunachal Himalayas	(data not available at present)			

Until recently geological studies of the Himalayan belt have tended to treat the region as a discrete structural province, but it is now acceptable to consider it in the context of a classic Alpine orogenic belt. Work of Huang Chi-ching (1977) in Tibet introduced concepts of Alpine tectonics in central Asia. Molnar and Tapponnier (1975) and Gansser (1977) drew similar conclusions from the study of earthquakes and from satellite imagery, respectively. Stocklin (1980) suggested a division into three major Domains for Alpine orogenic (mountain) belts after a structural comparison between Iran and central Asia. The Southern and Central Domains are characterized by the presence of a Precambrian basement consolidation whereas the Northern Alpine Domain is characterized by Hercynian-early Kimmerian folding, magmatism, and late Alpine reactivation. The Central Domain (central Iran, central Afghanistan, southern and eastern Hindu Kush, central and eastern Pamir, Karakorum) is considered to be a mosaic of fragments rifted from the Gondwana supercontinent in late Paleozoic time. The Northern Alpine Domain formed an integral part of Palaeo-Asia (itself a mosaic of Precambrian continental platform fragments welded together by other Palaeozoic orogenic belts). The welding comprised complex processes of rifting, ocean floor spreading, marine transgression, ocean narrowing, suturing, folding, metamorphism, and granitization during

the Baikalian, Caledonian, and Hercynian orogenic cycles. The present locations of central Asia and Mongolia are the result of these orogenic processes. Hercynian activity played the major role during the dominant folding event to the north in Tien Shan, and Kun Lun mountain ranges.

A notable feature of the Proterozoic and early Palaeozoic sediments south of the Gangetic plain is their general thickening toward the north. Late Palaeozoic marine beds are absent from the Indian Shield, but are found in drill holes beneath the lower Himalayas. Palaeozoic and older rock deposits do not appear to exist in the Indus-Tsang po eugeosynclinal zone. This zone may have evolved only in Triassic and perhaps have resulted from continental rifting.

There was a constant migration of orogenic activity from north to south. The general cause given for this is the successive northward drifting of the Gondwana fragments (Sengor, 1983) and their collision with, and accretion to, Eurasia.

Maximum crustal thickening is reached near the Indus-Tsang po suture but not below the Himalayas. This is supported by gravity data of Kono (1974) and Huang Chi-ching (1977). Gansser (1977) suggested that crustal thickening resulted from thrusting and folding associated with northward movement of the Indian plate. This movement is accommodated by strike-slip faulting in Tibet but not strictly by the thrusting in the Himalayas (Molnar and Tapponnier, 1975).

TECTONIC HISTORY:

The existence of the Tibetan Plateau (highest in the world), Indian Shield and broad Indo-Gangetic plain are important elements in the evolution of the "Himalayan orogeny" (Holmes, 1965; Sinha-Roy, 1981). Over the years, various theories have been offered to explain the formation of the Himalayas, but no one theory had gained acceptance until the "plate tectonic" theory was refined in the late 1960's (Dennis and Atwater, 1974). Since then this theory has revolutionized concepts in Himalayan geology. However, Saxena (1978) explained the Himalayan orogeny using the model of gravity tectonics (gravity glides) in contrast to geosynclinal and plate tectonic theories. According to him, the bulk geological observations, structural settings, and palaeontological contrasts in the Himalayan and Tethyan zone, changing geosynclinal conditions during the Himalayan tectonic cycle, synchronous orogenic and epeirogenic episodes in the Himalayan region and the Indian Shield do not support the above two principles.

Tethys geosyncline and continental drift theory:

Proposals about the evolution of the Himalayas date to Suess (1885) who considered that the present configuration of the continents was attained during the Jurassic period. Before that time the continents were clustered together in the northern hemisphere (called Angaraland) and in the southern hemisphere

(Gondwanaland) separated by the Tethys sea. This sea was believed to have been in existence since Cambrian time. Argand (1924) suggested that the drifting of Asia south towards the Indian sub-continent resulted in the sediments of the Tethysian geosyncline being uplifted to form the Himalayan mountain ranges.

The general concept (model) for the evolution of the Himalayas is as follows:

With the closing of the Tethys, thrusting either from the north or south, or both, had to occur. The most important event at the closing of the Tethys was the creation of the Indo-Gangetic trough or foredeep in which the sediments of the sub-Himalayas (Siwaliks) were deposited. Sedimentation was completed before the early Pleistocene and was followed by folding and thrusting which closed the foredeep. The Tethys sea that appeared in the Cambrian, was thus terminated in the Tertiary, and its sediments formed the sub-Himalayas during the mid Pleistocene (Sharma, 1977). Although the geosynclinal theory partly clarified Himalayan stratigraphy, it could not explain:

- (i) the ophiolite zone (along the Indus-Tsang po suture);
- (ii) consistent northerly dips of the rock units;
- (iii) the general increase in metamorphic grade from the south to the north; and
- (iv) the syntaxial bend structures in the two (east and west) extremities of the Himalayas. These features

are accounted for by the plate tectonic model, involving the collision of two continental masses (India and Asia).

