a traveller's guide to the geology of

EVEREST

(a traverse from Lukla to Everest)

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Dedication

This work is dedicated to my mother, Gisela, my father, Karl, to a friend, Steve Kearney; and to Oliver Allan. May their lives and times forever be remembered in the highest places on Earth.

Acknowledgements

A number of people have been involved in this dissertation, from both an academic and logistical perspective. Guidance on producing a guide book and primary supervision was provided by Prof. Paul Dirks, with co-supervision from Prof. Guy Charlesworth.

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Special thanks to my wife, Gail, for her consistent and unquestioning support.

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Additional Desk Top Publishing help was provided by Roxy Hoosen and Erika McCarthy, and Kimberly and Jacqueline Hochreiter helped with editing and correcting.

Proceeds from the sale of the Guidebook will go to the families of the 7 Sherpas, with whom I had climbed Ama Dablam, who died in Base Camp in the earthquake that caused the avalanche on 25th April 2015.

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Foreword

Geology is the science which deals with the physical structure and substance of the Earth, its history and the processes which act on it.

This traveller's guide is about the geology of Mount Everest and the Himalayas. It is written for the interested person as well as for the qualified geologist. It describes the collision of two continents, the deep burial of rocks and the elevation of these rocks to the highest points on Earth. This guidebook introduces the geology of the Himalayas and, with maps and photographs, takes the traveller on a guided geological tour from the town of Lukla in north-eastern Nepal all the way to the summit of Mount Everest. The mountain building processes and the great tectonic movements, thrusts and detachments that shaped the Himalayas are explained.

The ten tallest mountains in the world are listed in the table below. Most are in the Everest area and their geology is related to each other. The reason for their great height is that there are certain geological processes which uniquely occur only in the Himalayas and the Karakoram. These processes are described in this guidebook to help the traveller understand how these great mountains came to be concentrated in this part of the world.

The ten highest mountains in the world	
Everest, Himalayas, Nepal/Tibet	8,850 m
K2, Karakoram, Pakistan/China	8,611 m
Kanchenjunga, Himalayas, Nepal	8,586 m
Lhotse, Himalayas, Nepal/Tibet	8,516 m
Makalu, Himalayas, Nepal/Tibet	8,463 m
Cho Oyu, Himalayas, Nepal/Tibet	8,201 m
Dhaulagiri, Himalayas, Nepal	8,167 m
Manaslu I, Himalayas, Nepal	8,163 m
Nanga Parbat, Karakoram, Pakistan	8,125 m
Annapurna, Himalayas, Nepal	8,091 m

Of all the 8000m giants, Everest is the tallest and the most visited. It is likely to generate the most questions about its geological history from the thousands of travellers that visit the Khumbu Valley and the two to three hundred climbers that attempt to climb Everest each year.

Some interesting facts about the mountain are given in the table below:

Mount Everest and the Khumbu Valley	
Names for Mount Everest: • Mount Everest - English, named after the Surveyor General of India (1830 to 1843) Sir George Everest. • Sagarmatha – Nepalese, meaning "Goddess of the Sky". • Jomo Lungma – Tibetan, comes from Jomo which means Holy and Lungma, which means respected female. Hence the name could mean: "Holy or Sacred Mother". • Chomolongma – Tibetan, means "Mother Goddess of the World " • Jomo Gangkar – Tibetan, comes from the holy Goddess Tseringma, and Gang-kar means "as white as snow"; hence the meaning could be "Snow-White Holy Mother".	 Mount Everest – photo taken from Kala Pattar by Sean Disney, the South African expedition, 2006)
Location	27° 59' North, 86° 55' East
Altitude of Mt Everest	8,850 m (29,035 ft – 1999 measurement)
Altitude of Lukla	2,840 m (9,467 ft)
Altitude of Namche Bazaar	3,440 m (11,467 ft)
Distance from Lukla to Everest	46 km along the trail to Base Camp and 11 km from Base Camp to the summit
General rock types encountered along the way	Granite gneiss to Namche Bazaar, then sillimanite-biotite gneiss to Base Camp, then leucogranite to Camp II. Limestone, mudstone, metapelite, calc-silicate and mylonite from Camp II to the summit
Age of Everest summit rocks	485-443 million years old – Ordovician Period
Age of Everest metamorphism	32 million years and younger
Age of Everest leucogranite	16 to 32 million years

For the qualified geologist, reference is made to the works and theses of the many researchers who have worked on the geology of the Himalayas over the last century: Gansser, Jessup, Odell, Nelson and Searle, to name but a few. A selection of representative rock samples from outcrops has been described and includes rocks from the Khumbu Valley and Ama Dablam Mountain to Everest South Col and the summit of Everest.

Contents

Introduction

The 9 day hike from Lukla (2840m) along the Khumbu valley to Everest Base Camp (5364m) is undertaken by hundreds of travellers each year, usually in the months of April-May and September-October. Many of these people also attempt to reach the Everest summit (8848m). For those interested in the geology, this traverse across the roof of the World is also a journey through space and time along one of the classic geological sections of the world. The rocks exposed along the route range in age from 500 million years to around 6 million years and record the collision between the Indian and Asian continents.

Each set of rocks has an amazing story to tell, and a geologist studying them will ask, "What are they? How did the rocks get here? Why are they here? When did they get here? Where did they come from? How old are they? What is their history? What is the evidence of this history?"

The rocks along this traverse have been buried to depths of >45km, where they experienced temperatures sufficient to melt them. These melts and their residues were then exhumed by tectonic forces and erosion to their present positions as seen today. The tectonic stresses have fractured and displaced large blocks of rock kilometres thick and hundreds to thousands of square kilometres in extent, juxtaposing rocks of different ages and with different burial, metamorphic and uplift histories.

This guide book is designed to give an overview of these histories, descriptions of the rocks observed along the route, and explanations of the dynamic geological processes that have resulted in what is one of the greatest mountain chains on Earth today. The Himalayas provide a unique opportunity to study an active zone of continent-continent collision.

Structure of this guide book

The layout of this Guide is meant for ease of use and follows the journey from the town of Lukla to the summit of Everest.

Stops and special geological features along the route

A summary table indicating each stop along the route is shown in Table 1. The table explains what topics or themes are highlighted at each of the 14 stops, together with the special features that have been used as an illustration.

Text Boxes explaining geological features along the route

At each stop "Boxes" explaining an interesting and pertinent feature along that particular stretch of the route have been included.

Maps

Three geological maps and a route map are located near the beginning of the guidebook on pages 11 to 14. This is for ease of reference on the traveller's trek towards Everest, especially when thought processes become difficult near Base Camp and above.

Glossary of geological, mineral and related terms

A glossary is provided on pages 15 to 26 to provide easy access in the field. Although the language has been simplified as much as possible, not all geological terms have everyday synonyms.

Abbreviations commonly used in this book

Some abbreviations like MCT are used recurringly in this guidebook and are more convenient to use rather than "Main Central Thrust". A table of abbreviations commonly used is given on page 18 of the guidebook.

The Route and its stops

The geology of the trek from Lukla to Everest is explained via 14 stops along the route, with the last stop being the summit of Mt Everest. Geological concepts pertinent to the route travelled are introduced. Samples of typical rocks found are described and hand specimens and thin section photographs of these rocks are shown in illustrations.

For orientation purposes, the altitude of each Stop, what the traveller can expect to see in a north, south, east and west direction and the distance to the next Stop is given at the start of each Stop.

At each stop, a relevant cross-section of the area through which the traveller is passing, is provided. The surface trace or the position of each cross-section, e.g. section E – E', is shown on Maps 3 and 4.

References

References are given at the end of the guidebook, should the reader wish to pursue some of the topics discussed.

Convention

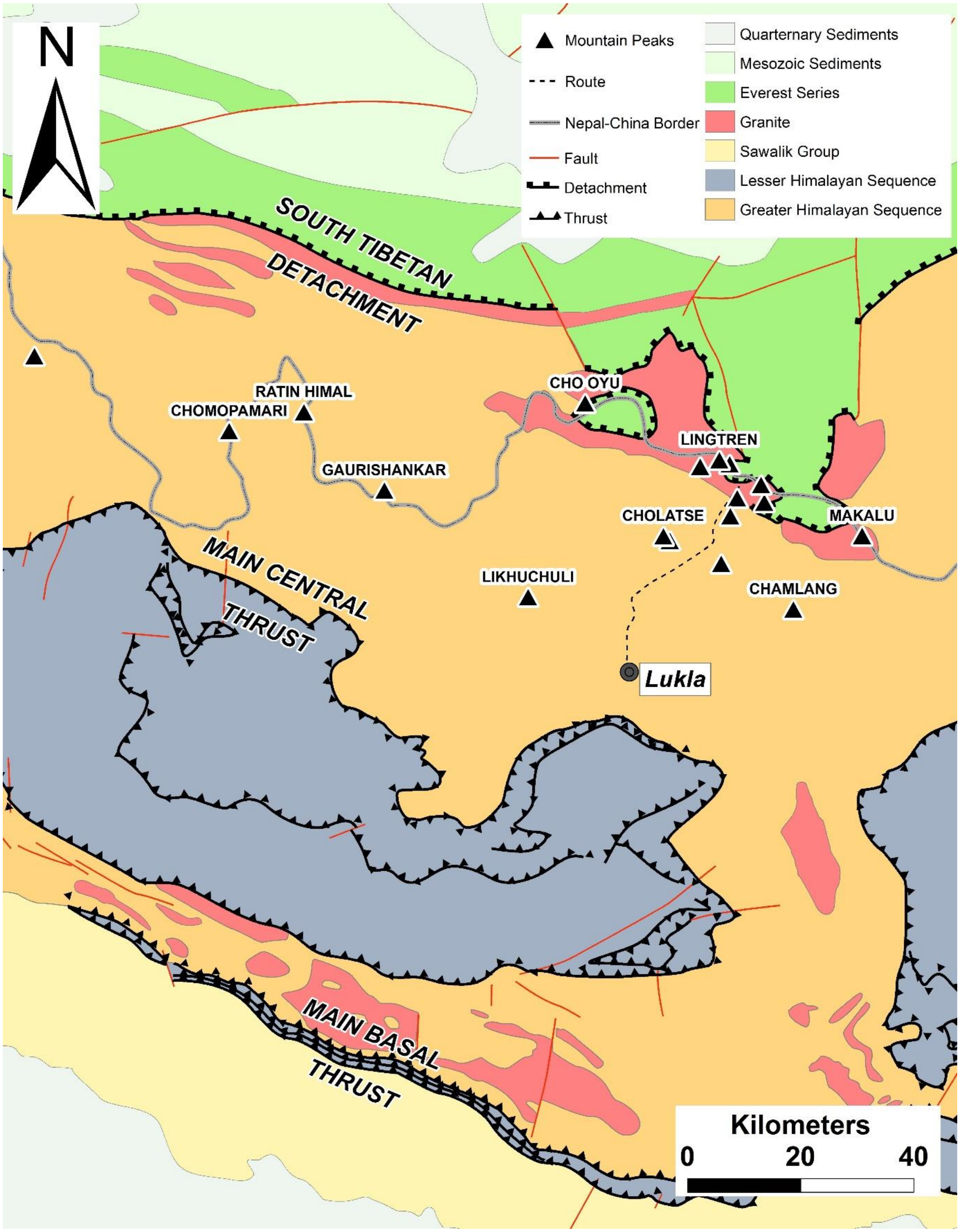
This guidebook follows engineering convention in that any landscape figure or map must be able to be read if the guidebook is turned 90° clockwise.

Table 1: Stops and special geological features along the route

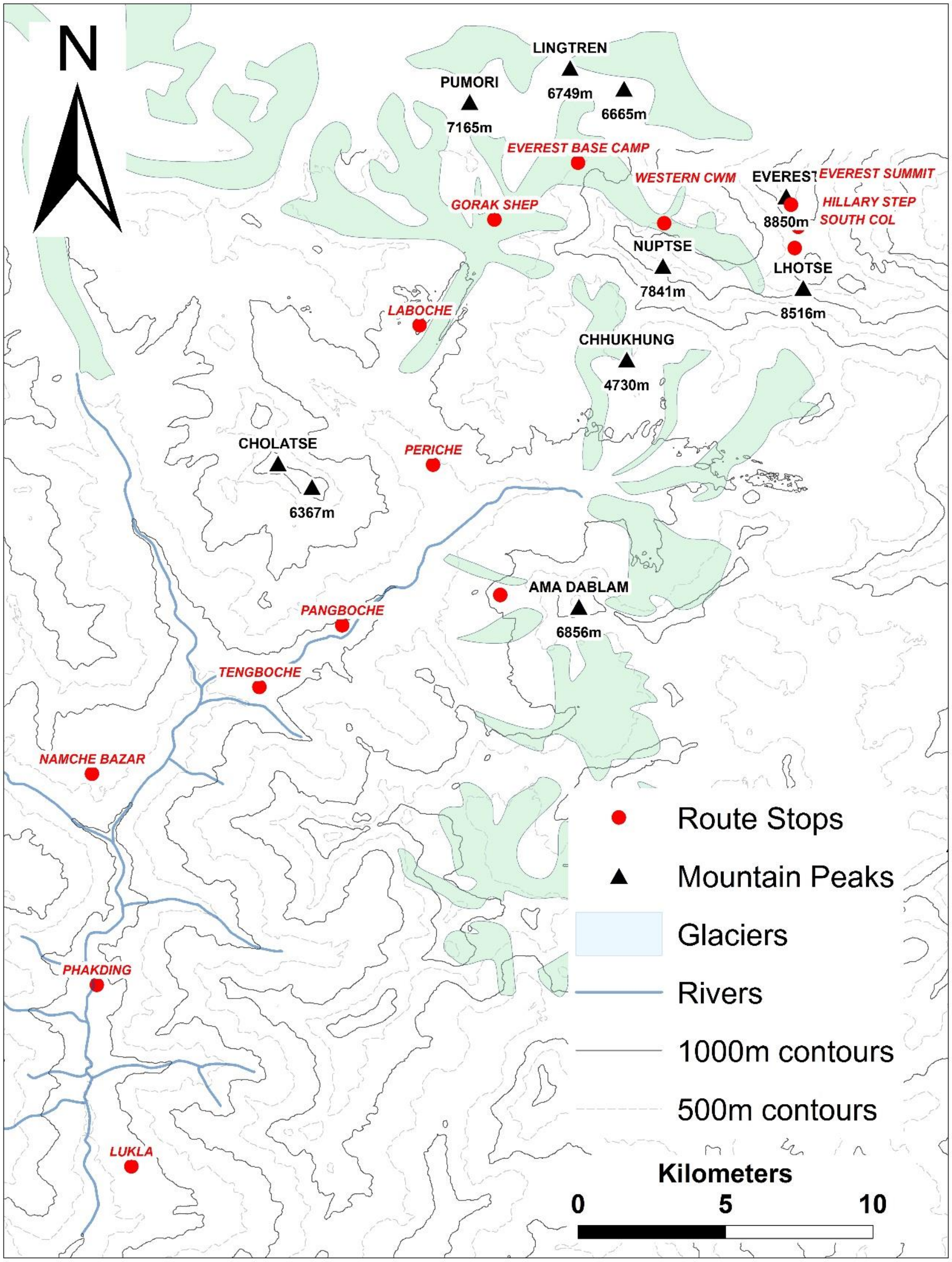
Stop	Location of the Stop	Theme
Stop 1	**Lukla: The most dangerous airstrip on Earth**	Introduction to the stratigraphy of the Himalayas Geological time and where the Himalayas fit in
Stop 2	**Phakding: Welcome to the highest mountains on Earth**	Introducing deformation episodes D_1 and D_2 in the Himalayas
Stop 3	**Namche Bazaar: The first view of Everest**	Introducing the geological history of the Greater Himalayan Sequence and the Everest Series
Stop 4	**Tengboche: Buddhist monasteries in sillimanite-biotite gneisss**	Entering the zone of sillimanite-biotite gneiss, migmatites and introducing the faults and structure of the high Himalayas
Stop 5	**Pangboche: Castles of granite**	Introducing the Higher Himalayan Leucogranites and their formation
Stop 6	**Ama Dablam: Southeast ridge and summit**	Continuing the concept of the Higher Himalayan Leucogranites and their compositional variation
Stop 7	**Periche: The realm of climbers and glaciers**	Introducing the concepts of glacial geomorphology and the role of glaciers as agents of erosion and sediment transport
Stop 8	**Laboche: Leucogranites exhumed**	Leucogranite and pegmatite intrusions and how they were brought to surface
Stop 9	**Gorak Shep: Approach to Base Camp**	Showing the Everest Series in detail for the first time, as well as the main discontinuities affecting the stratigraphy

Stop	Location of the Stop	Theme
Stop 10	**Everest Base Camp**	The intrusion of the Higher Himalayan Leucogranites and the exhumation of the gneisses of the Greater Himalayan Sequence from beneath Tibet as best explained by the channel flow theory. Recent earthquakes in the Everest region attest to the continued exhumation along this channel.
Stop 11	**Western Cwm: Amphitheatre of giants**	The face between Nuptse and Lhotse contains a large-scale fold structure linked to movement along the Lhotse Detachment
Stop 12	**South Col: The last camp before the summit**	Biostratigraphy, fossils and palaeoenvironments in the Everest Series
Stop 13	**Hillary Step: Rarefied geology – one small step to the summit**	Metamorphism and deformation history of the Everest Series
Stop 14	**Everest summit: Penthouse of the giants – the roof of the world**	The geology of Tibet and the lateral continuity of Himalayan Geology east-west along strike

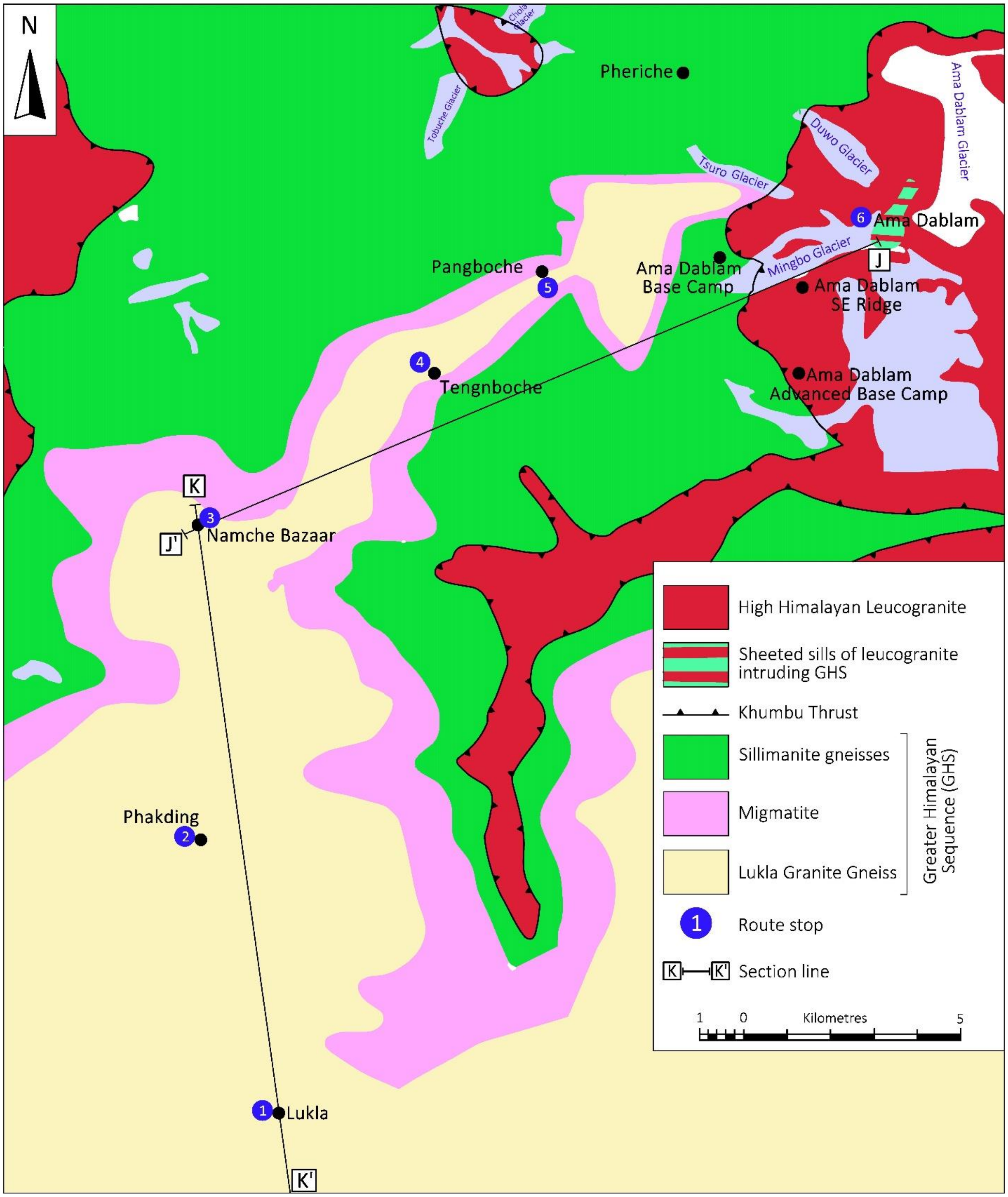
Map 1: Geological map of North Eastern Nepal (Drafted from maps by the Department of Mines and Geology, Nepal, and the People's Republic of China Ministry of Geology and Mineral Resources)



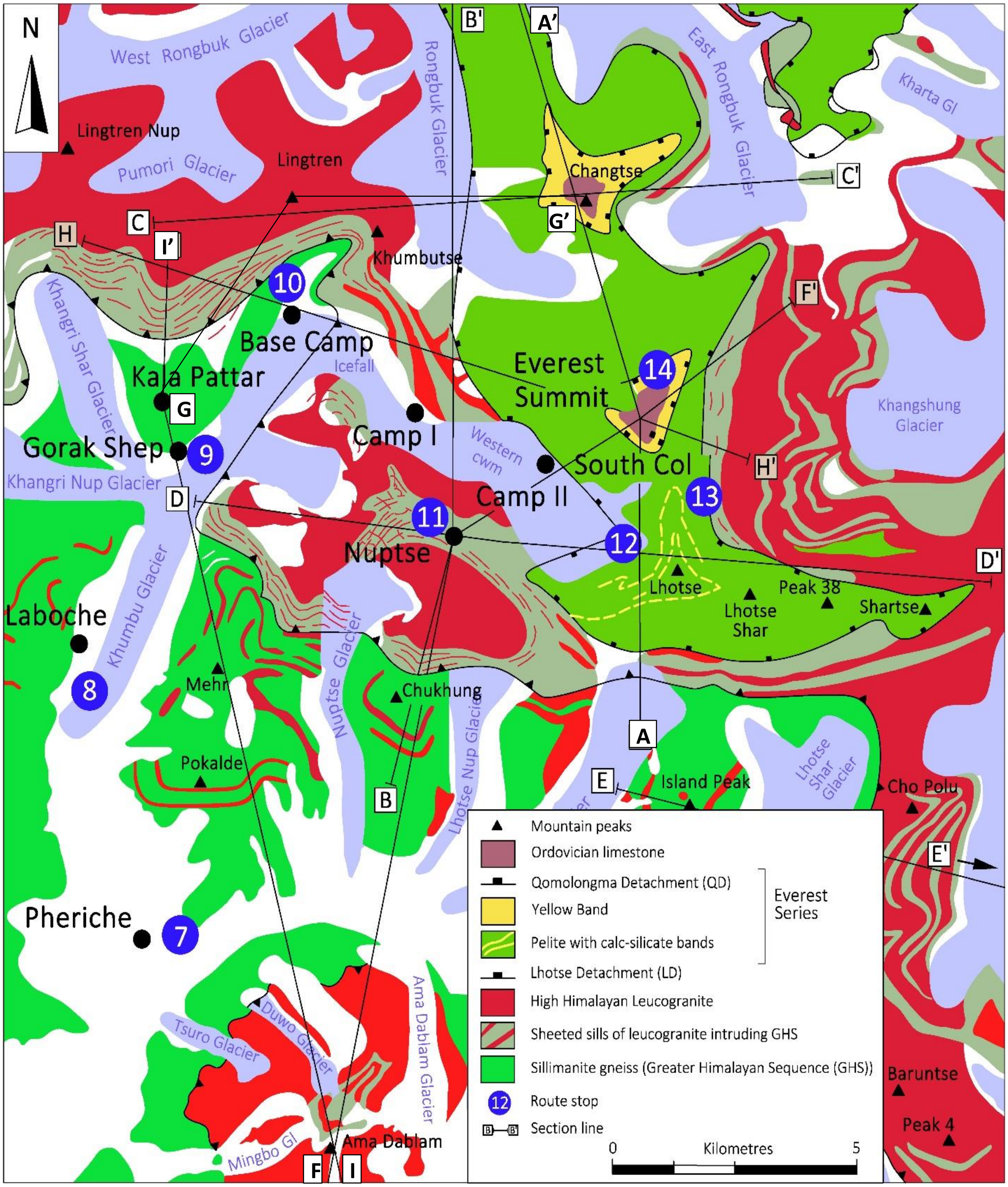
Map 2: Route map from Lukla to Everest (Amended after Himalayan Map House, Kathmandu, Nepal)



Map 3: Geological map of the Lukla to Ama Dablam area (After Searle (2007), modified based on 2006 and 2008 field work)



Map 4: Geological map of the Ama Dablam and Everest areas (After Searle (2007), modified after incorporating additional cross section lines and connected thrust/detachment planes.)



Glossary of Geological, Mineral & Related Terms

In many parts of the text, geological terms are used which may not be familiar to the lay person and as such, a glossary has been included right up front which explains the technical terms used in the text.

Accretionary Wedge	Sediments that are scraped off the top of the downgoing oceanic crustal plate and are appended to the edge of the over-riding continental plate. These sediments accumulate and deform where oceanic and continental plates collide, in an accretionary wedge or accretionary prism.
Ammonite	Spiral fossil marine mollusc animals which were swimming bottom-dwellers in open seas which preyed on fish and other mollusks; squid-like, from the Devonian to the Cretaceous period.
Amorphous	A mineral or other substance that lacks crystalline structure, or whose internal arrangement is so irregular that there is no characteristic external form.
Anatexis	Melting of a pre-existing rock.
Andean-type arc	A volcanic arc found where oceanic crust is subducted below continental crust (as is the case in the Andes, along the western margin of South America).
Augen	In metamorphic rocks such as schists and gneisses, large lenticular mineral grains or mineral aggregates having the shape of an eye in cross section, in contrast to the shapes of other minerals in the rock. From the German word meaning 'eyes', Augen.
Axial plane	The plane formed by the extension of the axis of symmetry along the length of a fold. An axial surface that is planar.
Axial surface	A surface that connects the hinge lines of the strata in a fold. A hinge line is a line connecting the points of flexure or maximum curvature of the bedding planes in a fold.
Barrovian Metamorphism	In complexes of regional dynamothermal metamorphism, one of the belts of increasing metamorphic grade, based on the first appearance of the index minerals chlorite, biotite, almandine, staurolite, kyanite and sillimanite. This now classical sequence, representing the commonest type of regional metamorphism, is named after George Barrow who first described and mapped zones of progressive regional metamorphism in the Grampian Highlands of Scotland in 1893.
Batholith	A large, generally discordant plutonic mass that has more than 100 km^2 of surface exposure and no known floor.
Biotite	A widely distributed and important rock-forming mineral of the mica group. It is generally black, dark brown or dark green and forms a constituent of crystalline rocks (either as an original crystal in igneous rocks of all kinds, or a product of metamorphic origin in gneisses and schists) or a detrital constituent of sandstones and other sedimentary rocks.[K_2Mg_6 $(Si_6Al_2O_{20})(OH,F)_2$].

Boudin	One of a series of elongate, sausage shaped segments occurring in boudinaged structure, either separate or joined by pinched connections, and having barrel shaped cross sections.
Breccia	A coarse grained clastic rock composed of angular broken rock fragments held together by a mineral cement or in a fine grained matrix; it differs from conglomerate in that the fragments have sharp edge sand unworn corners. Breccia may originate as a result of talus (rock fragments lying at the base of a cliff) accumulation, igneous processes, especially explosive, disturbance during sedimentation, collapse of rock material or tectonic processes.
Calcareous Rock	A calcium-rich rock like a limestone (Ca, Mg)(CO3). Carbonate-rich sedimentary rock, characterized by the abundance of $[CO_3]^{2-}$ e.g. $CaCO_3$ or calcite or $(CaMg)(CO_3)_2$ or dolomite.
Cataclasis	Rock deformation accompanied by fracture and rotation of mineral grains without chemical reconstitution. Associated with faulting.
Cephalopod	Any marine mollusc belonging to the class Cephalopoda, characterised by a definite head, with the mouth surrounded by part of the foot that is modified into lobelike processes with tentacles or armlike processes with hooklets or suckers or both.
Channel flow	A hypothesis proposed to explain the large-scale geology of the Himalaya whereby a 10 to 15km thick slab/layer ("channel") of crust, exhibiting evidence of intense strain and high temperature history, appears to have been extruded between layers of lower temperature, less deformed crust. Channel flow involves a viscous fluid-filled channel lying between two rigid sheets (of rock). This fluid is deformed through induced shear and pressure gradients within the fluid channel. In layman's terms, layers of plastic or molten rock are squeezed laterally (very much like toothpaste squeezed from a tube) owing to a pressure gradient, mainly caused by gravity.
Clastic Rock	A consolidated sedimentary rock composed principally of broken fragments that are derived from pre-existing rocks or formed during chemical weathering and which have been transported to their places of deposition e.g. sandstone, conglomerate, shale or limestone formed from particles from a pre-existing limestone.
Cleavage	In structural geology: The property or tendency of a rock to split along secondary, aligned fractures or other closely spaced planar structures or textures, produced by deformation or metamorphism. In a mineral: The breaking of a mineral along its crystallographic planes. Rock cleavage is designated as slaty, phyllitic, schistose or gneissic.

Compositional Zoning	A synonym for phase layering commonly used for with reference to metamorphic rocks. (Phase layering: The mineralogical layering of plutonic rocks caused by the generally sudden appearance and progressive disappearance of some mineral phase.) This is related to the changing stability of mineral compositions with changing temperature or pressure.
Conglomerate	A coarse grained clastic sedimentary rock, composed of rounded to subangular fragments larger than 2 mm in diameter (granules, pebbles, cobbles, boulders) set in a fine grained matrix of sand or silt, and commonly cemented by calcium carbonate, iron oxide, silica, or hardened clay; the consolidated equivalent of gravel both in size range and in the essential roundness and sorting of its constituent particles.
Cordierite	A light blue to dark blue or violet blue orthorhombic mineral $(Mg, Fe)_2Al_2Si_5O_{18}$. It exhibits strong pleochroism (showing many different colours when observed in polarised light in a mcrosope), is easily altered by exposure and is an accessory mineral in granites and a common constituent of metamorphic rocks formed under low pressure.
Corona	A zone of minerals, usually with radial arrangement, around another mineral. It is a general term that has been applied to reaction rims and originally crystallised minerals.
Crust	The outermost layer or shell of the Earth, defined according to various criteria, including seismic velocity, density and composition; that part of the Earth above the Mohorovicic discontinuity (the boundary surface that separates the Earth's Crust from the mantle). The solid outer shell of earth averages 35 km in thickness on continents and 5 km in thickness below the oceans.
Cwm (pronounced koom)	The term comes from the Welsh meaning a "valley". It is a half-open, steep sided hollow in a mountain region that has been, or is being, glaciated. Its form is due to a combination of glacial scouring and wearing down the rocks at the base of the glacier.
D_1, D_2, etc.	Deformation episode 1, 2, etc. Deformation is a general term for the process of faulting, folding, compression, shearing or extension of the rocks as a result of various Earth forces. Each distinguishable deformation event in a rock mass is named in the order in which it occurred. Thus the first deformation event in a particular rock would be D_1, the second would be D_2, etc.
Decompression	When rocks are brought to surface from deep within the crust, the pressure experienced by the rock decreases. If this happens relatively rapidly and at high temperatures, then evidence for this decompression can be preserved in mineral reaction textures.

Denudation	The sum of the processes that result in the wearing away of the Earth's surface by various natural agencies, which include weathering, erosion, mass wasting, and transportation; also the combined destructive effects of such processes.
Detachment	A major shallow-dipping fault in Earth's crust, accommodating extension.
Ductile	Said of a rock that is able to sustain, under a given set of conditions, 5-10% deformation before fracturing or faulting. Generally, rocks respond to stress in one of two ways: they break, or they bend. When a rock breaks, it is called **brittle** deformation. Any material that breaks into pieces exhibits brittle behaviour. When rocks bend or flow, like clay, it is called **ductile** deformation.
Dyke	A tabular igneous intrusion that cuts across the bedding or foliation (a planar arrangement of textural or structural features) of the country rock. Country Rock: the rock traversed or enclosing a mineral deposit. Originally a miner's term, it is less specific than Host Rock.
Eclogite Facies	The set of metamorphic mineral assemblages (facies) in which basic rocks are represented by omphacitic pyroxene and almandine-pyrope garnet. Also common is the association pyrope+olivine+diopside+enstatite. These associations indicate high pressure crystallisation, although a broad range of pressure-temperature conditions is possible. Pressures are in excess of 1.2 GPa (45 km depth) at >400–1000 °C, and usually in excess of 600-650 °C. Eclogite itself is a metamorphic rock of basaltic composition and may contain garnet, kyanite, rutile, quartz, corundum, and many more minerals as well as diamonds.
Erosion	The general process or the group of processes whereby the materials of the Earth's crust are loosened, dissolved, or worn away, and simultaneously moved from one place to another, by natural agencies, which include weathering, solution, corrosion, and transportation, but usually exclude mass wasting.
Exhumation	The uncovering or exposure by erosion of a pre-existing surface, landscape or feature that had been buried
Extensional movement	Movement along a fault in sedimentary rocks along which there has been bed-parallel elongation, giving rise to tectonic thinning. See Fault - Normal
Extinction (Optics in a microscope)	The more or less complete darkness obtained in a mineral at two positions during a complete rotation of a thin section between cross polarized light in a microscope used for examining thin sections of rock samples.
Extrusion	The squeezing out of molten or solid rock from between layers of rock.

Fabric	The complete special and geometrical configuration of all those components that make up a deformed rock. It covers such terms as texture, structure and preferred orientation and so is an all-encompassing term that describes the shapes and characters of individual parts of a rock mass and the manner in which these parts are distributed and oriented in space.
Facies	A facies is the characteristic of a rock mass that reflects its depositional environment for a sedimentary rock or the pressure and temperature environment of origin for a metamorphic rock. Through these characteristics, it can be distinguished from other rock masses.
Fault	A fracture or a zone of fractures along which there has been displacement of the sides relative to one another parallel to the fracture. The two main types of fault are: 1. Normal (extensional) – see *Extensional Movement* where rock strata are pulled apart across the fault and 2. Reverse (compressional) – see *Reverse Fault* where rock strata are pushed over each other across the fault
Feldspar	A group of abundant rock forming minerals of general formula: $MAl(Al, Si)_2O_8$, where M = K, Na, Ca, Ba, Rb, Sr or Fe. Feldspars are the most widespread of any mineral group and constitute 60% of the Earth's crust. They occur as components of all kinds of rocks (crystalline schists, migmatites, gneisses, granites, most magmatic rocks) and as fissure minerals in clefts and druse minerals in cavities.
Felsic	A mnemonic adjective derived from *fe*ldspar + *l*enad (feldspathoid) + *si*lica + c, and applied to an igneous rock having abundant light-coloured minerals in its mode. Light-coloured rock, aluminium rich, also referred to as leucocratic. A mnemonic derived from FEL for feldspar and SI for silica.
Fibrolite	A fibrous variety of sillimanite.
Flysch	A deep marine sedimentary facies that is deposited in a foreland basin of a developing orogen, characterised by a thick sequence of poorly fossiliferous, thinly bedded deposits composed chiefly of marls and sandy and calcareous shales and muds, rhythmically interbedded with conglomerates, coarse sandstones and greywackes. Flysch is typically deposited during an early stage of the orogen or mountain building.
Fold	A curve or bend of a planar structure such as rock strata, bedding plans, foliation or cleavage.
Fold limb	The area of a fold between adjacent fold hinges.

Forearc	The region between a subduction related trench and a volcanic arc. Typically forms a basin, filled with flat-lying sediments derived from the eroded volcanic arc.
Fossil	Any remains trace or imprint of a plant or animal that has been preserved in the Earth's crust since some past geologic or prehistoric time. Loosely, any evidence of past life, such as dinosaur bones, ancient clam shells, footprint of a long extinct animal or impression of a leaf in rock.
Geology	The study of the planet earth, the materials of which it is made, the processes that act upon these materials, the products formed, and the history of the planet and its life forms since its origin. Geology considers the physical forces that act on the Earth, the chemistry of its constituent materials and the biology of its past inhabitants as revealed by fossils.
Geosyncline	A mobile down warping of the crust of the Earth, either elongate or basin like, measured in scores of kilometres, in which sedimentary and volcanic rocks accumulate to thicknesses of thousands of metres.
Gneiss	A foliated rock formed by regional metamorphism, in which bands of granular minerals alternate with bands in which minerals having a flakey or elongate prismatic habits predominate.
Granite	A plutonic (igneous) rock in which quartz constitutes 10 to 50 % of the felsic components and in which the alkali/total feldspar is general restricted to the range of 65% to 90%.
Granulite Facies	The set of metamorphic mineral assemblages (facies) in which the basic rocks (rocks with a low silica content) are represented by diopside + hypersthene + plagioclase. Almandine (a garnet) is characteristic of basic and pelitic rocks. Pelitic assemblages show the association of sillimanite and kyanite with feldspar and almandine garnet, often also with cordierite.
Graptolite	Any colonial marine organism belonging to the class Graptolithina , characterised by a cup– or tube– shaped highly resistant external skeleton arranged with other individuals along one or more branches to form a colony.
Hangingwall	The overlying side of an orebody, fault or mine working esp. the wall of rock above an inclined vein or fault. Also the rocks above a particular layer of rock under discussion.
Inverted metamorphic gradient	For example: a conversion of shale to slate would be low grade thermal metamorphism (greenschist facies) whereas its continued alteration to garnet sillimanite schist would be high grade metamorphism. Typically, rocks get to higher metamorphic grades as one goes deeper in the earth's crust. Any instance where higher-grade rocks are found overlying lower-grade rocks is referred to as an inverted metamorphic gradient.

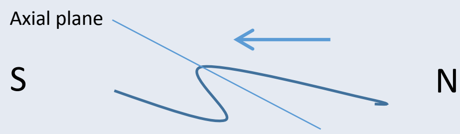
Igneous rock	A rock that solidified from a molten or partly molten material i.e. from magma.
Isostasy	The condition of equilibrium, comparable to floating, of the units of the lithosphere above the asthenosphere (Figure 1). Crustal loading as by ice, water, sediments or volcanic flows leads to isostatic depression or down warping; removal of load to isostatic uplift or up warping.
Isothermal	Pertaining to the process of changing the thermodynamic state of a substance e.g. its pressure and volume, while maintaining a constant temperature.
K-feldspar	A potassium rich feldspar – see Feldspar for the chemical formula.
Kilo-bar (kbar)	1000 bars – the air pressure at sea level is one bar. One kbar is the equivalent of 3 km of depth in the earth's crust.
Leucogranite	Granite containing much quartz and feldspar, light in colour and aluminium-rich. Tourmaline is common.
Leucosome	The light coloured part of a migmatite, usually rich in quartz and feldspar
Limestone	A sedimentary rock consisting chiefly (more than 50% by weight or by areal percentages under the microscope) of calcium carbonate, primarily in the form of the mineral calcite and with or without magnesium carbonate. specif. A carbonate sedimentary rock containing more than 95% calcite and not more than 5% dolomite.
M_1, M_2, etc.	As with deformation events, each distinguishable metamorphic event in a rock mass is named in the order in which it occurred. Thus the first metamorphic event in a particular rock would be M_1, the second would be M_2, etc.
Ma	Millions of years before the present or Mega Annum.
Mafic	An igneous rock composed chiefly of one or more ferromagnesian (dark coloured) minerals.
Magma	Naturally occurring mobile rock material, generated within the Earth and capable of intrusion and extrusion, from which igneous rocks are thought to have been derived through solidification and related processes.
Magnetic and Gravity Low	Magnetic field intensity is a region in which magnetic forces would be exerted on any magnetised bodies or electric currents present. A low force would indicate a region of low magnetic intensity and vice versa. Gravitational field intensity is the measure of the gravitational force, expressed as a vector quantity, exerted on a unit mass at a particular point. A low force on a unit mass would be a low gravitational intensity and vice versa. Geophysical techniques measure the intensity of the magnetic field in an area and gravity techniques measure the pull of gravity in a certain area. These techniques provide useful information regarding the rock types that could exist beneath an area.

Mantle	The zone of the Earth below the Crust and above the Core, which is divided into the Upper Mantle and the Lower Mantle, with a transition zone between.
Metamorphic isograds	A line on a map joining points at which metamorphism proceeded at similar values of pressure and temperature as indicated by rocks belonging to the same metamorphic facies.
Metamorphic rock	Any rock derived from pre-existing rocks by mineralogical, chemical and/or structural changes, essentially in the solid state, in response to marked changes in temperature, pressure, shearing stress and chemical environment, generally at depth in the Earth's Crust.
Metapelite	A metamorphosed pelite
Mica	A group of minerals of general formula: $(K,Na,Ca)(Mg,Fe,Li,Al)_{2-3}(Al,Si)_4O_{10}(OH,F)_2$. They readily split into thin, tough, elastic laminae or plates with a splendent pearly lustre in colours of silvery white, pale brown, yellow, green, black or are colourless.
Micrite	A descriptive term used for the semi-opaque crystalline matrix of limestones, consisting of chemically precipitated carbonate mud with crystals less than 4 microns in diameter, and interpreted as a lithified ooze.
Micritic Banding	Bands of Micrite.
Migmatite	A rock composed of igneous or igneous appearing and/or metamorphic materials which are generally distinguishable megascopically. Specifically, a rock composed of inter-fingered magma and invaded rock which is metamorphic.
Molasse	A partly marine, partly continental or deltaic sedimentary facies consisting of a very thick sequence of soft, ungraded, cross-bedded, fossiliferous conglomerates, sandstones, shales, marls, characterised by primary sedimentary structures and sometimes by coal and carbonate deposits. It is generally coarse-grained and found in terrestrial or shallow marine deposits in front of rising mountain chains
Mylonite	A compact chert-like rock without cleavage, but with a streaky or banded structure, produced by the extreme granulation and shearing of rocks that have been pulverised and rolled during over-thrusting or intense dynamic metamorphism. More simply, a fine grained rock formed from sliding of rock masses against each other. From the Greek "mylos" meaning "to mill" referring to the fine-grained nature of these rocks.
Nappe structure	A sheet-like rock unit which has moved on a predominantly horizontal surface for several kilometres. It may have a recumbent fold at its terminus.
Omphacite	A grass-green to pale-green granular aluminous mineral variety of pyroxene with chemical formula $(Ca,Na)(Mg,Fe^{2+},Fe^{3+},Al)Si_2O_6$, found as a common constituent in the rock type called *eclogite.*

Ophiolite	A group of mafic and ultramafic igneous rocks, derived by later metamorphism, whose origin is associated with an early phase of the development of a geosyncline. More simply, a sequence of lavas and intrusions associated with infilling of geosynclines associated with the collision process.
Orogen	Literally the process of formation of mountains.
Partial melt	In rocks made up of several different minerals, some will melt at lower temperatures than others. Partial melting is an important consideration in geology with respect to the chemical differentiation of crustal rocks.
Pegmatite	An exceptionally coarse grained igneous rock, with interlocking crystals, usually found as irregular dykes, lenses or veins, especially at the margins of batholiths.
Pelite or pelitic rock	A sedimentary rock composed of the finest detritus, clay or mud-sized particles or a calcareous sediment composed of clay and minute particles of quartz..
Phyllite	A metamorphosed rock intermediate in grade between slate and mica schist.
Plate Tectonics	A plate is a rigid thin segment of the Earth's lithosphere, which may be assumed to move horizontally and adjoins other plates along zones of seismic activity. Tectonics is a branch of geology dealing with the broad architecture of the outer part of the Earth; the regional assembling of structural or deformational features, a study of their mutual relationships, origin and historical evolution.
Pluton	An igneous intrusion.
Poikilitic	A texture of an igneous rock in which small grains of one mineral are irregularly scattered without common orientation in a typically anhedral larger crystal of another mineral.
Prograde (metamorphism)	Metamorphic changes in response to a higher pressure or temperature than that to which the rock last adjusted itself.
Petrographic Microscope Polarising Microscope	A microscope that uses polarised light and a revolving stage for analysis of petrographic thin sections of rocks. The thin section sample can be viewed in plane polarized light (pl) or cross polarized light (xp indicating crossed polars). In plane polarized light (pl) many of the grains can readily be identified, but crossing the polars (xp) allows further characteristics of minerals to appear, such as the parallel laminae showing the twinning of crystals in almost all plagioclase feldspar.
Proto mylonite	A mylonitic rock produced from contact-metamorphosed rock, with granulation being due to over-thrusts following the contact surfaces between intrusion and country rock. Or: A coherent crush breccia whose characteristically lenticular, megascopic particles faintly retain primary structures.

P-T-D-t paths	Pressure-Temperature-Deformation-time path of a rock as it moves through the earth's crust over time as a result of tectonic processes.
Quartz	Crystalline silica, an important rock forming mineral: SiO_2
Quartzite (metamorphic)	A metamorphic rock consisting mainly of quartz and formed by recrystallization of sandstone or chert by regional or thermal metamorphism. More simply, re-crystallized grains of quartz that develop an interlocking mosaic texture.
Recumbent Fold	An overturned fold, the axial surface of which is horizontal or nearly so.
Retrograde (metamorphism)	A type of metamorphism by which metamorphic minerals of a lower grade are formed at the expense of minerals characteristic of a higher grade of metamorphism, a readjustment necessitated by a change in physical conditions e.g. lowering of temperature or pressure.
Retrograde overprint	The superposition of a new set of structural features on an older set. Metamorphic reactions which took place on the cooling path and formed minerals which eliminated earlier (prograde) minerals. Retrograde reactions may not have completely overprinted earlier formed minerals and evidence for earlier metamorphism is often preserved.
Reverse fault	A fault on which the hangingwall appears to have move upward relative to the footwall.
S_1, S_2, etc.	Alignment of planar minerals (such as micas) during deformation leads to the formation of a penetrative 'fabric' in a deformed rock. These fabrics are named according to the deformation event with which they are associated (S_1 is the fabric formed during D_1, S_2 is the fabric formed during D_2, etc.).
S-C fabrics	A metamorphic fabric formed by the intersection of shear surfaces within rocks affected by dynamic metamorphism; often indicative of the movement direction, as C-surfaces are parallel to the margin of the shear surface whilst S-surfaces are oblique to the surface and show the vergence direction.
Schist	A strongly foliated crystalline rock formed by dynamic metamorphism, that can be readily split into thin flakes by or slabs due to the well-developed parallelism of more than 50% of the minerals present.
Sedimentary rock	A rock resulting from the consolidation of loose sediment that has accumulated in layers e.g. a clastic rock such as a conglomerate or tillite, consisting of fragments of older rock transported from its source and deposited in water or from air or ice; or a chemical rock formed from precipitation from solution, such as gypsum or rock salt, or an organic rock such as limestones, consisting of the remains or secretions of plants and animals.

Seismic Survey	A term used to describe the use of artificially generated seismic waves (using a mechanical hammer or light explosive) in determining depths of bedrock or faults or bedding planes of rock strata which reflect these seismic waves and which are measured and collected with "listening equipment". Usually done in traverse lines; these traverse lines can be connected in 3-D to give a computer generated model of the structure of rock units to a several kilometres in depth. A seismic survey can also detect liquid or plastic material.
Shear force (stress)	The component of stress which acts tangentially to a plane through any given point in a body.
Sill	A tabular igneous intrusion that parallels the planar structure of the surrounding rock.
Sillimanite	A brown, pale-green or white orthorhombic mineral: Al_2SiO_5 Together with its polymorphs, kyanite and sillimanite, it can be used to determine PT conditions of the rock in which they occur.
Staurolite	A brown to black orthorhombic mineral: $(Fe,Mg)_2Al_9Si_4O_{23}(OH)$.
Stockwork	Said of a mineral deposit consisting of a three-dimensional network of planar to irregular veinlets closely spaced.
Stratigraphy	The science of rock strata concerned with all characters and attributes of rocks such as original succession, age, form, distribution, lithologic composition, fossil content, geophysical and geochemical properties.
Strain	Usually referred to as shear strain: A measure by which parallel lines have been sheared past one another by deformation.
Stylolites	A surface or contact occurring in carbonate rocks marked by irregular and interlocking penetrations of the two sides. The seam is characterised by a concentration of insoluble constituents of the rock e.g. carbon, clay, or iron oxides and is commonly parallel to the bedding or cleavage. Mineral material has been removed by pressure.
Subduction	The process of one lithospheric or crustal plate descending beneath another. See Plate Tectonics.
Suture zone	The area or zone where two continental plates have joined together through continental collision. Younger suture zones may be marked by mountain ranges, e.g. the Himalayas or the Alps.
Symplectites	A rock texture produced by the intimate intergrowth of two different minerals.
Terrane	A fault-bounded body of rock of regional extent, characterised by a geologic history different from that of contiguous terranes.