The plate tectonic model:

In the late Palaeozoic, a super-continent (Pangea) broke into continental size plates. Since then these plates have drifted to their present locations at a rate of about 10 to 18 centimetres per year (at least 100 kilometres per million years), (Figure 4) (Barazangi and Ni, 1982; Molnar and Tapponnier, 1975; Powell and Conaghan, 1975; Sborshikov et al., 1981; Tapponnier and Molnar, 1976). During the past 80 million years, the Indian plate has drifted northeast across what is now the Indian ocean. By the end of the Mesozoic, India closed the Tethys sea gap, and began to subduct beneath the Asian continent. Plate movement then slowed down from 10 cms./yr. (in Late Cretaceous) to about 6 cms./yr., a rate which is still maintained. The collision zone (suture) is well defined by the long, broad valley of the Indus and Tsang po rivers in southern Tibet (Valdiya, 1984 a and 1984 b). The initial collision was accompanied by deformation of the formations along the leading edges. Some formations were uplifted and some were buried to great depths in a belt of greater geologic complexity. Ultrabasic rocks, presumed to be of mantle origin, are mixed with marine sediments along the suture zone. The terms "ophiolite" and "melange" have been applied to these rocks. Broad folding of the strata took place to the north and south. It was at this time that

Figure 4. Interaction of plates and microplates at the latest stage (after Sborshikov et al., 1981).

1. Present plate boundaries
2. Boundaries position at 10 million years before present
3. Areas of "non-rigid" interaction
4. Vectors of plate motion (arrows length indicate the velocities).

the Tibetan region began to rise. Crustal shortening was absorbed along the Indus-Tsang suture zone while plate movement continued. This led to thrust faulting: the Main Central Thrust and the Main Boundary Thrust were successively directed south in the advancing Indian crust, both dipping northward towards the suture zone (Figure 5). In contrast to subduction zones in the Pacific, these thrusts do not extend to the base of the continental crust, but flatten out at a depth of approximately 20-40 kilometres (Figure 5). Present movement on the suture zone is unknown but subduction of the Indian plate beneath the Asian plate continues. The Main Central Thrust was the first major thrust to form beneath Tibetan/Tethys sediments. Slices of these sediments were forced south, overriding the Indian Shield. Structures with imbrication and accompanying drag folds were produced. Net displacement was in the order of tens, and perhaps even hundreds, of kilometres. In time, when the Main Central Thrust had accommodated the maximum crustal shortening, the crustal deformation shifted further south. Then the Main Boundary Thrust took form and it continues to be a seismically active zone to-day (Seeber and Gornitz, 1983; and Seeber et al., 1981). At about the time this thrust was formed (early Miocene), the pre-Siwalik molasse became involved in subduction along the Main Boundary Thrust and started tilting towards the north. The rising mountains of the hanging wall (north

Figure 5. Diagram (to scale) showing the continental subduction structure in the Himalayas where thrusts like MBT, MCT flatten out at depth of approximately 20-40 kilometres (after Seeber et al., 1981).

Q Quaternary
 US Upper Siwalik
 LS Lower Siwalik
 MBT Main Boundary Thrust
 MCT Main Central Thrust
 ITSZ Indus-Tsangpo Suture Zone
 BTF Basement Thrust Front

side of the thrust) and depression of the foreland trough by the accumulated sediment load increased the rate of erosion of the former and deposition of the Siwaliks in the latter. This activity marks the true beginning of Siwalik (sub-Himalayas) sedimentation.

Crustal thickening accompanied the Himalayan orogeny. The thickness ranges from a normal 30-40 kilometres in the Indian Shield to perhaps double that amount (80 kilometres) beneath the Himalayas (Powell and Conaghan, 1975) and 60 kilometres under the Tibetan plateau (Fuchs, 1982). Formations forced to greater depths under high pressures and temperatures generated granites in place (anatectic melting). True igneous intrusions are comparatively rare, restricted to some derived aplites and pegmatites.

The sense of movements on thrust and transform faults have been determined from earthquake first motion studies (Chandra, 1978 and 1981; Das and Filson, 1975; Fitch, 1970), fault plane solutions (Baranowski et al., 1984; Molnar and Tapponnier, 1980; Ni, 1978; Tapponnier et al., 1981), and by examination of landsat imagery (Molnar and Tapponnier, 1975; Rastogi, 1974; Rastogi et al., 1973; Tapponnier and Molnar, 1976).

Rothery and Drury (1984) in their rhombohedral block tectonics concept mentioned 4 percent north-south contraction and 11 percent east-west extension in Tibet from the time India collided with Asia until the time of formation of strike-slip faults and grabens

(between stages in Figures 6a and 6c).

The "Indenter model" of Molnar and Tapponnier (1975) explains the deformation into the north of the Himalayas and formation of strike-slip faults and grabens in the light of the plate tectonic concepts. They postulate convergence of the two blocks with one block held fixed (Asia) and the other impinging block (India) triangular in outline (Figure 7). Triangular blocks move laterally away along the conjugate faults from the impinging Indian block with velocities proportional to the convergence rate (5 centimetres per year), in addition to such factors as the orientations of the boundaries between the blocks. They believe some crustal extension within the Asian block occurred due to the transformation of convergence by the strike-slip faults, resulting in the formation of the Baikal rift, Shansi graben system, and, in central Nepal, the Thakkhola graben (see Figure 9). During convergence in the Himalayas, its eastern end converged with the Arakan Yoma-Burma arc, creating the eastern syntaxial bend (Tapponnier and Molnar, 1976). In the same way, the western syntaxial bend came into existence between the Sulaiman and Himalayan arcs (Burtman, 1982).

While discussing convergence mechanisms in the Himalayan arc, Seeber and Armbruster (1984) mentioned a fundamental element of the Himalayan convergence front called the Basement Thrust Front (Figure 8). A small

Figure 6. Rhombohedral block tectonics sketch showing progressive deformation of part of the Tibetan plateau (after Rothery and Drury, 1984).

- a. Development of incipient fractures in response to the northward collision of India
- b. Internal deformation of the Tibetan plateau by the strike-slip motion along one set of faults (f_1) causes the blocks to pull apart (grabens g_1). Formation of additional grabens within the blocks g'_1 indicate the internal deformation as an extension process
- c. Neighbouring blocks (not shown) stop the motion along the first set of faults. Then the conjugate systems prevail. Strike-slip motion (f_2) occurs on the previously opened grabens g_1 , and on narrow zones through a block (where propagation of extension of a fault is common). Pull-aparts at the boundaries (g_2) and newly formed grabens that cut across the blocks (g'_2) generally connect the offset strike-slip faults.

Figure 7. Schematic diagram showing the "indenter model" (after Molnar and Tapponnier, 1975). Triangular blocks move laterally away along the conjugate faulting at the velocities proportional to the velocity (V) of the impinging block (India) and depending on the orientations of the boundaries between them.

Figure 8. Diagram showing the topography of the Himalayas and southern Tibet; and the Basement Thrust Front (BTF) (from Seeber and Armbruster, 1984).

circle (center at $42^{\circ}30'$ north, 91° east, near Shanshan, China, about 1,600 kilometres north northeast of the Indus-Tsang po Suture Zone; radius 1,695 kilometres) extends for 1,700 kilometres in the central portion of the Himalayan arc (76° east to 92° east). The length of the arc approximately follows the 4,000 metre contour line. This topographic break, together with the Main Central Thrust and the belt of thrust-fault related earthquakes, define the Basement Thrust Front. A radial convergence at this Front was noted by Seeber and Armbruster (1984). This indicates a lateral extension of Tibet at a rate similar to the convergence rate across the Basement Thrust Front. Furthermore, the Basement Thrust Front shows evidence of downdip movement along the basement thrust at a shallow angle ($20^{\circ} \pm 10^{\circ}$).

Right lateral (dextral) strike-slip faulting (for example, the Red River fault, Allen et al, 1984) is predominant to the east of the Himalayan mountain chain while to the west, Quetta-Chaman fault is left lateral (sinistral) (Figure 9). In central China, however, several major left lateral strike-slip faults that trend roughly east-west are noted including the Kun Lun fault, Altyn Tagh fault, and Kang Ting fault (Valdiya, 1984 a and 1984 b). Valdiya discussed the joining up of the sinistral Quetta-Chaman fault with the transform Owen Fracture zone in the Arabian Sea (not shown in Figure 9) in the west, and in the east, of the dextral Shan Boundary fault with the Nintyeast ridge (

Figure 9. Map showing the recent tectonic activity in Asia.

- (—) Major faults
 - (—) Sense of motion
 - () Region of crustal thickening
 - () Regions of crustal thinning
- (after Tapponnier and Molnar, 1976).

latter not shown in Figure 9) in the Bay of Bengal and further south (Indian Ocean). Between these sinistral and dextral faults, the Indian plate is believed to have moved and to be moving northwards.

The similarity in tectonic setting between the Himalayas and the eastern part of the Sveconorwegian fold belt in southeastern Norway and southwestern Sweden was discussed by Berthelsen (1978). He mentioned that about 1,000 million years ago, convergence along three major north-south trending low angle thrust faults took place, and was followed by emplacement of post-orogenic igneous intrusions. Other comparisons have been made, including:- between the Himalayan and Alpine mountain chains on the basis of plate tectonics (Chingchang, 1978); -between the Himalayas and New Guinea (Seeber and Gornitz, 1983) based on the continent-arc collision hypothesis; and -between the Himalayas and the Grenville Province, Canada (Barazangi and Ni, 1982; Dewey and Burke, 1973; Molnar and Burke, 1977) following the continental collision model (Figure 10).