Thin Section	A fragment of rock or mineral mechanically ground to thickness of approx. 0.03mm and mounted between two glasses as a microscope slide. This reduction renders most rocks and minerals transparent or translucent, thus making it possible to study their optical properties.
Thrust	An overriding movement of one crustal unit over another, as in thrust faulting.
Vergence	The direction in which the upper component of a fold is rotated e.g. in the diagram below, the top of the fold is rotated to the south , hence a south verging fold 
Vertebrates	Characterised by an internal skeleton of cartilage or bone, and by specialised anterior organisation of the animal; the front of the body is a head that bears organs of sight, smell, taste and hearing, and the front of the central nervous system is the brain.
Xenolith	A foreign inclusion in an igneous rock.

Source: Modified and added to from the Glossary of Geology (Bates and Jackson, 1987), and Penguin Dictionary of Geology, (Whitten and Brookes, 1972).

Abbreviations commonly used in this Book

	Minerals
Bt	The mineral Biotite
Ca	The element calcium
Cal	The mineral calcite
Crd	The mineral cordierite
Di	The mineral diopside
Grt	The mineral garnet
Hbl	The mineral hornblende
Kfs	The mineral potassium feldspar (the chemical symbol for potassium is K)
Ms	The mineral muscovite
Omph	The mineral omphacite
Opx	The mineral orthopyroxene
Pl	The mineral plagioclase (a feldspar)
Qtz	The mineral quartz
Sill	The mineral sillimanite
Tur	The mineral tourmaline
	Geological Sequences
GHS	Greater Himalayan Sequence
LHS	Lesser Himalayan Sequence
	Faults, thrusts and Detachments
KT	Khumbu Thrust
LD	Lhotse Detachment
MBF	Main Boundary Fault (south of the MCTZ).
MCT	Main Central Thrust
MCT 1	Main Central Thrust 1, the southern boundary of the MCTZ
MCTZ	Main Central Thrust Zone
QD	Qomolongma Detachment
STD	South Tibetan Detachment

The Geology of the Himalayas

The Himalayas are the product of the collision between two continents: India and Asia. Starting about 180 million years ago, the supercontinent Gondwana began to break up. This breakup eventually led to the configuration of the continents that are seen today, as South America, Antarctica, Australia, India and Madagascar moved away from Africa. India broke away from the east coast of Africa about 115 million years ago (Aitchison et al., 2007).

Box 1: The structure of the Earth and Plate Tectonics

The Earth consists of a Core, a Mantle and a Crust. Plates of oceanic and continental Crust move continuously on the asthenosphere of the Mantle (Figure 1) and collide with each other, changing their position on the Earths' surface (Figure 2).

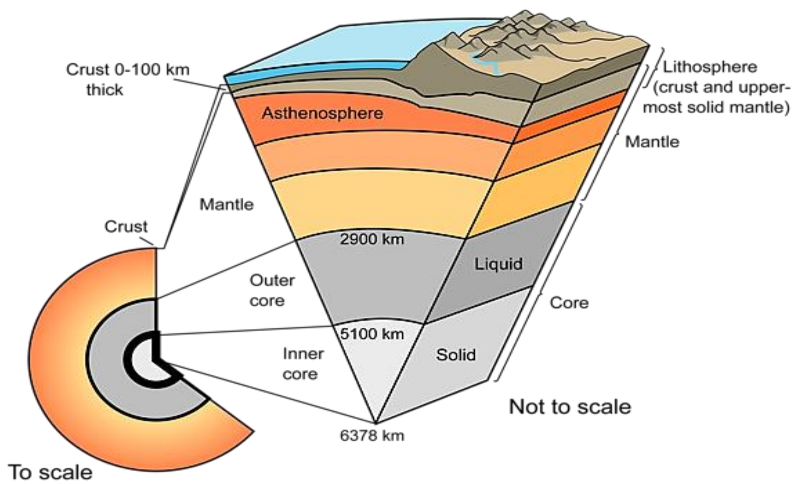


Figure 1: The structure of the Earth is essentially an outer shell covering called a crust, a solid uppermost Mantle which becomes progressively more "plastic" with depth. A liquid outer Core surrounds a solid inner Core. Crustal "plates" move around on a slippery Asthenosphere.(Source:http://www.study.com/academy/lesson/north-american-plate-tectonics-movement-facts, accessed 11/4/2016)

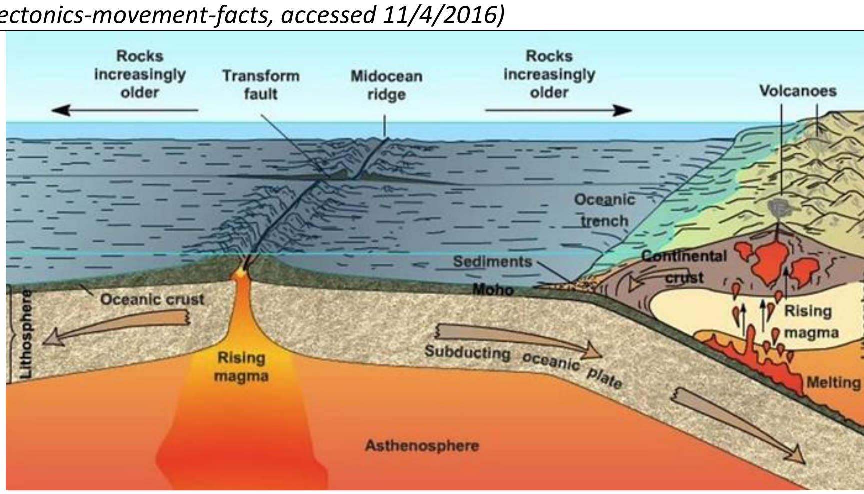


Figure 2: The earth is made up of a number of plates which move relative to each other as a result of magma being forced up along mid-ocean ridges and being subducted downwards below other plates, usually on the edge of an existing continent. The subducting plate causes a chain of events that result in mountain building through crustal thickening, rising magma which may or may not reach the surface and exhumation of deep crustal rocks that is accelerated through high rates of erosion, as is the case in the Himalayas. (Source:https://www.youtube.com/watch?v=sdCrn39Lv51andpsig=AFQjCNEcwge4o8fGd66gpeaVIUQHbw&ust=1460054757860881, accessed 11/4/2016)

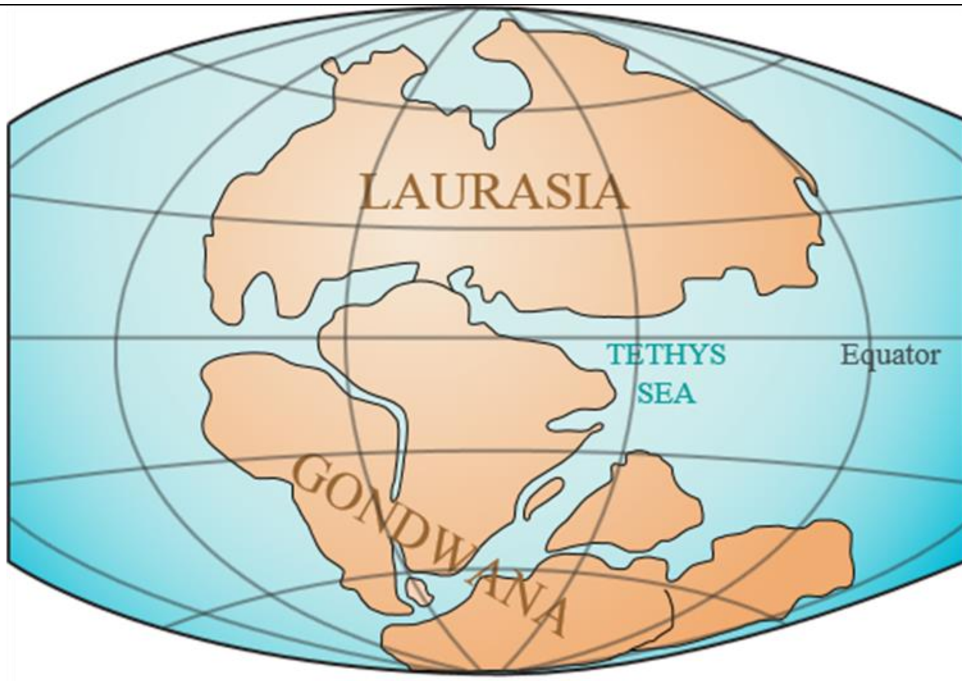


Figure 3: Every 500 million years or so, the Earth's continental plates combine to form a supercontinent or a Pangaea, like Gondwanaland and Laurasia, and then break apart again. Around 180 Ma, the continents began to break up. India was the last to leave the supercontinent and moved northwards towards Laurasia, colliding with it around 50 Ma. (Source:www.en.wikipedia.org, accessed 11/4/2016)

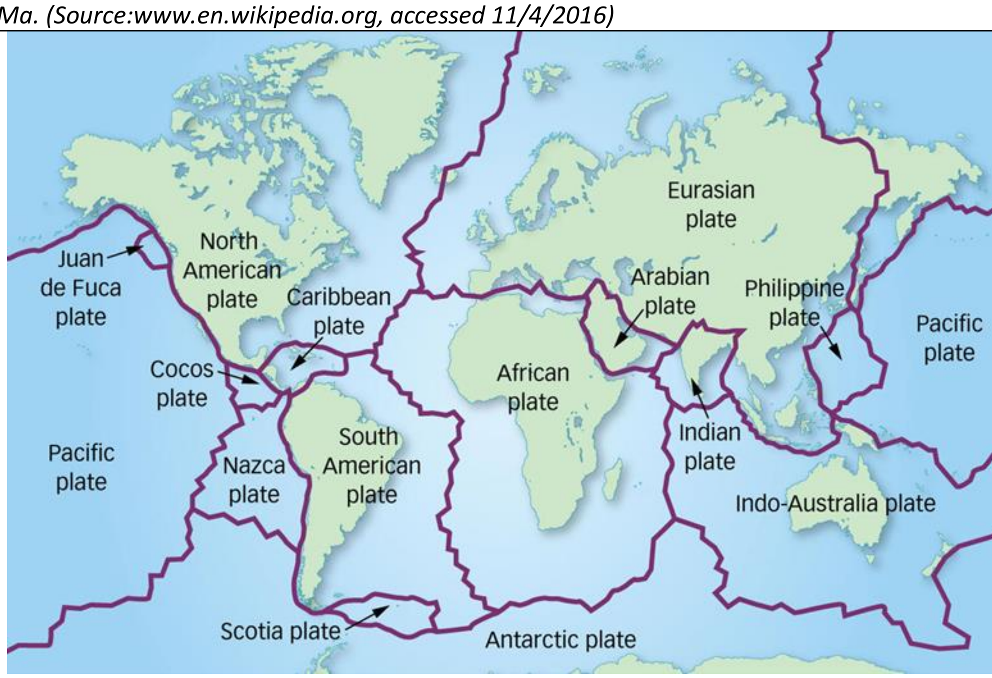


Figure 4: Map of the world showing present day plate boundaries in relation to the continents. (Source: http://www.hzv.dromgfl.top/c/tectonic -plates-map-with-countries, accessed 11/4/2016)

Following the breakup of Gondwana around 180 million years ago (Figure 3), India was the last continental fragment to separate from Africa and began to move northwards (Figures 4, 5 and 7). After more than 50 million years of northwards movement, the Indian continent collided with Asia around 50 million years ago (Figure 5A). As it approached the Asia plate, the denser oceanic crust of the Indian plate was subducted beneath the less dense Asian plate. Whilst this subduction occurred, a number of small micro continental fragments or terranes were accreted onto Asia (Van der Voo et al., 1999). India's speed northwards varied between ~15 to 17 cm/yr between 73 and 53 million years ago, the fastest of any of the post-Gondwana continents (Copley et al., 2010). It slowed down to ~9.5 cm/yr between 30 and 20 million years ago and slowed further from this rate since then (Aitchison et al., 2007). The collision forced the continental crust of India to follow its oceanic crust beneath the Asian continent and resulted in thickening of the crust to >45 km and the uplift of the Asian/Tibetan plateau to an average of 4000 m above sea level. Normally the continental crust is 30 to 35 km thick and the oceanic crust only about 15 km thick.

Although the speed of India's northwards movement has slowed, it continues to move northwards into Asia at about 2 cm/year (Aitchison et al., 2007), resulting in the continued rise of the Himalayan mountain chain.

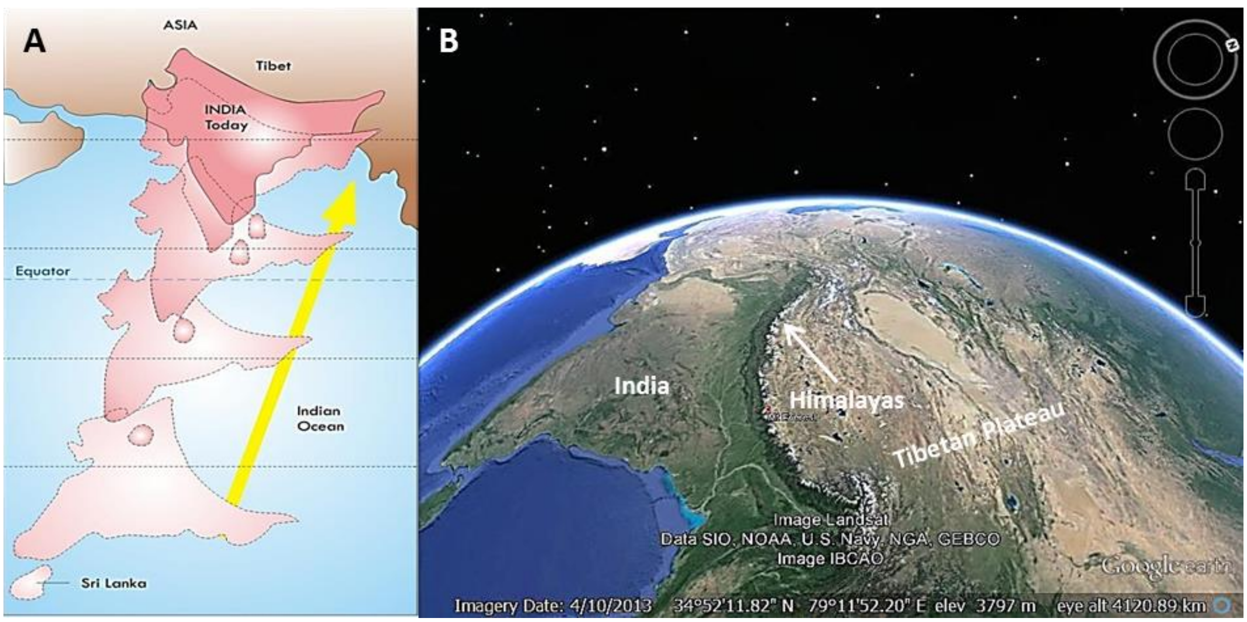


Figure 5: Over the last 100 million years, India has been moving northwards relative to Asia (A). Before the collision of the two, the Tethys Sea existed between India and Tibet, much like the Mediterranean Sea. Its sea-floor strata has been elevated to the Tibetan plateau and many summits in the Himalayas (B). (Source: http://pubs.usgs.gov/publications/text/himalaya.html; Google earth))

Box 2: How weathering and erosion compete with dynamic mountain building and isostatic forces to exhume deep crustal rocks

Weathering and erosion are two important processes which compete with dynamic mountain building forces to maintain in equilibrium the top half with the bottom half of a crustal segment.

When mountains are built by tectonics and volcanism, their high relief creates disequilibrium within the Earth's crust. Gravity and erosion redistribute mass from higher altitudes to lower elevations. Weathering then breaks up the mountain tops, converting rocks into sediment. Removal by erosion of large volumes of rock from high altitude deposition at lower altitudes results in a lightening of the weight on the lower crust and mantle, causing isostatic uplift as shown in Figure 6.

Rocks may move up or down in the crust, depending on the relative rates of erosion and thickening, and on their initial depth in the crust. Exhumation during thickening of the crust can only occur if rapid denudation accompanies the thickening process.

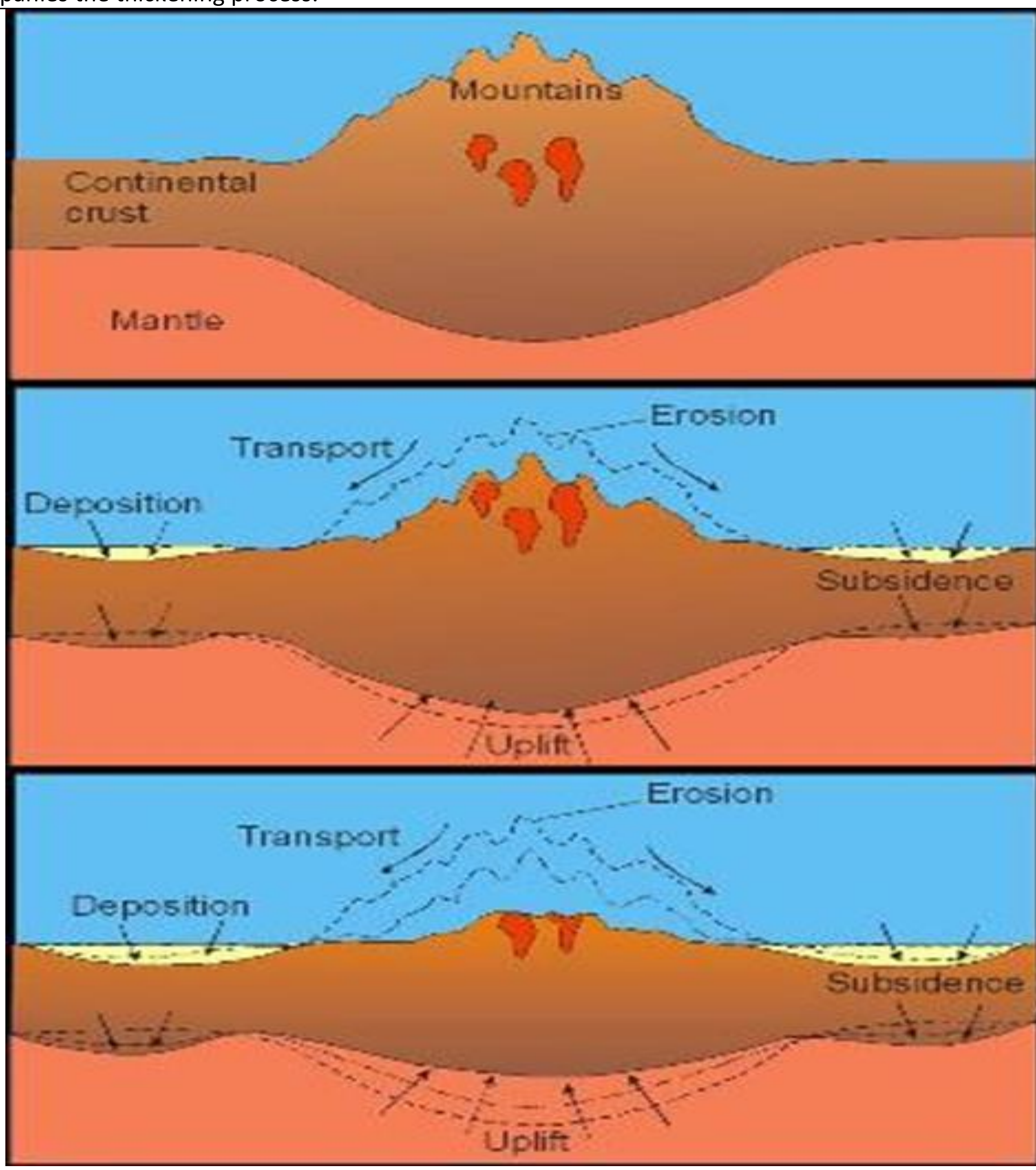


Figure 6: As an example of this, the red rocks shown here are exhumed because erosion removes their cover rocks whilst uplift is taking place either through uplift or thickening of the rocks through collision as would be in the case of the Himalayas. (Source:www.Wikipedia.org, accessed 11/4/2016)

The collision zone is defined by a curved range of mountains (Figures 7 and 5B) along the northern edge of India called the Himalayas or Himalayan Front, which have a maximum elevation of between 6,000 m and 8,850 m in height.

Figure 7: Faults and thrusts of the Indian, Himalayan and Tibetan regions (after Molnar and Tapponnier, 1975)

The Himalayan Mountains and the elevated region of Tibet are not the only consequences of this crustal thickening; it also thermally affected the deep crust. A layer of partially molten material containing aqueous (water-rich) fluid exists at 15-20 km depth in the crust beneath the Himalayas and Tibet (Nelson et al., 1996; Alsdorf et al., 1999). This was discovered by the INDEPTH project, a major geophysical transect across the Himalayas (Zhao et al., 1993; Nelson et al., 1996).

A satellite magnetic low suggests that there is hot or partially melted crust under southern Tibet (Alsdorf and Nelson, 1999). Deep seismic reflection profiling suggests a partial melt layer 15 to 20 km deep in southern Tibet (Nelson et al. 1996; Alsdorf and Nelson, 1999). A relatively cool mantle extends from the Himalayas northwards under the centre of Tibet (Owens et al., 1997; Kosarev, et al., 1999). A magnetic and gravity low over Tibet indicates hot crust and in-situ partial melting at depth (Alsdorf et al., 1999) in an area about 250 km north of Everest (Searle et al., 2003) where leucogranite bodies are in the process of being formed today (Nelson, et al., 1996).

What this means is that crust from the Indian Plate, which has been forced below the Asian Plate, has been heated to temperatures sufficiently high to cause the plate to melt (Figure 8). The heating of rocks that have been forced to great depths in collisional zones is a common phenomenon. This occurs because there is a geothermal gradient that increases with depth at between 10°C to 20°C/km depth. This increase in heat is the result of primordial heat, conductive heat from the mantle and the core, frictional heating from faults and shearing and radioactive decay of small amounts of uranium, thorium and potassium contained within rocks that cause them to heat up. Because rocks conduct heat slowly, once they reach significant depths, the trapped radiogenic heat can cause them to reach very high temperatures. Rocks will initially begin to melt above 650 °C, but significant melting doesn't really occur until at least 750-800 °C, depending on the rock type (Vielzeuf and Montel, 1994). The molten material formed at these high temperatures segregates and accumulates to form granites; consequently, granites are common products of collision zones.

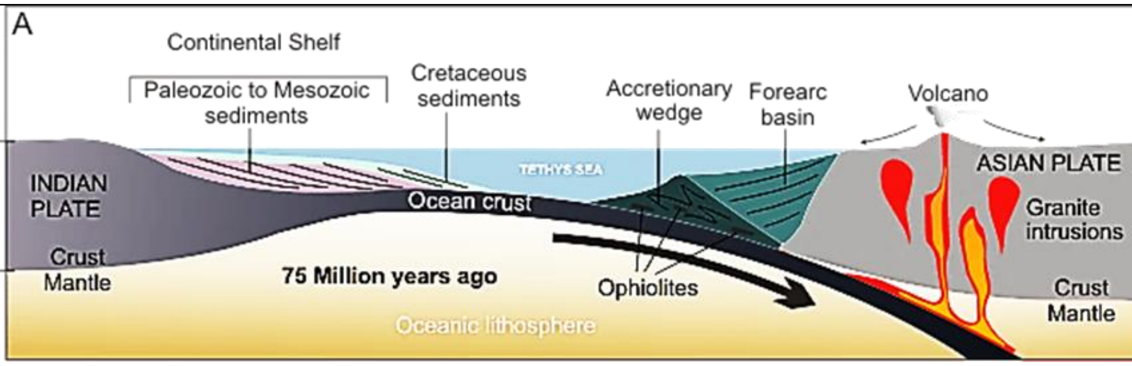
Another effect of the collision of India with Asia is the movement of rocks from the Asian continent laterally to the east and west of the main collision zone (Figure 7). As India has moved northwards it "dented" into Asia, and large blocks of Asian crust have been displaced sideways (Molnar and Tapponnier, 1975; Tapponnier et al. 1986). This lateral movement of large blocks of crust has been accommodated by a number of major strike-slip faults to the west and east that extend into China and Afghanistan (Figure 7).

The collision of India and Asia

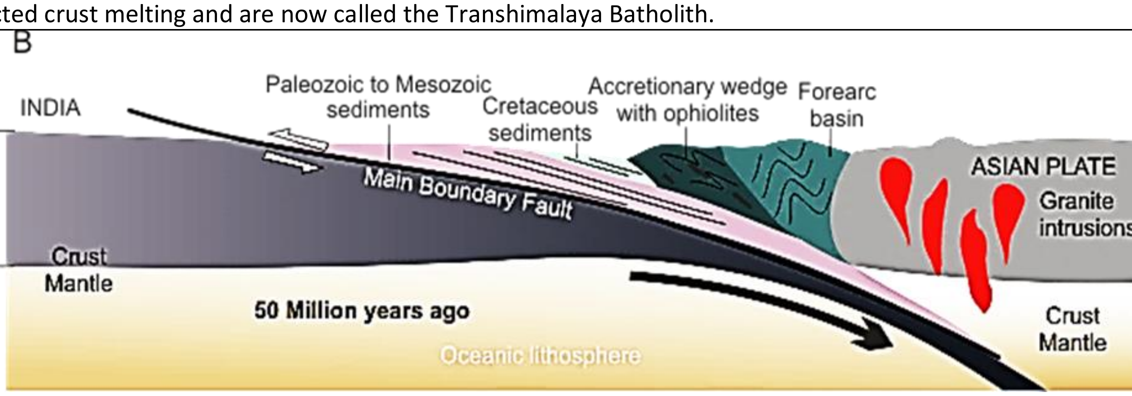
At the onset of the India-Asia collision, the Proterozoic to Mesozoic (541 to 66 million years ago) continental shelf sediments deposited on the northern margin of the Indian continent were thrust below Asia (Box 3, Figure 8A). As these sediments descended to mid-crustal levels, metamorphism to high-grades (granulite facies) caused them to partially melt and become ductile (Figure 8B). These hot, ductile, partially molten rocks then reversed direction and escaped upwards and southwards between two major north-dipping fault planes, the Main Central Thrust (MCT) (Figure 9) and the South Tibetan Detachment (STD) (Figures 8C and 9). Today these form the high-grade metamorphic core (Temperatures of >700°C) to the Himalayan orogen known as the Greater Himalayan Sequence. To the south of the MCT, is the Lesser Himalaya (also known as the Siwaliks), which were formed from the same Proterozoic to Mesozoic sediments but, since they were not as deeply buried (Figure 1.3), they have experienced lower-grade metamorphism (Temperatures of < 600°C). Similarly, to the north of the STD, the Tethyan Himalayas (of which the summit of Everest is part) were formed by Cambrian- (600 to 500 million years ago) to Cretaceous-age (120 to 80 million years ago, Figures 1.3 and 8D) sea floor sediments, which have been subjected to low-grade metamorphism (Temperatures of <600°C). The exhumed high-grade rocks of the Greater Himalayan Sequence are being eroded along the Himalayan Front and deposited in a foreland basin on the Indian Craton (Figure 8C).

Box 3: The collision of India and Asia

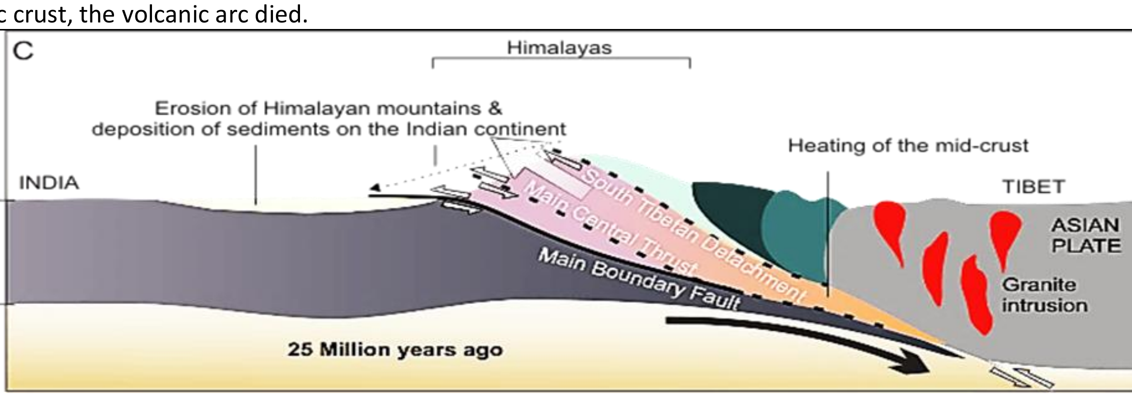
The collision of India and Asia is shown schematically at four different time horizons: Before collision (circa 75million years ago) with the Tethys Sea still in existence; closure of the Tethys Sea between the two continents circa 50 million years ago; the rise of the Himalayan mountains circa 25 million years ago and the landscape today.



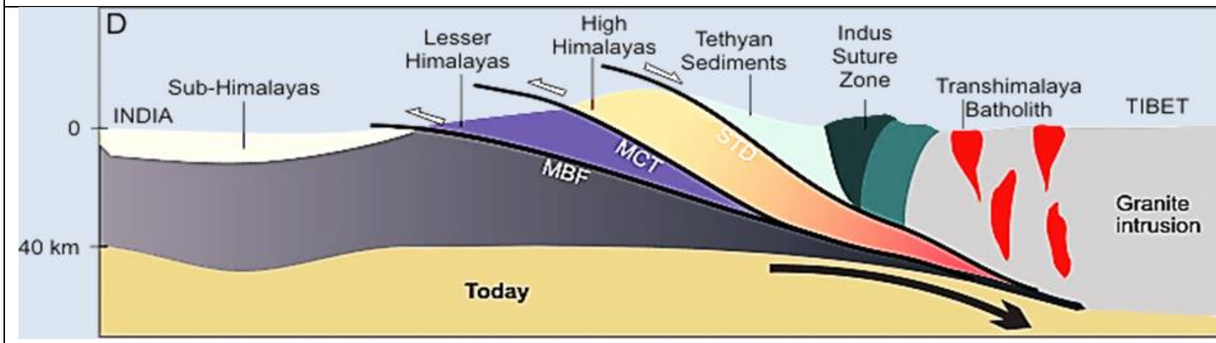
As India approached Asia during the Cretaceous period, sediments were deposited in the shrinking Tethys Sea (on top of older Palaeozoic to Mesozoic sediments) on the continental shelf of the Indian plate. These are different from sediments in the subduction zone accretionary wedge or forearc basin. A Forearc basin developed adjacent to an Andean-type volcanic arc on the Asian Plate, where granites were intruded. Slivers of subducting oceanic crust and abyssal sediments were caught in the accretionary wedge, and today form ophiolites found in the Indus Suture Zone (D). The granite intrusions north of the Himalayas resulted from subducted crust melting and are now called the Transhimalaya Batholith.



By 50 million years ago, the Tethys Sea oceanic crust had been dragged below Asia and continent-continent collision had commenced. This brought sediments from the edges of both continents together and caused the formation of the MBF, along which much of the subsequent movement has occurred. Starved of subducting oceanic crust, the volcanic arc died.



The mountains rise by being squeezed out of a wedge bounded by faults. Collision buried some of the Palaeozoic to Mesozoic sedimentary rocks to mid-crustal depths, where they were folded, deformed and heated to 600 to 850°C. These hot rocks then began to melt, and were extruded southwards out to surface along a channel between the Main Central Thrust and the South Tibetan Detachment.



The Cretaceous sediments deposited in the ancient Tethys Sea now form the Tethyan Sediments of Tibet. The subducted Indian crust became the Indus Suture Zone. Sediments eroded from the rising Himalayan mountains have been deposited on today's Indian Continent as the Sub-Himalayas.

Figure 8: Crustal sections through the collision of India with Asia showing the sequence of events that occurred over 25 million year intervals from 75 million years ago to today (modified after Allegre et al., 1984).

The geology of Tibet and its relation to the Himalayas

The geological evolution of the Tibetan Plateau is a protracted one. During the Palaeozoic and Mesozoic ages (541 to 66 million years ago), the successive accretion of five continental fragments or terranes onto the North China Craton, formed the complex geology underlying what is now Tibet. Each of these terranes extends about 2500 km east-west and between 200 km and 500 km wide north-south, and they are separated by major faults (Figure 10 A and B).

The northernmost of these, the Kunlun Terrane, is a composite batholith originating from two periods of magmatism (Figure 10 A). The initial period took place in the late Cambrian, 490 million years ago (Yuan, 1999), and the second took place between 215 and 210 million years ago (Yuan, 1999)

The Songpan-Ganze Terrane collided with the Kunlun Terrane in the late Permian (260 million years ago). It is associated with the Qiangtang Terrane (Figure 10 A), which was a continental fragment originating from the breakup of Gondwana. In the southward subduction of the Songpan-Ganze terrane, the ocean basin of this terrane formed a volcanic arc on the Qiangtang Terrane (Yin et al., 1999) during the Jurassic (200 – 145 million years ago). Subsequently, the Qiangtang Terrane collided with the Songpan-Ganze Terrane in the late Jurassic-early Triassic (around 200 million years ago; Dewey et al., 1988), becoming part of the Asian continent.

The southernmost terrane underlying the Tibetan plateau is the Lhasa Terrane. It is also a continental fragment from the breakup of Gondwana. It collided with the Qiangtang Terrane in the late Jurassic (Dewey et al., 1988), and was thus the last crustal fragment to accrete to the Asian continent prior to the collision of India with Asia (Figure 10 A).

Today, much of Tibet is like a giant bowl, with mountain belts along its rim and active depositional basins in its centre. Figures 5 and 10B show the margins of the Tibetan basin comprising mountain belts, whilst the centre of Tibet is a depositional basin with rivers draining into the basin and forming lakes. The plateau is elevated due to the erosion of the surrounding high mountains and deposition into the basin.

The main geological units of the area of collision are shown in Figure 10A. From the south, the Indian continent gives way to:

1. The sub-Himalayas and the Siwaliks where Kathmandu is located,

2. The Greater Himalayan Sequence, which is the geological unit that extends from Lukla to Base Camp of Everest

3. The Tethys Himalayas or the Everest Series, which is where Mount Everest is located

4. The Indus Suture Zone and the Transhimalayan Batholiths of southern Tibet

5. The geological terranes of Tibet and north China in the high plateau of Tibet

The main tectonic boundaries that separate the geological units of the area are the Main Boundary Fault (MBF), Main Central Thrust (MCT) and the South Tibetan Detachment (STD) (Figures 8D and 9). Although found south of Lukla and therefore not crossed along the route covered in this guide, the MCT is an important tectonic boundary and played a major role in the exhumation of the Greater Himalayan Sequence (Figures 8D and 9).

The STD is a zone of normal (extensional) movement separating the Greater Himalayan Sequence from the overlying Everest Series rocks of the Tethyan Himalayas; Two major faults define the STD: the Lhotse Detachment and the Qomolongma Detachment (See Stops 11 and 14).

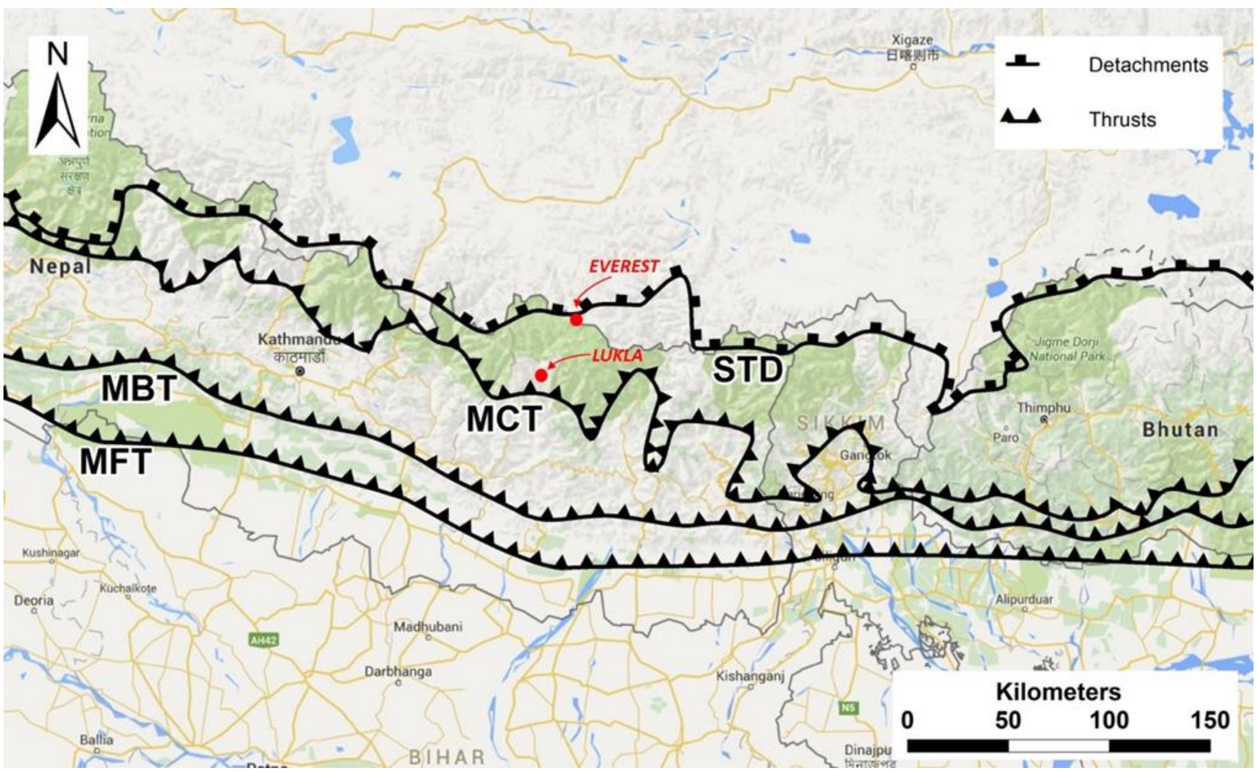


Figure 9: the main tectonic boundaries in the Everest – Lukla area and surrounds (Redrawn over a base map from Google Maps).

The Khumbu Thrust, which is a more recently postulated fault (Searle, 1999a), and shown in Figure 11, is found in the upper portions of the Greater Himalayan Sequence and located at the base of a series of leucogranite intrusions the Lhotse Detachment. These large scale faults are all east-west striking and dip northwards at shallow angles, sub-parallel to the northward dip of the strata of the Himalayas.

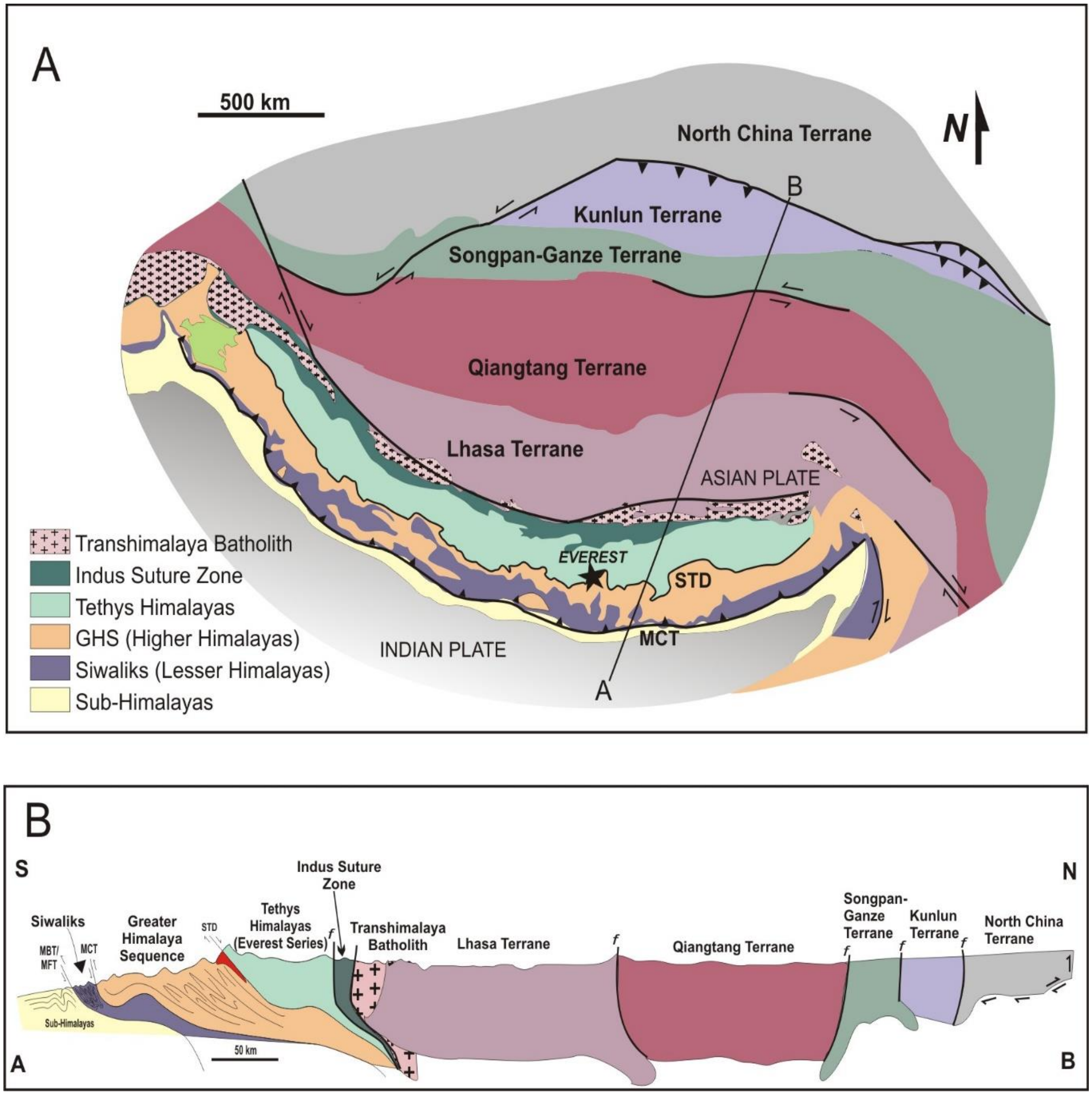


Figure 10 A and B: Geological map and cross section of the area from south (India) to north (China) showing the South Tibetan Detachment (STD), Main Central Thrust (MCT) and Main Frontal Thrust (MFT), sometimes called the Main Basal Thrust (MBT) and the main geological features including the Greater Himalayan Sequence, Everest Series, the and the terranes in Tibet and China in relation to Mt Everest.

The geology between Lukla and the summit of Mt Everest

Along the trek to Everest Base Camp, and further to the summit of Mount Everest, the traveller walks through the upper portions of the Greater Himalayan Sequence, consisting of gneiss and schist, followed by the Himalayan leucogranites and finally, the Everest Series schists and carbonates near the summit of Everest (shown in maps 1-4). The geology of 14 stops along this route is described, starting from Lukla and ending on the summit of Everest. Following a short introduction and description of each locality, the reader is introduced to the geological theme and highlights of each stop.

The town of Lukla in eastern Nepal is the start of most expeditions to Everest and the surrounding mountains. Geologically speaking, this town is situated almost midway between the Main Central Thrust (MCT), which lies to the south, and the South Tibetan Detachment (STD), to the north of Lukla (Figures 9 and 10). Between the STD and MCT is what is known as the Higher Himalaya, or Greater Himalayan Sequence, a suite of high-grade metamorphic rocks which have been rapidly exhumed (raised to the surface) from beneath the Tibetan Plateau though a process known as Channel Flow (explained in Stop 10).

As one treks northwards from Lukla through the Greater Himalayan Sequence toward Everest, the geology of the first five stops in this guide (Lukla, Phakding, Namche Bazaar, Pangboche and Ama Dablam Base Camp) is dominated by the Greater Himalayan Sequence. Typically, the rocks one sees are gneiss, schist and migmatite, with pegmatite and leucogranite locally found. The gneiss and schist commonly contains large amounts of sillimanite, indicating that these rocks were formed at high temperatures (above 500°C), with a greater range of pressures indicating depths of burial of up to 48km) from a source rock rich in aluminium, probably a clayey (muddy) type of sediment. Although evidence of eclogite-facies metamorphism (rocks which were exposed to very high pressures with burial to depths of around 45 km) is found in the Greater Himalayan Sequence, these outcrops are found further East in Nepal and are not encountered on this trail.

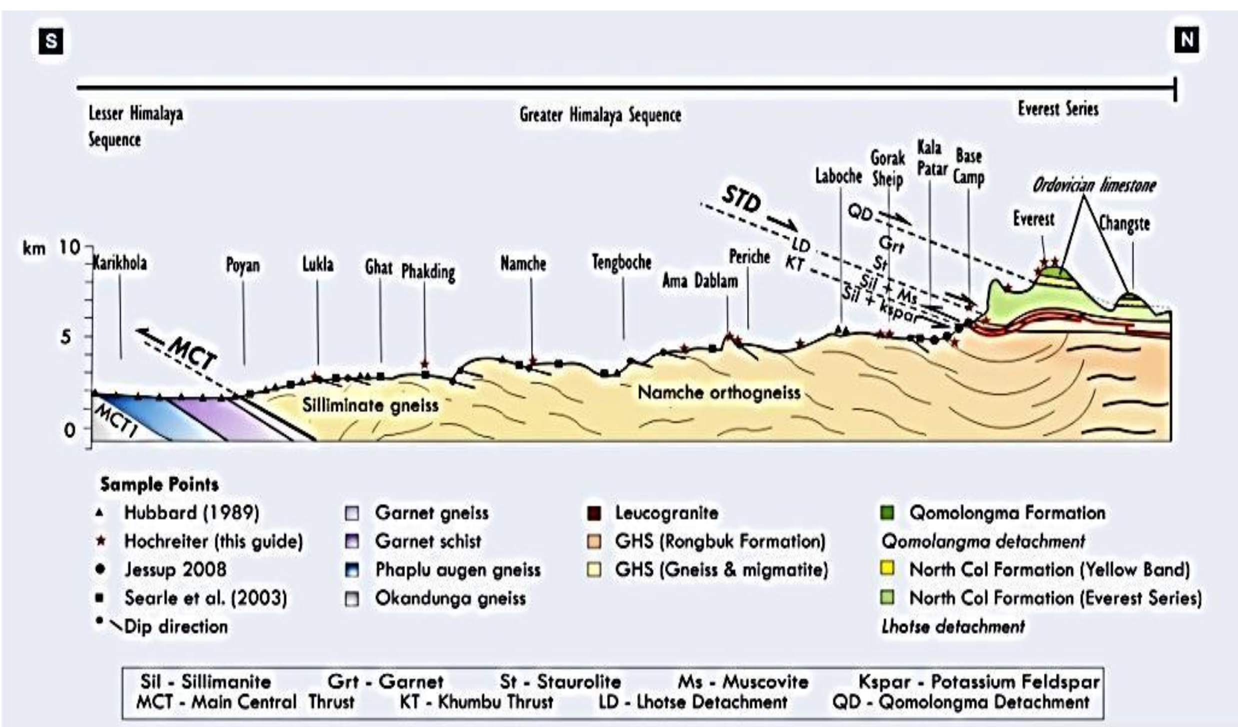


Figure 11: Geological cross section of the Everest massif, Tibet-Nepal (modified after Jessup et al., 2008).

Migmatite (partially melted rock) is common along the route especially above Namche Bazaar (Figures 2.2 and 4.5). With migmatite, melting is commonly accompanied by deformation, leading to preferred orientations of light coloured (leucosome) veins and a strong (tectonic) fabric. The contrast between the generally light colour of the leucosomes and the darker residual rocks (typically sillimanite-biotite gneiss) generally makes migmatites visually striking, and easily noticeable.

Surrounding Base Camp, leucogranite intrusions (Figures 10.3, 10.4 and 10.6) associated with sheeted sills and dykes are common. Across the Khumbu glacier from Base Camp, there is an excellent example of a leucogranite outcrop containing sillimanite-biotite gneiss inclusions. This site is easily accessible from Base Camp (Figure 10.6).

The concept of Channel Flow (Box 10.1) also helps to explain how these rocks come to be on the surface, directly beneath the sedimentary rocks that comprise the summit of Mt Everest. The granite zone is capped by the Lhotse Detachment.

Throughout the Western Cwm, the leucogranite dominates up to the base of the Lhotse face. Here the traveller enters the Everest Series rocks near the South Col, which extend to the summit of Everest (Figure 12). From Camp 2 one crosses the gneiss (intruded by leucogranite), schist and mylonite (a rock fault type found in faults) of the Rongbuk Formation, followed by the North Col Formation pelitic (clayey) rocks, and the slaty rocks on the South Col (Figure 12), which marks the location of the Lhotse detachment.