The author's proposed model for the evolution of the Himalayas and southern Tibet is based on a summary of work by Dewey and Bird (1970), Fuchs (1982), and Powell and Conaghan (1973 and 1975) (Figure 11). Large scale collision and convergence between the Indian plate and the Asian plate, and the evolution of the Himalayas following this convergence are the two basic elements

MBT Main Boundary Thrust
 MCT Main Central Thrust
 ITSZ Indus-Tsangpo Suture Zone

Figure 10. Schematic diagram illustrating the geometric styles of converging plates in the Himalayan-Tibetan plateau region:
 a. India underthrusting Tibetan plateau
 b. Grenville province may be exhumed equivalent of Himalayan-Tibetan model (after Barazangi and Ni, 1982).

1. Late Triassic and Early Jurassic

2. Late Cretaceous and Early Tertiary

3. Early-Late Eocene (Subduction along India-Tsangpo and Shyok sutures)

4. Late Eocene - Late Oligocene (Final collision between India and Asia)

S

N

5. Early Miocene - Pliocene

S

N

Explanation:

cc	continental crust (India)
oc	oceanic crust (Asia)
N	North
S	South
MFT	Main Frontal Thrust
MBT	Main Boundary Thrust
MCT	Main Central Thrust
→	Direction of movement of plate
ITSZ	Indus-Tsang po Suture Zone
SSZ	Shyok Suture Zone
NTL	North Transhimalayan Lineament
Mesozoic	(shelf sediment)
Palaeozoic	(shelf sediment)

Figure 11. Schematic diagrams showing the evolution of the Himalayas and southern Tibet. For more information: see text and maps-1 and 2 in pocket.

46
considered in this model. It differs from the previously
proposed models in that it attempts to explain the
evolution of the entire Himalayas and southern Tibet in
a series of general cartoons rather than by one that is
applicable to a particular region in the Himalayas.

MINERALIZATION:

Until recently, no mineral deposits of economic significance had been found in the Himalayas. With the discovery of several metallic and non-metallic mineral deposits and fossil fuel occurrences in different parts of the Himalayas, it appears possible that major mineral deposits will be found along the entire Himalayan region. Two hundred and eighteen mineral localities throughout the Himalayas are shown on maps- 1 and 2 in the pocket and are listed in Appendix B. Most of them represent occurrences which await complete geological investigation and economic assessment. Small amounts of copper and coal have been mined in the Himalayan region from earliest times to meet local needs. Generally, the metallic mineral occurrences reported here are from the sub-Himalayas (Siwaliks), lower Himalayas, and higher Himalayas. Fossil fuels may occur in the northern part of the Indo-Gangetic plain.

In the Siwaliks belt there are significant deposits of all grades of coal and some potential for uranium-vanadium-copper mineralization (Mitchell, 1979). Stratiform copper with minor strata-bound lead-zinc and phosphorites occur in the lower Himalayas. Zinc-lead occurrences, as well as minor showings of copper and silver are found in carbonates in the higher Himalayas. Also in the higher Himalayas, tin, tungsten, and copper occur in veins and skarns. Phosphorite

deposits occur in the Kumaon Himalayas, but recently interest in these formations has extended into the western and eastern Nepal Himalayas. Magnesite and talc in these areas are irregularly produced in small amounts. Gems such as world-famous sapphires (Sumcham), rubies and emeralds are found in Kashmir (Punjab Himalayas), while aquamarine and tourmaline (both zoned and transparent), and amber and jade come from the Nepal Himalayas (Hyakule) and Burma, respectively.

Several gas seeps and oil occurrences are present in Kashmir. Some unusual gas seeps in the contorted phyllite of Far-western Nepal are thought to rise from Eocene strata which lie below the Ranimatta and north of the Main Boundary Thrusts (Nepal Himalayas) but are not considered indicative of a large reservoir. Taking into consideration the structural complexity, a reservoir of economic size is unlikely to be present in this environment. Lower to middle Tertiary rocks, however, occur in the Brahmaputra valley (east to southeast of the Sikkim/Bhutan Himalayas), and if they continue beneath the Indo-Gangetic plain and below the Siwaliks, they constitute a favourable site for possible oil and gas occurrences.

A second place with petroleum potential lies beneath the northern part of the Indo-Gangetic plain. There the base of the Ganga plain is considered to be a major unconformity which is partly subducted beneath

the Himalayan belt along the Main Boundary Thrust. Because the Ganga basement surface becomes a thrust fault as it plunges below the mountains, it may represent a permeable channelway (carrier) for oil and gas.

Ophiolites along the Indus valley (in Punjab and Kumaon Himalayas), Manipur and Nagaland (Burmese arc) contain chromite, titanomagnetite and nickel and asbestos occurrences (Nair and Mithal, 1976).

Tewari and Gaur (1977) stated that the pyrite-polymetallic occurrences in the Himalayas are "the product of the multiphase metallogeny with no lithological or structural control of mineralization". In general, most are epigenetic hydrothermal occurrences associated with basic and acid intrusive rocks. They noted, however, that copper mineralization seemed to be associated with medium-grade metamorphism, and lead and zinc with carbonate rocks.