Above this, limestones occur, capped by the famous Yellow Band, which is a limestone that has weathered to a yellowish colour. At the top of the Yellow Band is the Qomolongma detachment and from here to the summit, the rocks are made up of limestone and marble. The geologist-traveller should keep an eye out for evidence of fossils, starting from Stop 12.

In Figure 12 the main geological features are superimposed on a sketch of Mount Everest: Everest Series. The summit of Mount Everest is composed of limestone, and is called the Qomolongma Formation. This formation is separated by the Qomolongma Detachment (QD) which is located at the top of the yellow Band. Below the Yellow Band is the Rongbuk Formation which extends to the Lhotse Detachment (LD).

Higher Himalayan leucogranite, a thick layer of light grey granite, underlies the Everest Series from the LD downwards. A layer of dark sillimanite-biotite gneiss, a metamorphic rock at the top of the Greater Himalayan Sequence, underlies the leucogranites, and is separated from the leucogranite by a major fault called the Khumbu thrust (KT).

This sequence of sedimentary rocks (the limestone of the Everest Series), the igneous rocks (the leucogranite) metamorphic rocks (the dark gneiss) separated by a number of faults (normal faults or detachments and reverse faults or thrust faults) are the result of the Indian Craton having been buried beneath Tibet and then subsequently exhumed by a process known as Channel Flow. This exhumation, enhanced by high rates of erosion in the Himalayas, has resulted in these deeply buried rocks now being found on the surface.

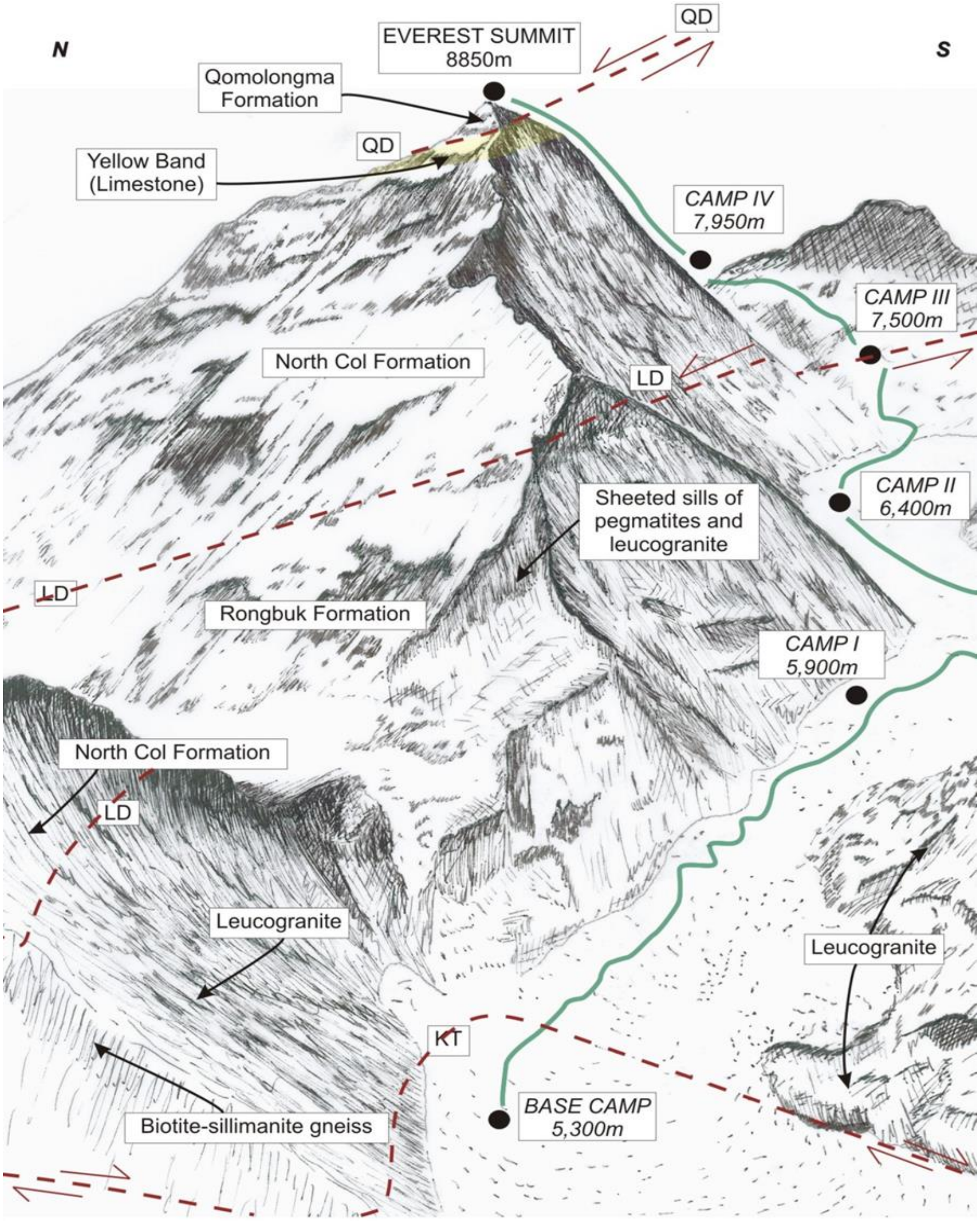


Figure 12: The main features of the geology of Mt Everest. Metamorphosed limestone sedimentary rocks of the Qomolongma Formation form the summit. The Qomolongma Detachment (QD) separates these limestone rocks from underlying metamorphosed mudstones and limestones of the North Col Formation. Both of these formations are part of the Everest Series, and were originally deposited on the floor of the Tethys Sea. They extend from summit of Everest to the Lhotse Detachment (LD), a fault which separates them from the underlying sheeted sills of pegmatite and leucogranite of the Rongbuk Formation. Near Base Camp, the Khumbu Thrust fault (KT) marks the start of underlying dark sillimanite-biotite gneiss of the Greater Himalayan Sequence. These features all dip to the north at about five degrees.

Stop 1: Lukla: The most dangerous airstrip on Earth

Alt: 2,840 m

North: The Khumbu Valley with 6,000 m high peaks

East: A vegetated mountainside of granite gneiss

South: The Khumbu valley and the foothills of the Himalayas

West: Crystalline granite Gneiss Mountains around 5,000 m high

Distance to next Stop: 8km

After a week in Kathmandu, making last minute purchases and psyching up for the start of the trek, it is a relief to land safely in Lukla (Maps 2 and 3). The tiny airstrip landing is always an adrenalin rush, especially if there is cloud about (Figure 1.1). On stepping out of the legendary Twin Otter airplane with its short take-off and landing ability, the air is palpably thinner than the soup of Kathmandu. The grandeur of the Himalayas hits one between the eyes. Massively high peaks tower 6,000 m above sea level and great walls of rock some 2,000 m high, with glistening white snow at their summits, dominate. This is the start of our trek through the geological history of two colliding continents. In Box 1.1 the geological processes resulting from the collision of India and Asia are explained and the resulting stratigraphy and the major faults and thrusts of the area are introduced.

Figure 1.1: Westward view of the world famous landing strip at Lukla, angled at 15° with a deep gorge at the west end and a vertical mountain face on the east end. Unlike above 4000m, the slopes are heavily vegetated.

The Greater Himalayan Sequence extends from Mount Everest southwards the town of Lukla. It comprises a crystalline gneiss sequence (Lukla Granite Gneiss) approximately 10 km thick \\\metamorphic minerals including sillimanite, biotite, kyanite and staurolite. These are highly deformed rocks which show evidence of intense folding, plastic deformation and melting. Recumbent folds with horizontal fold axes and shallow, north-dipping fold planes occur in the Greater Himalayan Sequence with limbs from a few centimetres to many kilometres in length. The northern limit of the Greater Himalayan Sequence occurs on the slopes of Mount Everest itself.

Box 1.1: Age of the Himalayas and introduction to the stratigraphy of the area

To put the age of the Himalayas into perspective, Figure 1.2 shows the important events in the Earth's history. The Earth was formed 4.55 billion years ago. The Himalayas are amongst the youngest mountain chains in the world, having been formed between 50 million years ago and the present. The rocks on the summit of Everest are older, between 600 million years ago and 440 million years ago, but the collision of India and Asia to form the Himalayas only began about 50 million years ago (Jameison et al. 2004). The metamorphism of the Greater Himalayan Sequence following collision took place between 50 and 12 million years ago, and the formation of the granitic rocks below the slopes of Everest occurred between 32 and 5 million years ago, having only been exhumed back to surface from 13 million years ago.

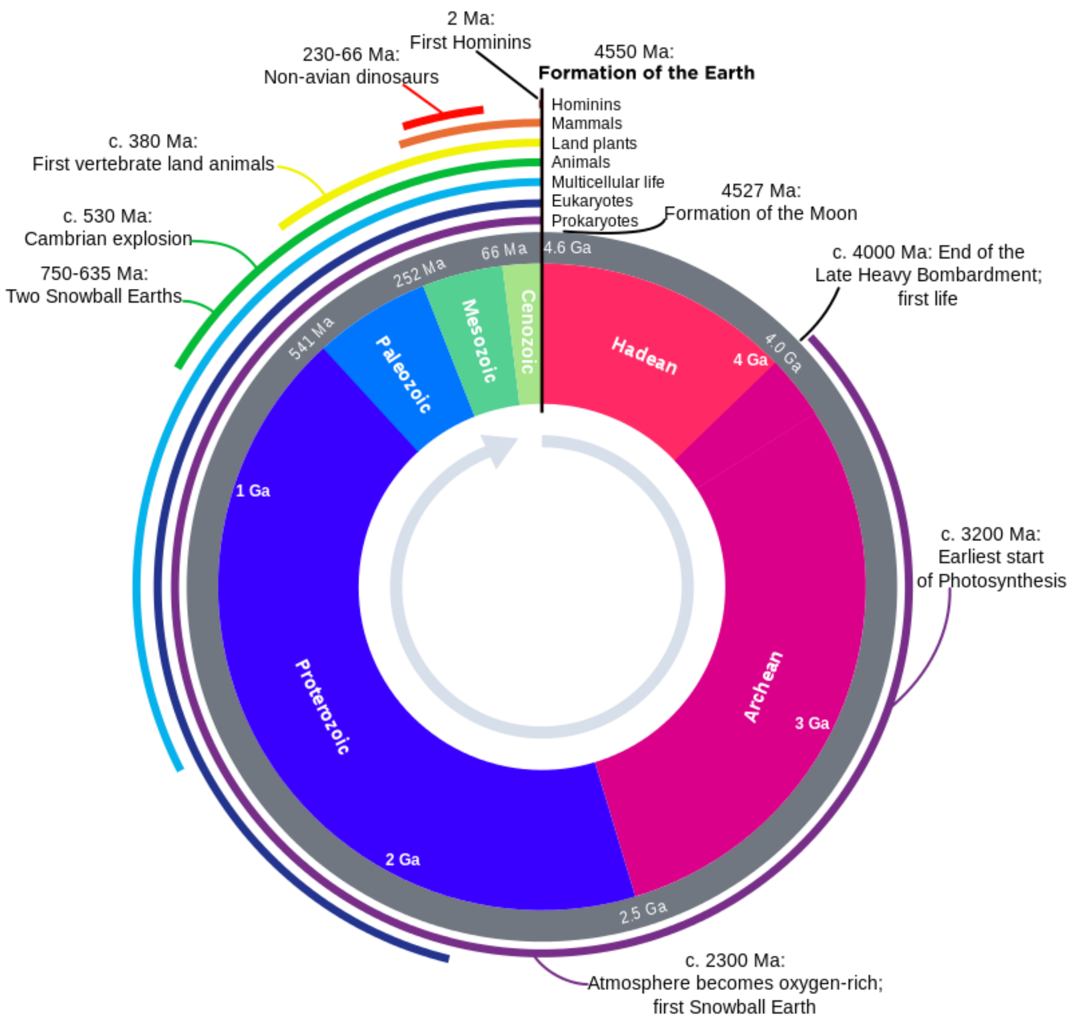


Figure 1.2: Important events in geological time. The Himalayan rocks originated from the late Proterozoic to early Paleozoic eras, through the Cambrian and Ordovician eras (Figure 1.3) and through to the Mesozoic and Cenozoic eras.(Source:https://upload.wikimedia.org/wikipedia/commons/7/77/Geologic_Clock_with_events_and_periods.svgWikipedia).

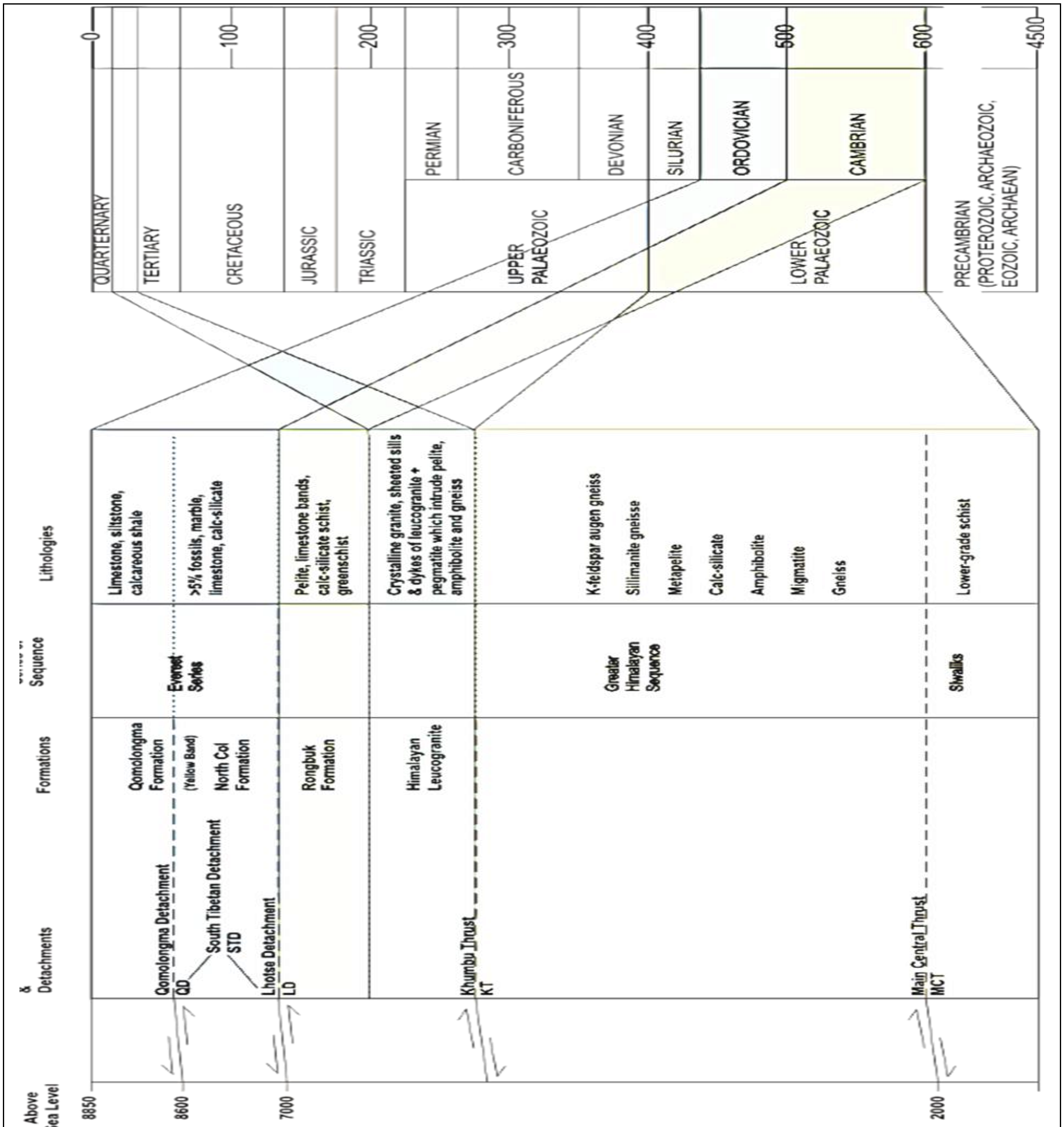


Figure 1.3: Stratigraphy of the area from Lukla to the summit of Mount Everest, shown in relation to the geological timescale. The main rock sequences are separated by three main faults (detachments and thrusts). This faulting has resulted in the oldest rocks appearing at the top of the mountains with younger rocks beneath them. The youngest rocks, the leucogranite, abut against the Cambrian rocks of the Rongbuk Formation. The Greater Himalayan Sequence extends from the Leucogranites down through the Main Central Thrust into the Siwaliks. Beneath the Siwaliks, the Precambrian rocks of the Indian continent occur.

Near the top of the GHS, a sillimanite-rich gneiss located just below the augen gneiss differs from the gneisses closer to the base of the GHS and in the Siwaliks in that the latter have little or no sillimanite in them. Figures 1.8 (granite gneiss) and Figure 3.6 (sillimanite biotite schist and gneiss) show the difference between the two rock types.

The lower portion of Everest consists of high-grade gneisses of the Greater Himalayan Sequence and Higher Himalayan leucogranites, whilst the upper parts of the mountain are made up of the lower-grade metasediments of the Everest Series. The two are separated by the STD, a zone which comprises the Qomolongma Detachment at the top of the famous “Yellow Band” and, further down, the Lhotse Detachment (Figure 1.3). The Greater Himalayan Sequence and the Everest Series have been further sub-divided into the Rongbuk, North Col and Qomolongma Formations. The Rongbuk Formation lies below 7000 m altitude and is part of the Greater Himalayan Sequence which extends southwards to Lhotse (Map 4). It consists of sillimanite and K-feldspar gneiss which has been intruded by sills and dykes of leucogranite. It is separated from the North Col Formation by the Lhotse Detachment (part of the STD).

The North Col Formation extends from the North Col (7000 m) to the top of the Yellow Band at 8600 m elevation and consists of limestone, marble and calc-silicate. The lower parts of this formation consist of deformed marble and schist. These rocks are the products of low-grade metamorphism of a deep-sea flysch deposit (mudstone, clayey sandstone, greywacke and sandy limestone). The upper part of the North Col Formation consists of the distinctive Yellow Band, a 400 m thick unit of middle-Cambrian rock comprising marble and phyllite that has weathered to a distinctive yellow-brown colour. It is estimated that 5% of this unit is composed of recrystallized crinoid ossicles or other fossils. The North Col Formation has a tectonic contact along the Qomolongma Detachment with the overlying Qomolongma Formation. This uppermost unit extends from 8600 m to 8850 m, and is composed of Ordovician limestone, calcareous shale and siltstone (Figure 1.3). The top 10 m of Mount Everest comprise deformed re-crystallised calcite with cubes of pyrite (iron sulphide) and traces of carbonaceous matter, possibly from re-existing fossils (Figures, 14.3 and 14.4).

General geology along the route

A cross section of the route from Lukla to Namche Bazaar is given in Figure 1.4. It traverses mainly gneissic, highly deformed rocks of the Greater Himalayan Sequence.

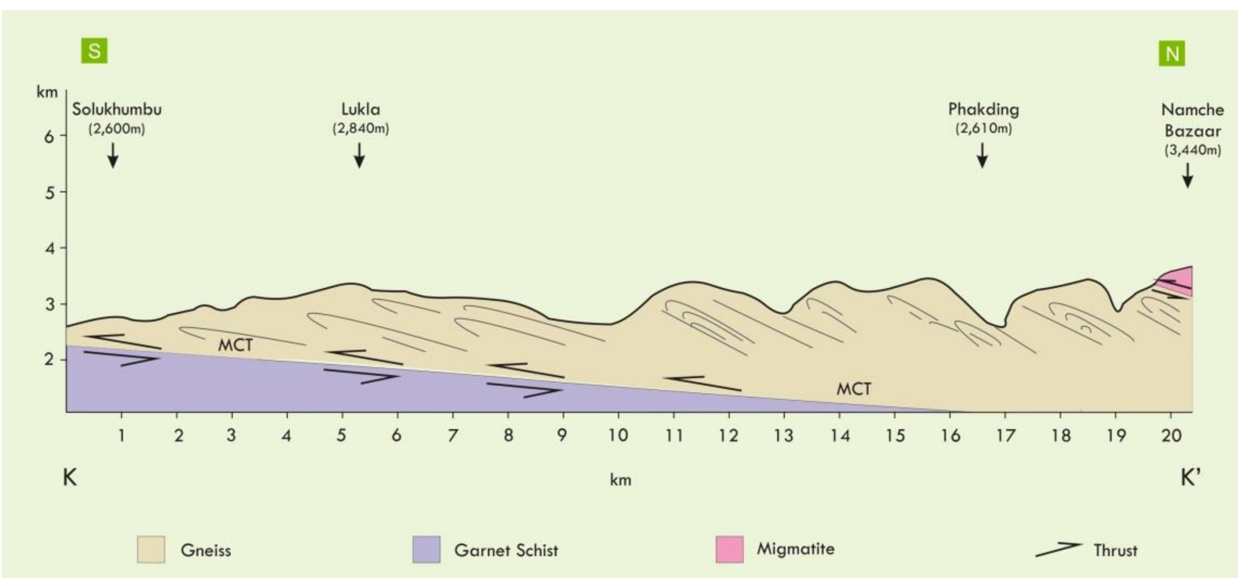


Figure 1.4: Cross section K-K’ (Map 3) - a cross section from Lukla through Phakding to Namche Bazaar.

The Main Central Thrust lies 5 km south of Lukla (Figure 1.5) and is the main thrust fault marking the base of the Greater Himalayan Sequence. Several smaller faults or thrusts are found throughout the gneisses of the Greater Himalayan Sequence, with the Khumbu Thrust being the main thrust near the top of the Greater Himalayan Sequence.

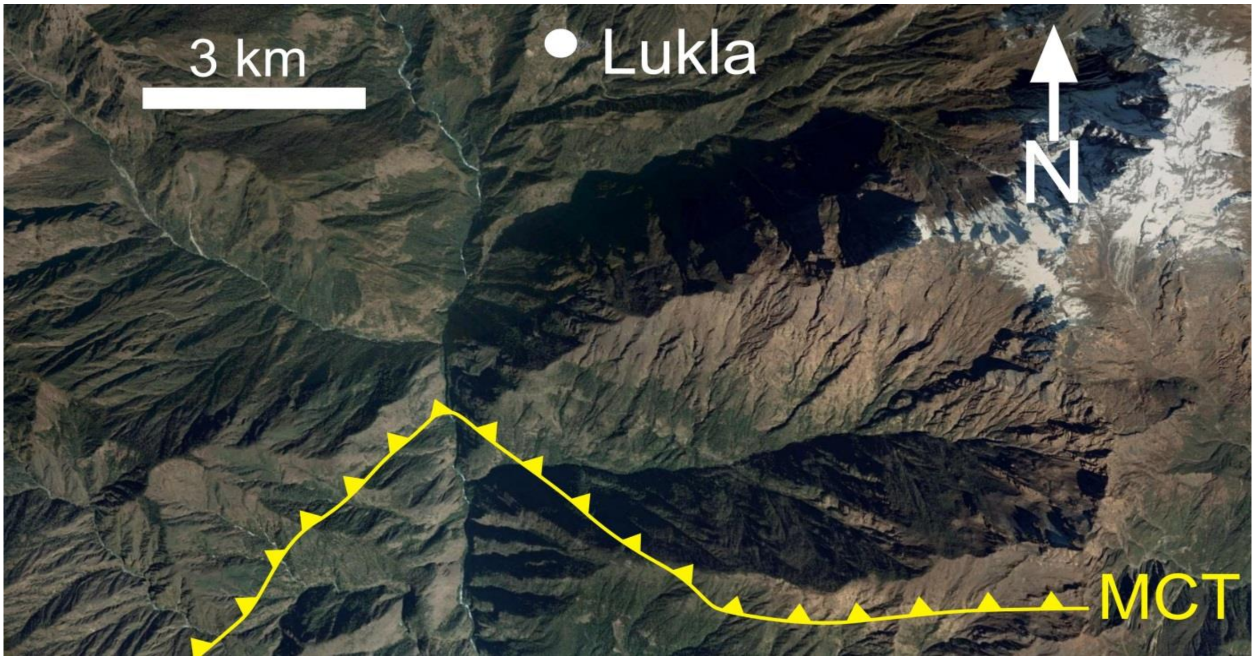


Figure 1.5: A Google Earth view of the Main Central Thrust (MCT) 5 km south of Lukla. The MCT is one of the main faults in the Himalayas along which most of the movement of the buried Indian continent has taken place (the others are the Indus Suture Zone, the South Tibetan Detachment and the Main Boundary Fault). It strikes east-west and dips to the north at a shallow 5° angle. The barbs along the fault line point to the rocks above the MCT. It is best seen when leaving Lukla as the aircraft flies at a lower altitude on the way back to Kathmandu.

As one walks through the streets of Lukla, one sees that most of the houses are built with hand-hewn bricks of granite gneiss typical of the Greater Himalayan Sequence (Figure 1.6). Examination of these bricks shows typical crystalline gneiss with distinct bands of lighter and darker minerals. The dark minerals (biotite) are aligned to form a planar fabric whilst the minerals quartz (clear), and K-feldspar (milky white) and plagioclase grains (white) form the lighter coloured parts of the rock. Quartz and the feldspars form poikilitic grains (i.e. grains of different minerals within a larger different mineral grain). Quartz-feldspar intergrowths are found, as well as numerous grains with irregular grain boundaries. These suggest that the rock may have partially melted during high-grade metamorphism. Large poikilitic grains may be up to 5 mm in size (Figure 1.8), whilst other minerals are less than 1 mm in size. Both strained and unstrained quartz found in the rock (Figure 1.8), indicate that the rock has experienced deformation. Folds are also evident and some zones in the rock have been melted to form leucosomes. Some pegmatite dykes, and structures such as micro-faulting and boudinaged (stretched) pegmatite veins, are also visible. These gneisses were formed at pressures and temperatures of 4-6 kbar and 650-750°C, resulting from the burial of the Indian continental crust to about 25 km depth during collision. The original rocks that were metamorphosed into these gneissic rocks were deposited in the forearc basin of the Indian Plate (Figure 8A), buried (Figure 8B) and then exhumed (Figure 8C).

The origin of the GHS rocks is likely to have been northern Indian continental crust, which has been dated at around early Palaeozoic age (± 500 million years in age) (Jameison et al. 2004).

Figure 1.6: Examples of gneiss and migmatite: the bricks in the houses built Lukla, Phakding, Namche Bazaar, Pangboche and other villages show the intensely folded and banded gneissic textures of high-grade metamorphic rocks.

Examination of the granite gneiss (Figure 1.8) shows zones of lighter and darker minerals with a strong directional orientation. The white and glassy minerals are feldspar and quartz; the darker grey/black mineral is biotite.

The beautiful granite peaks surrounding Lukla are like a magnet to the eyes. The high peaks and in fact, the entire mountain chain's topography are a product of the interaction between very high rates of erosion and the rapid uplift of the mountain chain. As the rocks are uplifted, the extreme weather of the Himalayas causes them to be carved into deep valleys and soaring peaks. One often hears rockfalls, a sign of the active erosion in these mountains. The high erosion rates help to accelerate the exhumation of rocks by decreasing friction along thrust planes. The relationship between erosion and rapid exhumation is explained in Box 1.2.

Box 1.2: Age of the Himalayas and introduction to the stratigraphy of the area

In order to maintain the dynamic equilibrium of the orogenic wedge, the high rate of erosion in the Himalayas is balanced by high rates of uplift and exhumation (Malavielle et al., 2008). Because of the gravitational instability of mountain belts, as a mountain gets higher (because of underplating), there will be an increase in the rate of erosion to balance this mountain growth. If the rates of erosion were lower, the higher friction on thrust planes would result in slower exhumation of buried rocks, lateral spreading would occur and higher mountains would result. Exhumed wedges may contain stacks of thrusts (Figure 1.7). In the Himalayas, many low-angle, northwards-dipping planes are observed in the Greater Himalayan Sequence, which may have resulted from such a wedge-stacking process. The rate of exhumation, which is typically between 2 and 4 cm/year in most orogens, is estimated at 5 to 7 cm/year in the Everest region (Malavielle et al., 2010).

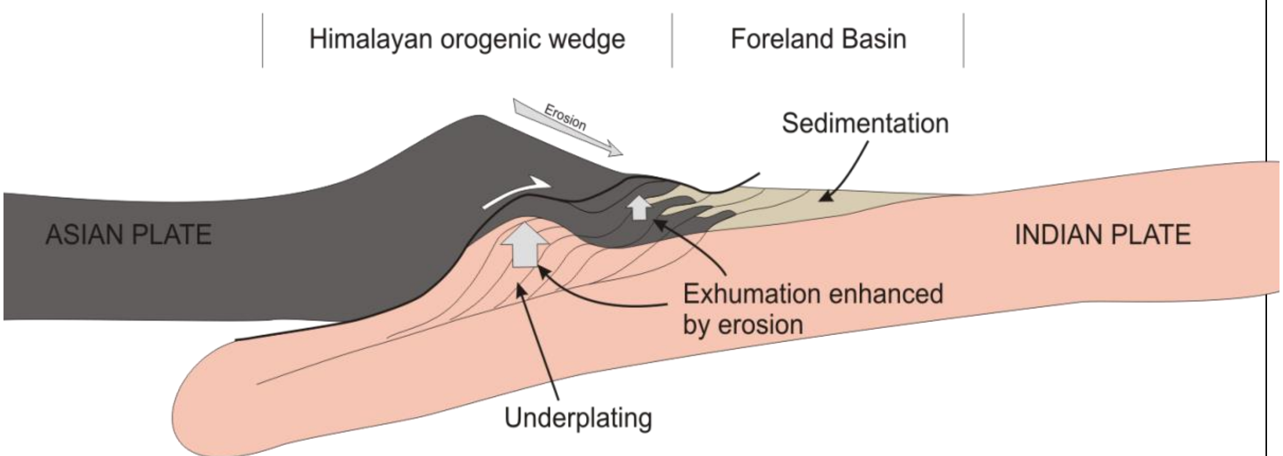


Figure 1.7: Interaction between surface processes and exhumation in orogenic wedges. High rates of erosion allow underplated crust to be exhumed more rapidly along thrust planes (after Malavielle et al. 2008).

Granite gneiss

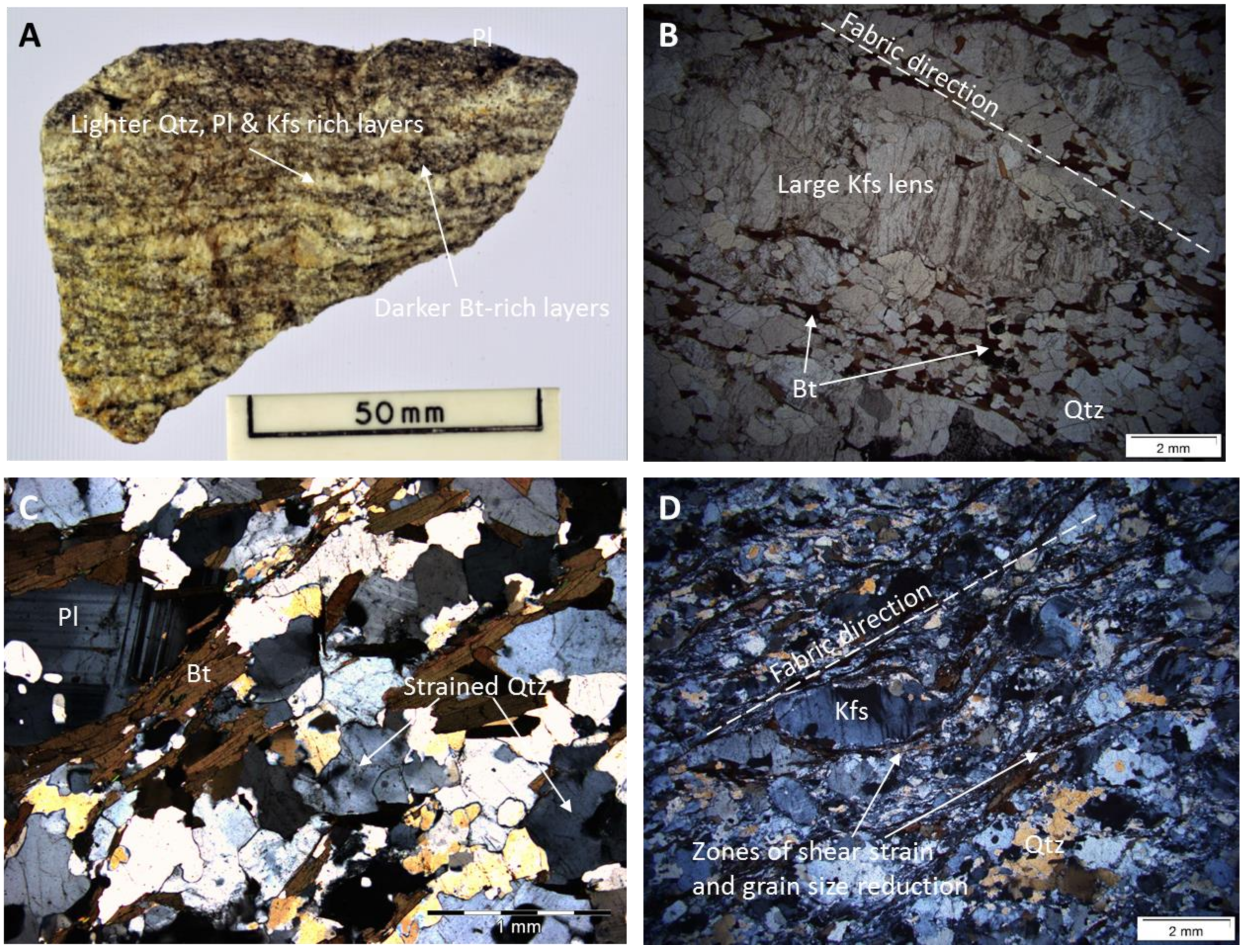


Figure 1.8: The main rock type along the route between Lukla and Phakding is granite gneiss. A – hand sample of granite gneiss collected near Lukla. Note the banding of darker minerals (typically biotite) and lighter minerals (quartz and feldspar) – this is known as gneissic banding is characteristic of gneiss. B – photomicrograph (plane light) of granite gneiss. Note the large grain of K-feldspar (Kfs) which forms a lens surrounded by the fabric, defined by aligned biotite (Bt) grains. C – photomicrograph of granitic gneiss) showing evidence for strain – strained quartz (Qtz) which is the result of deformation of the crystal structure of the quartz caused by strain. D – photomicrograph showing an intensely strained and sheared gneiss. Strained quartz has a wavy, irregular pattern of extinction under the microscope, whilst unstrained quartz grains show regular extinction. Note the strong fabric surrounding a lens of K-feldspar (Kfs), surrounded by the fabric. Unlike image B, the fabric is more intense, with grain size reduction and a strong alignment of minerals caused by intense strain in zones of shear.

Stop 2: Phakding: Welcome to the highest mountains on Earth

Alt: 2,610m

North: Khumbu Valley

East: Vegetated mountainside of gneiss

South: Khumbu Valley and Kusum River

West: Granite gneiss mountains

Distance to next Stop: 8km

From Lukla (2,840 m), trekkers walk to Phakding (2,610 m) and spend their first night on the trail in this picturesque town (Maps 2 and 3). The trail crosses some long suspension bridges, high above the swirling waters of the Dudh Kosi, the river in the Khumbu valley. The air is thin compared to Kathmandu, but this is the thickest it will be on this trail. The vegetation is prolific, owing to the high rainfall. Rhododendrons in red bloom cover the hillsides. At Phakding, Nupla (5,880 m) dominates the west view. As this section of the route is traversed, massive boulders of banded granitic gneiss are seen in the rivers. These are examples of the so-called Namche migmatites, found in the lower (southern) part of the Greater Himalayan Sequence. Large south-verging folds can also be seen on the slopes of the high granite peaks west of Phakding. These folds are associated with the exhumation of the Greater Himalayan Sequence, and many of these folds may be examples of nappe structures that form when wedges of rock are exhumed along thrust faults.

In Box 2.1 an explanation is given of how both the Greater Himalayan Sequence and the Everest Series rocks were deformed through two deformation episodes, the fabrics resulting from the deformation (called C and S fabrics) and the inclusions of eclogite and granulite in the sillimanite-biotite gneiss which show that they were buried to great depths before being brought back up to surface (exhumed).

General geology along the route

The massive boulders of banded granite gneiss in the rivers along this part of the route are examples of the Namche migmatite shown in the photographs below where metapelite (metamorphosed mudstone) rocks in the Phakding area show migmatitic textures (Figure 2.2) with signs of partial melting. The white veins (leucosomes) in the photo show a central quartz zone, flanked by feldspar, in turn flanked by darker biotite- and amphibole-bearing zones. This alignment of darker and lighter minerals occurred during D_1 deformation and is related to the burial and high-temperature metamorphism of the Greater Himalayan Sequence. The fabric formed is the S_1 fabric. The folding of the leucosomes indicates that deformation occurred whilst rocks were in a hot, plastic state. Deformation also continued after the rocks solidified as brittle deformation is also evident, with crenulation textures present in some parts of the rock. This is related to D_2 deformation when the Greater Himalayan Sequence was being exhumed (Figure 2.3).

Box 2.1: The two deformation episodes named D_1 and D_2

Both the Greater Himalayan Sequence and the Everest Series were buried during the collision between India and Asia (Figure 8A), and have been exhumed (Figure 8C). Although the depths of burial were greater for the Greater Himalayan Sequence (the presence of eclogite lenses indicates burial to > 45 km for the GHS), the deformation histories of both rock units are similar, and record both burial and exhumation.

During burial, the original sedimentary layering in the rocks was intensely folded and sheared, and low-grade metamorphic minerals (such as biotite and muscovite) were aligned to form a fabric. This deformation event is known as D_1, and the fabric formed is known as S_1 (see Glossary). At the peak of metamorphism (i.e. following burial) later metamorphic minerals grew over this fabric and evidence of the D_1 deformation event is only preserved in the cores of these minerals.

During the exhumation of these buried rocks, another episode of shearing took place. Deformation features produced during this event have deformed and rotated earlier-formed metamorphic minerals. This event is termed D_2, and the tectonic fabric formed during the event is referred to as S_2.

Owing to the pervasive presence of D2 deformation in rocks of the Greater Himalayan Sequence and Everest Series, few D_1 features are visible in the field. Near the base of the Greater Himalayan Sequence, the Namche Migmatites have S-C fabrics (Figure 2.1) indicating a top-to-south movement over the underlying Siwaliks and which is related to exhumation during the D_2 event (Figure 2.1). Similarly, extensional shear bands related to D_2 deformation indicate a top-to-north movement near the top of the Greater Himalayan Sequence (Figure 2.1).

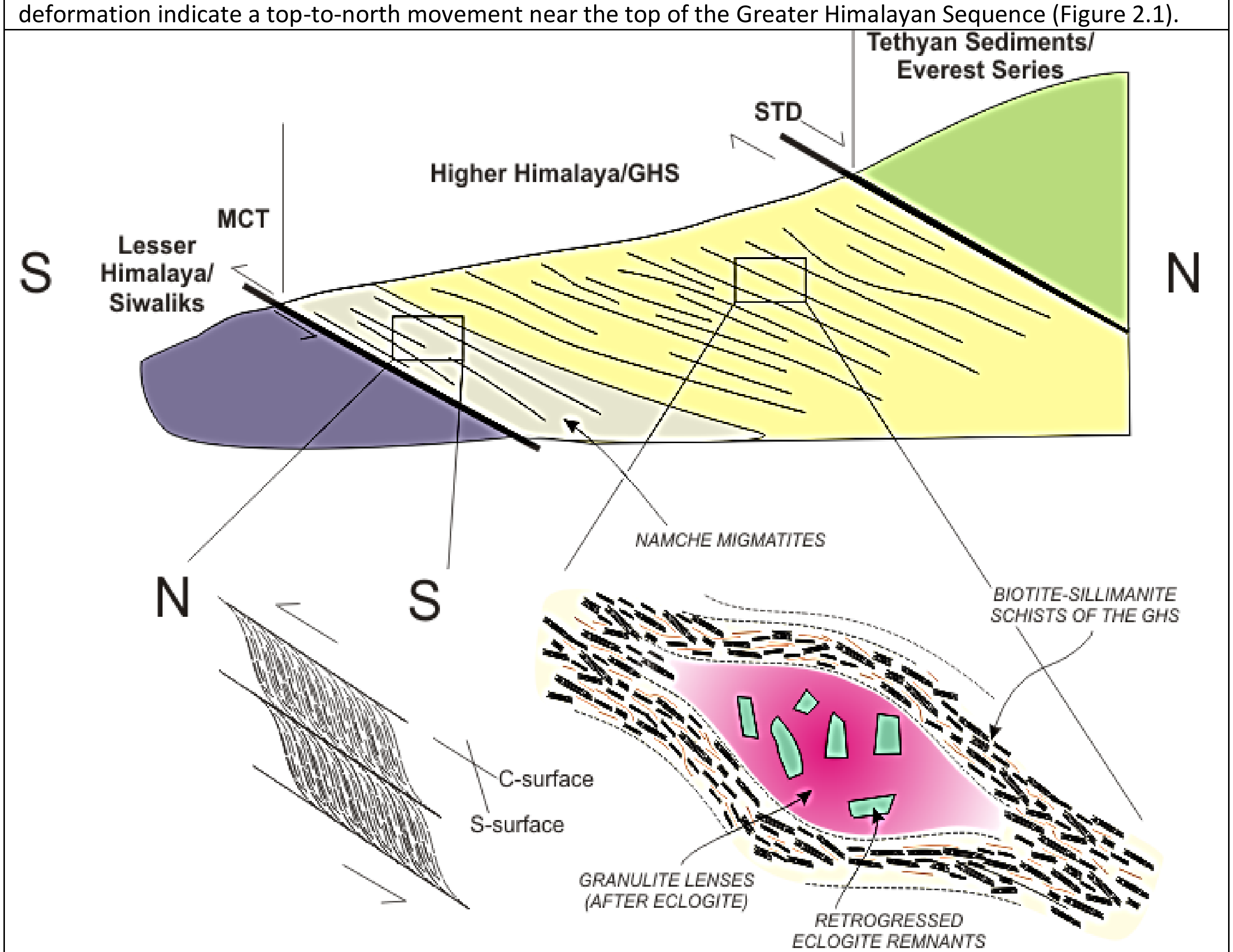


Figure 2.1: Schematic cross section through the Greater Himalayan Sequence showing the key relationships between deformation and metamorphism. An S-surface ("Schieferung" from the German) refers to foliation, either bedding or cleavage, and a C-surface ("cisaillement" from the French) refers to shear fabric.

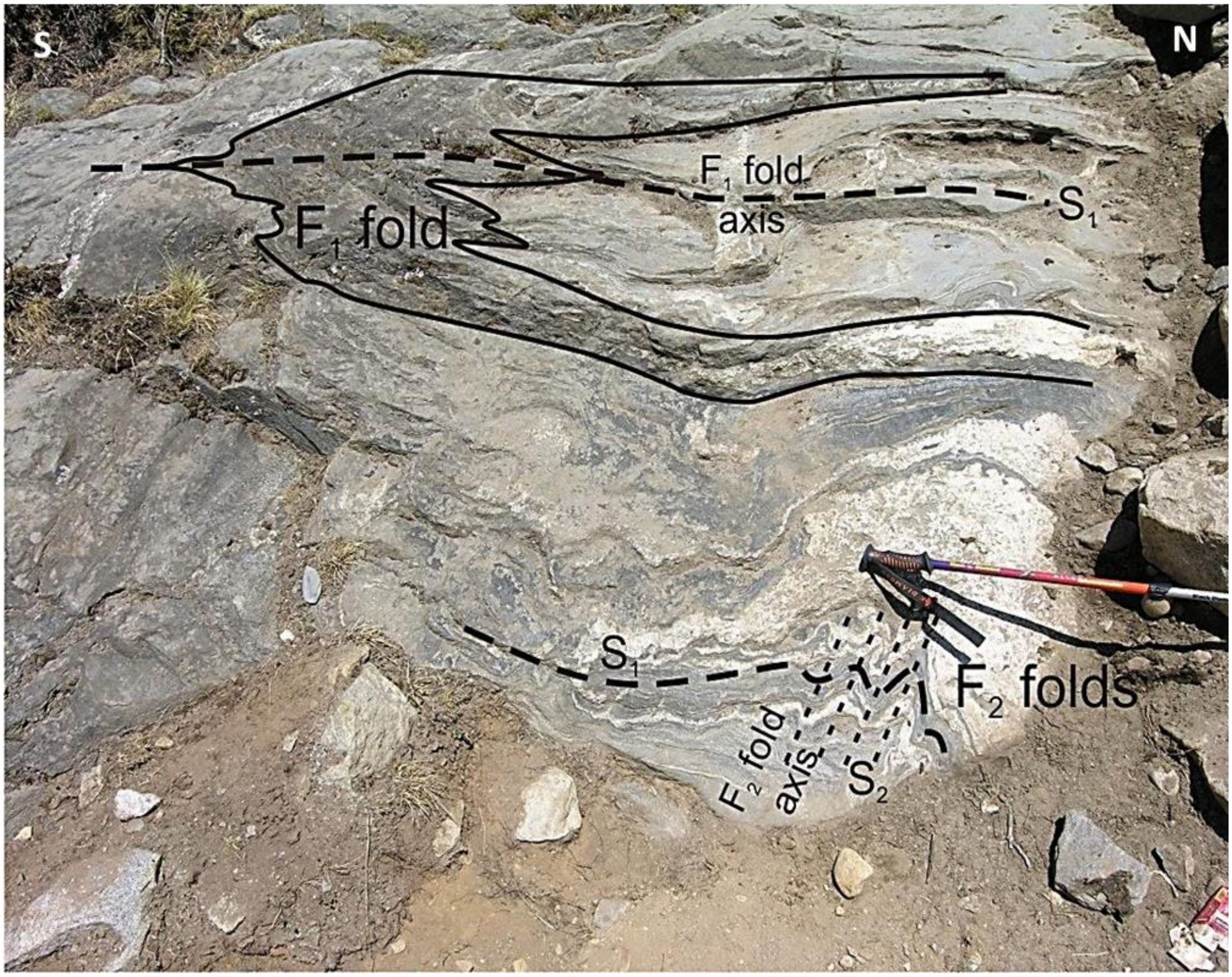


Figure 2.2: Example of the Namche migmatite. There are two generations of folds in this outcrop, an early recumbent fold and S_1 axial-planar fabric and an upright S_2 overprint, which can be seen in the lower right hand side of the outcrop, as indicated. The upright F_2 folds can be seen as indicated. The handle of the hiking pole is 14 cm in length. Photograph taken at GPS co-ordinates 27°48'57.14"N, 86°43'50.53"E.

Figure 2.3: In this boulder, which has rotated clockwise by an estimated 25° (faults generally dip between 5° and 15° north in the GHS and Everest Series), a recumbent fold occurs in quartz-feldspar-biotite gneiss south of Phakding. A thrust plane visible at its base shows vergence of the fold to the south. This folding and faulting is part of the D_2 deformation event in the Greater Himalayan Sequence which is related to exhumation of the Greater Himalayan Sequence along the Main Central Thrust. The handle of the hiking pole is 14 cm in length. *Photograph taken at GPS co-ordinates 27^{o}42'57.27"N, 86^{o}42'46.51"E. Length of handle of walking pole is 12cm.*

Stop 3: Namche Bazaar: First view of the Everest massif

Alt: 3,440 m

North: A peak (Khunde 3840 m) composed of sillimanite-biotite gneiss

East: Everest, Ama Dablam and other peaks (seen from the ridge above and east of Namche Bazaar) composed of limestone (Everest) and leucogranite (Ama Dablam)

South: The Khumbu Valley

West: High crystalline granite peaks of Nupla and Kongde Ri

Distance to next Stop: 7km

From Phakding, one crosses the last few suspension bridges over the Dudh Kosi River before the long hard slog up to the town of Namche Bazaar (Maps 2 and 3). on the western side of the valley one can see south-verging folds on the slopes below the peaks of Nupla and Kongde Ri (Figure 3.4). At 3,440 m, the climb to Namche ends in an 830 m altitude gain for the day. A day's acclimatisation here is recommended, with a walk up to the top of Namche en route to Tengboche, where a first glimpse of Everest may be obtained on the ridge above the town.

The route traverses through the Greater Himalayan Sequence, where evidence for the burial and uplift history of the rocks is exposed. In general, the rocks consist of gneiss and granite with varying textures and differing amounts of biotite (a dark brown mineral) and feldspar/quartz (white/glassy minerals). Box 3.1 explains how different minerals grow in response to a change in pressure and temperature and the path they follow on a pressure-temperature diagram.