Nair and Mithal (1977) mentioned six linear metallogenic zones in the Himalayas. From north to south, they are:

- Transhimalayan zone: copper (porphyry), tin, tungsten, bismuth, and molybdenum.
- Ophiolite zone: chromium, also nickel, copper, minor platinum and iron
- Tethys Himalayan zone: lead, zinc, copper, minor antimony, mercury, barium, and iron
- Central Himalayan zone: tungsten, bismuth, molybdenum, antimony

- the lesser Himalayan zone: lead, zinc, copper, uranium, magnesium, barium, antimony, and possibly mercury and tungsten mineralization, and
- the southernmost sub-Himalayan zone: copper and uranium.

These zones are based on general rock types and largely speculative, but they provide a general guide for regional metallic mineral exploration.

Sillitoe (1979 a) describes three types of mineralization based upon studies in Pakistan. These are: mineralization related to the anatectic granites, metamorphic mineralization, and pre-Mesozoic mineralization. This classification of mineralization applied to most of the Himalayas could help to find minerals in the respective environments. Other workers have attempted to compare the magmatism and metallogeny of the Himalayas with those of the Alps (Nair and Mithal, 1976); with those of the Caucasus (Nair and Mithal, 1977; Tewari and Gaur, 1977); and with those of Taiwan (Mitchell, 1979). In each case, it was noted that mineralization occurred in similar geological environments and was affected by similar tectonic styles.

Looking at the geological similarities in these areas, it is suggested that there is good mineral potential in the Himalayas, which needs more investigation.

CONCLUSIONS:

The Himalayas formed as the Indian sub-continent collided with Asia, beginning about 50 million years ago (Besse et al., 1984; Patriat and Achache, 1984). The mountain belt is subdivided into five longitudinal geological subdivisions on the basis of depositional environments.

Universally north-dipping rock units, with youngest at the bottom, mark the thrust-repeated structural style in the Himalayas. The major thrust systems parallel the main Himalayan trend and represent a broad schuppen zone. North- to northeast-plunging lineations indicate movement along these planes and thereby the direction of the thrusting. Also, linear features in the northern part of the Indo-Gangetic plain are interpreted as the possible surface expression of structural planes of weakness in the bedrock below.

The tectonostratigraphic synthesis presented here for the Himalayas and southern Tibet combines all the major regional stratigraphic information published by previous workers.

Features such as ophiolites (along the Indus-Tsang po suture), consistent north dips of the rock units, increase in metamorphic grade from south to north, and formation of syntaxial bends in the two extremities of the Himalayan mountain belt are all consistent with plate tectonic theory involving collision of India with

Asia. Secondary effects include the formation of the Baikal rift as well as the Shansi and Thakkhola grabens. The northward movement of the Indian plate (ten centimetres per year in late Cretaceous; six centimetres per year in recent times) has been accommodated mainly by dextral (in the east) and sinistral (in the west and north of the Himalayas) strike-slip faults and in lesser amount by thrusting within the mountains themselves. Also, the migration of orogenic activity from north to south has resulted from thrust movements being transferred into successively lower and more southerly fault planes.

Discovery of several mineral occurrences and deposits, coal and gas (in Siwaliks), and oil and gas (in Kashmir) in different parts of the Himalayas suggest the possibility of major potential (in the region).

Because the Himalayas have similar structural style to the Alps, Caucasus and Taiwan, mineralization of the types found in these other belts may be present in equivalent settings in this mountain belt. The present geological data base suggests that significant mineral potential exists in the Himalayas and more research work including geological as well as mineralogical investigation, is needed.

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(* Referred to in the text and/or on maps- 1 and 2, in pocket; annotations in parenthesis).

These abbreviations have been used:

AAPG--American Association of Petroleum Geologists
CNRS--Centre National de la Recherche Scientifique
GSA or Geol. Soc. Amer.--Geological Society of America
HMG Nepal--His Majesty's Government of Nepal
LRMP--Land Resources Mapping Project
UNDP--United Nations Development Programme

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Appendix A. Lithostratigraphic legend of the Himalayas⁸⁵
and southern Tibet as used in maps- 1 and 2
LEGEND (in pocket).

SEDIMENTARY AND METAMORPHIC ROCKS

CENOZOIC	QUATERNARY		
	Pleistocene and Recent		
	P/R		Mainly unconsolidated sediments of Indo-Gangetic plain:- Includes alluvium deposits, alluvial fans, river terraces, talus, colluvium, minor aeolian and glacial deposits.
	TERTIARY		
	Oligocene-Pleistocene		
	O-Ps		Siwalik Formation(undivided):- Molasse sediments and sedimentary rocks.
	Pliocene-Pleistocene		
	P-Pus		Upper Siwalik Formation:- Coarse clastics. Includes boulder conglomerate, sandstone, mudstone, marl.
	Oligocene-Miocene		
	O-Mis		Lower Siwalik Formation:- Fine clastics. Includes sandstone, siltstone, shale; Murrees Formation of Salt Range region.
PRECAMBRIAN-MESOZOIC	Eocene		
	E		Mainly limestone, shale, nummulitic in places and their equivalents:- Subathu Formation (India), Jarbutta Formation (Nepal), Dzongbuk shale (Tibet).
	PERMIAN-CRETACEOUS		
	P-K	K J-K	Indus flysch sediments and their equivalents:- Tal/Krol Formation of northwest India; Giumal sandstone, Everest limestone, Chikkim limestone, Giri limestone, Kampa shale, Tillite-type conglomerate, Talchir boulder beds, Penjal traps; Abor volcanics (Bhutan); Sallyan series (Nepal).
	PROTEROZOIC-JURASSIC		
	P-JT		Tibetan Formation(undivided):- Tethys sediments. Includes sedimentary and metamorphic strata in High Himal region.
	O-S, T-JuT		Upper Tibetan Formation:- Sedimentary rocks, unmetamorphosed or of very low grade; fossiliferous (Ordovician-Silurian, Triassic-Jurassic).
	P-OIT		Lower Tibetan Formation:- Includes gneisses of many varieties, some marble.
	PRECAMBRIAN-CAMBRIAN		
	PC-CMM		Midland Metasedimentary group of Nepal and equivalents (e.g.:- Salkhalas 'Schists'):- Includes phyllites, quartzites (Muth quartzite), schists (quartz-mica, quartz-garnet); some carbonates (Baxa Formation, Tejam limestone, Jutogh limestone).
PRECAMBRIAN	PRECAMBRIAN		
	PC HG		Himalayan Gneiss Group:- Includes gneisses (mica-, garnet-, kyanite-, sillimanite-, tourmaline-) e.g.:- Darjeeling gneiss (India); Barun gneiss; migmatitic gneiss; marble lenses, augen structure, small granitoid bodies in places.

IGNEOUS ROCKS

VARIOUS AGES

gr.gd

Granites and related equivalent rocks:- Ladakh granite, Kailas granite; tourmaline granites (Neogene), granodiorites.

op

Ophiolites:- Basic intrusions (diorite, gabbro); ultrabasics, ultramafic rocks, peridotites.

22
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Appendix B. Location of mineral deposits and fossil fuel occurrences in different parts of the Himalayas as plotted in maps- 1 and 2 (in pocket).

Mineral occurrence number	Mineral type	Latitude (North)	Longitude (East)	Source
1.	Fe, Al	33°11'	74°39'	Met.Min.Map of India, 1963
2.	Fe	31°59'	76°50'	"
3.	Fe	34°09'	76°09'	"
4.	Pb, Zn	32°02'	77°20'	"
5.	Pb, Zn	32°03'	78°17'	"
6.	Pb, Zn	33°26'	74°21'	"
7.	Pb, Zn	34°05'	74°10'	Raina, 1977
8.	Pb, Zn	34°30'	73°44'	Ahmad, 1969
9.	Cu	33°00'	75°06'	Met.Min.Map of India, 1963
10.	Cu	33°03'	75°33'	"
11.	Cu	33°25'	75°16'	"
12.	Cu	33°38'	75°25'	"
13.	Cu, Pb, Zn	35°19'	75°48'	"
14.	Cu	33°10'	77°42'	"
15.	Cu	34°15'	75°12'	"
16.	Cu	34°17'	74°48'	"
17.	Cu	34°32'	74°17'	"
18.	Cr	32°47'	79°04'	"
19.	Cr	34°31'	75°51'	"
20.	Cr	34°30'	75°39'	"
21.	Sb, Pb, Zn	32°15'	77°35'	Srikantia, 1977
22.	Cr	34°34'	71°31'	Ahmad, 1969
23.	Mn	33°40'	71°23'	Ali, 1971
24.	P	34°16'	73°22'	Bhatti, 1981
25.	cy	33°49'	72°28'	Jehan et al., 1975
26.	Mn	33°23'	70°31'	Meissner et al., 1975
27.	rs, gyp	33°10'	70°57'	"
28.	Pd, Pt, Rh	34°32'	71°52'	Page et al., 1980
29.	tk	34°03'	71°03'	Abbas et al., 1967
30.	ba	33°58'	73°38'	Ahmad, 1969
31.	Pb, Zn, U	34°14'	73°06'	Sillitoe, 1979 a
32.	Cu	35°54'	73°57'	"
33.	Pb, Zn	35°38'	72°42'	Ahmad, 1969
34.	W	34°28'	73°04'	Sillitoe, 1979 a
35.	Cu	34°55'	71°31'	"
36.	emd	35°01'	72°29'	"