Box 3.1: Introducing the metamorphic history of the Greater Himalayan Sequence and Everest Series

The following sequence of events describes the history of deformation and metamorphism experienced by the rocks of the Greater Himalayan Sequence:

1. Collision of the Indian and Asian continents between 55 and 32 Ma. During this collision, rocks of the Indian continent were thrust below the Asian continent resulting in crustal thickening. The deformation associated with this burial formed isoclinal (very tight) folds and an S_1 fabric (formed when there is differential stress on the rock under ductile conditions) in the rocks of the Greater Himalayan Sequence (Figure 3.1) and also resulted in deformation in the Everest Series (Figure 3.2A to 3.2E).

2. Eclogite-facies metamorphism. In the Pressure-Temperature-Deformation-time (P-T-D-t) path, crustal thickening is suggested as the earliest metamorphic event in the Everest Series (Jessup et al., 2008). Although both the Greater Himalayan Sequence and Everest Series experienced similar P-T loops (i.e. burial followed by heating, Figure 3.1 A, B and C), the granulitised eclogites found in the Greater Himalayan Sequence indicate that these rocks were buried to much greater depths than the Everest Series rocks and experienced an early (pre-M_1) eclogite-facies metamorphic event. (M_1 refers to the first metamorphic event in these rocks).

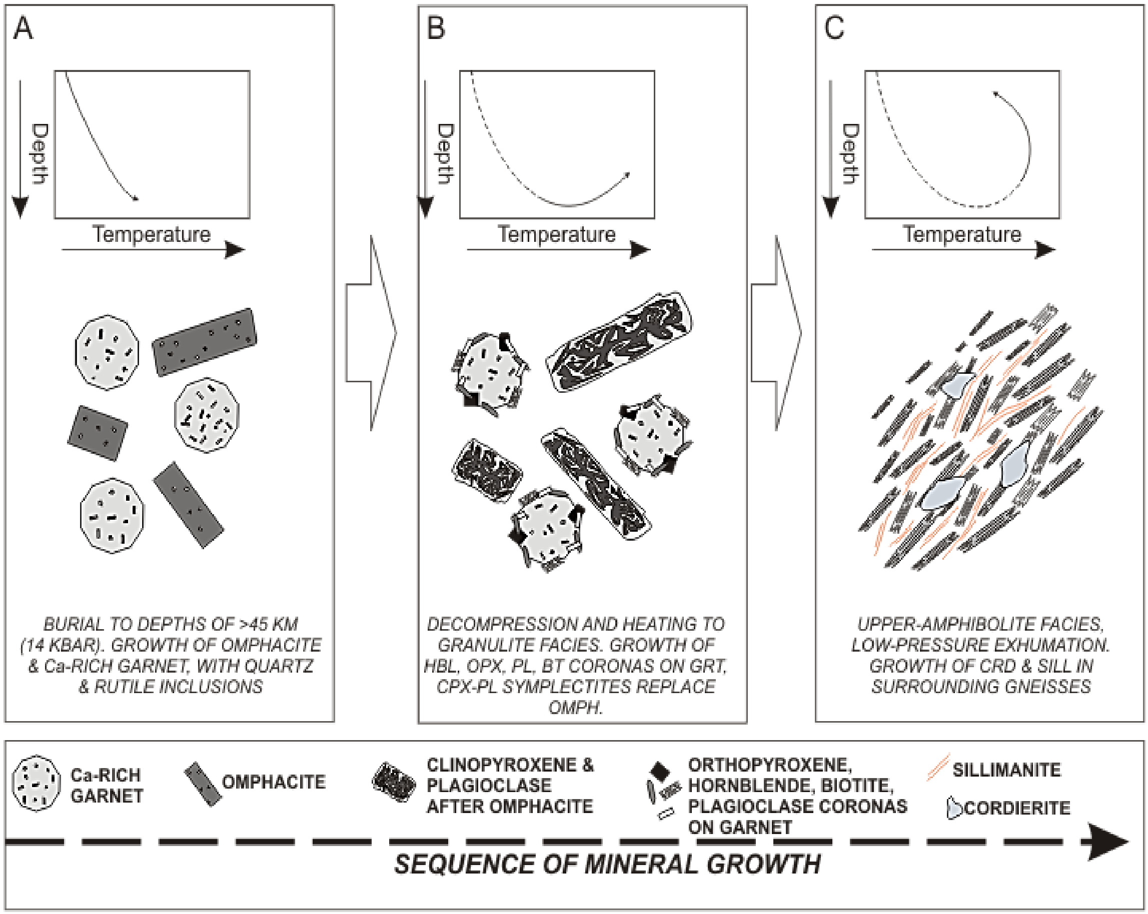


Figure 3.1: History of metamorphism and deformation recorded in Greater Himalayan Sequence (after Lombardo and Rolfo, 2000; Jessup et al. 2008).

The timing of this high-pressure metamorphism in the Everest area is unclear (Cottle et al., 2009), but may be similar to the 54-46 million year eclogite event from the western Himalayas, as described by Lombardo and Rolfo (2000); Parrish et al. (2006); Leech et al. (2005).

3. Heating – 'M_1' metamorphism. Following burial, rocks were heated to granulite facies conditions in the centre of the Greater Himalayan Sequence (Figure 3.1B) or upper-amphibolite facies (Figure 3.1C). These conditions were most likely reached between around 32 million years ago (Jessup et al., 2008) and 13 million years ago (Cottle et al., 2009), respectively. At the peak of metamorphism, granites began to form from the melting of these rocks. At the thermal peak, rocks also began to be exhumed. Owing to the fact that the Everest Series was far less deeply buried, it only experienced greenschist-facies metamorphism (Figure 3.2C).

4. Exhumation. Following heating, rocks of the Greater Himalayan Sequence were exhumed (Figure 3.1C). Because they were hot and contained melt, these rocks were highly ductile. Thrusting along the Main Central Thrust brought these hot, ductile rocks up over the lower-grade Siwaliks, whilst extensional movement along the South Tibetan Detachment brought lower-grade rocks of the Everest Series (also being exhumed, Figure 3.2E) into contact with the higher-grade Greater Himalayan Sequence. Movement along both structures appears to have been simultaneous, with exhumation younger than 16 million years ago (Jessup et al., 2006).

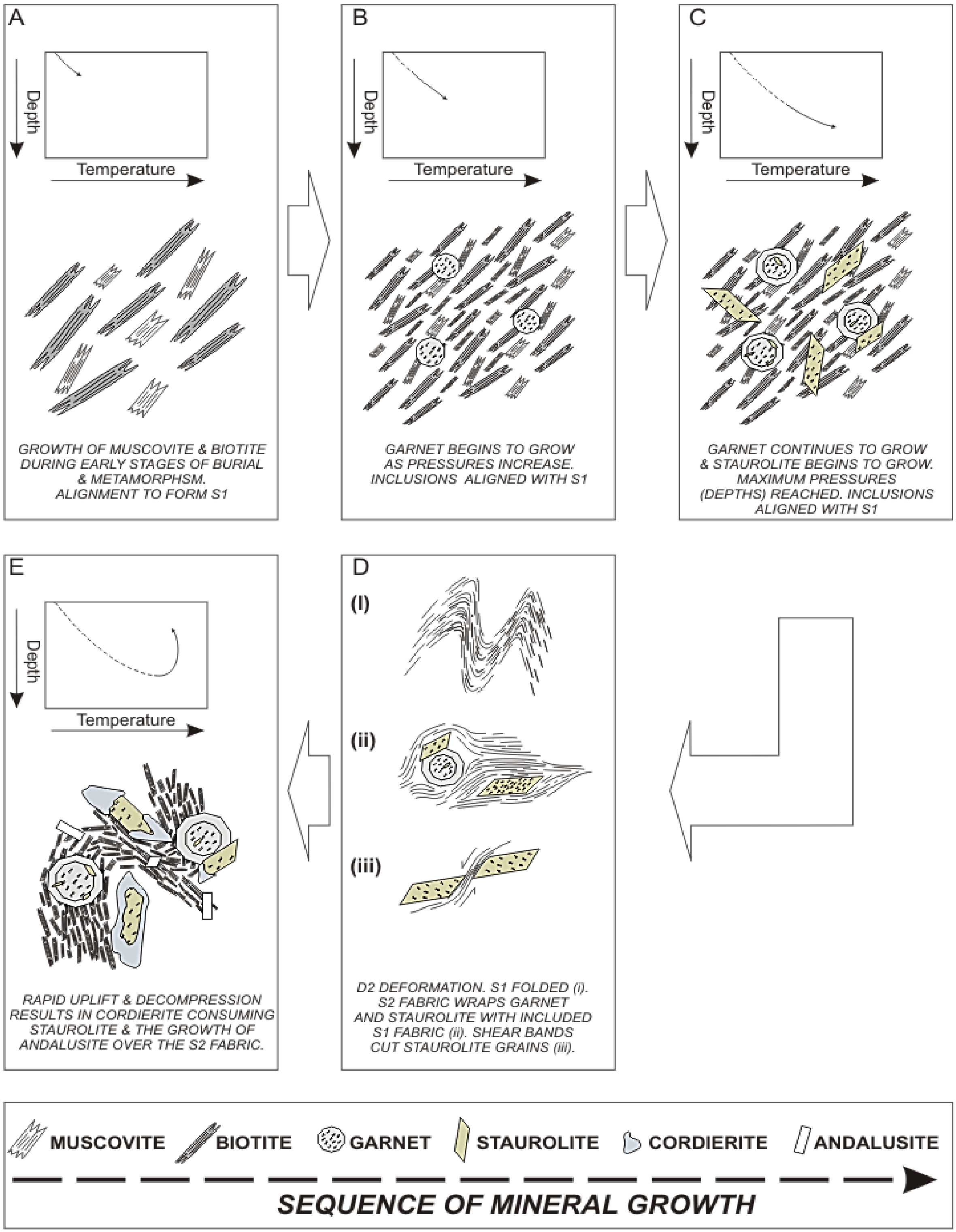


Figure 3.2: History of metamorphism and deformation recorded in Everest Series schists.

The following sequence of events describes the history of deformation of the Everest Series:

1. Early in the metamorphic history of the Everest Series, muscovite and biotite were aligned by intense shearing and folding of the original sedimentary layering in the rock during burial (Figure 3.2A). This early deformation event occurred during early collision. This resulted in the formation of the early S_1 fabric (Figure 3.2B), which was subsequently overgrown by garnet and staurolite as the temperature and pressure increased (Figure 3.2C). The term 'S_1' refers to the earliest fabric formed (i.e. that formed during the D_1 deformation event).

2. Following the growth of staurolite at maximum pressures, the S_1 fabric was crenulated (folded) by D_2 (the second deformation event, Figure 3.2D, which occurred with exhumation. Shearing along the S_2 plane then took place which rotated garnet and staurolite grains. A stretching lineation developed during this shearing and staurolite grains were cut by extensional shear bands (Figure 3.2D).

3. Some Everest Series schists record lower pressures after the D_2 event and show cordierite consuming staurolite, and andalusite is also found (Figure 3.2E). Both these minerals are indicative of fairly low pressures (<15 km depth), and show that the rocks were being exhumed during D_2. This cordierite and andalusite growth over the S_2 fabric was the final phase in the P-T-D-t history (Figure 3.2E).

General geology along the route

The gneissic rocks of the area around Phakding give way to migmatites and sillimanite-biotite gneiss above the town of Namche Bazaar (Figure 3.3).

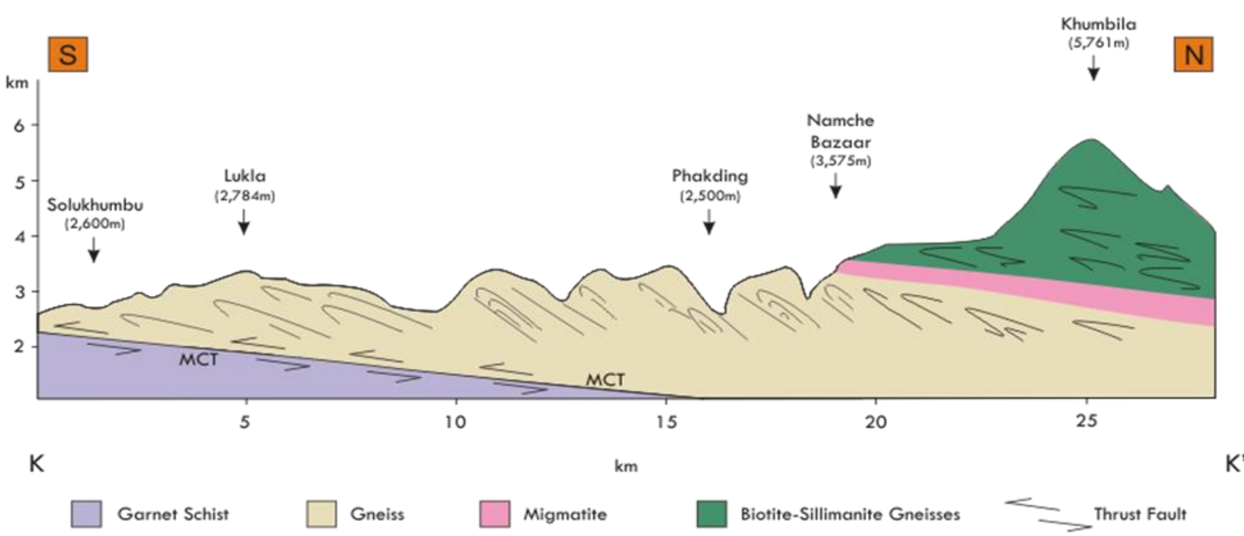


Figure 3.3: Cross section K-K' (Map 3) - from Lukla to Namche Bazaar showing the stratigraphic change from the garnet schist across the Main Central Thrust (MCT) into the gneiss, migmatite and sillimanite-biotite gneiss of the Greater Himalayan Sequence.

From the lodge at Namche Bazaar (Figure 3.4), the view to the west reveals a large, recumbent fold between the leucogranite peaks of Nupla (5,885 m) and Kongde Ri (6,187 m), the result of deformation during D_1 crustal thickening. Beneath the fold is the dark sillimanite-biotite gneiss of the Greater Himalayan Sequence. Thrust planes dip at low angles to the north.

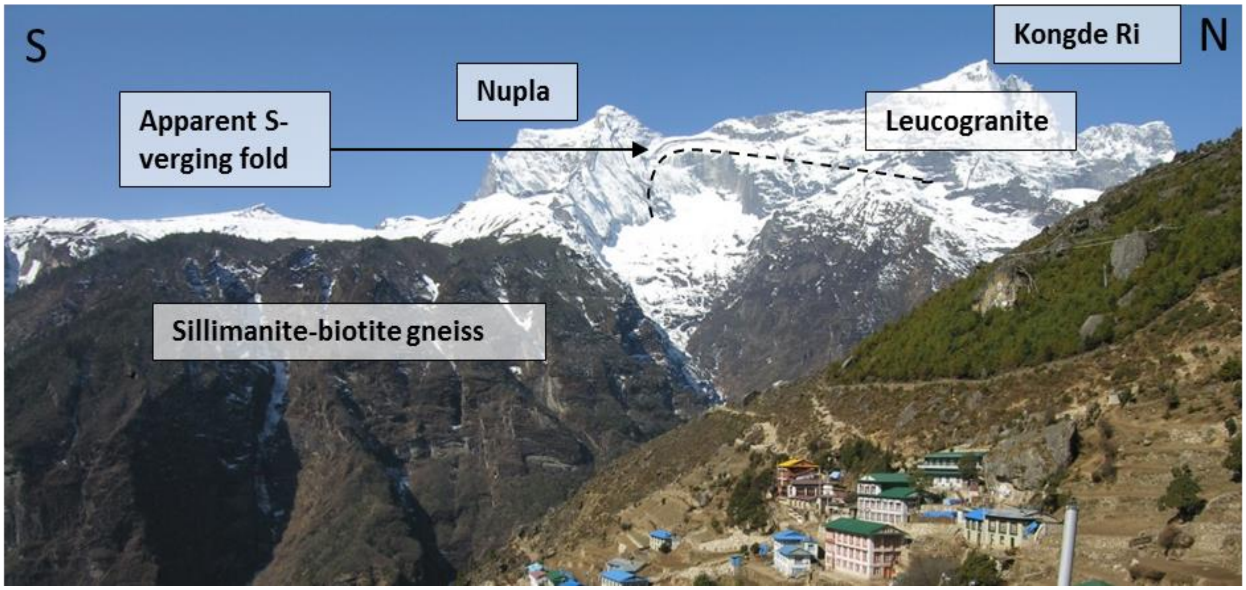


Figure 3.4: Interpretation of the geology between Nupla and Kongde Ri, looking west, showing a recumbent fold and thrust planes. The movement direction is top-to-south, consistent with the thrusting of the Greater Himalayan Sequence southwards over the Siwaliks. Photograph taken from GPS co-ordinates 27°48'19.22"N, 86°42'41.20"E looking eastwards (after Lombardo and Rolfo, 2000; Jessup et al. 2008).

Over the hill to the east of Namche Bazaar one can see one of the greatest panoramas in the world (Figure 3.5) with Everest (8,850 m), Lhotse (8,501 m), and Nuptse (7,861 m) still 25 km distant. The Yellow Band is near the summit of Everest. The rocks below the Nuptse Ridge are composed of metamorphosed calcareous rocks of the Everest Series. These have been intruded by leucogranites of the Greater Himalayan Series. The location of the Lhotse and Qomolongma Detachments is shown. Brown rocks along the sides of the valley are sillimanite-biotite gneiss of the Greater Himalayan Sequence. The summit of Ama Dablam (to the left of the photograph, not in view) is made up of Higher Himalayan Leucogranite which formed from the anatexis (melting) of the Greater Himalayan Sequence rocks.

Dark biotite-rich rocks are the dominant rock type above Namche Bazaar. The dark platy minerals are biotite whilst the specks of white are quartz with minor feldspar. Samples often contain abundant sillimanite, a mineral which indicates high-temperatures (T>550°C), as well as lesser amounts of the metamorphic minerals sillimanite and cordierite.

These rocks (schists and gneisses) generally have has a very strong fabric defined by the alignment of biotite and highly recrystallized quartz which is also elongated and aligned. This alignment was caused by deformation associated with top-to-south thrusting of the Greater Himalayan Sequence southwards over the Siwaliks. Many of the lighter bands in the biotite-sillimanite gneisses are The light bands in this sample are crystallised melt or leucosomes, indicating that this sample experienced simultaneous deformation and high-grade metamorphism leading to melting. This deformation and melting is most the result of the burial and exhumation of the Greater Himalayan Sequence.

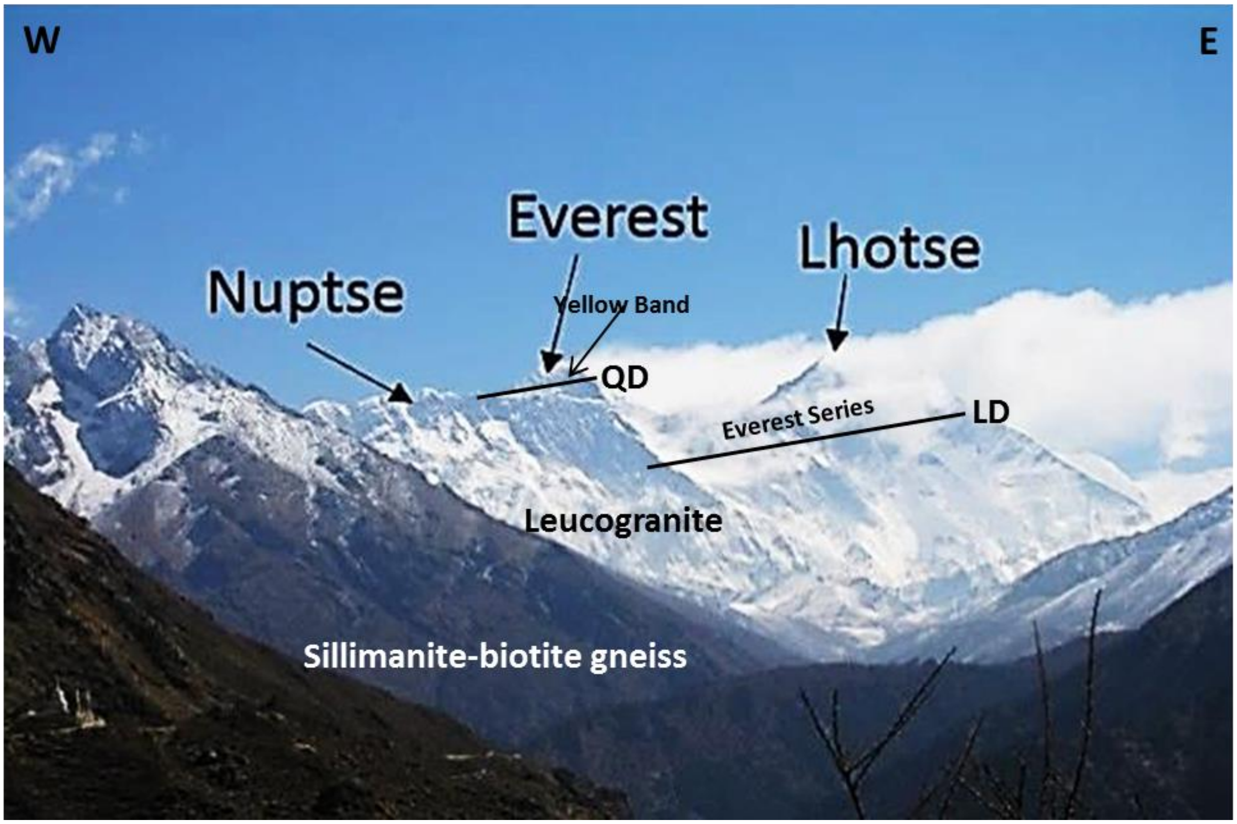


Figure 3.5: View from Namche Bazaar towards Everest. The summits of Everest, Lhotse and Nuptse are composed of Everest Series rocks whilst below these are the leucogranites and gneisses of the Greater Himalayan Sequence

Microscopic examination of deformed sillimanite biotite schist and gneiss, commonly found along the trail from Namche Bazaar onwards, is given in Figure 3.6.

Sillimanite-biotite schist & gneiss

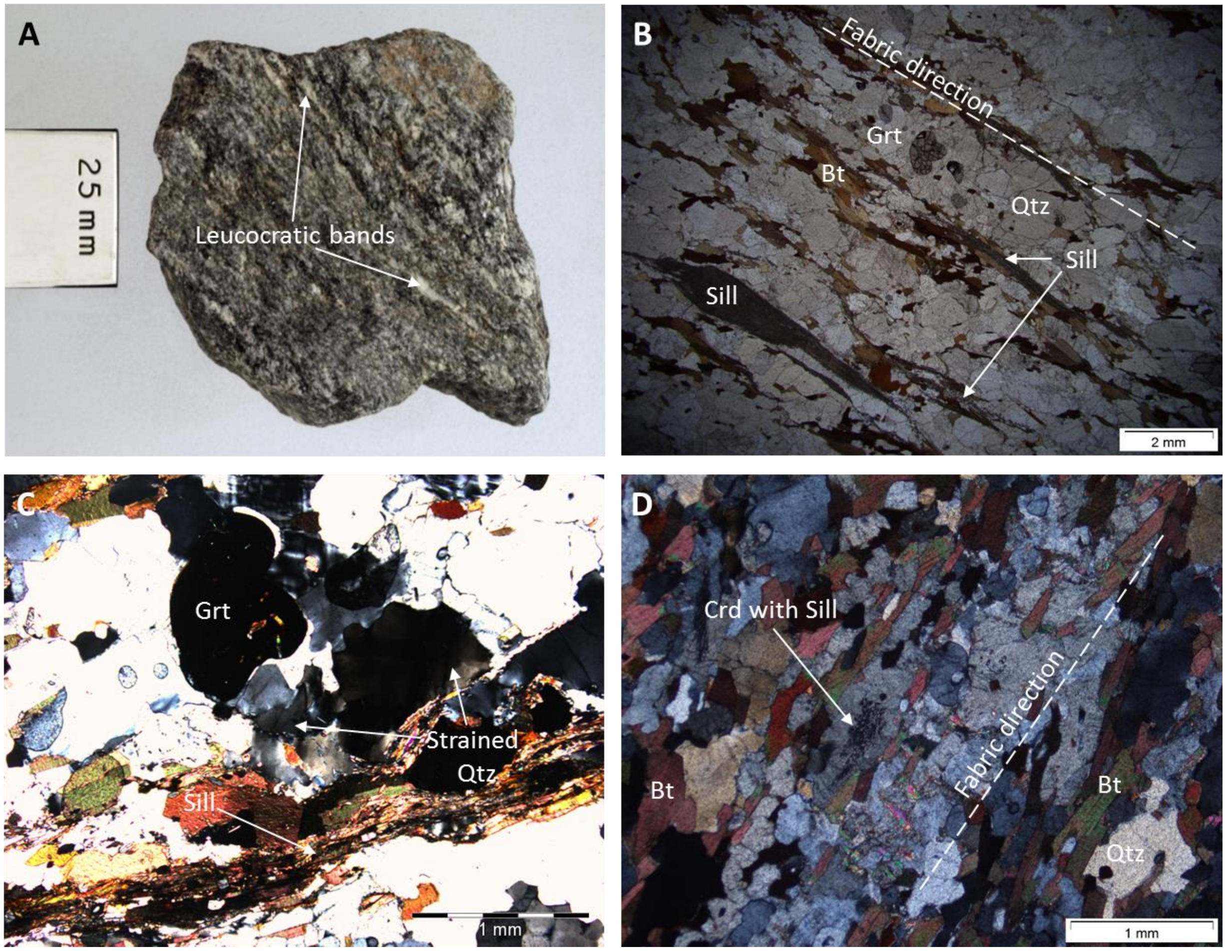


Figure 3.6: The main rock type along the route from Namche Bazaar to Everest Base Camp is biotite sillimanite schist and gneiss. A – hand sample of biotite-sillimanite gneiss, the dark shade being due to the mineral biotite, which makes up much of the rock. Note the lighter leucocratic bands, made up of quartz and feldspar, and which distinguish the gneiss from schist (which has a more uniform, unbanded texture). B – photomicrograph of biotite-sillimanite gneiss). Note the fabric, made up of alignment of biotite crystals and fine-grained patches of grey sillimanite. A small garnet grain is also found. C – photomicrograph of garnet, sillimanite and strained quartz. Garnet is a metamorphic mineral commonly found in medium- to high-grade metamorphic rocks. D – photomicrograph showing a grain of cordierite with inclusions of sillimanite. Cordierite typically grows from a reaction between biotite and sillimanite during metamorphism (Searle et al. 2003).

Stop 4: Tengboche: Buddhist monasteries in sillimanite-biotite gneiss

Alt: 3,860 m

North: The Khumbu valley with views of the Everest massif and Ama Dablam

East: A vegetated mountainside of gneiss

South: The Khumbu Valley and Namche Bazaar

West: Sillimanite-biotite gneiss

Distance to next Stop: 5km

From Namche Bazaar to Tengboche (Maps 2 and 3), the air becomes thinner, there is a feeling of light-headedness and the panorama of Everest, Lhotse, Nuptse and Ama Dablam never leaves one. The walk is along a horizontal path almost to Tengboche, where a torrential river must be crossed before climbing for an air-sucking hour, to emerge in the Tengboche hilltop village with its beautiful monastery (Figure 4.1) and welcome bakery.

Figure 4.1: The Buddhist Monastery at Tengboche is worth a visit, its tranquility inspiring one to further endeavour. The steep dip of biotite sillimanite gneisses west of the Monastery is typical of part of the lower limb of a nappe structure common in the Himalayas (Searle and Rex, 1989).

Having climbed through the pale migmatitic gneiss of the Namche migmatites, at Tengboche one is surrounded by sillimanite-biotite gneiss, a rock metamorphosed from an originally fine grained clayey or mud-rich sedimentary rock called a pelite and found higher up in the Greater Himalayan Sequence (Figure 4.3). These rocks could originally have been deposited on the distal northern edge of the granite basement of the Indian sub-continent before collision (Jameison et al. 2004). These black coloured gneisses are rich in biotite and contain variable amounts of a fibrous mineral called sillimanite (Searle et al. 2003).

A large migmatite zone occurs above Namche Bazaar (Figure 4.2). Numerous examples of migmatite outcrops are encountered along the route from Namche Bazaar through Tengboche to Pangboche.

Box 4.1: The origin of migmatites and their role in the leucogranites

Once a rock starts to melt, it weakens significantly, focusing deformation, which "helps" push some of the melt upwards. This melt has accumulated to form the leucogranites. Some granite melt remains trapped in the source region (granite leucosome).
Migmatite is a rock formed by partial melting, and is composed of palaeosome (the part of the rock that did not melt) and neosome (the melted part of the rock). Neosome is made up of melanosome (darker residual material) and leucosome (lighter-coloured material made up mostly of quartz and feldspar). This zone gives rise to large volumes of melt, which segregate from the migmatites and risen to the top of the Greater Himalayan Sequence to form the Higher Himalayan Leucogranites. The ductile nature of these partially molten migmatites also facilitated deformation and the rapid exhumation of the so-called "channel" of the Greater Himalayan Sequence.

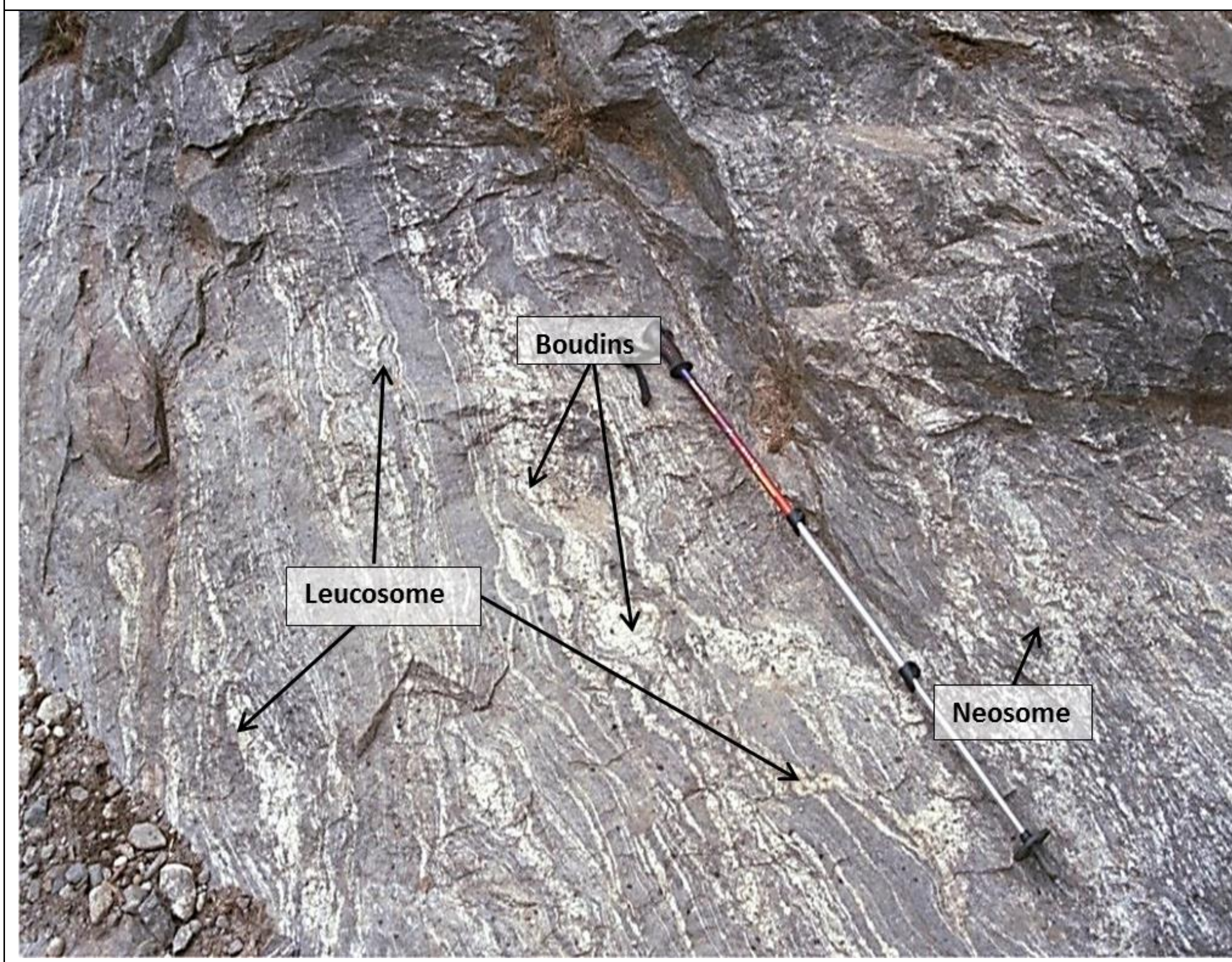


Figure 4.2: Migmatite outcrop on the path overlooking Tengboche showing interfingered melt (the lighter coloured parts are called leucosomes) intruding the pre-existing sillimanite-biotite gneiss. Some leucosomes have been further deformed or stretched into shapes that resemble a string of sausages called boudins. Some leucosomes, which cut across the original leucosome layers, are called neosomes. The handle of the hiking pole is 14 cm in length. GPS co-ordinates 27°48'18.64"N, 86°43'2.66"E.

General geology along the route

Evidence of high rates of erosion, and the resulting high rate of exhumation of subducted layers of rock, are the high mountains rapidly being eroded – clearly evidenced by the steep-sided valleys and large amounts of loose rubble and boulders in the valleys and the lower slopes of the mountains all along the route. The large amounts of debris and boulders along the trail and in the rivers along the route, in fact, make outcrops of the Greater Himalayan Sequence rocks quite rare.

As one approaches Tengboche and Pangboche, leucogranite begins to make its appearance in the faces near the summits of e.g. Ama Dablam and Taboche, (Figures 4.3 and 5.5). The peak of Ama Dablam is an example of such a leucogranite. This granite is different from the migmatitic rocks in that it is medium to fine grained and light grey in colour compared with the coarse grained, pegmatitic banded migmatites.

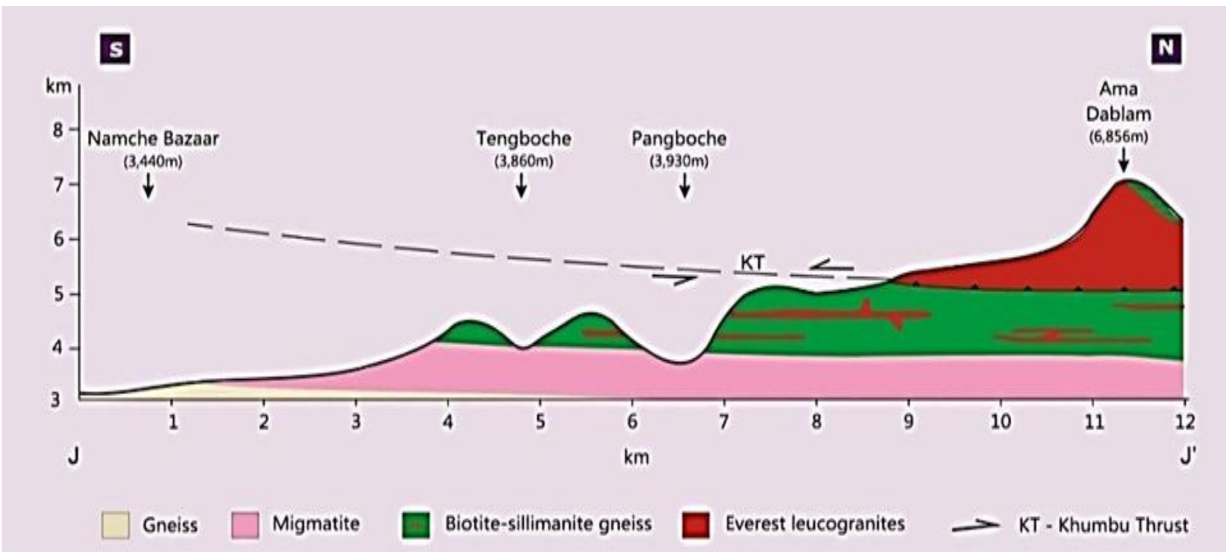


Figure 4.3: Cross section J-J' (Map 3) - from Namche Bazaar to Ama Dablam (Map 3), showing the change in stratigraphy through the migmatites and gneisses across the Khumbu Thrust (KT) into the leucogranite of the Ama Dablam peak. The geology of Tengboche is dominated by sillimanite-biotite gneiss.

Northwards, there are spectacular views of Everest, Lhotse, Nuptse and Ama Dablam (Figure 4.4). The lower parts of the entire wall below the peak of Everest from the Nuptse (on the left) to the Lhotse peaks (on the right) are composed of crystalline leucogranite, intruded into the high-grade gneiss of the Greater Himalayan Sequence. These are separated from the lower grade Everest Series pelite by the Lhotse Detachment (LD). Above the LD, the Everest Series rocks extend to the summits of Everest and Lhotse. (Figure 4.4)

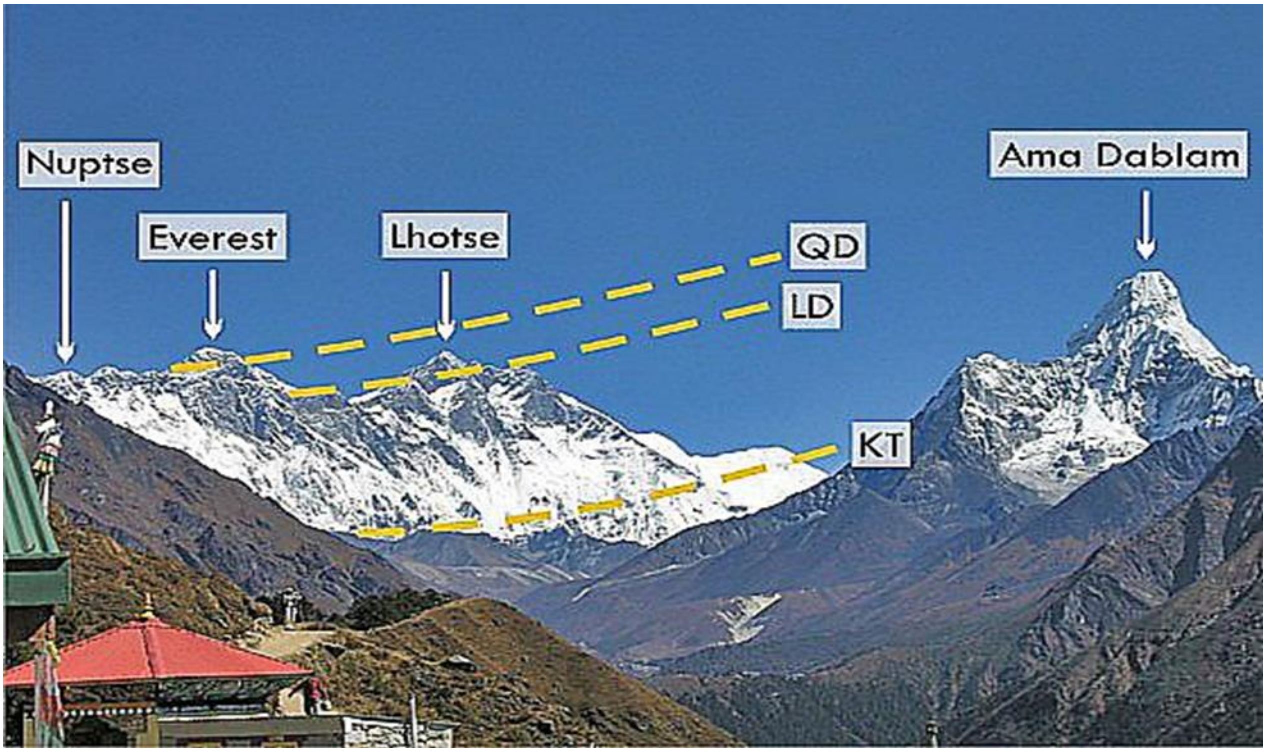


Figure 4.4: View from Tengboche: the summit of Everest is composed of Everest Series rocks which are low-grade metamorphic rocks. The view from the approach to Tengboche shown in this photograph gives a good illustration of the upper Greater Himalayan Sequence where leucogranite intrusions become more common up to the Lhotse Detachment (LD). A second detachment, the Qomolongma Detachment (QD), occurs above the Lhotse Detachment. Together, the Qomolongma and Lhotse Detachments make up the South Tibetan Detachment (Searle 1999). The Khumbu Thrust (KT) forms the base of the Everest Series pelites and the leucogranite.

Leucogranites form when migmatites begin to partially melt and the melt rises upwards through zones of weakness such as faults and shear zones. A large migmatite zone occurs above Namche Bazaar (Figure 4.5). Numerous examples of migmatite outcrops are encountered along the route from Namche Bazaar through Tengboche to Pangboche. Box 4.1 explains how leucogranites form with a study done by Searle et al. 1997 on the Shisha Pangma (8027 m) leucogranite, approximately 100 km west northwest of Everest.

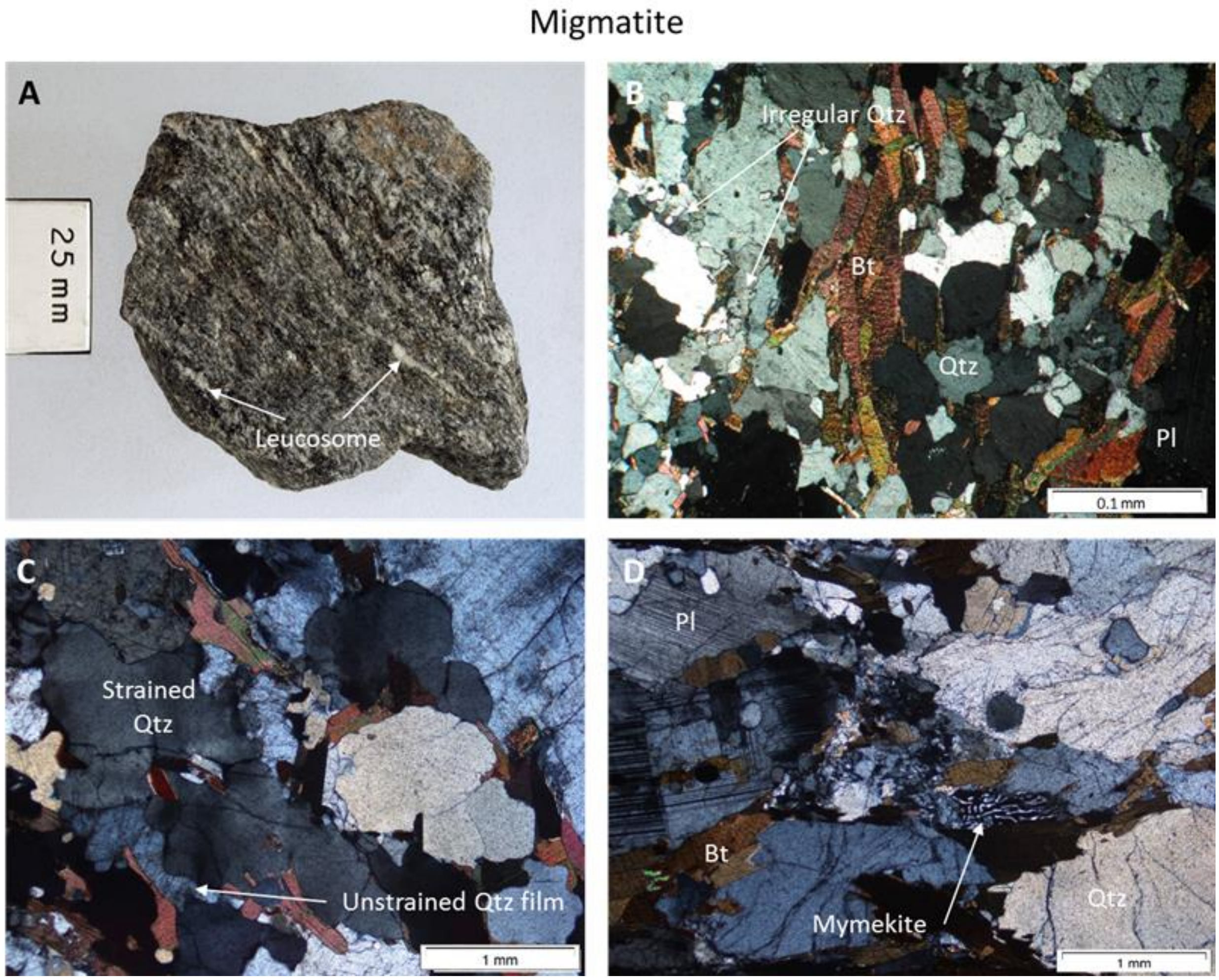


Figure 4.5: Migmatite examples. Migmatite is a term for a rock that shows evidence for partial melting (also known as anatexis). A: Typically, migmatites have lighter layers or zones known as leucosomes that are relicts of melt, and are made up of quartz and feldspar. In this example, a sample of biotite-sillimanite gneiss (sample RH02) has a number of leucosomes. B-D: Microscopic evidence of relict melt including irregular quartz grains that have not yet annealed (B), thin films of unstrained quartz between grains of strain quartz (C) - the unstrained quartz is crystallized melt and myrmekites (D), which are intergrowths of quartz and feldspar that form during crystallisation of trapped leucosome.

Stop 5: Pangboche: Castles of granite

Alt: 3,930 m

North: Taboche and Everest

East: Ama Dablam and its foothills

South: The Khumbu Valley

West: Sillimanite-biotite gneiss

Distance to Ama Dablam Base Camp: 4km and a further 2km to the southeast ridge

Distance to Periche: 4km

The trail to Pangboche provides dramatic views of Ama Dablam (Maps 2 and 3). The name of this peak (translation: Mother's Necklace) is related to the numerous hanging glaciers below the summit that give the appearance of a necklace around the summit. Everest and Lhotse also remain. Pangboche itself is a picturesque village with many small fields under cultivation. The Sherpa lodges are very pleasant and the great mountains can be seen from most of the restaurants. The feeling of light-headedness is more acute and sleep is a little more difficult. Numerous good examples of migmatisation are apparent along the route.

As one approaches Everest along the trek from Lukla (Map 2), a striking feature of the landscape is the number of high mountain peaks, many of which exceed 6,000 m. The summits of many of these peaks consist of leucogranite, a pale granite dominated by the presence of white coloured minerals such as feldspar, quartz and muscovite mica.

Mapping and correlation of the structure and stratigraphy of the Higher Himalayas has shown that these leucogranites form a distinct horizon near the top of the Greater Himalayan Sequence (Figure 5.1). Although the granites now form the tops of mountain peaks and are separated by extensive valleys, it is likely that they were once connected in a massive granite sheet, rather than being discrete plutons (Searle et al. 1997).

In Box 5.1 the formation of the higher Himalayan leucogranites is discussed.

Box 5.1: The origin of The Higher Himalayan leucogranites

Once a rock starts to melt, it weakens significantly, focusing deformation, which "helps" push some of the melt upwards. This melt has accumulated to form the leucogranites. Some granite melt remains trapped in the source region (granite leucosome).

Migmatite is a rock formed by partial melting, and is composed of palaeosome (the part of the rock that did not melt) and neosome (the melted part of the rock). Neosome is made up of melanosome (darker residual material) and leucosome (lighter-coloured material made up mostly of quartz and feldspar). This zone gives rise to large volumes of melt, which segregate from the migmatites and risen to the top of the Greater Himalayan Sequence to form the Higher Himalayan Leucogranites. The ductile nature of these partially molten migmatites also facilitated deformation and the rapid exhumation of the so-called "channel" of the Greater Himalayan Sequence.

Migmatisation, when widespread enough and over enough time, leads to the segregation of partial melt from the migmatites (Figure 5.1) and accumulation of rising melt to form the granites which make up the peak of Ama Dablam, Pumori, Lingtren, Nuptse and many other peaks in the Himalayas.