Mineral occurrence number	Mineral type	Latitude (North)	Longitude (East)	Source
37.	aqm	35°29'	75°15'	Sillitoe, 1979 a
38.	Au	35°40'	74°39'	Ahmad et al., 1976
39.	Au	35°24'	74°07'	Ahmad et al., 1976
40.	Au	33°56'	72°22'	
41.	ng	34°04'	74°44'	Butt, 1968
42.	ng	34°22'	74°19'	,,
43.	of	32°51'	75°08'	,,
44.	of	33°43'	74°05'	,,
45.	of	33°06'	74°52'	,,
46.	Sb	33°34'	70°31'	Ahmad, 1969
47.	Sb	32°44'	73°04'	,,
48.	Sr	32°40'	71°40'	,,
49.	Cu	35°08'	74°03'	,,
50.	Cu	35°10'	72°53'	,,
51.	Cu	35°10'	72°15'	,,
52.	Cu	32°51'	72°34'	,,
53.	Au	35°34'	72°02'	,,
54.	Au	33°19'	71°35'	,,
55.	Fe	33°00'	71°10'	,,
56.	Al	33°50'	72°56'	,,
57.	Al	34°54'	73°52'	,,
58.	Al	33°18'	72°20'	,,
59.	Pb, Zn, Cu	35°45'	72°39'	Sillitoe, 1979 a
60.	Mn	34°18'	73°30'	Ahmad, 1969
61.	asb	34°09'	71°09'	,,
62.	ba	33°51'	73°10'	Sillitoe, 1979 a
63.	ba	34°09'	73°16'	,,
64.	by	34°39'	73°09'	Ahmad, 1969
65.	by	35°36'	73°20'	,,
66.	cy	32°22'	74°45'	,,
67.	cy	34°46'	73°09'	,,
68.	cy	35°26'	72°09'	,,
69.	fl	34°26'	72°10'	,,
70.	fl	34°10'	73°08'	,,
71.	gf	35°01'	74°21'	,,
72.	gf	34°20'	73°04'	,,
73.	gyp	32°15'	71°00'	,,
74.	mgs	34°34'	71°55'	,,
75.	mb1	34°01'	71°10'	,,
76.	mb1	34°48'	72°27'	,,
77.	mi	34°55'	74°16'	,,
78.	mi	34°44'	73°08'	,,
79.	P	32°27'	72°29'	,,
80.	P	32°41'	72°30'	,,
81.	P	32°47'	71°46'	,,
82.	P	33°36'	70°55'	,,

Minerral occurrence number	Mineral type	Latitude (North)	Longitude (East)	Source	89
83.	U	34°21'	73°19'	Sillitoe, 1978	
84.	rs	33°30'	70°55'	Ahmad, 1969	
85.	rs	32°37'	71°58'	"	
86.	rs	32°51'	72°24'	Min. Resour. of the Punjab, 1972	
87.	tk	33°55'	70°11'	Ahmad, 1969	
88.	tk	34°10'	73°02'	"	
89.	tk	34°24'	73°36'	"	
90.	S	33°37'	72°00'	"	
91.	S	33°22'	71°14'	"	
92.	S	33°39'	72°49'	"	
93.	co	32°56'	71°26'	"	
94.	co	33°38'	73°17'	Qaiser et al., 1970	
95.	co	33°21'	72°16'	Ahmad, 1969	
96.	co	34°21'	73°35'	"	
97.	co	33°22'	71°43'	"	
98.	co	33°18'	73°48'	"	
99.	of	33°02'	72°28'	"	
100.	of	33°16'	72°15'	"	
101.	of	33°22'	72°36'	"	
102.	sph	32°35'	76°35'	Jangpangi et al., 1978	
103.	Fe	30°47'	77°21'	Met. Min. Map of India, 1963	
104.	Pb, Zn	30°59'	77°04'	"	
105.	Fe	31°30'	77°10'	"	
106.	Pb, Zn, Cu	31°51'	77°15'	"	
107.	Pb, Zn	31°11'	77°11'	"	
108.	Pb, Zn	30°50'	77°19'	"	
109.	Pb, Zn	30°37'	77°25'	"	
110.	Pb, Zn	30°46'	77°51'	"	
111.	Pb, Zn	31°06'	77°51'	"	
112.	Pb, Zn	31°04'	77°39'	"	
113.	Pb, Zn	30°54'	78°22'	"	
114.	Pb, Zn	31°28'	77°51'	"	
115.	Cr	31°30'	78°03'	"	
116.	Fe	29°21'	79°19'	"	
117.	Fe	29°20'	79°28'	"	
118.	Fe	29°29'	79°33'	"	
119.	Fe	29°27'	79°40'	"	
120.	Fe	29°32'	79°56'	"	
121.	Pb, Zn	30°13'	79°08'	"	
122.	Fe	30°28'	79°15'	"	
123.	Pb, Zn, Cu	29°52'	79°56'	Pande, 1977	
124.	Pb, Zn	29°49'	79°45'	"	
125.	Pb, Zn	29°48'	80°18'	"	