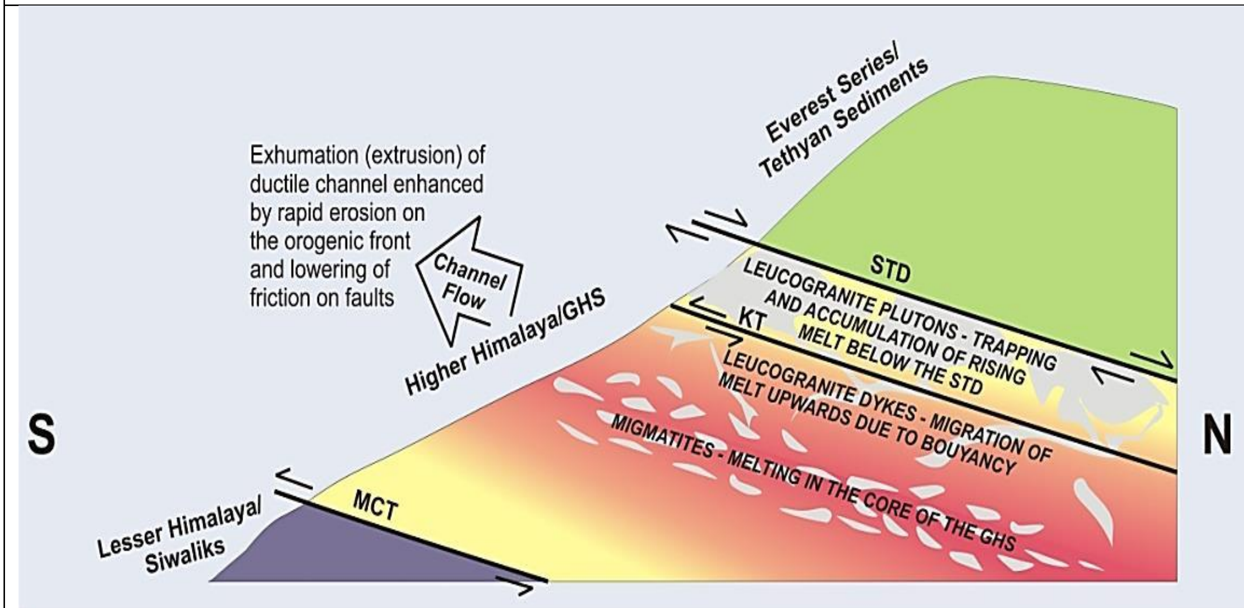


Figure 5.1: The segregation of partial melt from the migmatites results in a leucogranite melt rising to the South Tibetan Detachment (STD) . The exhumation of the channel of material in a southwards direction is known as channel flow.

When a rock begins to melt, the molten liquid that is formed is generally hydrous and of a lower density than the surrounding rock which has not yet melted. This melt then coalesces and, because of its low density, it begins to rise through the crust along structures as a buoyant liquid (Figure 5.1). Local pressure variations and the effects of deformation force the melt into structures, after which it begins to migrate upwards, under buoyancy, towards the surface. This phenomenon explains how magma moves upwards through the crust and why it may eventually reach the surface to form volcanoes, occur (on account of the lower density magma (molten material) trying to reach the surface).

In the Himalayas, high-temperature metamorphism (T >700°C) of the Greater Himalayan Sequence has formed a broad zone of migmatites (partially molten rocks) near the centre of the Greater Himalayan Sequence (Figure 5.1). Melting of the granites begins at 700°C, the melt-weakening threshold (Jameison et al. 2004). High temperatures (>620°C) were maintained for 15 million years from 32 million years ago to 16.9 million years ago along the top of the Greater Himalayan slab (Searle et al, 2003). Melt from these migmatites accumulated and migrated upwards, but never made it to the surface. This is because the melt was trapped during its upward rise through the crust by the Everest Series metasediments, which formed a “cap” to the magma. This melt has accumulated at the top of the Greater Himalayan Sequence, below the Everest Series, and has crystallised to form the Higher Himalayan Leucogranites (Figure 5.1). Structures in these leucogranites indicate that they were emplaced near the top of the Greater Himalayan Sequence at roughly the same time as deformation was occurring (circa 23 to 17 million years ago (Searle et al. 1997), when the gneiss of the Greater Himalayan Sequence was partially melting to form migmatite. Rapid cooling of the Everest leucogranite occurred between 19 and 17 million years ago. This partial melting and extrusion of a molten slab has become known as Channel Flow (Burchfield and Royden, 1985), which is explained more fully in Stop 10, Box 10.1.

A detailed model of the mechanism of intrusion of a granite pluton from migmatite melt is shown in Figure 5.2.

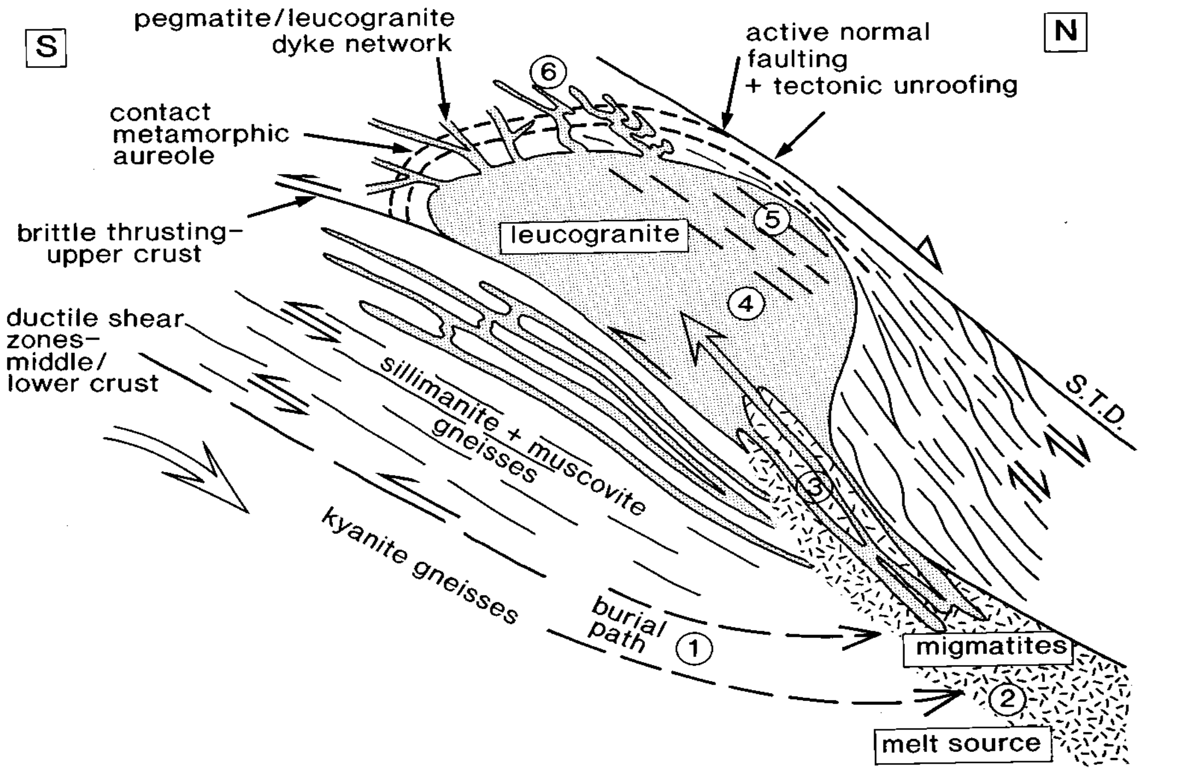


Figure 5.2: A model presented by Searle et al.(1997) shows the burial path of sillimanite and kyanite grade metapelites (1) leading to migmatisation (2), the separation of leucosome leading to granitic melt injection (3) into dykes. Buoyancy segregation and diapirism lead to intrusion of granitic magma into high structural levels (4) and active shear zones (5) with late-stage intrusion of high level pegmatitic dykes (6) (Searle et al. 1997).

General geology along the route

The summit of Ama Dablam (6,856 m) is made up of leucogranite (Figure 5.3). The Khumbu Thrust is located at the base of Ama Dablam. It is along this fault that southwards thrusting of the exhumed leucogranite occurred.

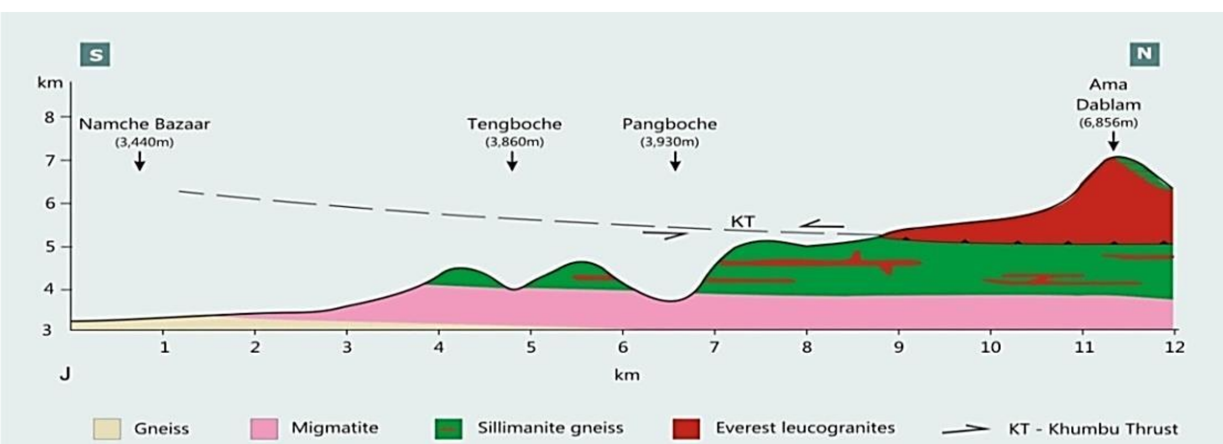


Figure 5.3: Cross section J-J' (Map 3) - The geology of the area around Pangboche is dominated by sillimanite-biotite gneiss and migmatite (drawn from Searle 2003).

Ama Dablam and Taboche are (Figures 5.4 and 5.5) are examples of a low density melt, rising through the crust, being exhumed and transporting with it xenoliths or rafts of sillimanite-biotite gneiss and amphibolite in the granite. The granites are tourmaline bearing on Ama Dablam.

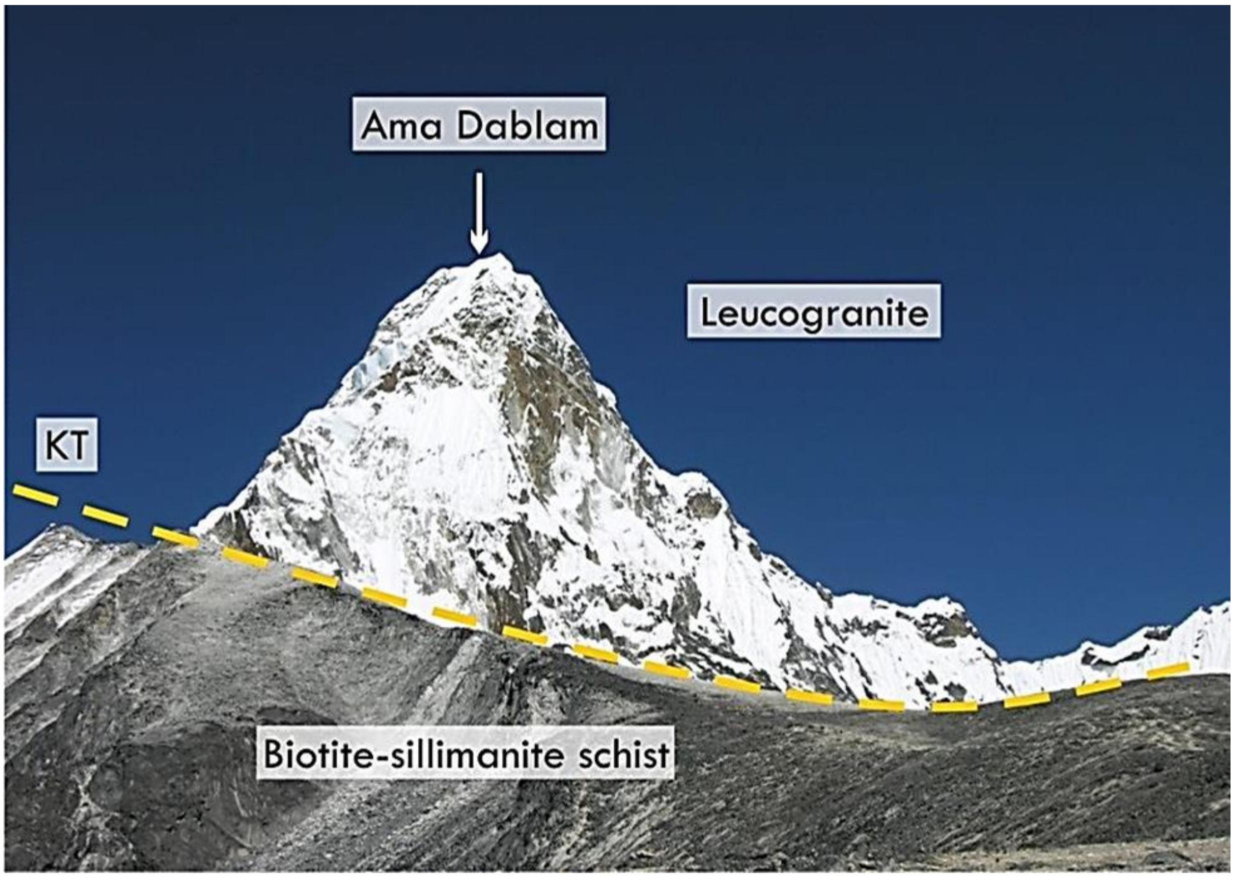


Figure 5.4: Tourmaline-bearing leucogranite is found all the way along the Southwest summit ridge of Ama Dablam. The white bands in the sillimanite biotite gneiss are composed of pegmatitic rocks and also contain tourmaline. A large boudin of amphibolite can be seen in the sillimanite biotite gneiss. The Khumbu Thrust is located at the base of the mountain, dipping northwards into the photo and separating the leucogranite from the sillimanite-biotite gneiss below. The higher parts of the Ama Dablam mountain are made up of leucogranite which is more resistant to erosion. A hanging glacier on the summit of Ama Dablam is possibly the source of the mountains name in Sherpa: "mother's necklace".

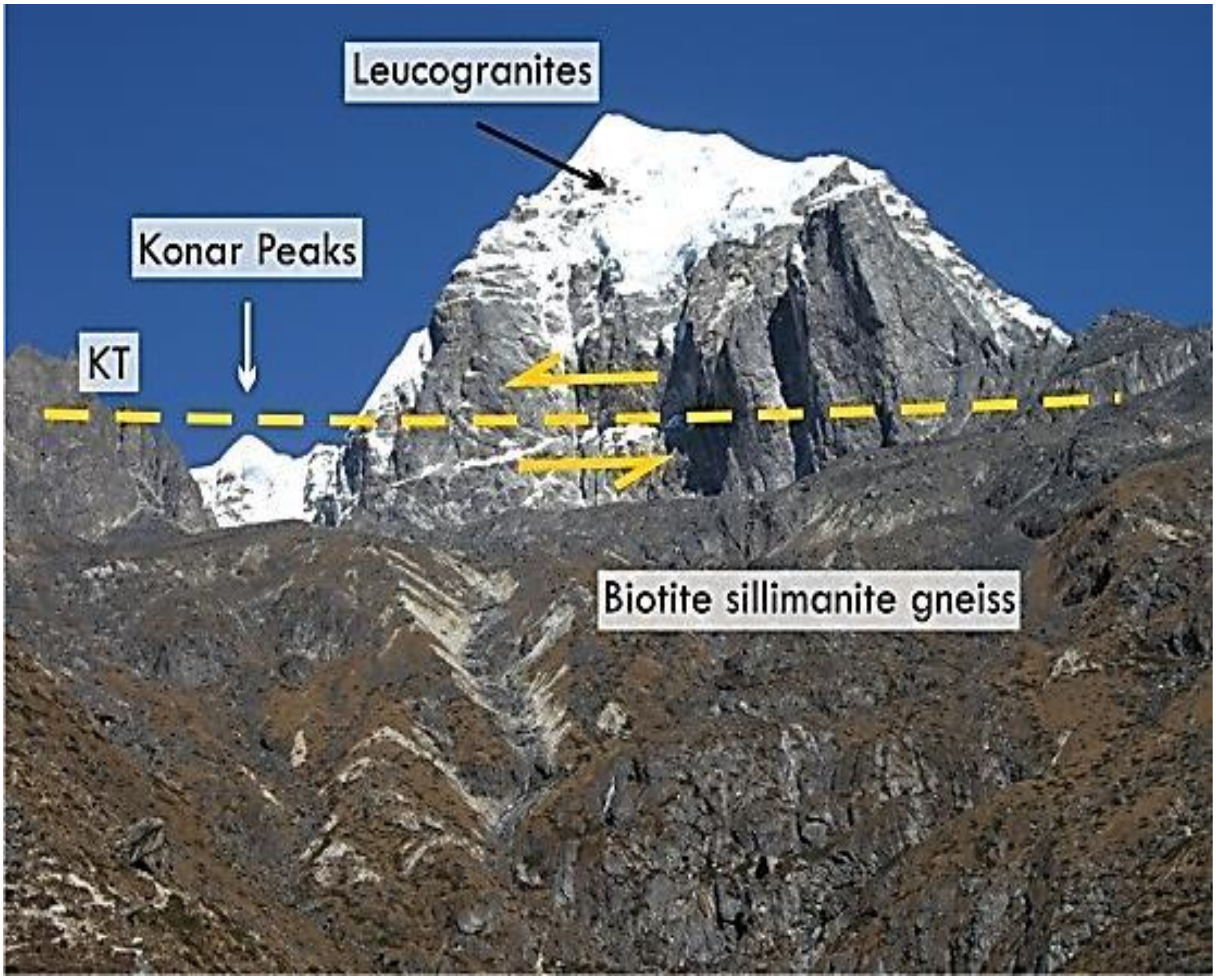


Figure 5.5: Looking west from Pangboche, the peak of Taboche (6,542 m) is composed of dark sillimanite-biotite gneiss, with leucogranite outcrops above the snowline. The estimated position of the Khumbu Thrust (KT) and the sense of movement on the Khumbu Thrust is shown.

An excellent view of the Nuptse-Everest-Lhotse range, underlain by intrusions of leucogranite, can be seen looking northwards from the slopes of Ama Dablam. An interpretation of the geology is given in Figure 5.6. This layer of leucogranite is widespread and indicates the extent of melting that occurred following underplating of the Indian crust beneath Tibet. As the granitic magma intruded overlying strata, local pressure variations and structures guided the molten granite into planes of weakness, which resulted in granite dykes and sills forming above the main granite intrusion.

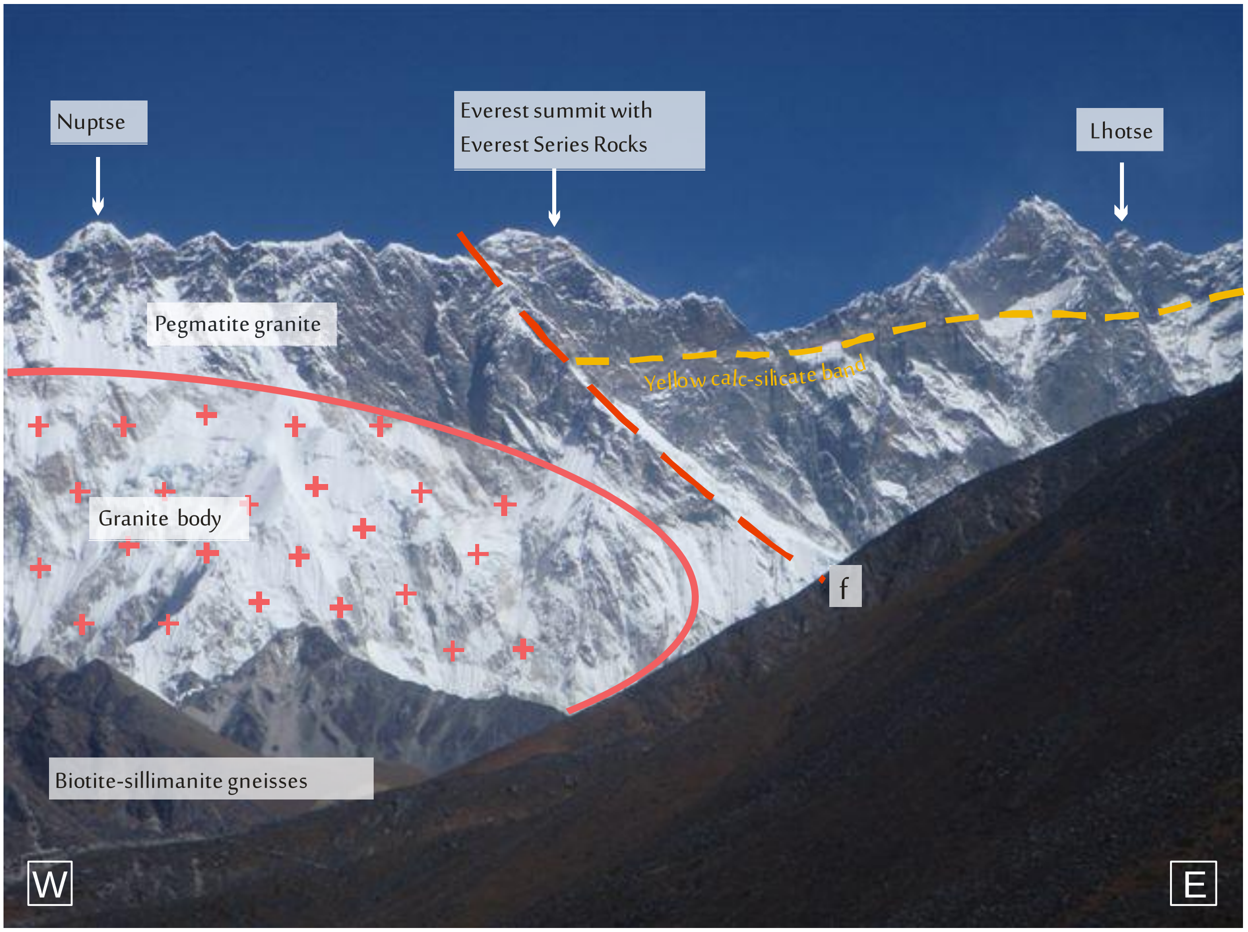


Figure 5.6: View looking at the Nuptse–Lhotse massif from the northern slopes of Taboche. In the foreground are the sillimanite biotite gneisses situated in the valley behind the ridges. The lower slopes of Nuptse show a large granite intrusion (See Figure 8.2 for geological interpretation). In the centre background is Everest. The Lhotse ridge shows yellowish calc-silicate bands above the Lhotse Detachment (LD), dipping into the ridge to the north at ~10˚. These calc-silicate bands are truncated by the LD running diagonally across the ridge. This same calc-silicate band can be observed later along the route in the Western Cwm, at Stop 11 Figure 11.1).

Stop 6: Ama Dablam: Southeast ridge and summit

Alt: 5,400 m

North: Ama Dablam and the south east summit ridge

East: The Mingbo La Pass (5,845 m)

South: Leucogranite peaks of Kangtega and Thamserku

West: Low ridge of sillimanite-biotite gneiss

Distance to Periche at Stop 7 back through Pangboche: 10km

"A long hard slog" is an apt description of the hike to the summit ridge of Ama Dablam (Maps 2, 3 and 4). The rarefied air makes for tough walking. The mountain peaks are of granite and pegmatite capped by ice and snow. The hike is mostly over glacial moraine on the sillimanite-biotite gneiss horizon until the Khumbu Thrust is crossed at 5300m, immediately below the leucogranite that makes up the upper portions of Ama Dablam. The overlying granites have been thrust southwards. This is the uppermost thrust found in the Greater Himalayan Sequence (Figure 6.1).

Geologically, this is the stratigraphic level of the Higher Himalayan Leucogranites, the great zone of granite found at the top of the Greater Himalayan Sequence. In Box 6.1, leucogranite and its origin are briefly discussed.

Box 6.1: Tourmaline bearing leucogranite

Granites are intrusive magmatic rocks composed almost entirely of quartz and feldspar, with minor amounts of biotite or other mafic minerals. These rocks form when pre-existing rocks are heated up sufficiently to begin melting. When a rock begins to melt, certain minerals start melting before other minerals and the rock is said to be partially melting. When partial melting occurs, the lighter elements (Si, K, Na, and Ca) tend to accumulate in the melt, whilst other elements (Fe and Mg) tend to remain behind in the (unmolten) residue. The molten material will coalesce, segregate and rise to form intrusive igneous bodies (or extrusive volcanics if they rise to the surface).

Because of the partial melting process, the new magma is enriched in the elements Si, K, Na and Ca, which are major components of quartz and feldspar, and therefore it crystallises to form granite. Granite melts are also enriched in other trace elements that are not compatible in the crystal structures of common rock-forming minerals. These elements (known as incompatible elements) include B, Zr, Rb, Li, U, Th and, amongst others the Rare Earth Elements. When only a very small degree of partial melting occurs, the melt produced will be deficient in minerals containing Fe and Mg but enriched in the lighter elements. Such granite is known as a leucogranite. Boron (B), a mineral which is common in the Himalayan granites, is an element which is found in the mineral tourmaline.

Examples of tourmaline bearing leucogranites are the slabs of loose rocks and light coloured outcrops shown in the foreground of Figures 6.2 and 6.3. The black markings on the rocks are black tourmaline crystals, described in Figure 6.4.

A sheet of leucogranite known as the Higher Himalayan Leucogranite forms most of the high peaks in this region of the Himalayas. This sheet is the result of partial melting of the Greater Himalayan Sequence deeper in the crust below the Tibetan plateau. The leucogranite has accumulated at the top of the Greater Himalayan Sequence and is separated from the overlying low-grade Everest Series metasediments by the gently northwards-dipping STD.

General geology along the route

Ama Dablam is located mainly in the Everest leucogranite layer of the Greater Himalayan Sequence with its base in the sillimanite-biotite gneiss as shown in Figure 6.1.

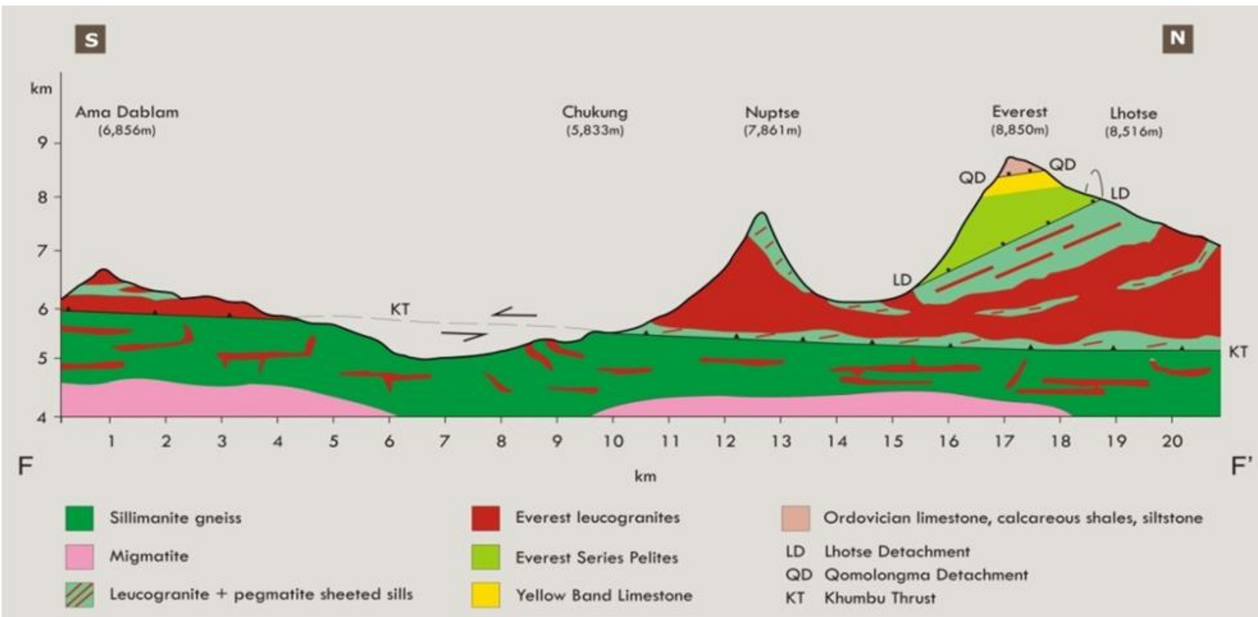


Figure 6.1: Cross section F-F' (Map 4) (Cross section drawn from Searle's Maps, 2003, 2007)

The main rock type on Ama Dablam (Figure 6.2) is tourmaline-bearing leucogranite. Near the top of Ama Dablam, sheeted pegmatite sheeted sills occur. These indicate that the leucogranite intrusion was nearing the overlying Everest pelites and began to intrude into planes and points of weakness, forming sills and dykes. The lower parts of the mountain consist of leucogranite with xenoliths of dark sillimanite-biotite gneiss detached from the Greater Himalayan Sequence gneiss during intrusion (Figure 6.3). The tourmaline-granites found on Ama Dablam are one of two types of granite making up the Higher Himalayan Leucogranites, the other being the two-mic granites. Although both granites are likely to have originated from the partial melting of the underlying GHS, with the melt segregating and subsequently ascending to be emplaced as plutons and sheets at the top of the GHS, they were formed by different processes. The tourmaline granites were locally derived, having not travelled far from their source, and were produced by muscovite dehydration melting in a muscovite rich metapelites at lower temperatures than the two-mica granites (Le Fort et al. 1987). The tourmaline content of these granites is usually > 2.2% (Le Fort et al. 1987). The two-mica granites (tourmaline content < 2.6%), were generated by melting at higher temperatures in biotite-rich gneiss, resulting in hotter magmas. These intruded upwards by a network of dykes and sills, and solidified below the cooler rocks of the STD (Visona and Lombardo, 2002).

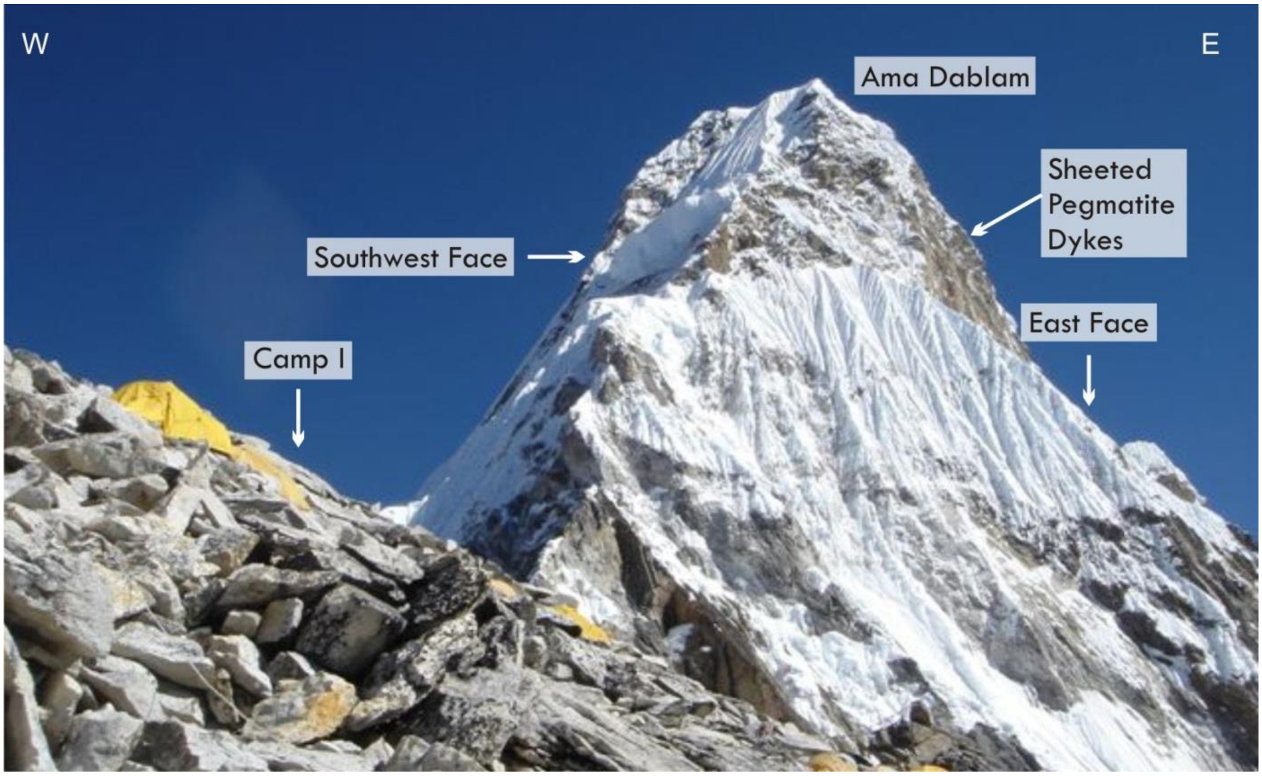


Figure 6.2: The Ama Dablam south-east ridge is a mass of broken rocks composed of tourmaline-bearing leucogranite which is shown in the foreground. The summit and the north face are composed of sheeted sills of leucogranite and pegmatite-intruding sillimanite-biotite gneiss, calc-silicate and amphibolite.

The granites are made up of mostly quartz, plagioclase feldspar, and K-feldspar, are generally coarse-grained (>0.5 mm) and do not contain a strong fabric. Very minor amounts of biotite are found but large amounts of pale muscovite mica and dark tourmaline occur. Both muscovite and tourmaline are common in granites generated by the melting of metasedimentary rocks such as the sillimanite-biotite gneiss near the base of Ama Dablam. Tourmaline is a boron (B) mineral and is indicative of the enrichment of the leucogranites in the incompatible elements.

Figure 6.3: The south-east ridge is composed mainly of tourmaline-bearing leucogranite and contains numerous xenoliths of sillimanite-biotite gneiss (the black rock). These were likely to have been detached from in-situ wall rocks isolated by sill-dyke intrusion and expansion of the pluton/sill. Photograph taken at GPS co-ordinates 27^{o}51'24.35"N, 86^{o}51'17.23"E.

Microscopic examination of tourmaline granite (Figure 6.4) shows the minerals, textures and length of tourmaline crystals generally found in the rock.

Tourmaline granite & 2-mica granite

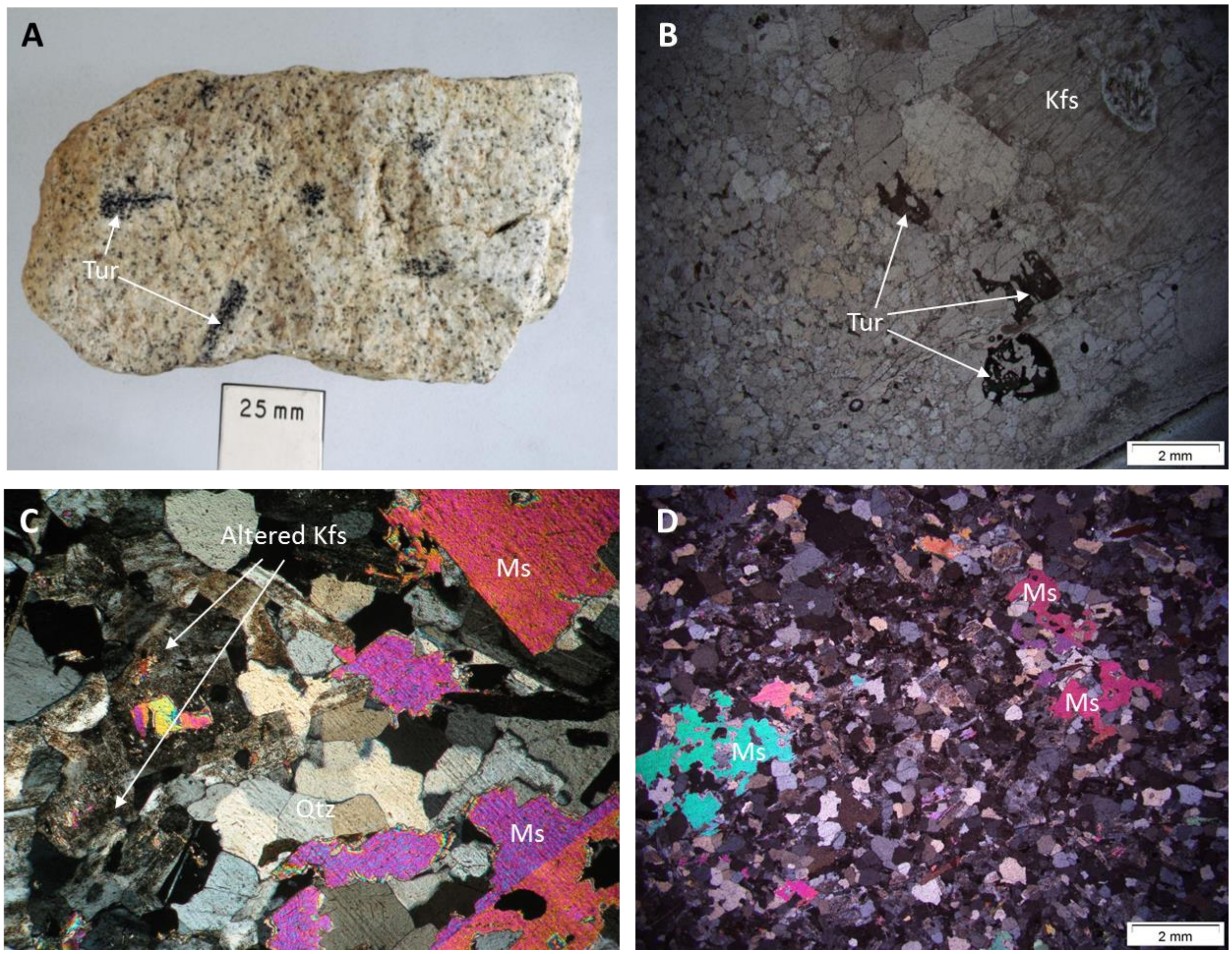


Figure 6.4: The main rock type along the south-east ridge of Ama Dablam is a tourmaline-bearing leucogranite, with *large crystals of black tourmaline up to 5 cm in length in places. Elsewhere, two-mica granites with only minor amounts of tourmaline are found. Both of these granite types were generated by the melting of the gneisses lower down in the Greater Himalayan Sequence. A – hand sample photo, showing large, distinctive tourmaline (Tur) crystals in an otherwise pale rock. B – photomicrograph showing tourmaline under the microscope, as well as a large K-feldspar (Kfs) crystal. C –K-feldspar from a two-mica granite from closer to Everest has been heavily altered to sericite by late-magmatic fluids. D – photomicrograph of a two-mica granite, showing large muscovite crystals typical of this granite.*

Stop 7: Periche: The realm of climbers and glaciers

Alt: 4,250 m

North: The Khumbu Valley

East: Ama Dablam (6,854 m)

South: The Khumbu Valley

West: Taboche and Cholatse

Distance to next Stop: 8km

Periche (4,250 m) is a desolate place but it has the last hospital en route to Everest (Maps 2 and 4). Outside the hospital is a list of those who have died on Everest and in the Khumbu Valley. There are altitude sickness lectures at 3 p.m. each day, a sombre reminder of the hostile environment. A feeling of immense loneliness descends on one when leaving Periche and continues through the loose, ankle-spraining rubble dumped by the retreating Khumbu glacier.

In Box 7.1, the role of glaciers as agents of erosion is described.

Box 7.1: The role of glaciers as agents of erosion and sediment transport at high altitudes

Glaciers are the main erosional force at altitudes above the tree line and above 4,000m above sea level. At these altitudes, temperatures are too low for water to exist in liquid form. Chemical weathering has no significant effect and organisms are scarce and hence biological weathering is insignificant. Thus, physical or mechanical weathering by ice is the dominant process. Glaciers contribute to erosion through plucking of boulders and rock fragments from the underlying rocks and through abrasion of the underlying rock by the rocks and sediments carried at the base of the glacier. They can carry significant amounts of rock material over distances of many kilometres and can have erosion rates of up to 10 mm/year, even faster than uplift rates in the Himalayas although generally, glacial erosion rates are lower, at around 0.5-1 mm/year (Malavielle et al, 2008).

Very striking are the steep-sided U-shaped glacial valleys in and around Periche (Figure 7.1) and the large mounds of glacial moraine left by the retreating Khumbu Glacier around the town. Retreating glaciers are a feature of global warming and the Khumbu Glacier has retreated around 5 km since 2006. Glaciers are formed by the compaction of snow in high valleys. Rain does not fall above the snow line, which in the Himalayas is at around 4,000m above sea level. As air is squeezed out of the snow, ice is formed. Glaciers typically move at 1 m per day, although speeds of 20 to 30 m per day have been recorded in parts of Alaska.

Where there are high erosion rates, as in the Himalayas, rock debris from rockfalls and avalanches deposit rock debris onto glaciers. This rock debris, called moraine on glaciers is carried, sometimes in distinct bands which are formed when two or three glaciers merge, to the snout of the glacier where it is deposited as heaps of rubble where the glacier ends through melting. On top of the Khumbu glacier, large amounts of rocks are deposited as the rate of erosion results in some erosional movement was observed every six seconds on average around base camp. This erosional movement could vary from a pebble falling into a crevasse to a large rockfall, a serac collapse or an avalanche. As a result, large volumes of rubble have accumulated on the Khumbu glacier. (These rocks are used to shape platforms for tents to be pitched at base camp.) The U-shaped valley (Figure 7.1) indicates that, at some stage, the Khumbu glacier extended to Periche and further down the valley almost to the base of Ama Dablam. At lower altitudes, rivers become the main agents of erosion.

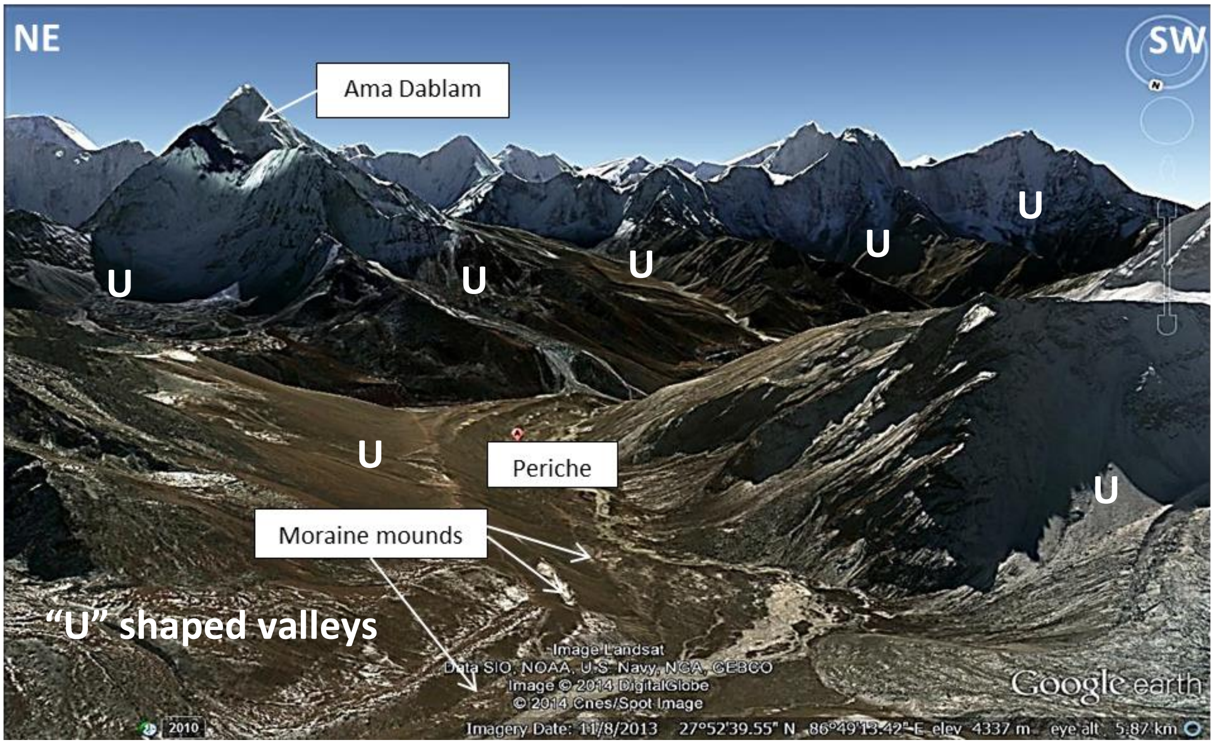


Figure 7.1: A Google Earth view, looking SSE, of U-shaped valleys typical of erosion from a pre-existing glacier with the settlement of Periche at the centre and the pointed summit of Ama Dablam at the top left of the valley. The flanks of the valley are composed of sillimanite-biotite gneiss. Retreating glaciers, such as the one on the right-hand side of the image, leave behind moraine which comprises a variety of rock types, some of which come from high on the slopes of Everest. Jessup et al. (2008) used samples of moraine from the Khumbu Glacier to describe the metamorphic history of the Everest Series.

General geology along the route

On the trek from Periche to Gorak Shep, one is walking on glacial moraine and loose rubble resulting from high erosion rates. Underlying the rubble is mostly sillimanite-biotite gneiss (Figure 7.2).

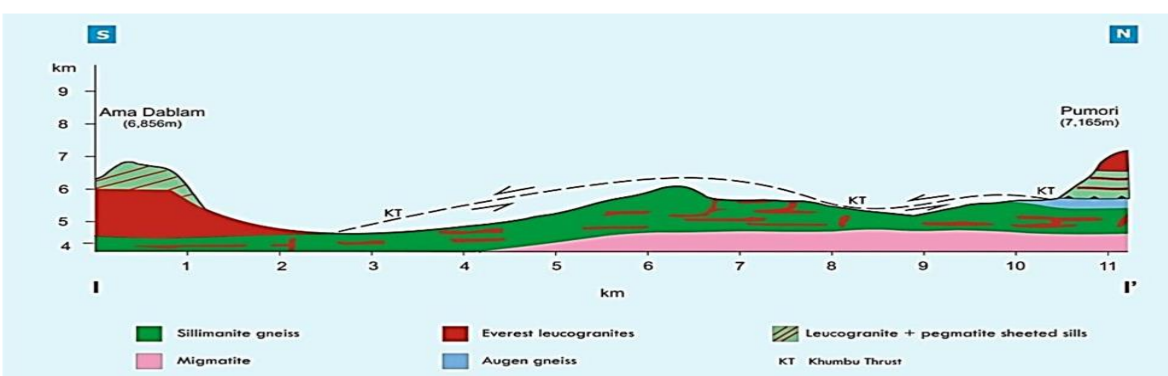


Figure 7.2: Cross section I'- I (Map 4) (Cross section drawn from Searle's Maps, 2003, 2007)

Stop 8: Laboche: Leucogranites exhumed

Alt: 4,910 m

North: The Khumbu Valley and glacier

East: Khumbu Glacier and Nuptse ridge

South: The Khumbu Valley

West: Sillimanite-biotite gneiss and gneiss

Distance to next Stop: 5km

After a big altitude increase, walking past numerous Chorten (Buddhist religious monuments shown in Figure 8.1) one arrives at Laboche (4,910 m) (Maps 2 and 4). Temperatures are around zero most of the day and night. Moraine from the Khumbu Glacier covers the valley to the east. Laboche is located in dark sillimanite-biotite gneiss and gneiss below the Khumbu Thrust and below the summit of Nuptse. In the region of this stop, a large face of granite is exposed on the face below Nuptse (Map 3). This zone of granite is exposed between the Khumbu Thrust and the Lhotse Detachment.

In Box 8.1, the tragedy of 1996 is described where a number of people lost their lives as a result of a sudden storm whilst high on the upper slopes of Everest.

This part of the route offers a good opportunity to study the leucogranite intrusions of the middle Khumbu Valley. Beneath Nuptse and Lhotse there are large bodies of leucogranite that were prevented from rising further by the Everest Series rocks which overlie the South Tibetan Detachment.

The Everest leucogranite can be seen from Laboche onwards, occupying both sides of the Khumbu valley. Vast walls of leucogranite form the faces of many of the mountains along this part of the trek (Figure 8.2) and this gives us the opportunity to study some of the igneous processes associated with the formation of these rocks. In Box 8.2, intrusions of leucogranite into the overlying rocks of the Rongbuk Formation of the Everest Series are described.

Further features of rising leucogranitic magma are massive dome structures caused by low density magma pushing up overlying strata (Searle et al., 2003). This massive ballooning structure, which occurs beneath Nuptse(Figure 8.2), Lhotse and Everest (Figure 5.6) 3000m thick on average, and is mainly responsible for the extreme altitudes of these mountains (Searle et al. 2003).

Box 8.1: Special interest feature along this part of the route - The 1996 tragedy on Everest

Climbing Mt Everest has been commercialised through mountain guiding companies. People with little high altitude or mountain climbing experience can now climb Everest for roughly US$ 60,000 before personal equipment and transport costs. Two commercial companies, which are still active today (Mountain Madness from the USA, originally run by Scott Fischer, and Adventure Consultants from New Zealand, originally run by Rob Hall), had a large number of inexperienced climbers near the summit (near Stop 13 in this guide) on 10th May 1996.

Some summited, whilst weaker climbers needed help from the mountain guides. A storm caught many unawares and Scott Fischer, Rob Hall and other guides from both companies tried to assist their clients. Some were lost in the storm and died of exposure; some slipped and fell near the summit or lower down; some died of exhaustion. Most fatalities occur when climbers get lost in a blizzard and then freeze to death.

Both Scott Fischer and Rob Hall died as they were unable to get themselves off the mountain due to exposure in the storm. Scott Fischer suffered a high-altitude cerebral edema and Rob Hall died as a result of frozen limbs. Nine people died in this particular storm and a total of 12 people died in 1996 on Mt Everest. The story has been described in the best-seller “Into Thin Air” by John Krakauer, one of the climbers on the mountain on that fateful day.

Figure 8.1: Scott Fischer’s Chorten on the route to Base Camp between Periche and Laboche – Fischer died high on Everest in the 1996 debacle when climbers were caught in a sudden storm. Such storms can arise within an hour or two of perfect climbing weather, with dire consequences for climbers who spend 12 to 14 hours between South Col and the summit on summit day, especially if a climber runs out of energy-giving and warmth-giving oxygen.

Climbers carry one 7 litre, 200-bar oxygen bottle in their backpacks, giving 1400 litres of oxygen, whilst a Sherpa will carry a spare bottle for the climber. Two bottles should be enough for a climber taking 12 hours to climb to the summit and back to South Col at a flow rate of 3 litres per minute. Available flow rate is 3.88 litres per minute using 2 bottles, i.e. 2800 litres/12 hours/60 minutes = 3.88 litres/minute.

A Chorten is a Buddhist memorial stone, the equivalent of a Christian gravestone. The rocks surrounding the Chorten in Figure 8.1 are composed of sillimanite-biotite gneiss as well as rocks dumped by the retreating snout of the Khumbu glacier, including some Everest Series schist, calc-silicate and limestone.

Box 8.2: The pegmatite intrusions into Everest Series

As low density leucogranite magma intrudes cooler rocks, it will move along the easiest paths, which are usually pre-existing planes of weakness in a rock. As the magma intrudes the host rock, numerous sills (horizontally intruded magma sheet), dykes (vertically intruded magma sheet) and plutons (a large rounded body of magma which moves upwards, intruding into pre-existing rocks) are formed as the magma is emplaced into fractures such as shear zones, joints, faults or the bedding planes of the country rocks. Away from a large granitic intrusion, this can give rise to a stockwork-like appearance of granite veins intruding host rocks (Figures 8.2 and 8.4). These intrusions may also be folded by subsequent deformation or may appear folded if they intruded along previously folded bedding planes.

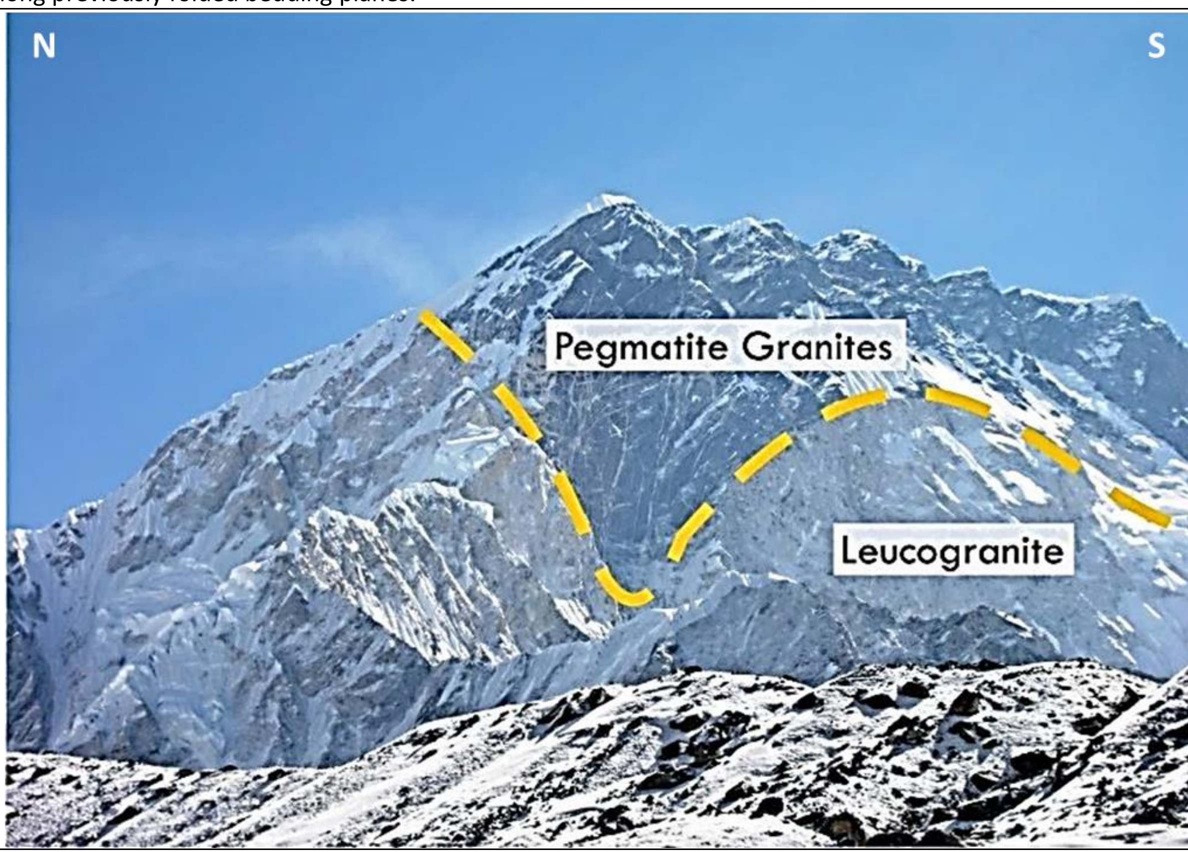


Figure 8.2: On the west face of Nuptse, a large leucogranite pluton can be seen in the lower part of the photo. In the foreground is sillimanite-biotite gneiss. The roof of the pluton is criss-crossed by a network of dykes and sills that intrude the sillimanite-biotite gneiss. Photograph taken from the Kala Pattar summit, looking eastwards. GPS co-ordinates 28^{o}59'7.45"N, 86^{o}49'39.38"E.

General geology along the route

This part of the route traverses the Khumbu glacier with Nuptse on the right hand side. Figure 8.3 shows a cross section through the Nuptse-Lhotse massif indicating the zone of leucogranite.

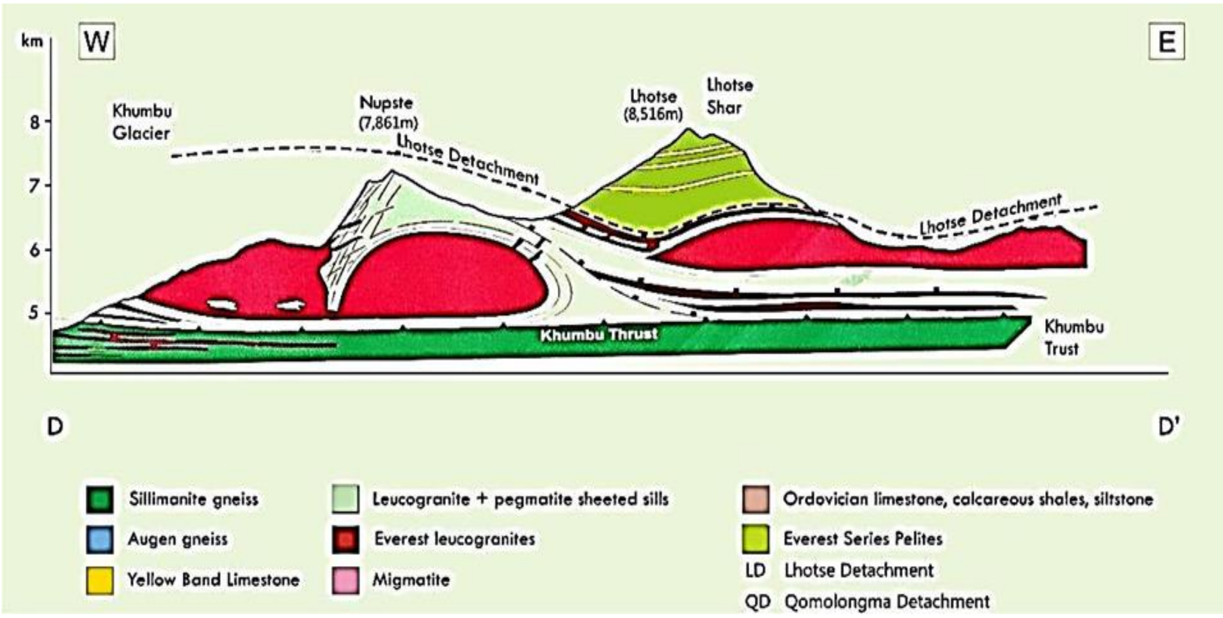


Figure 8.3: Cross Section D-D' (Map 4): From the Khumbu Glacier to Lhotse Shar (8,382 m). The Laboche area is a good example of an exhumed leucogranite unit which extends above the Khumbu Thrust to below the Lhotse Detachment (from Searle, 2007). Figures 8.2 and 8.4 correspond to the west side of the section.

On the west face of Nuptse (Figures 8.2 and 8.4), one can see a good example of a stockwork of dykes and sills as shown in Figure 8.3 below the summit of Nuptse. These are vertical and horizontal igneous intrusions into pre-existing rock. Where there is a concentration of these intrusions, it is called a stockwork because it resembles brickwork in a building.

Figure 8.2 shows a large intrusion at the base of Nupste called a pluton, also depicted in Figure 8.3. A granitic melt rose to a level just below the Everest pelites and the Lhotse Detachment, and sills and dykes intruded the rocks above the leucogranite.

Similar features are seen on many of the rock faces surrounding Base Camp.

When looking at the sheeted sills and dykes in more detail in Figure 8.4, one sees the pale coloured leucogranite intruding vertical and horizontal planes of weakness in the darker sillimanite-biotite gneiss. When the main body of magma intruded these planes of weakness were exploited by the rising magma and formed the spectacular stockwork seen in these rocks. The jagged nature of the cracks into which the leucogranite was intruded suggests that the surrounding rock was solid and a brittle deforming layer above a rising pluton of granite resulted in the injection of granitic magma into cracks in the country rock. The pressure of the rising magma was so great that the fracturing was caused by the intrusive melt itself. This type of fracturing is called hydraulic fracturing.

From Figures 8.3 and 9.2, it can be seen that sheeted leucogranite sills and dykes also occur below the leucogranite plutons as well as above (Figure 8.4) and form an integral part of the process of intrusion and channel extrusion (Box 10.1).

Figure 8.4: More detailed view of the pelitic west face of Nuptse (See Figure 8.2) showing a stockwork of intruding light-coloured dykes and sills, and a leucogranite pluton at its base.

Stop 9: Gorak Shep: Approach to Everest Base Camp

Alt: 5,140 m

North: Pumori, Lingtren, Khumbutse, Changtse

East: Nuptse ridge

South: Khumbu Valley

West: Changri, Laboche West and a large flat rubble-strewn lake bed, now dry

Distance to next Stop: 4km

Everest is clearly visible, together with the surrounding peaks (Map 4). The nearby trekking summit rocks of Kala Pattar (5545 m) are composed of granite that contains elongate tourmaline crystals. One is now in the upper parts of the Greater Himalayan Sequence between the Lhotse Detachment and the underlying Khumbu Thrust. Views of Pumori, Changtse and Everest (Figures 9.1, 9.3 and 9.4) as well as Nuptse, Lingtren, Makalu and many more peaks can be seen from the summit of Kala Pattar. All are largely composed of Higher Himalayan Leucogranites. Numerous folds and faults are visible in the surrounding valley walls.

Gorak Shep itself is located on the Khumbu Thrust, as evidenced by shearing and well-defined fabrics in the surrounding sillimanite-biotite gneiss. Figure 9.2 shows a cross section of the area, which describes the geology of Kala Pattar, Pumori and Lingtren mountains as seen from Base Camp.

A view of Changtse from the top of Kala Pattar offers a good opportunity to see the limestones and pelites of the Everest Series. The distinctive Yellow Band is clearly visible, sandwiched between blue and grey limestones. Figure 9.1 shows the detailed geology of the mountain.

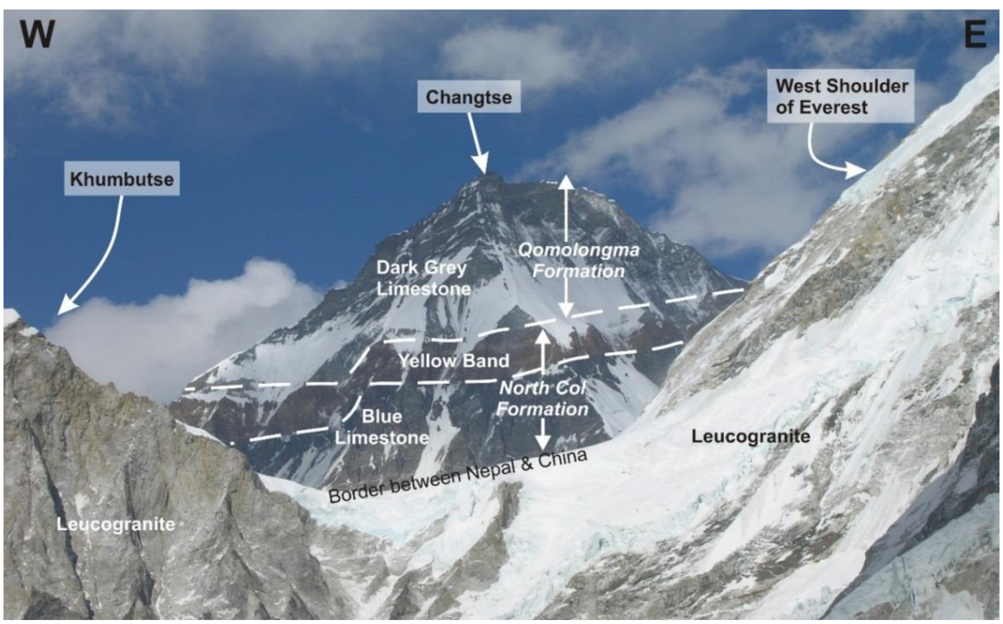


Figure 9.1: View of Changtse from the summit of Kala Pattar showing the Everest Series on Changtse.

General geology along the route

The geology here comprises the Everest leucogranites, which can be seen on Pumori, the Everest Series rocks, which can be seen in the peaks of Changtse and Everest, and the sillimanite-biotite gneiss of the Greater Himalayan Sequence around Gorak Shep near Kala Pattar (Figure 9.2).

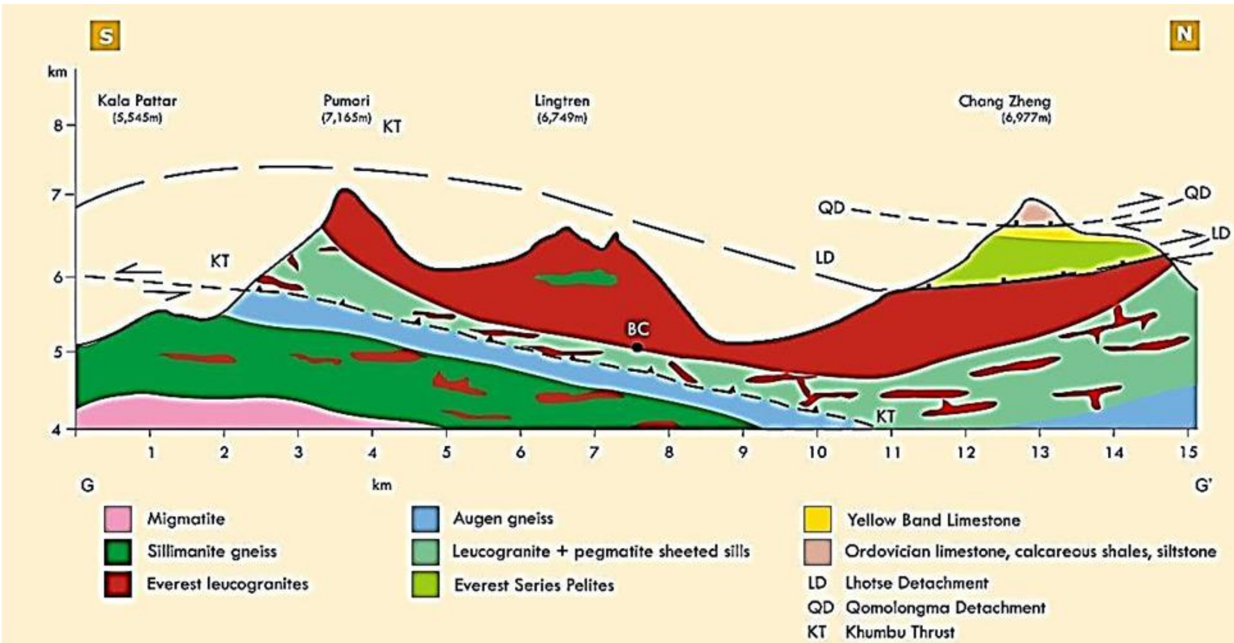


Figure 9.2: Cross section G-G' (Map 4)

On the climb up to the Kala Pattar summit, Pumori dominates the view. This is a peak typical of the high Himalayas, composed of leucogranite and separated from the sillimanite-biotite gneiss underfoot by the Khumbu Thrust.

Everest leucogranite containing black tourmaline crystals intrusions are encountered in the sillimanite-biotite gneiss. From here, the summit leucogranite of Pumori can be seen (Figure 9.3).

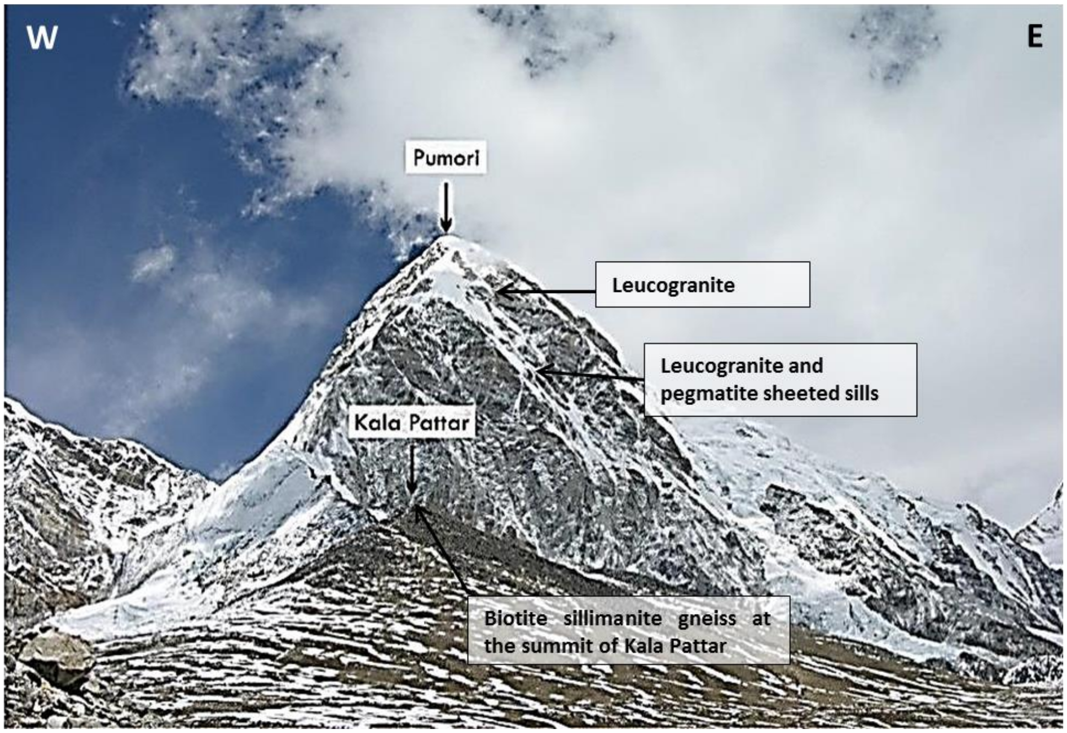


Figure 9.3: View of Pumori looking north-west with Kala Pattar in the foreground. from GPS co-ordinates: 27°59'35"N, 86°49'42" E

The top of Kala Pattar is an excellent viewpoint for observing the geology surrounding Everest. From here, the peaks of Pumori, Lingtren, Khumbutse, Changtse, Lhotse, Nuptse and the western shoulder of Everest are clearly visible (Figure 9.4). Further south, Makalu, Taboche and Cholatse can be seen. This gives one the chance to get a clear view of some key geological features, preferably with a pair of binoculars.

Looking northwards from the Kala Pattar summit one can see the amphitheater around Everest Base Camp comprising the Everest massif. The dark rocks of Mount Everest lie behind its leucogranitic, pegmatite-intruded, west shoulder (Figure 9.4).

Changtse (Figure 9.1) and the upper portions of Everest are composed of Everest Series pelite and limestone. Between the Qomolongma Detachment (QD) and the Lhotse Detachment (LD), Everest Series pelites (metamorphosed mudstones) are the main rock type. These samples (such as the sample from near Camp 2 – Figure 9.6), have experienced low-grade metamorphism and may show evidence of D_2 deformation in the Everest Series (see Figure 3.2D). These schists are made up of biotite, muscovite and quartz. No high-grade minerals such as sillimanite, or leucosomes containing large grained feldspar are found in these rocks, which are either fine-grained (<0.1 mm) slate or slightly coarser grained (~0.25mm) schist that is strongly foliated. – this foliation is typical of the S_1 fabric found throughout the Everest Series, and was formed during prograde (or burial) metamorphism. The S_1 fabric was later folded into asymmetrical kink-folds during exhumation, and these so-called kink-bands are typical of D_2 deformation in the Everest Series (See Figure 3.2D).

Between the Lhotse Detachment and the Khumbu Thrust (KT), leucogranite is the dominant rock type. Here the high-grade metamorphic rocks of the Greater Himalayan Sequence can be seen juxtaposed against the low-grade

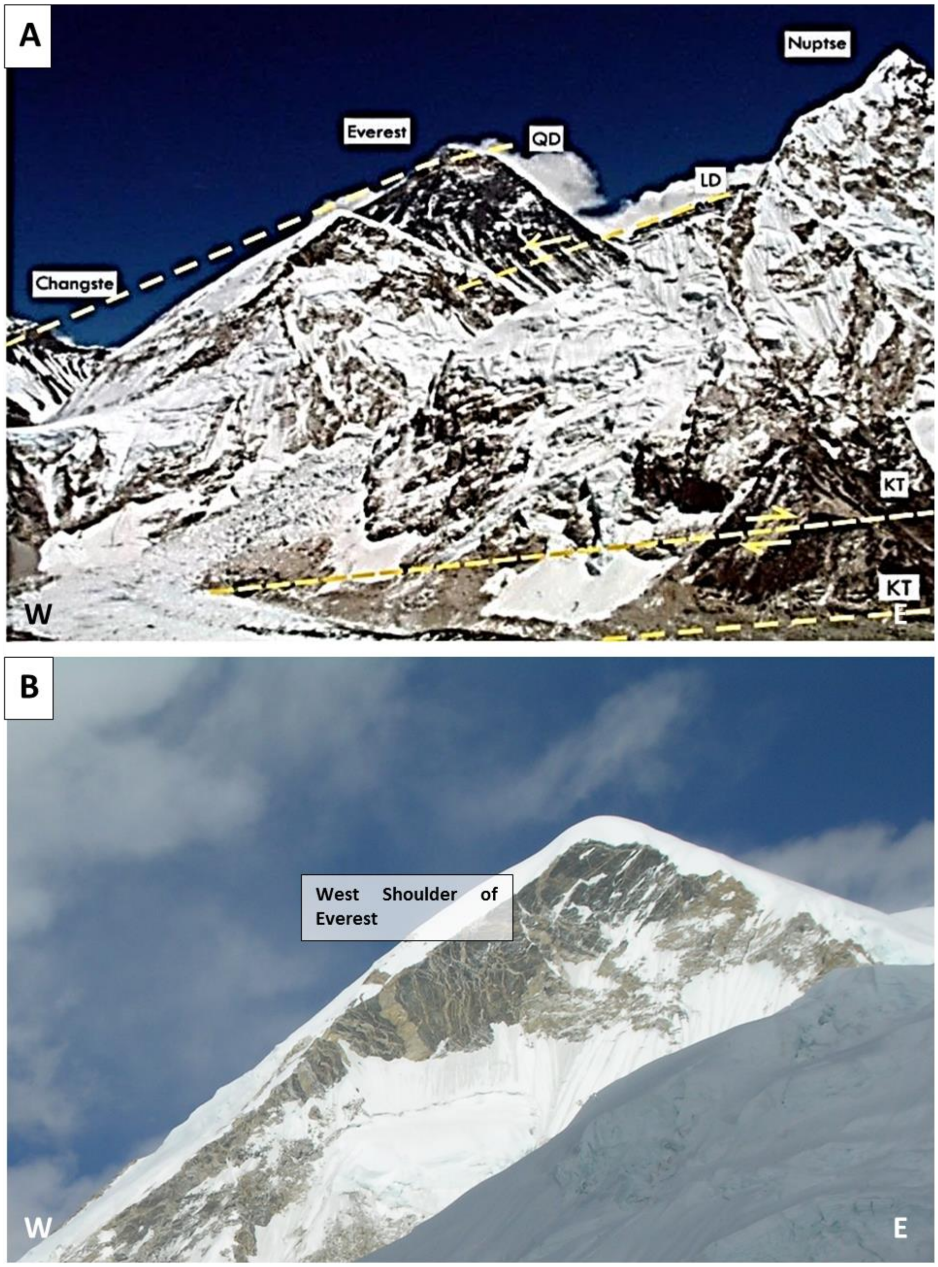


Figure 9.4: View of the Everest massif from Kala Pattar showing Everest with the position of main faults in yellow (A). The thickness of the KT fault zone is estimated to be 100m. A blow-up of the West Shoulder of Everest shows the stockwork of pegmatite sills and dyke near its summit (B). View from GPS co-ordinates: 27°59’45”N, 86°49’42”E.

Towards the south-west, a granite pluton intrusion has folded the overlying strata into a dome structure (Searle et al., 2003) with a stockwork of dykes and sills from the pluton intruding the overlying rocks (Figure 9.5). This is a further example of a leucogranite intrusion into the sillimanite-biotite gneiss of the overlying Greater Himalayan Sequence. This is typical of this area where the remaining melt of the intrusion has been injected into overlying and adjacent planes of weakness, as also so spectacularly shown in Figure 8.4 and near the top of the West Shoulder of Everest (Figure 9.4).

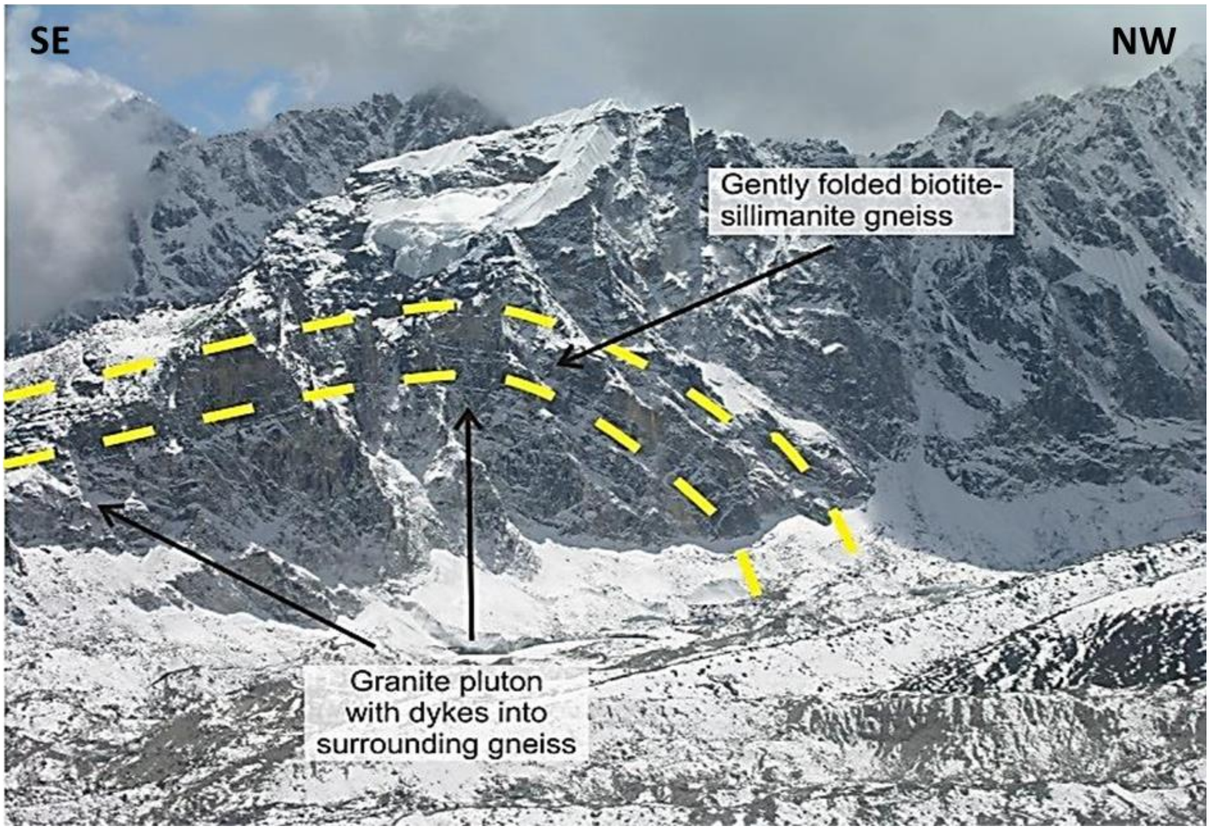


Figure 9.5: View from Kala Pattar summit looking south-west showing a large pluton intrusion.

An example of slate and low-grade schist from the Everest Series is shown in Figure 9.6.

Slate and low-grade schist

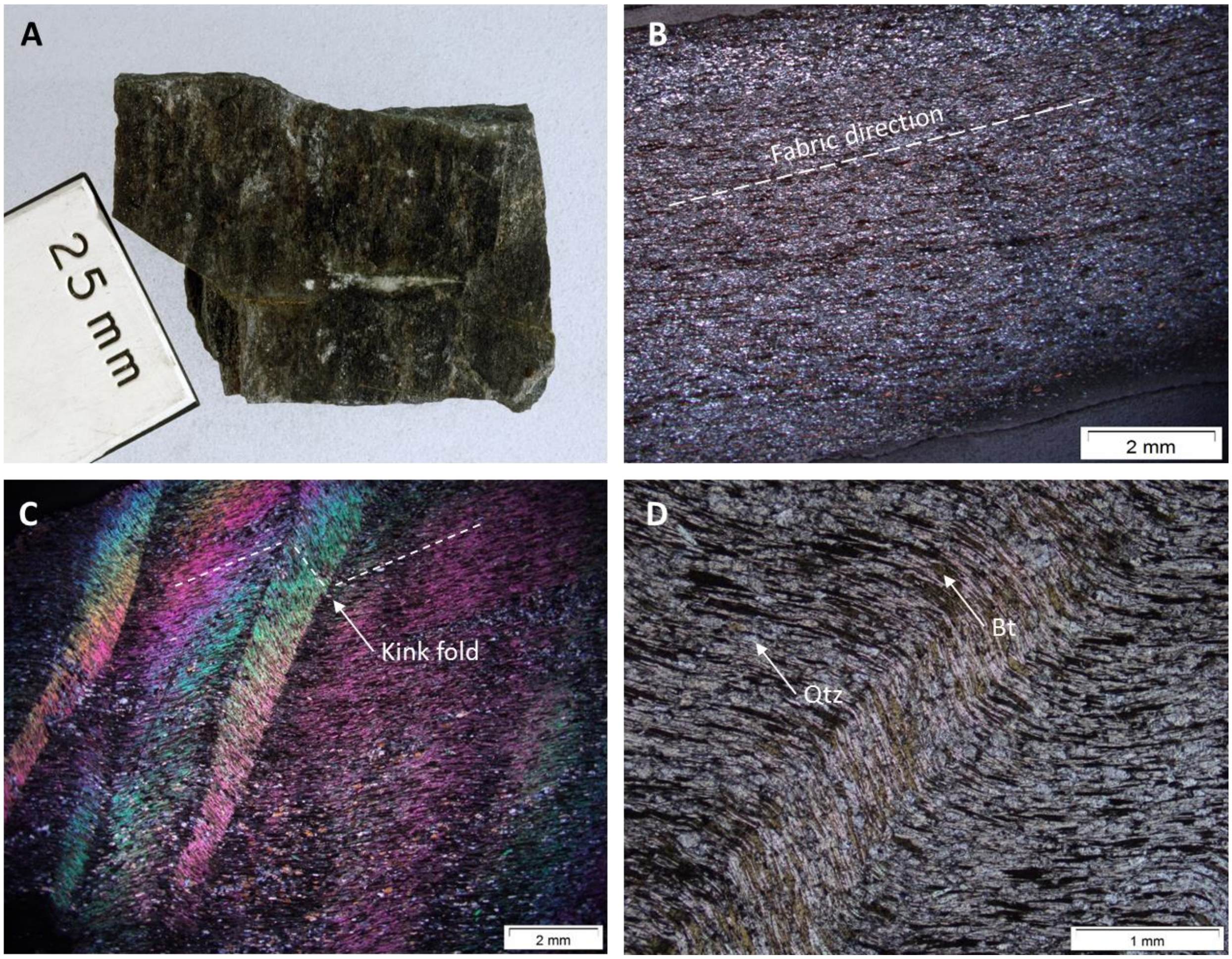


Figure 9.6: Everest series low grade schist and slate. Samples of low-grade slate and quartz-biotite schist from the Everest Series. A: Hand sample photograph of slate, a fine-grained, dark rock. B: photomicrograph (XPL) of slate, showing alignment of very fine-grained biotite and quartz to form a fabric. C: Photomicrograph (XPL) of low-grade quartz-biotite schist. This schist is slightly higher-grade than the slate, and shows coarser biotite and quartz that are aligned to form the schistose fabric. The fabric has been deformed (likely during exhumation – the late stages of D_2 deformation) into kink folds. D: photomicrograph (PPL) showing a closer view of a kink fold in the quartz-biotite schist.

Stop 10: Everest Base Camp: A pause to reflect

Alt: 5,364 m

North: Khumbutse, Lingtren II, Lho La Pass (Northwest Col)

East: West shoulder of Everest, Lhotse, Nuptse, the Khumbu icefall

South: Himalayan 6,000 m Peaks, Khumbu Glacier

West: Pumori, Lingtren peaks

Distance to next Stop: 6km

Arrival at Base Camp (Maps 2 and 4) is an achievement in itself. A cozy, private tent surrounded by personal belongings can significantly uplift the spirit. After some good food and plenty of sleep, the sights all around begin to garner attention. One can almost feel the movement of the giant rock units all around. Every six seconds, on average, one hears an avalanche, rock fall, serac collapse, pebble clatter or some other movement whilst lying in one's tent. These are extreme rates of erosion and this erosion is both a consequence of the extreme rate of uplift as well as being a driver of the rapid exhumation of the Greater Himalayan Sequence. The shallow, northwards dip of the rocks here has not changed since the journey began in Lukla, although locally, steep dips indicate folding of the rocks in many places. The layering of the leucogranites, sillimanite-biotite gneiss and Everest Series sediments creates a striking effect.

In Box 10.1, Channel flow is discussed and the mechanism of extrusion of large slabs of partially molten (weak) rock is described.

Box 10.1 The channel flow theory

Burchfield and Royden (1985) were the first to suggest that the "Himalayan wedge" (the Greater Himalayan Sequence) had been extruded beneath the South Tibetan Detachment (STD) system of normal faults. The concept of channel flow arose when geophysical surveys led by Doug Nelson (Nelson et al., 1996) suggested that there was a molten layer in the crust beneath Tibet. Channel flow is the generally accepted mechanism to explain the geology of the high Himalayas (Law et al., 2006) and is an elegant theory that describes what we see in the Himalayas today.

Channel flow initiated at circa 30 million years ago and channel extrusion begins at circa 15 million years ago (Jameison et al. 2004).

The recent exhumation of the Higher Himalayan Leucogranites and gneisses of the Greater Himalayan Sequence from beneath Tibet can be explained by the channel flow model. Searle et al. (2003) used structural geology, thermobarometry and geochronology to evaluate models for channel flow and ductile extrusion of the crust.
Channel flow describes a protracted flow of a weak, viscous crustal layer between relatively rigid, yet deformable, bounding crustal slabs (Godin et al., 2006). This weak crustal layer (the Higher Himalayan Leucogranites and the Greater Himalayan Sequence) flows almost laterally owing a lithostatic pressure gradient caused by the very thick Tibetan crust and the normal crustal thickness in the Indian foreland (Godin et al., 2006). A high rate of erosion at the mountain front enhances the exhumation of this channel material. If both channel flow and denudation are acting at the same time, then extrusion of the mid-crustal channel material can occur with a normal-sense fault at the top (i.e. the STD), and a thrust-sense fault at the bottom of the channel (i.e. the Khumbu Thrust or MCT) (Godin et al., 2006), as shown in Figure 10.1.

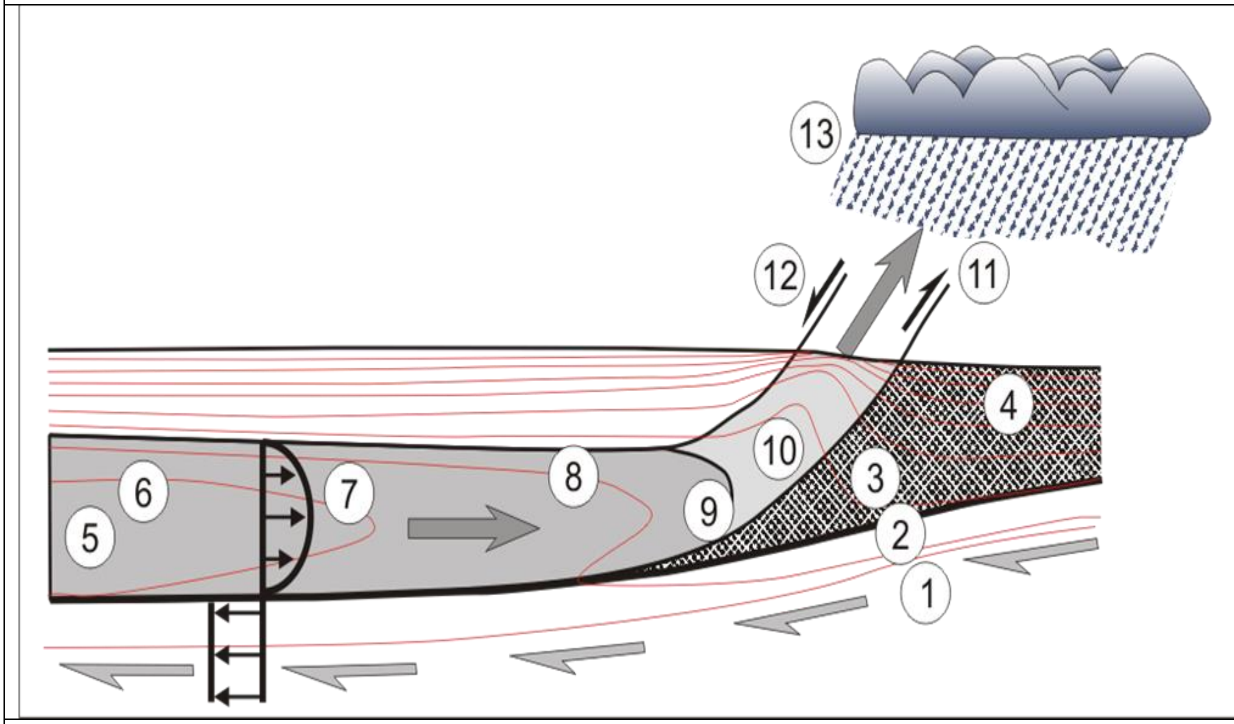


Figure 10.1: Schematic diagram of the relationship between channel flow and extrusion of a palaeochannel (after Godin et al., 2006). 1 – Mantle, 2 – Lower Crust, 3 – Mid Crust, 4 – Upper Crust, 5 – Weak Crustal Channel, 6 – Isotherms (from Beaumont et al., 2004), 7 – Schematic velocity profiles, 8 – 750°C isotherm, structurally below which partial melting occurs, 9 – Rheological tip of channel, , 10 – Extruding crustal block, 11 – Lower thrust zone of extruding block (e.g. Khumbu Thrust or the Main Central Thrust), 12 – Upper shear zone/detachment zone of extruding block (e.g. the South Tibetan Detachment or the Qomolongma Detachment), 13 – Focused surface denudation through snow, rain and ice erosion.

General geology along the route

At Base Camp, one can see more detail in the leucogranite, the gneiss and their deformation, and how it is related to the concept of Channel Flow. A section through the general geology of Base Camp is shown in Figure 10.2.

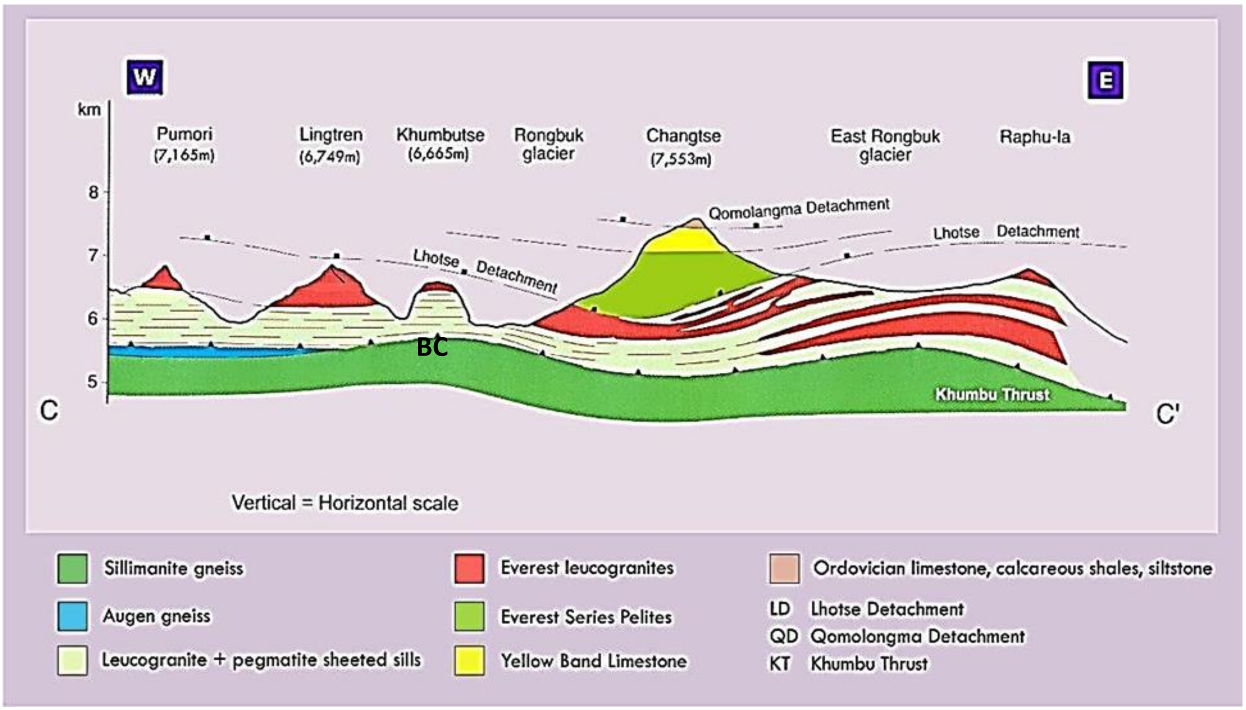


Figure 10.2: Cross section C-C' (Map 4) - from Pumori through Changtse. From Base Camp, Pumori, Lingtren and Khumbutse can be seen (after Searle, 2007).

The geology of the Pumori-Lingtren ridge (as seen from base camp, looking west) is shown in Figure 10.3. Sillimanite-biotite gneiss underlies the leucogranite of Pumori and Lingtren and dips gently to the north. The dip of the layering is sub-parallel to the dip of the major structures along which exhumation has taken place.

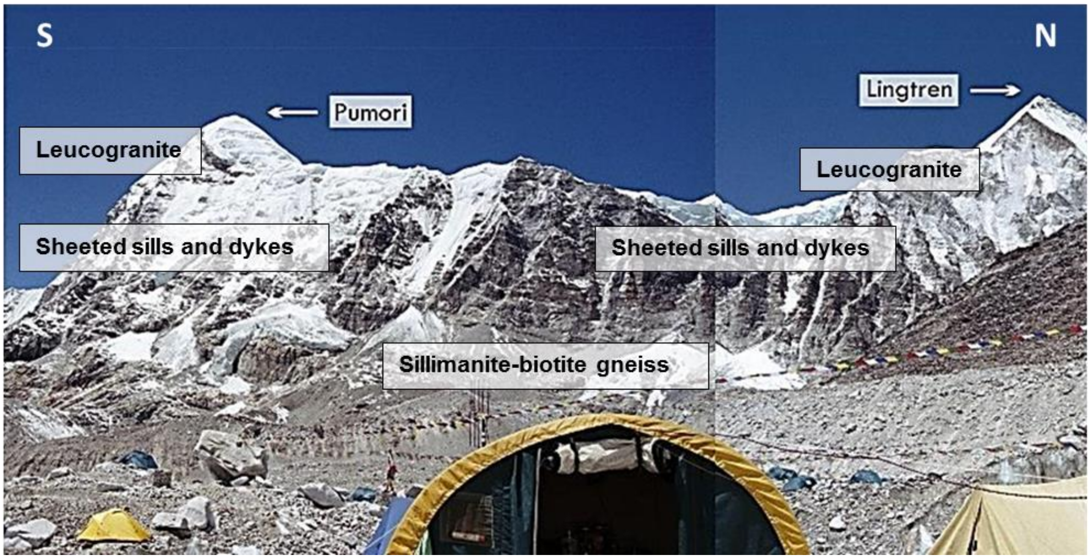


Figure 10.3: The east faces of Pumori and Lingtren above the Khumbu glacier showing exhumed leucogranite intruding sillimanite-biotite gneiss. Photo taken from GPS co-ordinates 28°00'24"N, 86°51'42"E.

A closer look at the east face of Lingtren and Lingtren II, as seen from Base Camp, shows it is composed almost entirely of leucogranite (Figure 10.4).

Figure 10.4: The east face of Lingtren above the Khumbu Icefall showing a xenolith of sillimanite-biotite gneiss and strongly layered sillimanite-biotite gneiss at the base of the leucogranite, which is also the location of the Khumbu Thrust. Photo taken from GPS co-ordinates 27°58'54"N, 86°49'48"E.

The ridge is interpreted as an intrusion of leucogranite between the sillimanite-biotite gneiss and the Lhotse Detachment (Searle et al. 2003) (Figure 10.4). Restoration of the Pumori Lingtren Everest profile (Figure 10.5) shows that melting of the leucogranite occurred at around 20km depth (P=7 kb) and, depending on the dip of the LD samples taken from Kala Pattar show that these rocks have been displaced southwards for a distance of between 90 to 216km (Searle et al. 2003). The Pumori – Lingtren ridge is therefore the top part of a channel extruded between the STD (of which the LD and the QD for part of) and the MCT.

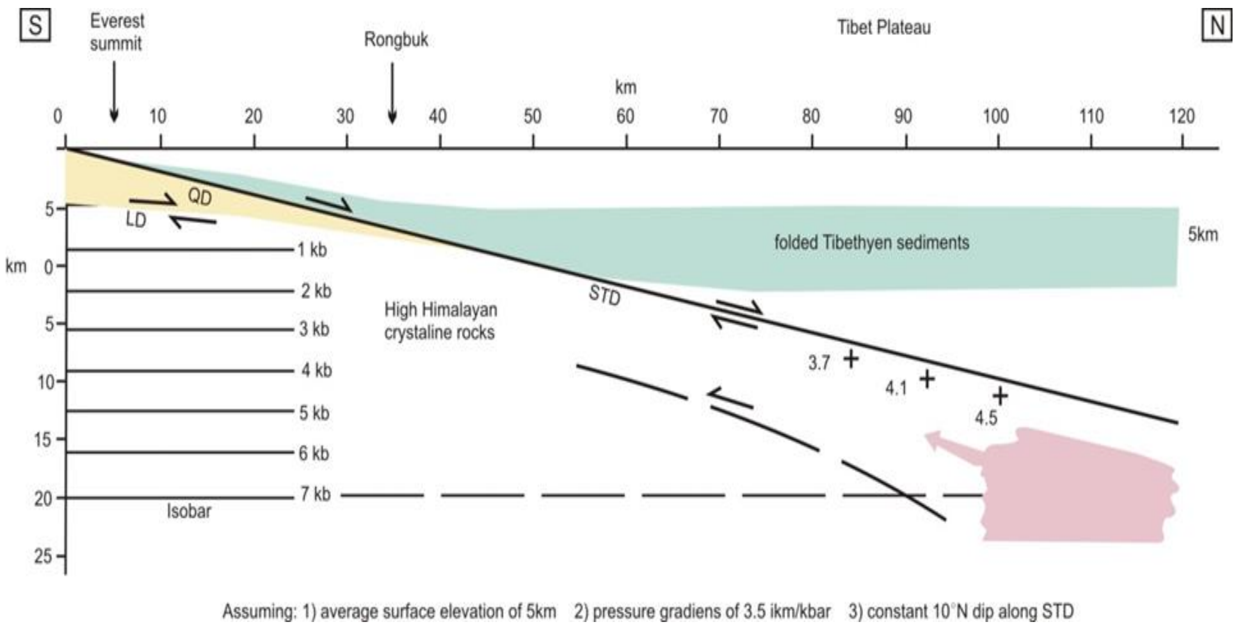


Figure 10.5: Restored Pumori – Everest profile before emplacement of the leucogranite. Crosses mark samples from Kala Pattar, 12km west of Everest (Map 4) which record pressures of 3.7, 4.1 and 4.5kb. at a true dip of 3° to 5°N measured on the N face of Everest, relative displacement is would be 180-216km (After Searle et al., 2003).