Mineral occurrence number	Mineral type	Latitude (North)	Longitude (East)	Source
126.	mgs	30°30'	79°28'	Gaur et al., 1977
127.	Pb,Cu, mgs	29°50'	79°39'	Banerjee, 1977
128.	mgs,As, Pb,Zn, Cu	29°40'	80°21'	Chattopadhyay, 1977
129.	P	29°38'	80°15'	Negi, 1978
130.	Cu	31°45'	77°15'	Sharma,V.P., 1977
131.	ba,Cu, Sb	30°23'	80°17'	Sinha, 1977 a
132.	ba,Cu, Sb	30°07'	80°31'	,,
133.	ba,Cu, Sb	30°46'	79°58'	,,
134.	Cu,W	29°19'	80°40'	Kaphle and Adhikari, 1982
135.	Sn	29°17'	80°45'	,,
136.	Pb,Zn	29°47'	81°24'	Geol.Rept., 1982
137.	Cu	28°38'	82°38'	,,
138.	Cu	28°17'	83°27'	Khan and Tater, 1969
139.	Cu	27°58'	84°22'	,,
140.	Fe	27°55'	84°28'	Shrestha, 1982
141.	Pb,Zn	28°08'	85°11'	Chakrabarti, 1982
142.	Fe,Pb, Zn,mbi	27°34'	85°27'	Khan and Tater, 1969
143.	mgs,tk	27°47'	86°02'	,,
144.	Fe,W	27°37'	86°20'	,,
145.	Cu,Pb, Zn	27°34'	86°39'	,,
146.	Cu	27°42'	86°48'	,,
147.	aqm	27°39'	87°27'	,,
148.	mi	29°33'	81°02'	,,
149.	mi	27°18'	87°09'	,,
150.	mgs	26°52'	86°50'	,,
151.	Cu	27°01'	88°04'	,,
152.	Cu,Pb, Zn,Fe	27°15'	88°34'	Sarkar and Banerjee, 1976
153.	W	27°14'	88°28'	Roy et al., 1976 a;1976 b
154.	Fe	29°38'	80°55'	Talalov, 1977
155.	Mo	29°02'	81°08'	,,
156.	of	28°52'	81°38'	,,

Mineral occurrence number	Mineral type	Latitude (North)	Longitude (East)	Source
157.	ng	28°45'	81°46'	Talalov, 1977
158.	co	27°58'	82°45'	,,
159.	co	27°42'	82°29'	,,
160.	Cu	27°50'	83°39'	,,
161.	ng	28°43'	83°49'	,,
162.	Sn	28°28'	83°50'	,,
163.	Co, Cu, Pb	27°40'	85°00'	,,
164.	co	26°51'	87°18'	,,
165.	co	26°44'	87°50'	,,
166.	Cu	29°48'	80°52'	,,
167.	Cu	28°29'	81°48'	,,
168.	Pb, Zn, Ag	29°40'	81°47'	,,
169.	Fe	29°34'	80°42'	,,
170.	co	26°48'	88°14'	Met.Min.Map of India, 1963
171.	Cu, W	26°57'	89°05'	Raghavan et al., 1976
172.	co	25°20'	90°56'	Met.Min.Map of India, 1963
173.	Fe	25°22'	91°50'	,,
174.	co	25°13'	91°57'	,,
175.	co	25°13'	91°46'	,,
176.	co	26°58'	92°23'	Hazarika and Chaudhuri, 1978
177.	Cu	27°17'	93°48'	Met.Min.Map of India, 1963
178.	Cu	24°54'	94°22'	,,
179.	Cr	25°51'	94°57'	,,
180.	co	27°10'	95°39'	,,
181.	co	26°47'	94°55'	,,
182.	Cu	24°20'	96°13'	Map of the Min.Depo. of the Union of Burma, 1971
183.	Cu	24°39'	97°03'	,,
184.	co	24°03'	96°52'	,,
185.	Pb, Zn, Cu, Ag, Au	24°09'	95°40'	,,
186.	co	24°07'	95°28'	,,
187.	co	26°27'	96°59'	,,
188.	co	25°32'	96°20'	,,
189.	co	25°04'	96°39'	,,
190.	Pt	26°35'	96°57'	,,
191.	Cr	25°38'	96°22'	,,
192.	Cr	25°45'	96°33'	,,
193.	gf	25°51'	96°53'	,,
194.	gf	25°35'	96°47'	,,

Mineral occurrence number	Mineral type	Latitude (North)	Longitude (East)	Source
195.	Fe	25°48'	97°40'	Map of the Min. Depo. of the Union of Burma, 1971
196.	Fe	25°34'	97°14'	,,
197.	gf	25°55'	97°58'	,,
198.	gf	25°39'	97°52'	,,
199.	Pb, Zn, Cu, Ag, Au	27°46'	97°55'	,,
200.	Pb, Zn, Cu, Ag, Au	27°27'	97°50'	,,
201.	amb	26°18'	96°34'	,,
202.	jd	25°27'	96°33'	,,
203.	cy	25°02'	90°13'	Ahmad, 1969
204.	cy	24°57'	91°54'	,,
205.	cy	24°55'	90°43'	,,
206.	cy	24°53'	89°24'	,,
207.	cy	25°15'	89°18'	,,
208.	co	24°27'	91°36'	,,
209.	co	24°29'	91°44'	,,
210.	co	25°09'	91°12'	,,
211.	co	24°53'	91°20'	,,
212.	ng	24°58'	92°05'	,,
213.	ng	25°03'	91°33'	,,
214.	ng	24°08'	91°16'	,,
215.	ng	24°12'	91°23'	,,
216.	ng	24°48'	92°03'	,,
217.	Pb, Zn	26°50'	91°50'	Sillitoe, 1979 a
218.	Sn	28°02'	89°52'	,,

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