Melting of the leucogranite that we see on surface today took place circa 21 million years ago. The deformed sills and cross cutting dykes on the west shoulder of Everest (Figure 9.4) and under the Nuptse ridge (Figure 8.4) have an age of 16 to 17 million years and deformation resulted from ductile shearing on the STD around 17 million years ago. Some of the undeformed cross-cutting dykes are younger than 16 million years (Searle et al. 2003) and have not been affected by ductile deformation.

Leucogranite can be examined in an outcrop just east of Base Camp on the other side of the Khumbu icefall (Figure 10.6). There is evidence of a number of intrusive episodes of granite with fine grained granite intruding into coarse-grained rocks (Figure 10.6A). There is also evidence of younger granite intruding amphibole and pre-existing granite, with numerous xenoliths (Figure 10.6B). This can be linked to channel flow: as the molten channel edges cooled and solidified, so new liquid granitic material was injected into the cooled rocks which included both granite and amphibolite.

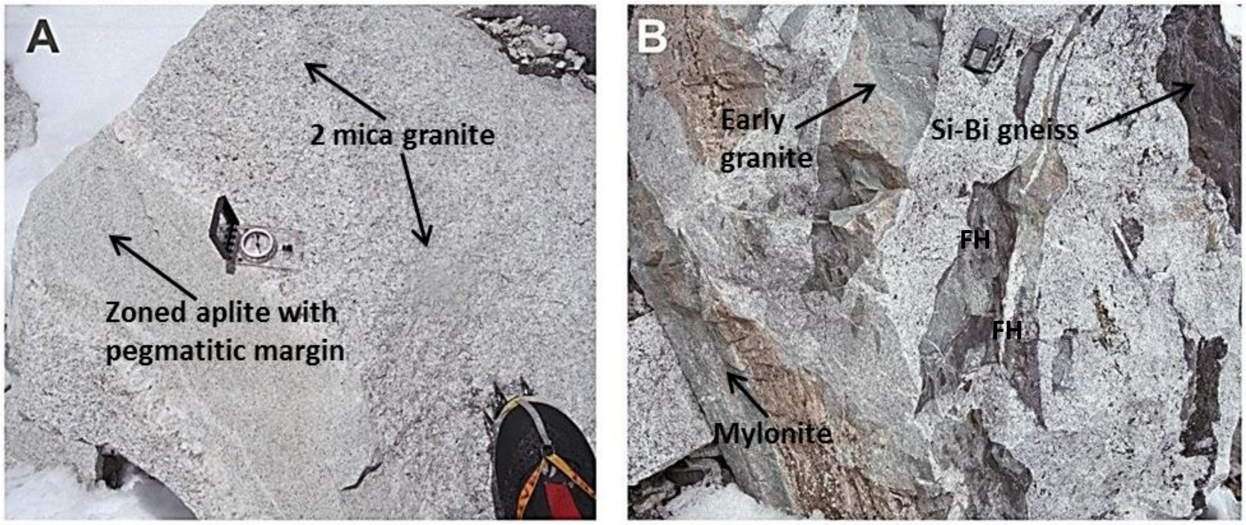


Figure 10.6: Different grain sizes of leucogranite in an outcrop near Base Camp below the summit of Nuptse (A) and granite-intruding amphibolite and pre-existing granite in moraine rock from Base Camp (B). The angular inclusions of dark gneiss and earlier sheared granite and mylonitic zones can be seen in B. A Boudin with a granite vein in it, which is very "strung-out" at the top can also be seen in B indicating very ductile conditions. Dark amphibolite "Fish-Head" boudins (FH) can be seen in the sheared granite in B indicating continued deformation and thinning at the edges of the black amphibolite inclusions with the less viscous amphibolite elongated and leucosome melt forming between the inclusions. Photograph taken at GPS co-ordinates 28^{o}0'6.58"N, 86^{o}51'49.03"E.

On the west face of Nuptse above the Khumbu Icefall (Figure 10.7), leucogranite sills have intruded parallel to the layering in the host sillimanite-biotite gneiss. The granite follows the layering in the gneiss and appears to have been folded. Recumbent folding is common in the gneiss of the Khumbu valley. This folding is the result of deformation during the exhumation of the Greater Himalayan Sequence. Intense shearing in the vicinity of major thrust planes, such as the Khumbu Thrust, resulted in the widespread occurrence of mylonite.

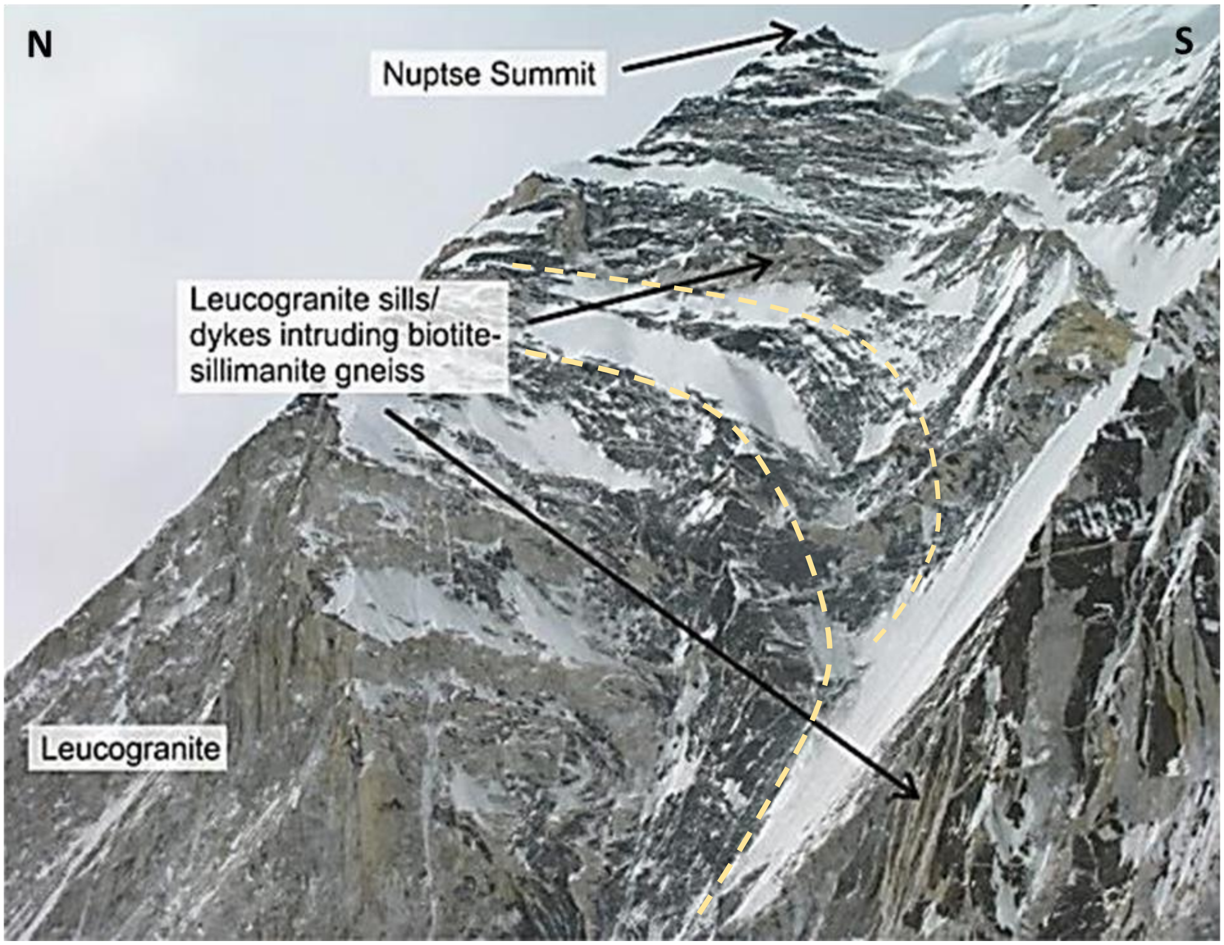


Figure 10.7: The west face of Nuptse above the Khumbu ice-fall showing folding of the leucogranite sills and dykes.

Box 10.2 Earthquakes and Mylonite

Mylonite is produced when there is movement along a fault. This is called an earthquake.

Many earthquake epicentres have been recorded along the line of the Himalayan Front along faults, owing to the continued movement of the Indian sub-continent underneath Tibet and the escape of material away from the Himalayas.

Earthquakes such as the recent event on 25th April 2015 have a massive one-time impact with collapses of huge faces of rock. The epicentre of the earthquake (28.15°N 84.7°E) has been estimated at 1 5 km depth, northwest of Kathmandu. In Base Camp, the 7.8 magnitude earthquake triggered a rock and ice-fall on the east face of the Pumori-Lingtren massif and resulted in 17 deaths with much of the Camp being devastated.

A second earthquake (magnitude 7.3) on the 12th May 2015, whose epicentre (27.84°N, 86.1°E) was virtually beneath Everest at a depth of 18.5 km, was reported as being the result of a thrust movement. This was probably again on the MCT (USGS Earthquake Hazards Program).

Around 20 >magnitude 7 earthquakes, as shown in Figure 10.8, have occurred over the last 114 years. Although infrequent, the last big earthquake prior to 2015 is reported to have occurred in 1934.

With the epicentre of the earthquake having occurred at around 15 km depth northwest of Kathmandu (Figure 10.9), movement is thought to have occurred on the Main Frontal Thrust (Figures 10.8) as Kathmandu lies above the MFT. The maximum vertical movement indicated by the German Aerospace Centre (DLR) shown in Figure 10.9 is 2.7 m. The horizontal movement resulting from a 2.7 m vertical movement at an angle of 5° (the dip of the MCT (Searle et al., 2003)), is approximately 30 m. If only the 1.2 m vertical movement is considered, then the horizontal movement at 5° dip is 13.7m.

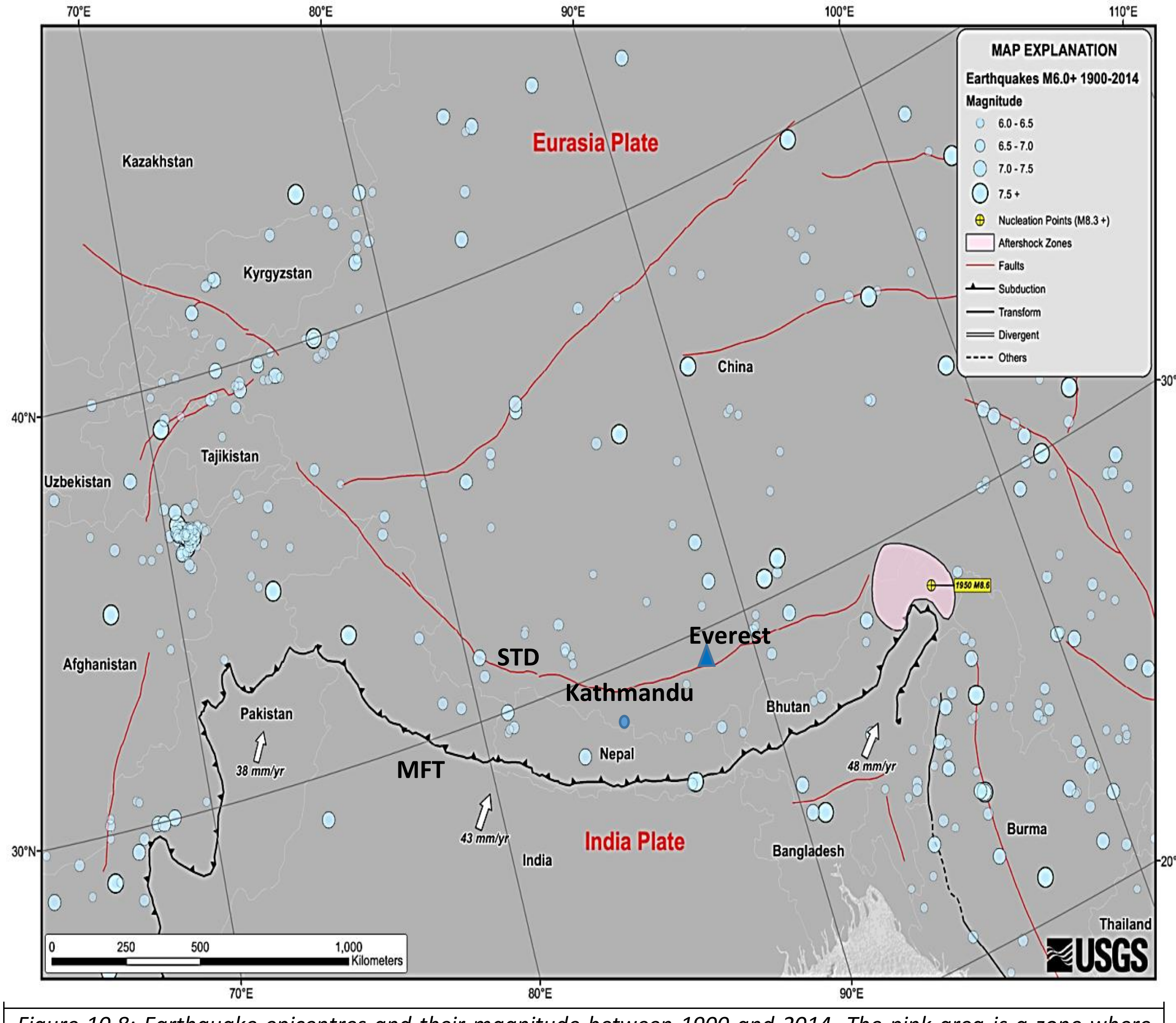


Figure 10.8: Earthquake epicentres and their magnitude between 1900 and 2014. The pink area is a zone where most aftershocks occur. This is the zone where the South Tibetan Detachment (STD) and the Main Frontal Thrust (MFT) are closest together, and hence the area of most seismic activity.
(Source: http://earthquake.usgs.gov/earthquakes/tectonic/images/himalaya_tsum.pdf, accessed July 2014).

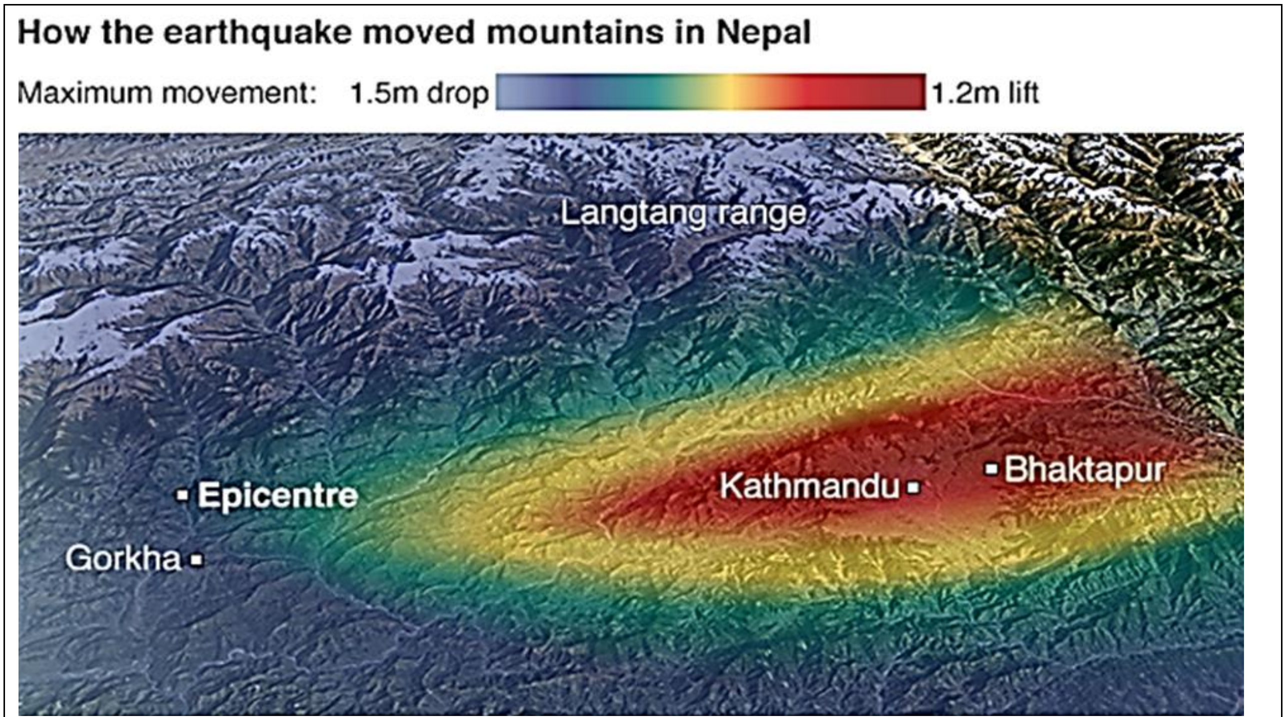


Figure 10.9: Map showing lift and drop associated with the earthquake of 25th April, 2015 with epicentre west-north-west of Kathmandu. (Source: Google Earth/DLR earth Observation Centre/Sentinel -1 satellite operated by ESA.)

Since the start of the collision of India and Asia, estimates of slip along the Main Himalayan Front of greater than 400 km have been postulated by Coward and Butler (1985), Hauck et al. (1998), and Murphy and Yin (2003).

Microscopic examination of a mylonite sample from near Base Camp (GPS co-ordinates 28^{o}0'42.75"N, 86^{o}51'24.57"E) is given in Figure 10.10. Mylonite is fairly abundant both at Base Camp and above it, likely owing to the proximity to the KT, a major zone of deformation, or possibly one of the major detachments found on the slopes of Everest, along which large amounts of movement have taken place. Mylonite is formed as a result of dynamic grain-size reduction caused by straining the rock in shear zones. Whilst the mineralogy of mylonites can be variable, they are fine-grained to extremely fine grained, with small (<0.1 mm) as intense deformation has led to grain size reduction.

Mylonite

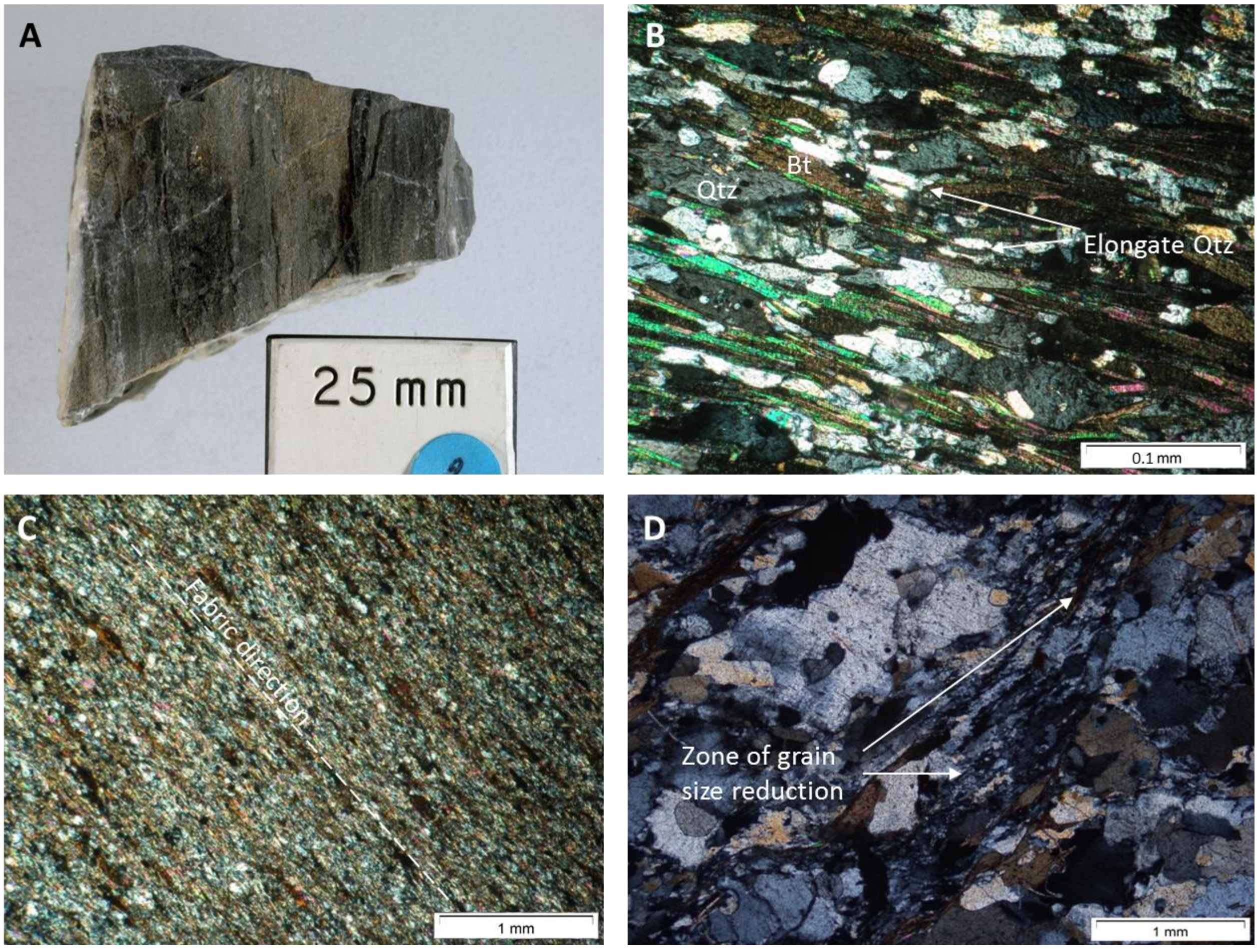


Figure 10.10: Mylonite is a fairly common occurrence from Base Camp to the South Col of Everest. It has formed as a result of movement along major faults such as the Khumbu Thrust, Lhotse Detachment and Qomolongma Detachment. A: hand sample photograph of fine-grained mylonite. B: photomicrograph (XPL) showing the elongate nature of quartz grains and the alignment of quartz and biotite to form the fabric in a mylonite. C: Photomicrograph (XPL) showing the fine grained nature of the mylonite sample. D: Photomicrograph (XPL) of a proto-mylonite. This sample has not yet undergone wholesale grain size reduction, but zones in the sample show incipient grain-size reduction through crystallisation.

Stop 11: Western Cwm: Amphitheatre of giants

Alt of Camp 2: 6,500 m

North: West Shoulder of Everest

East: The Lhotse face

South: The north face of the Nuptse ridge

West: Pumori, Lingtren and Khumbutse

Distance to next Stop: 3.5km (2km to Camp 3 site and a further 1.5km to Camp 4 (South Col)

The Icefall has 14 ladder-crossings and it takes around eight hours of climbing to reach Camp I and a further four hours to reach Camp II (Maps 4). Avalanches are common. Both are powerful agents of erosion. Camp I is located in the zone of leucogranites at the top of the Greater Himalayan Sequence, with numerous sills and dykes of granite. Temperatures range from -30 to -40°C, to well into the +20°s adding another force to erosion as expansion and contraction of rocks can breaks them. High winds, sometimes in excess of 60 km/hr, can dislodge rocks leading to rockfalls and further assist erosion. These are the conditions that are normally experienced on Everest.

At Camp II, the fantastic geology of the Cwm is revealed. Here one can observe the folded yellow calc-silicate bands of the North Col Formation high up on the Lhotse face, the dark brooding Everest Series pelites and carbonates, and the Nuptse leucogranite. The Lhotse Detachment, across which high-grade rocks and granites are juxtaposed with low-grade metapelite, is located just below the top of the Geneva Spur.

Western Cwm fold

The face between Nuptse and Lhotse contains a fold structure as shown in Figure 11.1. Three prominent bands of calc-silicate marbles occur on the Lhotse south face (Searle et al 2003). The structure is a recumbent fold of yellow calc-silicate bands (Searle 1999), part of the Everest Series pelites, with what appears to be a southwards vergence (vergence of a fold is the direction in which the fold is inclined or overturned). Higher up on the Lhotse face, a small thrust fault is visible, also displacing rocks upwards towards the south. The Lhotse Detachment is located below the calc-silicate bands (Searle 1999).

The upper parts of the Greater Himalayan Sequence, and the Everest Series, are dominated by normal faulting or extensional movement. The folds are related to extensional movement along the Lhotse Detachment. Such apparent reverse folding can occur, when associated with movement in ductile extensional shear zones (Harris et al., 2002).

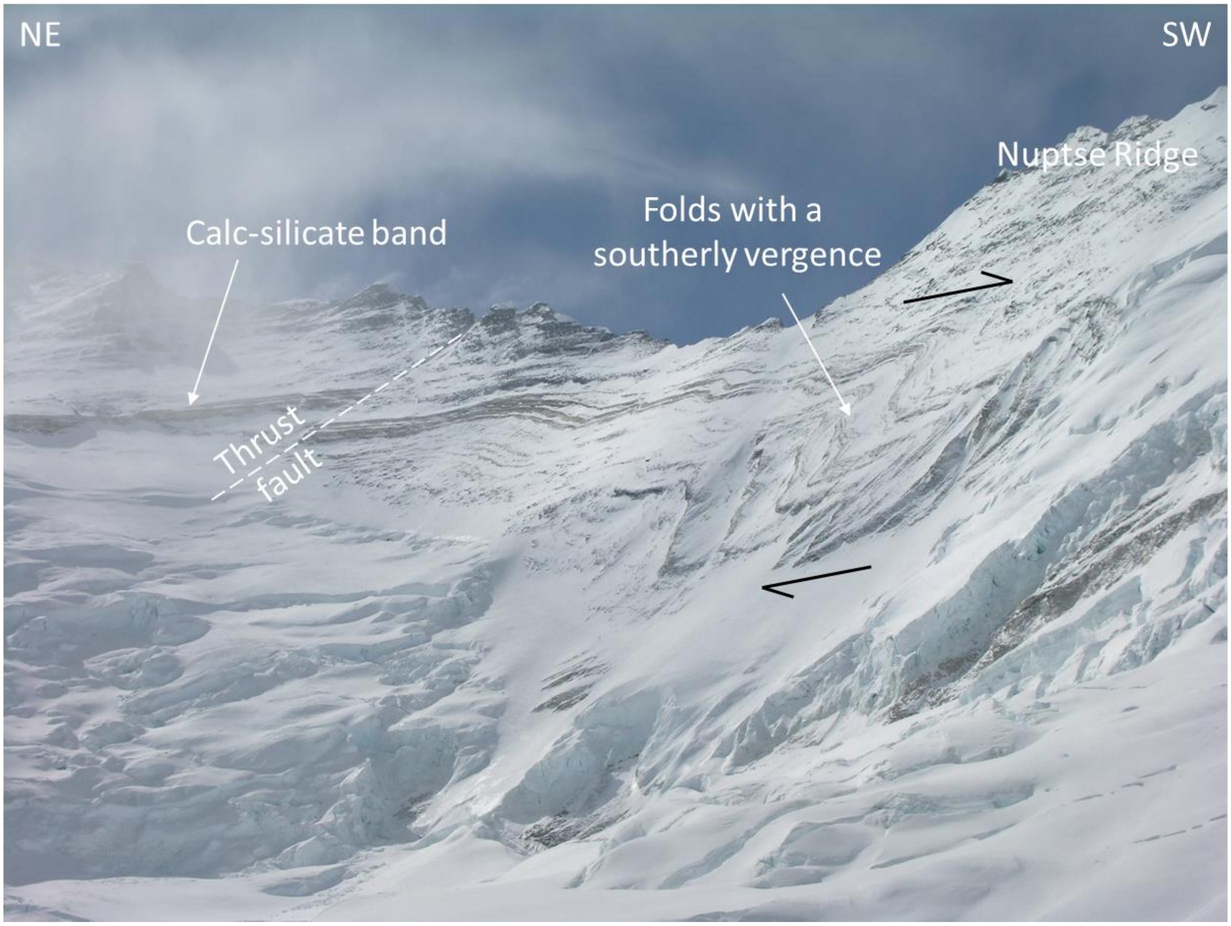


Figure 11.1: The Western Cwm fold seen looking eastwards from Camp II. A thrust (reverse) fault can be seen high up on the Lhotse face. The limbs of the fold appear to be buckled (B). Fold axial planes dip to the north at a low angle (estimated at 5° to 15°), and are likely to be related to extensional deformation (normal faulting) along the Lhotse Detachment (Searle, 1999). Photograph taken from GPS co-ordinates 28°0'42.75"N, 86°51'24.57"E looking southeast.

General geology along the route

There are leucogranite outcrops on both sides of the Western Cwm. Above the Lhotse Detachment on the Lhotse face and on Everest, pelite outcrops dominate. In Figure 11.2, Searle (2003) indicated a folded sequence of Everest leucogranite and pegmatite sheeted sills located below the Qomolongma Detachment (QD). This recumbent folding may have influenced the fold described in Figure 11.1 with extensional movement causing the S-verging folding seen in the south-eastern part of the Western Cwm (Figure 11.1).

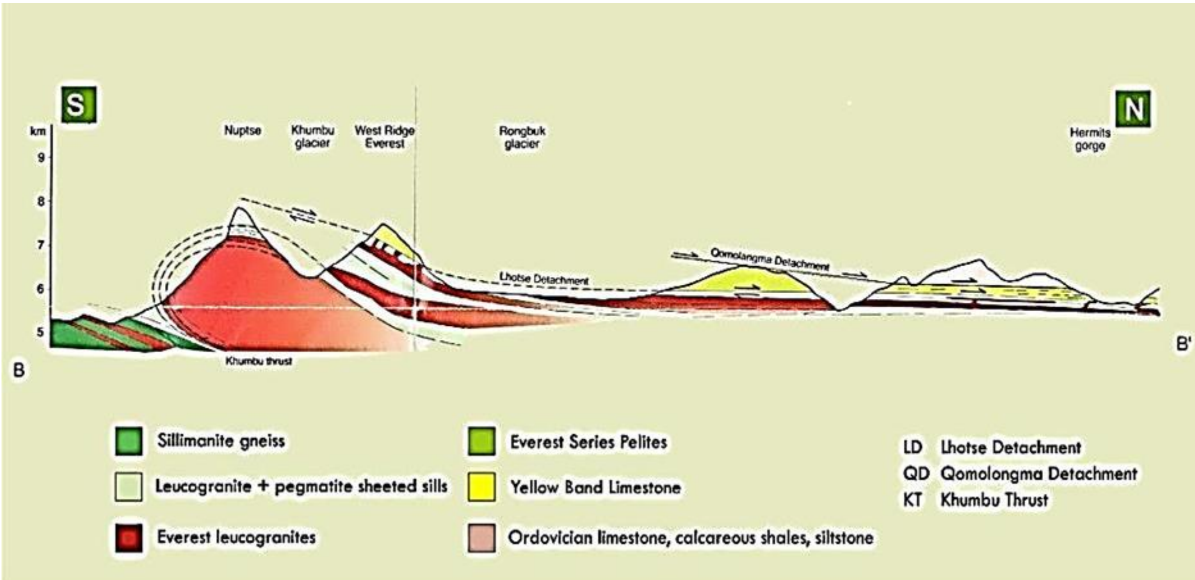


Figure 11.2: Cross section B-B' (Map 4): From Nuptse northwards through the west shoulder of Everest, to Hermit's Gorge (Map 4). According to Searle (2003), a large leucogranite outcrop is found on the south face of Nuptse. Folded yellow calc-silicate bands on the Lhotse face are separated from this leucogranite by the Lhotse Detachment. Searle shows the leucogranite as a recumbent fold. However, it may also be that it is an intrusion of leucogranite.

In the eastern part of the Cwm, the jagged Lhotse peak dominates the view (figure 11.3). Below the peak is a striking yellow band of calc-silicate starting from the Geneva Spur (left, or north, side of the Lhotse face) to the south side of the face, and broken by a clear thrust fault. The yellow band of calc-silicate can be seen at the base of the Geneva Spur and these calc-silicates (part of the North Col Formation) are separated from the Himalayan Leucogranites by the Lhotse Detachment (LD) found near the base of the Geneva Spur (Figure 11.3). These calc-silicates could be part of the Lhotse Detachment (LD), resembling the mylonite specimen described in Figure 12.4, which was recovered from the South Col.

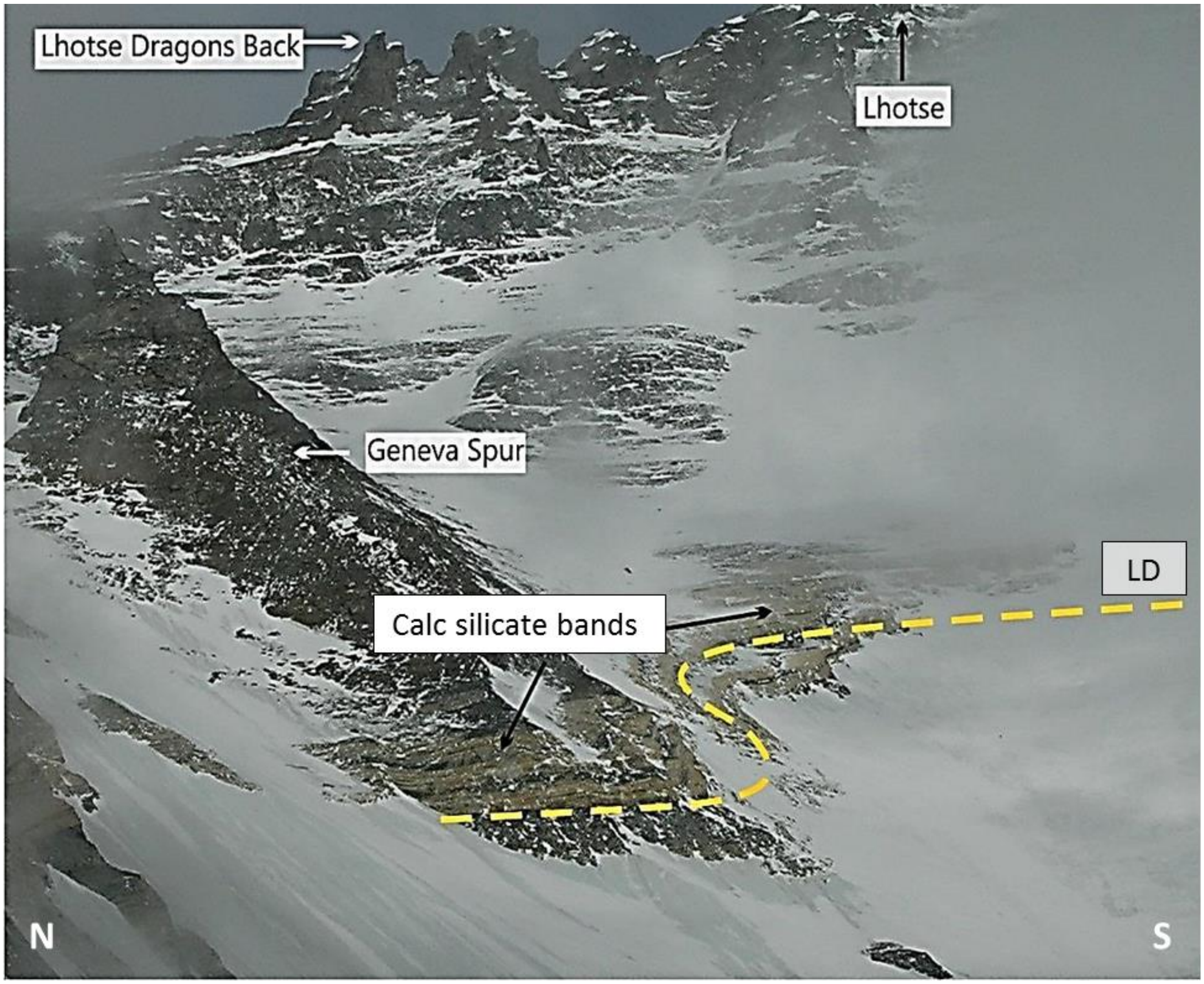


Figure 11.3: The Geneva Spur consists of Everest Series pelite and calc-silicate rocks. The Lhotse Detachment (LD) is located immediately below the calc-silicate at the base of the spur. Photograph taken from GPS co-ordinates 28^{o}0'42.75"N, 86^{o}51'24.57"E looking east.

Common along this part of the route is calc-silicate and slate (Figure 11.3) above the Lhotse Detachment. There is also evidence of intense deformation associated with the Lhotse Detachment because an abundance of intensely sheared mylonite is found in this area. Microscopic examination of a calc-silicate and slate (similar to that on the Geneva Spur) is given in Figure 11.4.

Calc-silicate and slate

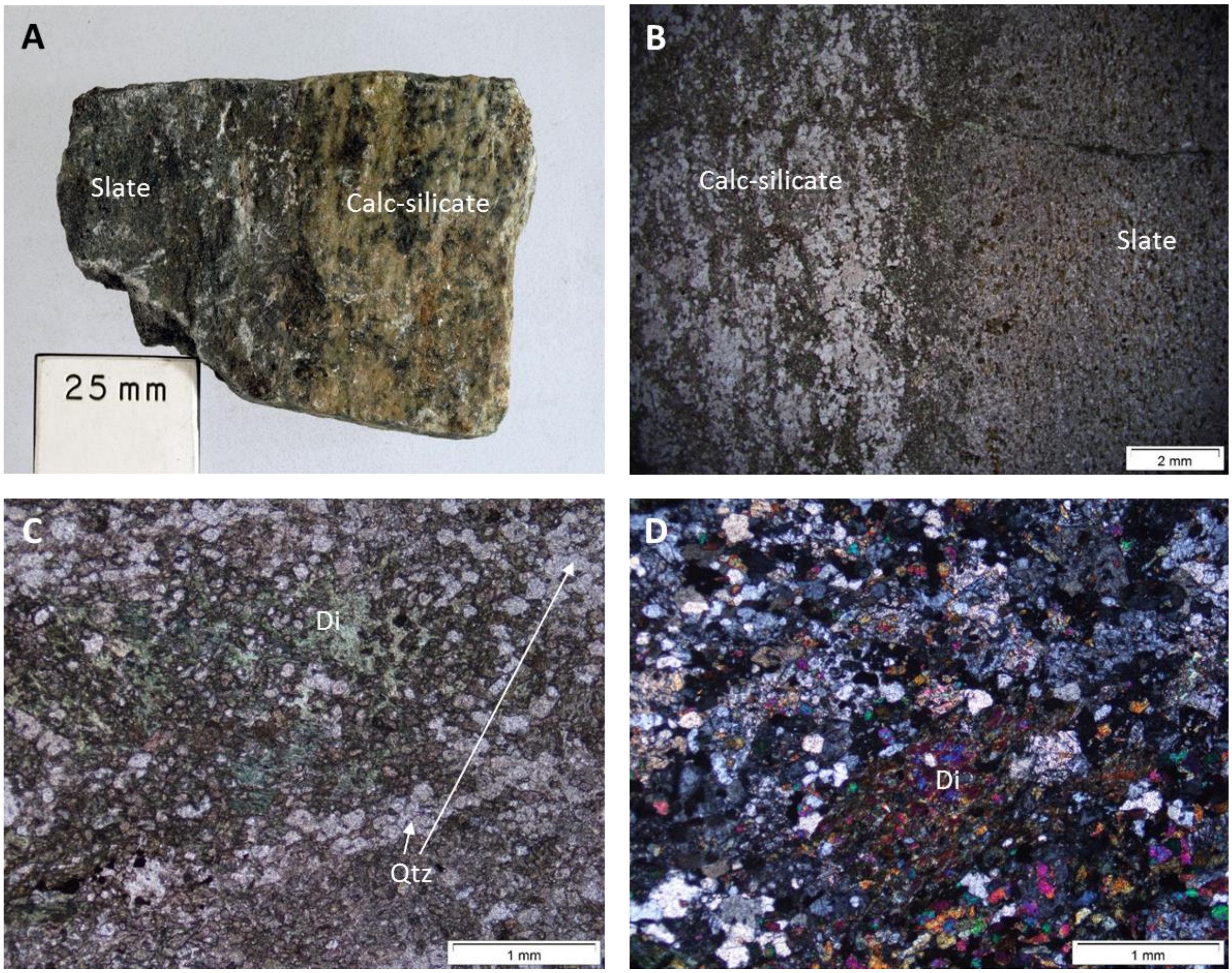


Figure 11.4: Sample with slate in contact with calc-silicate. A – hand sample, showing dark, fine-grained slate on the left, and yellow and green calc-silicate on the right. B: Photomicrograph (PPL) showing the contact between calc-silicate (left) and slate (right). C: Photomicrograph (PPL) of calc-silicate, showing green diopside (calcium pyroxene) and quartz. D: Photomicrograph (XPL) of brightly coloured, highly birefringent diopside in the calc-silicate.

Stop 12: South Col: The last camp before the summit

Alt: 7,906 m

North: Everest

East: Kangshung Glacier

South: Lhotse

West: Nuptse, Pumori, Western Cwm

Distance to next Stop: 1.5km

The South Col has slaty rocks of the Everest Series and mylonite from the Lhotse Detachment (Maps 2 and 4). The oxygen mask is never far from one’s face, the wind blows strongly and temperatures rarely climb above minus 15 °C. A five-minute walk around South Col without oxygen is all one can manage. The Sherpas tell of fossil imprints in the rocks but most of these have already found their way into curio shops in Kathmandu. The rocks above South Col are part of the low-grade Everest Series, with calc-silicate and other calcareous lithologies dominating. Fossils that could be encountered here are crinoid plates and stems, belemnites, cephalopods and brachiopods (Gansser 1964). The South Col lies approximately 200m above the Lhotse Detachment.

In Box 12.1, fossils of the Everest Series are described. Even though the Everest Series and the Greater Himalayan Sequence are of similar age, they experienced different burial and exhumation histories. The early history stratigraphic subdivision of the Himalayas was based on fossils. The Yellow Band is made up of an estimated 5% by volume of fossils, but detachments and shearing destroyed some of the evidence.

Box 12.1: Biostratigraphy, fossils and palaeoenvironments in the Everest Series

The sedimentary rocks of the Tethyan Himalayas are Palaeozoic or younger in age (Figures 1.2 and 1.3 in Box 1.1). The Palaeozoic is the period in Earth’s history when multicellular organisms evolved. Starting in the Cambrian Period (which preceded the Ordovician Period), large organisms were rare and vertebrates had not yet evolved. However, the Ordovician was characterized by an explosion of life forms, especially marine fauna. Carbonate shell-secreting animals, as well as the trilobites, flourished (on continental shelves and in shallow marine environments such as the Tethys Sea) between 527 million years ago (in the Cambrian Period) and 250 million years ago (the end of the Permian Period). Finely fragmented remains of these animals are found in the Himalayas.

There should thus be numerous fossils in rocks at the summit of Everest (the calc-silicate and limestone of the Qomolongma and North Col Formations) and northwards into Tibet. These low-grade metasediments and their fossil contents have been altered through low grade metamorphism below the Qomolongma Detachment (QD).
Once the collision of India and Asia began from around 50 million years ago, these rocks were first buried, and then uplifted to form the summit rocks of Mt Everest and much of the Tibetan Plateau. Odell gave the earliest report of fossils high on Mt Everest and in 1965 he wrote a paper titled The Highest Fossils in the World. The fossils of the Himalayas have been classified by a number of other workers (e.g. Heim and Gansser, (1939); Arkell, (1956). Gansser (1964), included photographs of microscopic fossils in his book (shown in Figures 12.1 A and B).

Because the limestone of the summit of Mt Everest has been subjected to medium-grade metamorphism, many of the fossils have been re-crystallised into calcite with an outline of the original shape being all that is left of these organisms.

Other, more recent, fossils such as ammonites are found elsewhere in the Himalayas (Figure 12.1 C). Ammonites are the shell remain°°s of the cephalopod family that first appeared 400 million years ago (Devonian Period) and became extinct around 65 million years ago (Doguzhaeva, 2007) at about the same time as the dinosaurs. They were swimming bottom-dwellers in open seas and preyed on fish and other molluscs. Ammonite fossils are common in Tibet but other fossils from the Tethyan sediments include belemnites (an extinct group of marine cephalopods similar to today's cuttlefish), brachiopods (marine animals which are bi-valves with different upper and lower shells), algae, fossil oysters and fossilized coral. Examples of all these fossils can be viewed at the Ministry of Mines and Geology Museum in Kathmandu.

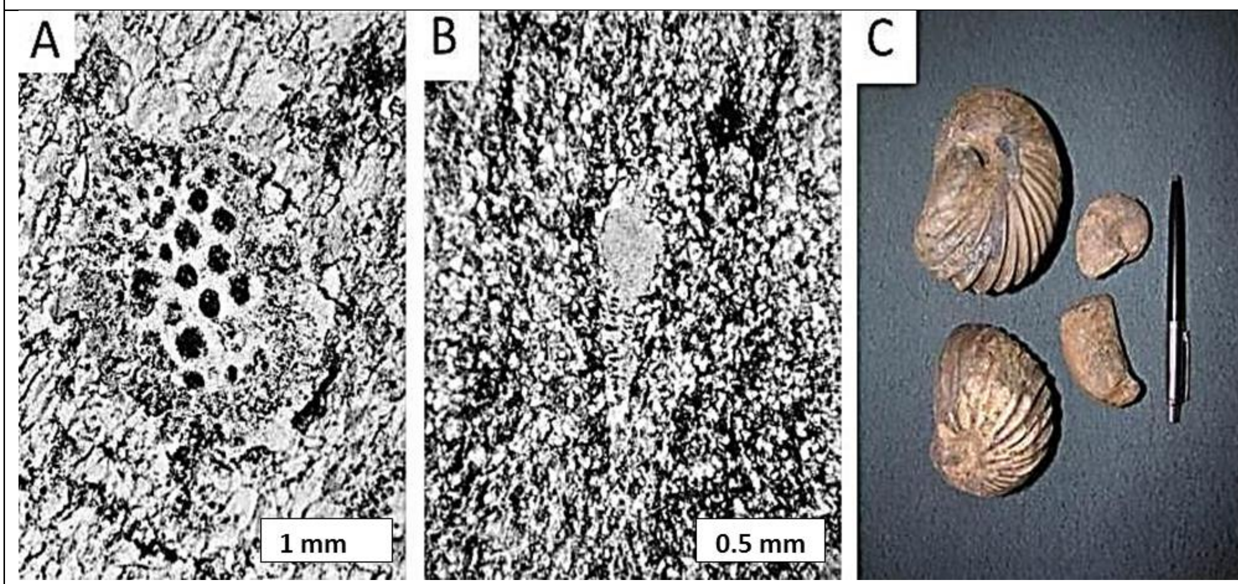
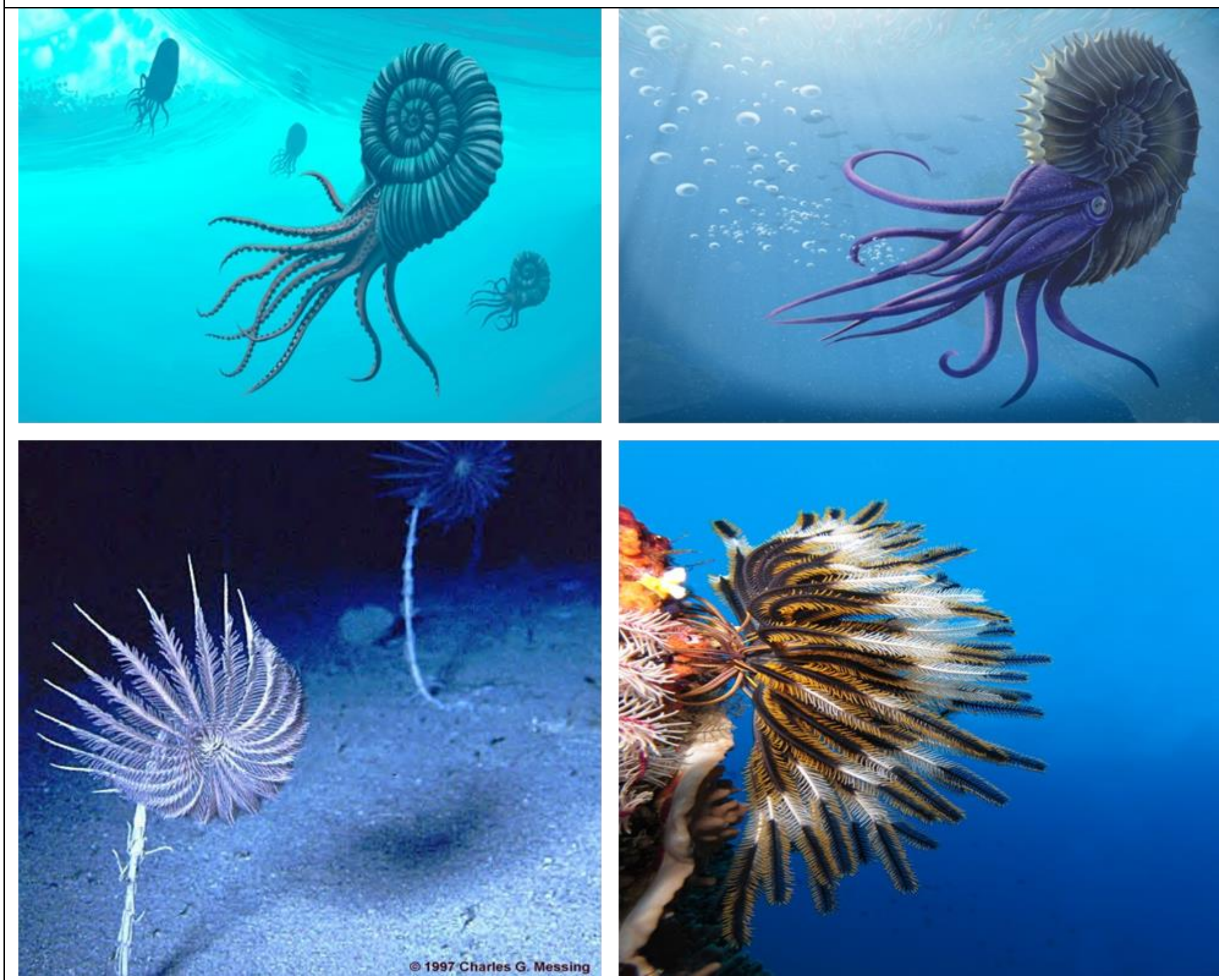


Figure 12.1: Fossils of the Everest Series: A: Crinoid plate with well-preserved perforations from the summit of Everest (enlarged 17x, plain polarised light; Gansser, 1964). B: Stem fragment of crinoid in fine-grained limestone from the summit of Everest (enlarged 35x, plain polarised light; Gansser, 1964). C: Ammonites (left) and a bi-valve mollusc (right) which are on display in Kathmandu at the offices of the Department of Mines and Geology.

In Box 12.2, modern equivalents of the fossils found in the Everest Series are shown.

Box 12.2: Sketches of the original animals represented by the fossils found in the Everest Series

The ammonite fossil shown in Box 12.1 C was a squid-like marine animal similar to the nautilus species of today, as shown below. It was free swimming and its shell, once the animal died, was filled with sand and thus preserved when covered over by sediments (from http://en.wikipedia.org/wiki/crinoid).



The crinoid plate and stem fragment shown in Box 12.1, Figure 12.1 A and 12.1 B, is a relative of the crinoid sea-fan of today. The stem fragment from the stem and the plate fragment comes from the centre hub of the crinoid fan shown below (from http://thezt2roundtable.com and http://www.suggestkeyword.com).

General geology along the route

To the north, the dark grey Everest limestone dominates the view. Layering can be seen in the strata which dips at shallow angles of around 5° to 10° north (Figure 12.2). Underfoot are the slaty and mylonitic rocks that make up the South Col area. The mylonite comes from the South Tibetan Detachment (STD) fault system which comprises the faults called the Lhotse Detachment and the Qomolongma Detachment. On the South Col, one is standing within the lower half of the STD with the Lhotse Detachment located near the base of the Geneva Spur (Figure 11.3) and the Qomolongma Detachment located at the top of the Yellow Band (Figure 13.3).

Higher on Everest, fossils may be found, especially in the rocks of the Yellow Band which are made up partly (up to 5% of volume) by fossil fragments. Metamorphism of the summit Everest Series rocks, of which the Yellow Band is part, indicates a temperature range of between 150°C and 250°C (Searle et al 2003). This is likely to have altered the original fossils preserved from the Ordovician period, but is still identifiable as fossils. Further down the stratigraphy, below the LD, the Rongbuk Formation indicates a temperature range of 600 °C to 650°C and burial depths of between 10 km and 20 km (Jessup et al., 2008). Here, fossils are likely to have been obliterated by the high temperatures and pressures.

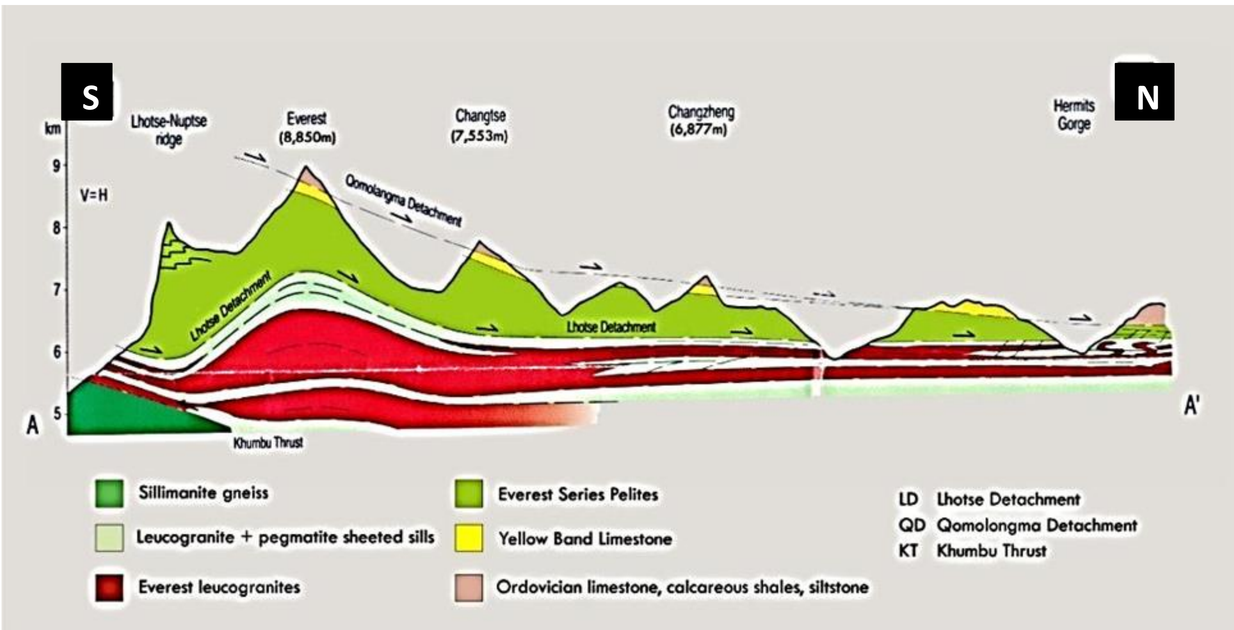


Figure 12.2: Cross section A-A' (Map 3): From the Lhotse ridge to Changtse and Hermits Gorge showing the geology of Mt Everest and its satellites (from Searle, 2007).

A stratigraphic column for Mt Everest and the Greater Himalayan Sequence is shown in Figure 12.3. It shows the stratigraphy of Mt Everest and the location of fossils in the Everest Series rocks mainly in, or near, the Yellow Band.

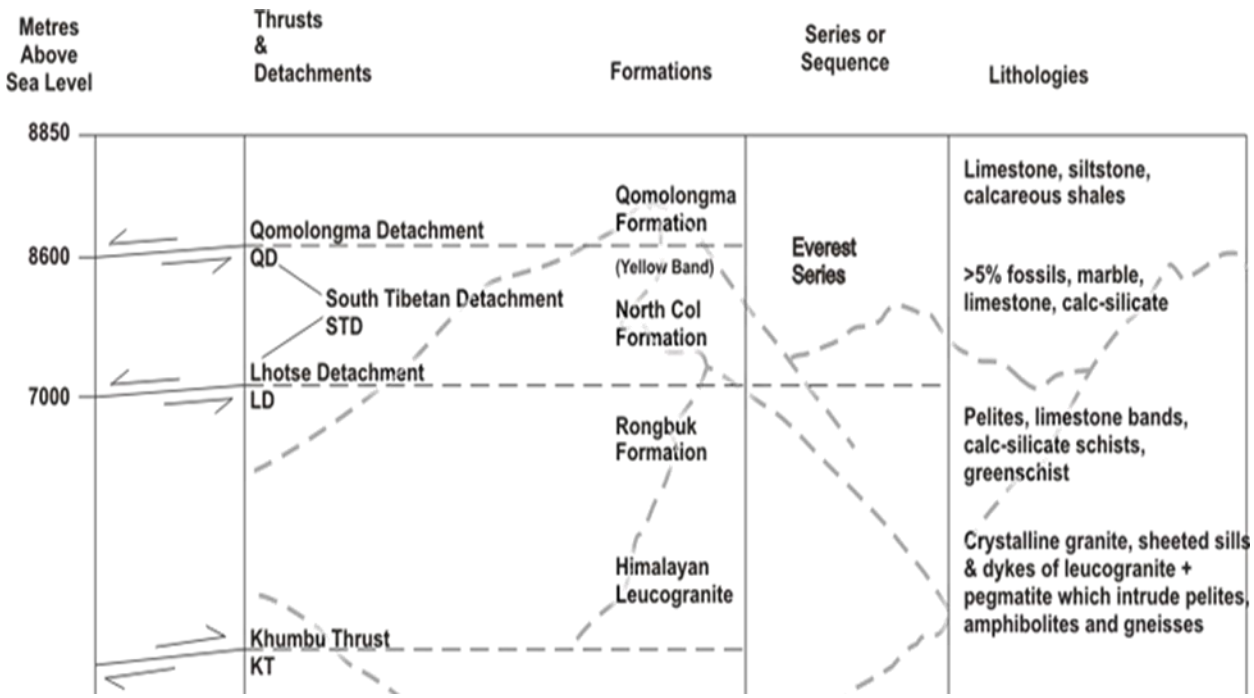


Figure 12.3: Stratigraphic column for Mt Everest and the Everest Series showing the formations where fossils are found.

As the South Col is in close proximity to the Lhotse Detachment (Figure 11.3), a word on mylonite (from the Greek word "mylos", which means "to mill") is appropriate: These are extremely fine-grained rocks are formed from tectonic sliding of rock masses, resulting in brittle deformation of some minerals. In the field it is difficult to distinguish between mylonite formed from brittle deformation and one formed by plastic flow, which have a different "fine-ness" to their matrix. In the field, therefore, these are all defined by the term "Mylonite". (Brodie et al. 2007).

When rocks adjacent to a fracture move in opposite directions, they are ground against each other, to a fine powder. Many faults, shear zones and thrusts contain mylonite which could vary from millimetres to several metres in thickness, as in the Lhotse Detachment zone (Figure 11.3).

Microscopic examination of a mylonite sample from the South Col is given in Figure 10.10.

Stop 13: Hillary Step: Rarefied geology – one small step to the summit

Alt: 8,749 m

North: Everest summit

East: Makalu and Kangshung glacier

South: Lhotse and the South Col

West: Cho Oyo, Pumori

The Yellow Band, a striking yellowish-coloured limestone unit which was mentioned by the early climbers of Everest, can be seen as one looks up towards the summit of Everest (Maps 2 and 4). This unit contains numerous fossils from the Ordovician Period such as crinoid stems, ostracods and trilobites which can make up as much as 5% of the Yellow Band. Above the Yellow Band is the Qomolongma Formation, a calcareous unit extending to the summit rocks of Everest. Once the Yellow Band has been crossed, one's chances of reaching the summit are excellent.

The first man to climb Everest was Sir Edmund Hillary together with Sherpa Tenzing Norgay in 1957. They chose the South Col route. The last obstacle in their way was a 12 m high rock face which he says he climbed "with a push here and a shove there". Hillary saw a means to wedge his way up a crack in the face between the rock wall and the ice, and Tenzing followed.

Controversy will always surround the story of whether George Leigh Mallory (together with Andrew Irvine) was the first man to summit Mount Everest. They chose the North Col route in 1924 where the Yellow Band also presented a distinct obstacle in the climb, called The Second Step. It is likely that at least Mallory reached the summit but failed to return. His body was found 75 years later by an expedition led by Eric Simonson. Famous climbers such as Conrad Anker, who found the body, and Reinhold Messner, speculated whether Mallory had had the ability to climb the Second Step. There is no doubt that Mallory had the ability to climb a 5.10 grade rock climb (Conrad Anker assessment), even at 8,610 m altitude. Further evidence of his reaching the summit is that a picture of his wife, which he is known to have taken with him, was not amongst his clothing when he was found in 1999. Speculation is that he left it on the summit.

In Box 13.1, metamorphism and the deformation history of the Everest Series is discussed.

Box 13.1: Metamorphism and deformation history of the Everest Series

As a result of the continent-continent collision of India and Asia, rocks from the original Indian sub-continent have been pushed below the rocks of Tibet (Asia) and then exhumed back to the surface of the Earth. During this process of burial to depths of greater than 45 km and subsequent exhumation, the rocks in the Himalayas have been subjected to a range of pressures and temperatures. Because many common minerals in rocks are only stable under certain temperature and pressure regimes, when rocks are subjected to great pressure and temperature ranges (such as during burial and exhumation), the minerals in the rocks change (metamorphose) according to the changes in condition of the rock.

Certain diagnostic minerals are known to be stable under specific temperature and pressure ranges and the wide range of pressures and temperatures which rocks may experience have been categorised into different pressure-temperature (P-T) ranges or facies. Searle (1999a) mapped a large scale, low angle normal fault, the Lhotse Detachment, which separates the sillimanite-biotite gneisses and leucogranites below from the greenschist grade rocks of the Everest Series above. From the mineral assemblages in the Everest Series rocks that were collected by climbers at South Col and above, none contained minerals necessary to accurately determine temperatures and pressures experienced by the rocks, but the minerals assemblages present suggests middle to upper greenschist facies grade of metamorphism (Searle, 1999a). This implies temperatures of 600°C to 650°C and depths of burial of 20 to 30km (Jessup et al. 2008).

The process whereby the mineralogy of a rock changes to changing pressure and temperature conditions is called metamorphism and in the rocks of the Himalayas, many metamorphic minerals can be seen. Assemblages of metamorphic minerals provide pressure and temperature (P-T) estimates of the metamorphic events that were experienced before the rocks were exhumed to surface. Usually, only the rocks that exist on the surface can be observed and hence, only the minerals present are observed even though, at great depths today, new metamorphic minerals are growing or altering to other minerals as P-T conditions change.

The combination of the metamorphic history and the deformation history (linked in a chronological sequence) leads to a so-called P-T-D-t (pressure-temperature-deformation-time) path which is a means of looking back at the various processes that a rock experienced over time. On the face of Everest, rocks with distinctly different metamorphic histories are preserved adjacent to one another and this reveals much about how the Himalayas came to be formed The medium grade metamorphic rocks, evident in the Everest Series, preserve a record of burial and heating, peak metamorphism and subsequent exhumation and cooling (Figures 3.1 and 3.2).

One of the fundamental differences between the Greater Himalayan Sequence and the Everest Series is the metamorphic grade. The rocks which give lower pressure conditions have preserved retrograde reaction textures, proving that they record decompression from higher pressures (i.e. the rocks reached 20 km depth and were then exhumed back to shallower depths of around 10 km during metamorphism). Early in the history of collision between India and Asia, rocks that today make up the Everest Series were buried. This burial was accompanied by intense shearing and isoclinal, or very tight, folding of the original sedimentary layering. This is known as D_1 deformation. During this event, minerals such as muscovite and biotite (which were growing because of the increasing metamorphic grade during burial) were aligned, resulting in the S_1 fabric (Figure 3.2 A). This fabric was subsequently overgrown by garnet and staurolite as the temperature and pressure increased. Subsequently, the Everest Series was exhumed and the S_1 fabric was crenulated or folded by deformation during exhumation (D_2 deformation, an example of which is shown in Figures 3.2 D and 9.6). This resulted in an S_2 fabric along which recrystallised biotite grew. D_2 deformation was extensional and a stretching lineation developed together with shearing along extensional structures.

Some Everest Series schists record lower pressures, post-dating D_2 with overgrowths of cordierite on staurolite and the mineral andalusite is present in places. The latter minerals indicate low pressures and show that the rocks were rapidly exhumed during D_2. The cordierite and andalusite growth over the S_2 fabric was the final phase in the P-T-D-t history of the Everest Series.
Thus, metamorphic minerals that were growing in response to varying P-T conditions tell us about the depths of burial and rates of exhumation, whilst various deformation events that were occurring are recorded in the microstructures. Together, this allows us to piece together the geological history of the Everest Series.

General geology along the route

Everest Series limestone, calcareous shale and siltstone comprise the summit rocks of Everest (Figure 13.1)

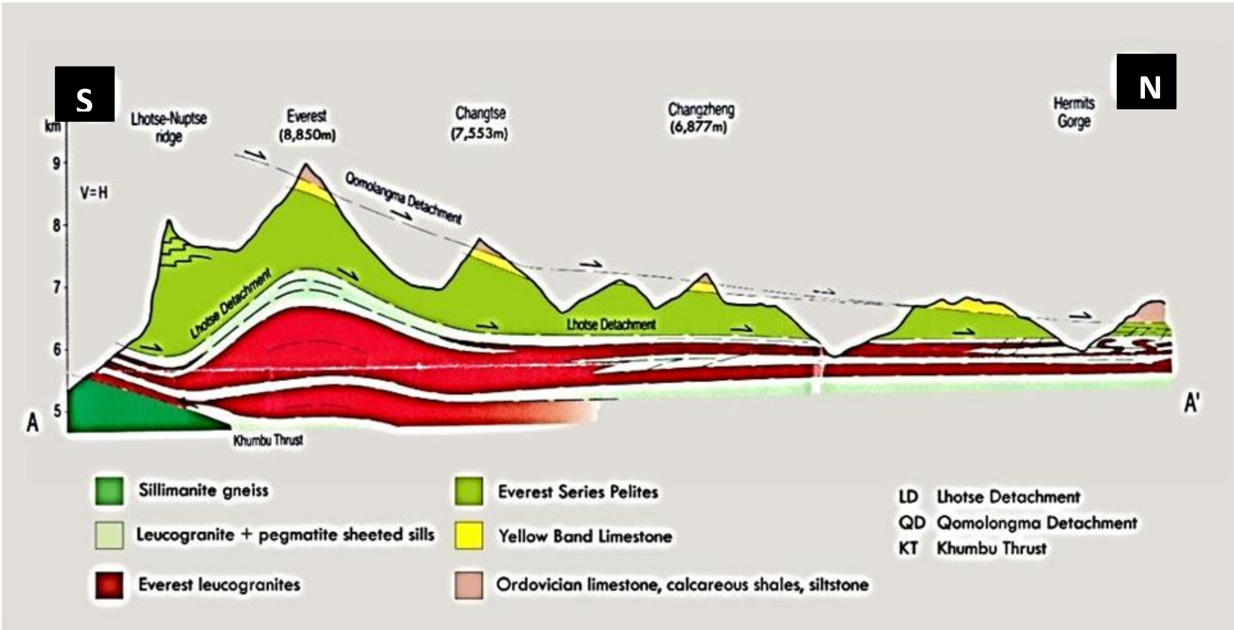


Figure 13.1: Cross section A-A' (Map 3): From the Lhotse ridge through Everest and Changtse showing the summit geology of Mt Everest and its satellites (from Searle, 2007).

As shown in Figure 13.2, the Lhotse ridge extends southwards from Everest with the summit of Lhotse above the layered pelites which can be seen from the South Col. The plane of the Lhotse Detachment is located on the ridge dipping down below Everest (i.e. through the South Col below the climbers).

Lhotse is composed of Everest Series calcareous shale and thin limestone bands to the level of the South Col. Below the col and below the Lhotse Detachment, in the Greater Himalayan Sequence, leucogranite intrusions make their appearance. The pelite contains muscovite, biotite, quartz, feldspar, staurolite and garnet. Cordierite and andalusite are also present but is less common. These minerals are indicative of low pressures (<20 km depth) at intermediate temperatures and show that the rocks were being exhumed during D_2. This exhumation caused the drop in pressure shown in Figure 3.2 E, and the growth of cordierite and andalusite through the consumption of staurolite. These rocks contain retrograde-reaction textures indicating burial to over 20 km and decompression to about 10 km.

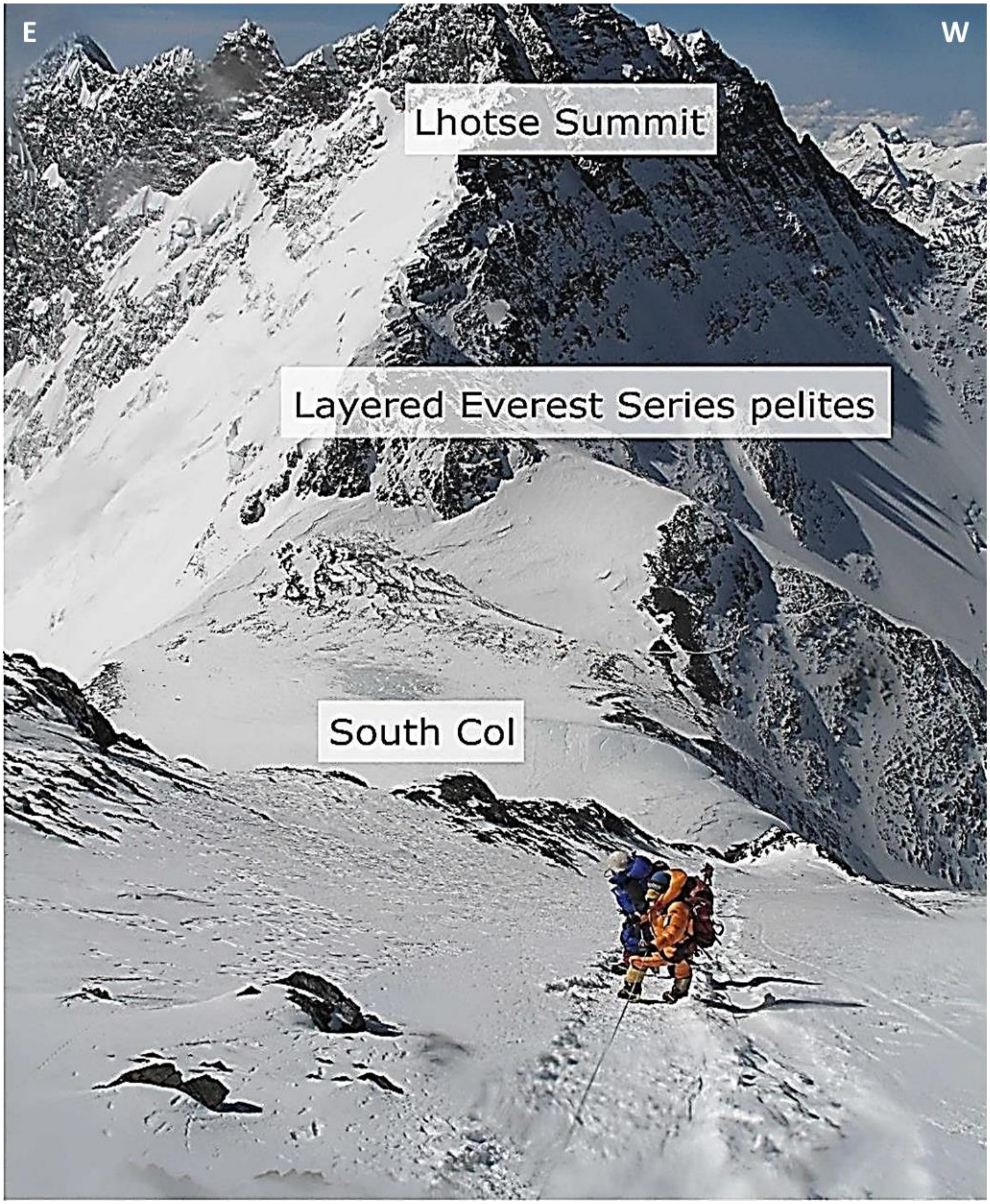


Figure 13.2: Looking south towards South Col and the Lhotse north ridge from Everest's South summit (Source: Disney, 2006). The rocks in the foreground, as well as the rocks on Lhotse, are composed of low-grade Everest Series pelites dipping at a shallow angle towards the north. Photograph taken from GPS co-ordinates 27^{o}59'12.31"N, 86^{o}55'26.76"E looking north west towards Lhotse summit.

The Yellow Band, shown in Figure 13.3, is composed of a yellow limestone that is prominent on some of the peaks in the Everest area. A closer study of the Yellow Band shows it contains carbonaceous material that represents deformed fossils (Figure 14.3). Since Everest Series schists record temperatures of between 600 °C and 650 °C (Jessup et al., 2008), the limestone above the schists was most likely subjected to the same metamorphic grade. The rocks of the Everest Series, such as the Yellow Band, would have the same record of burial and heating, peak metamorphism and subsequent exhumation and cooling. The Yellow Band is, in fact, a marble with the presence of sparry calcite showing abundant twinning.

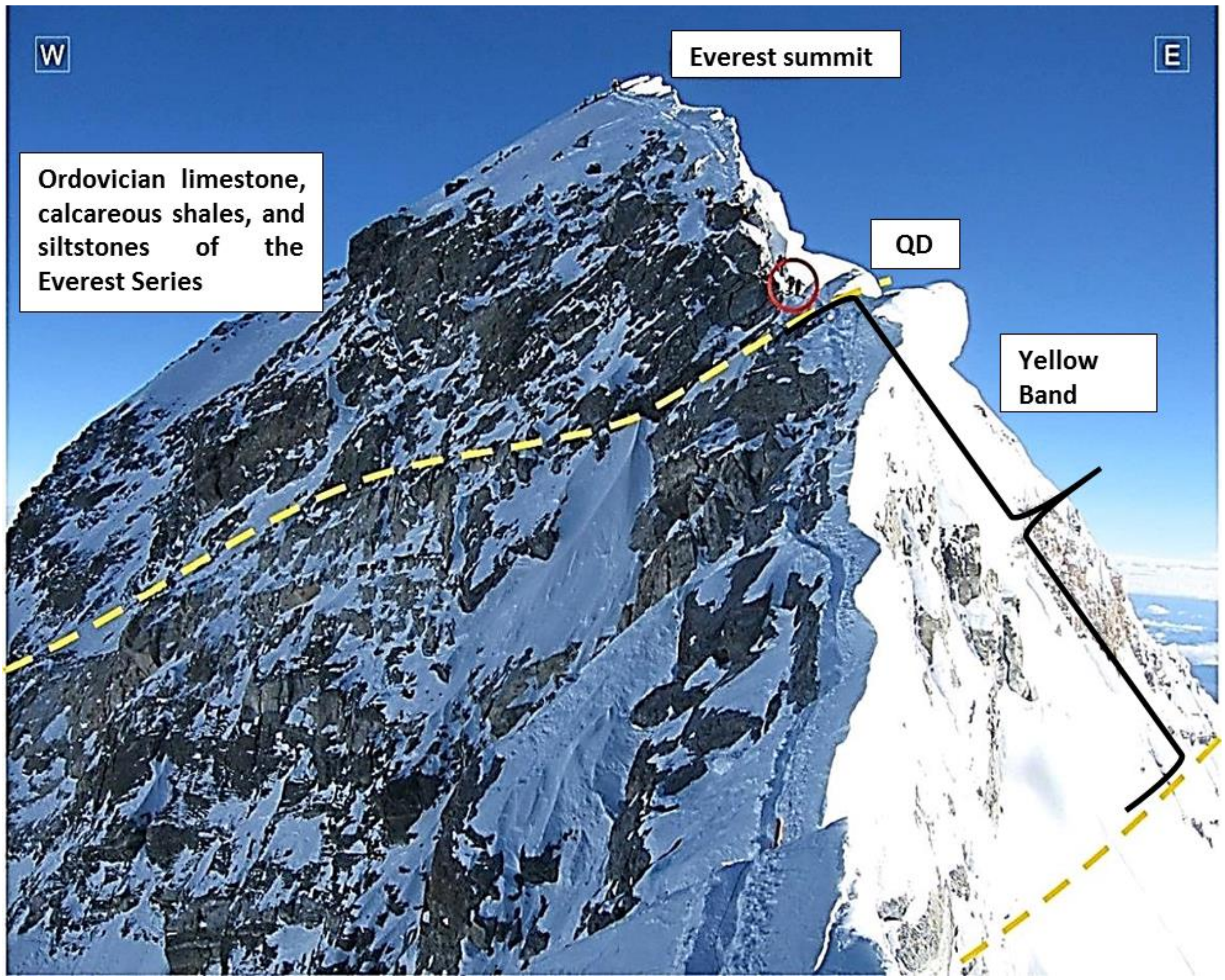


Figure 13.3: The Yellow Band and the Qomolongma Detachment (QD), as seen from the South Summit looking towards the Hillary Step (Source: Disney, 2006). The two figures circled in red are at the base of the Hillary Step (above the top dotted line). Photograph taken in 2006 from GPS co-ordinates 27°59'12.31"N, 86°55'26.76"E looking north west towards the Everest summit.

Above the Yellow Band it is the Qomolongma Formation (Ordovician limestone, calcareous shale and siltstone) that extends to the summit of Everest. The top of the Yellow Band is the location of the Qomolongma Detachment. Below the Qomolongma Detachment are the greenschist facies limestone and the pelite of the North Col Formation. Microscopic examination of a carbonate samples from the Yellow Band to the summit of Everest Schist Figures 14.3

Stop 14: Everest Summit: The roof of the world

Alt: 8,850 m

North: Changtse and the Rongbuk Glacier

East: Kangshung glacier, Makalu

South: Lhotse, South Col, Nuptse

West: Pumori, Cho Oyu to the north east

The summit of Everest! (Maps 2 and 4). One can see Tibet stretched out beneath to the north (Figure 14.1) and the Himalayan range stretching east and west for many hundreds of kilometres. To the east, one can see Makalu (8,463 m), close-by to the south is Ama Dablam (6,828 m) and further away to the south-east is Kanchenjunga (8,586 m). To the west are Cho Oyo (8,201 m) and Pumori (7,165 m), and further north-west, Shishapangma (8,008 m). The lateral continuity of the Himalayan Mountains is astounding when viewed from the top of the world (Box 14.1).

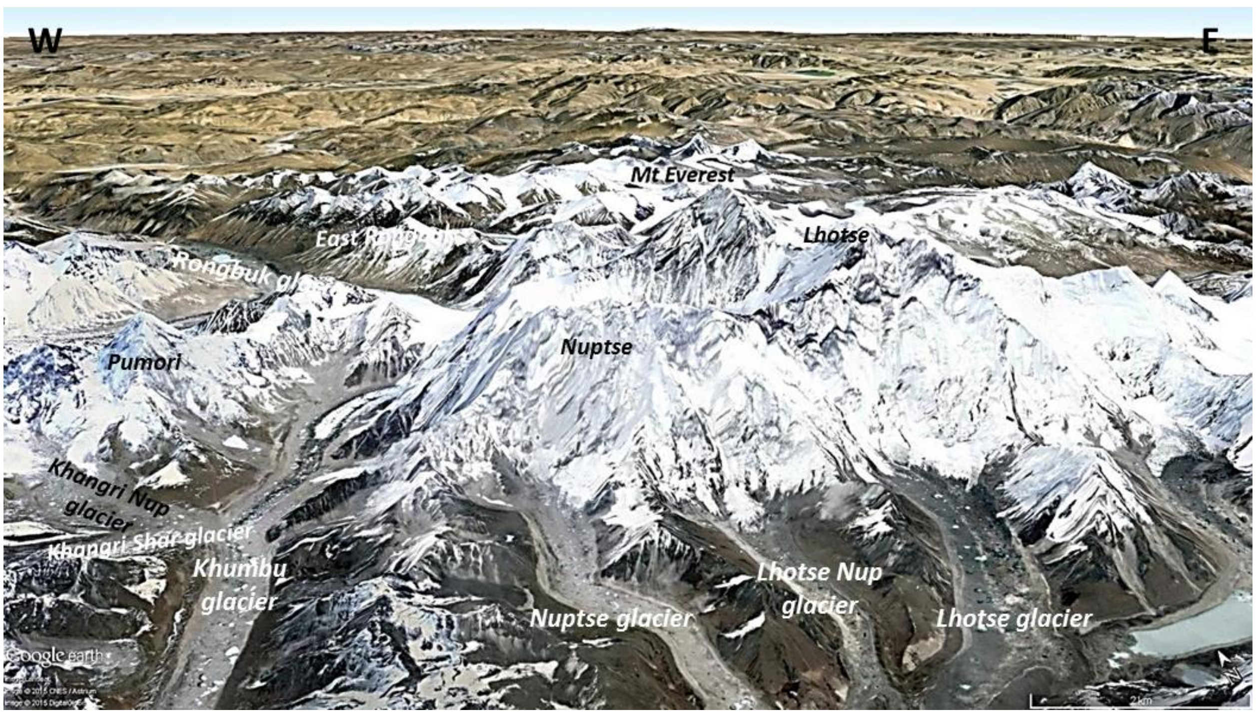
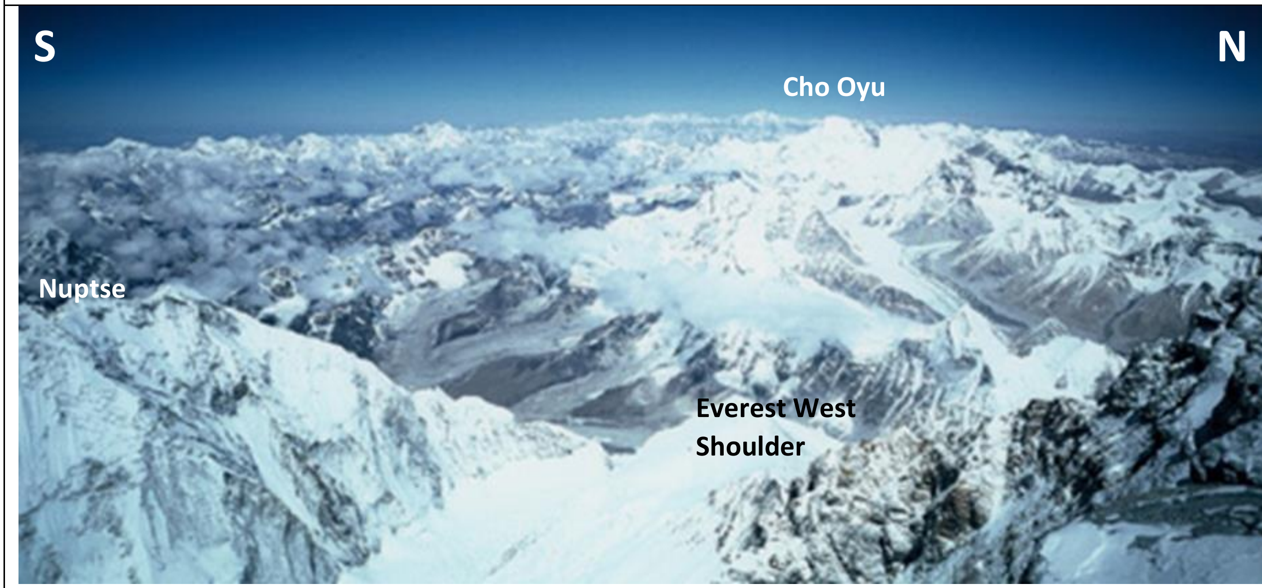
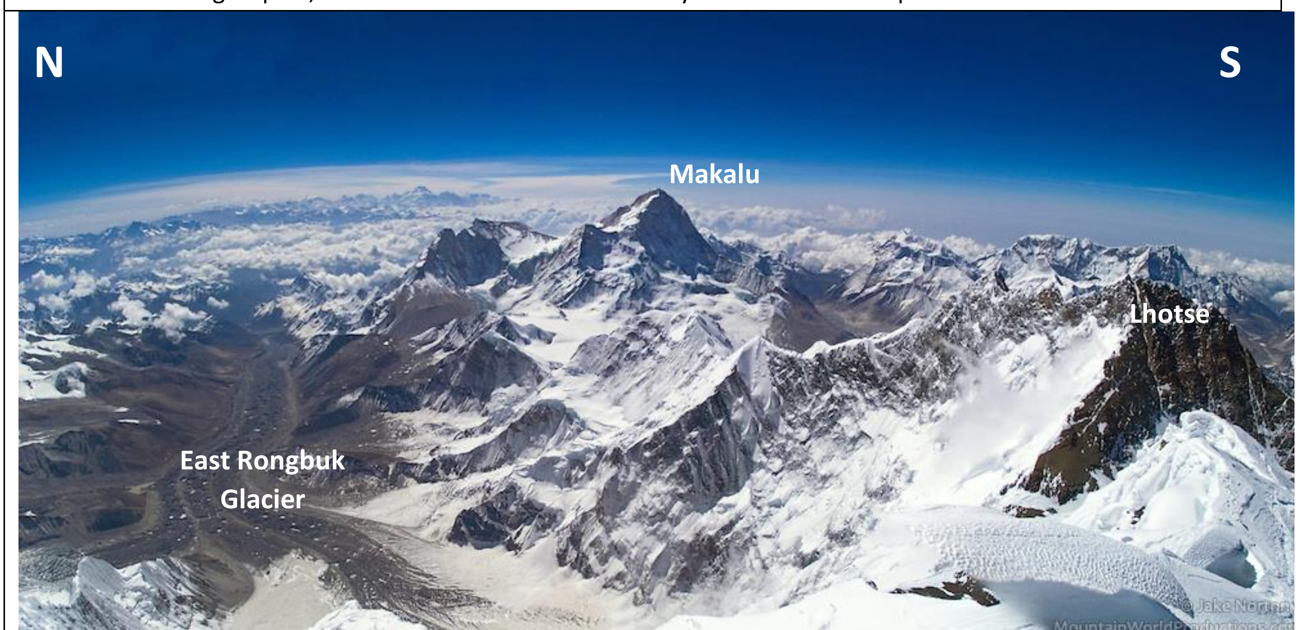


Figure 14.1: Oblique Google Map View of the Everest area from the south. Note the many U-shaped glacial valleys which are found in the Everest region. Glaciers are a powerful erosive force in the concentrated denudation of the high Himalayas. In the Everest massif area, 8 major glaciers can be seen in this photograph. In the foreground from the left, the Khangri Nup, the Khangri Shar, the Khumbu, the Nuptse, the Lhotse Nup and the Lhotse glaciers can be seen. North of Everest from the left, the Rongbuk and the East Rongbuk glaciers can be seen. The east Rongbuk glacier is directly behind Everest and cannot be seen here.

Box 14.1: View from the summit



View wast showing Nuptse, Everest west shoulder and Cho Oyu. Source: everestspeakersbureau.com



View east shows Lhotse and Makalu. Source: mountainworld.photoshelter.com

General geology along the route

En route to the summit, the Yellow Band and the Ordovician limestone of the Everest Series are traversed. The last rocks to be seen before the summit of Everest in a normal season are those of the Hillary Step (Figures 13.3). In a dry season, as in 2006, rocks closer to the summit may be exposed. These consist of Everest Series limestone (Figures 14.3 and 14.4). The distinctive Yellow Band is a marble and is composed almost entirely of sparry calcite with a number of large calcite crystals showing twinning. Minor amounts of quartz and black carbonaceous material are found. Fossils can make up 5% by volume of the Yellow Band, although none can be seen in the sample collected, likely owing to its sheared nature (Figure 14.3). Although the deformation in this sample may have destroyed fossil evidence, the wavy black carbonaceous material visible at the bottom of both photos could have originated from fossiliferous material. Samples from above the yellow band lack the distinctive yellow colour, but are also marbles, although they may be very fine-grained and show evidence of high-strain (Figure 14.3). The numerous shears cutting through the samples often give the rock a strong fabric, and calcite grains form elongate lenses between the shear planes and meandering veins of black carbonaceous (organic) material (called stylolites). It is likely that these samples were sheared during D_2 deformation. In some samples, opaque pyrite forms euhedral to subhreral cubes. All samples collected from the Qomolongma Formation have experienced low-grade metamorphism typical of the Everest Series.

From the summit of Mount Everest, the Everest Series rocks (also known as the Tethyan Sediments) extend northwards for some 150 km (Map 1). However, they extend about 800 km eastwards and about 1200 km westwards. The lateral extent of these terranes is shown in Figures 5 and 10 viewed from the summit of Everest.

The summit rocks of Everest are composed of carbonates which have been subjected to greenschist facies metamorphism. The Everest summit limestone originates from the Ordovician Period, known for its abundance of invertebrate life.

Today's cold and frigid summit rocks were formed in a warm sea. These were teeming with life in a warm sea much like the Mediterranean of today. In the Ordovician, life-forms developed in the seas with the highest density levels of life seen during the Palaeozoic Era. All the common invertebrate fossils and some vertebrate fossils were present by the end of this era. Starfish, crinoids and echinoids appeared first. Trilobites, graptolites, primitive jawless fish called ostracoderms, gastropods, brachiopods and tabulate colonial corals evolved in the Ordovician.

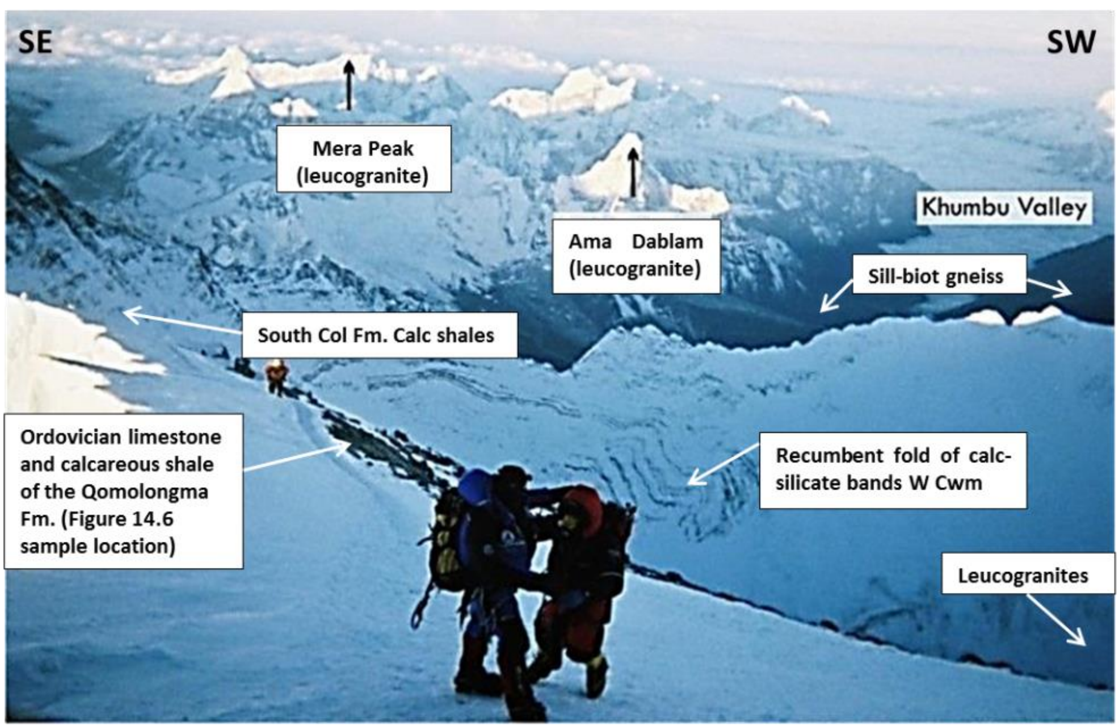


Figure 14.2: The south-view from the summit of Everest showing the Khumbu Valley, and the leucogranite peaks of Ama Dablam and Mera Peak. The Western Cwm recumbent fold in the zone of the Everest pelite is visible beyond the climbers. Photograph taken at GPS co-ordinates 27°59′17″N, 86°55′31″E.

Looking back down the south-east ridge (Figure 14.2) the north ridge of Lhotse rises up to the left of the photograph, with the leucogranite peaks of Ama Dablam and Mera in the background. The rocks on the lower slopes of Lhotse, showing the folded nappe behind the t0wo climbers, were exhumed from below the Lhotse Detachment during D_2 deformation.

A sample of the sheared limestones taken from the top of the Hillary Step, which is the location of the Qomolongma Detachment and part of the wider South Tibetan Detachment system of faults, is described in Figure 14.3.

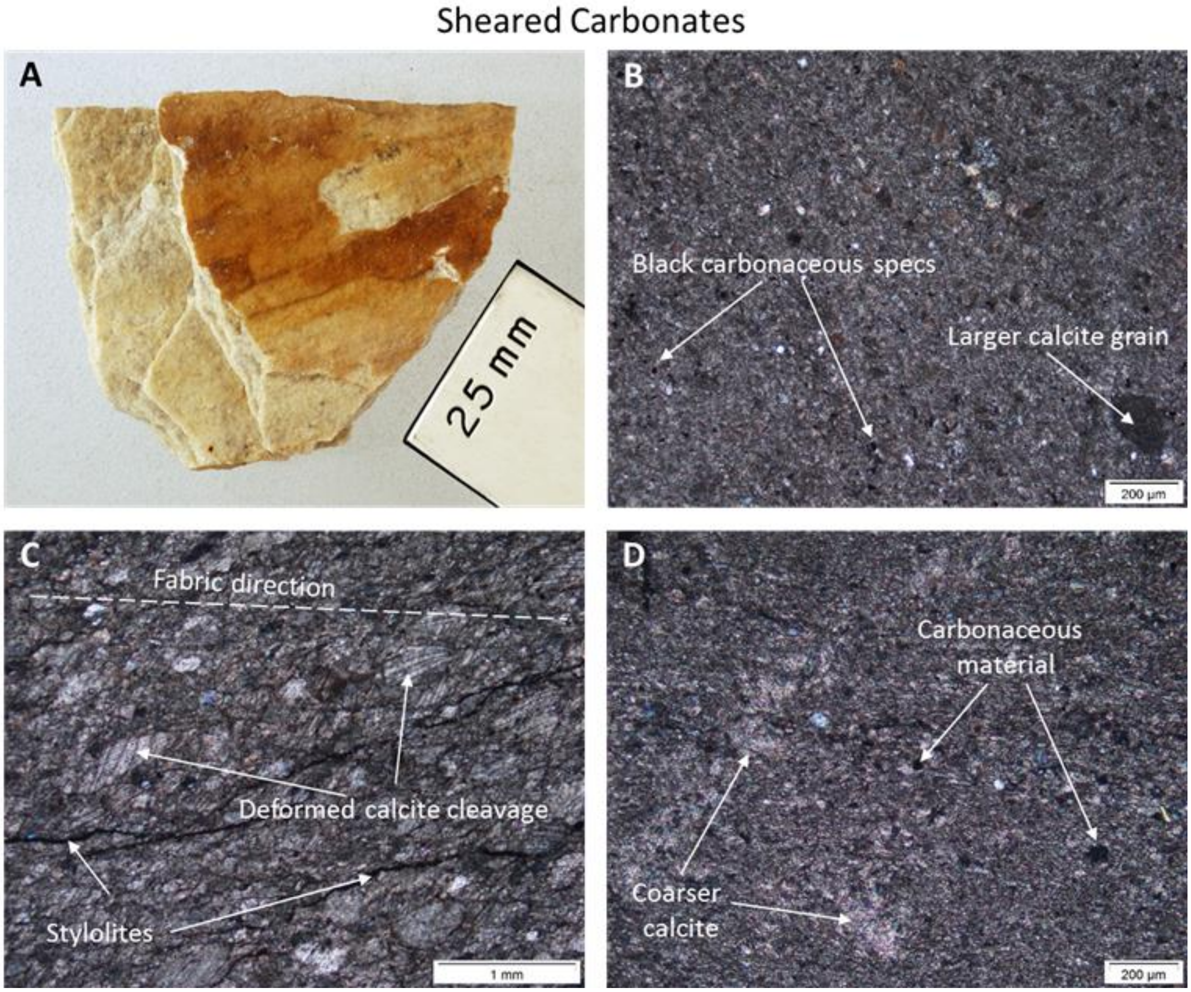


Figure 14.3: Description of the calcareous rocks of the Everest Series from the Hillary Step. A – hand sample of sheared marble from the Yellow Band. B –photomicrograph (XPL) of fine-grained marble from the Hilary Step. This sample has experienced intense deformation leading to grain size reduction, with few larger calcite grains remaining. A number of small carbon-rich grains are visible. C - photomicrograph (XPL) of sheared marble from the Yellow Band, showing elongate shear planes and meandering veins of black carbonaceous (organic) material (stylolites). Bent cleavage planes in some calcite crystals are further evidence of deformation. D - photomicrograph (XPL) of marble from the summit of Everest (one of the highest geological samples on the planet). This shows fine-grained carbonate and carbonaceous specs with some slightly coarser relict calcite; the fine-grained nature is the result of shearing related to movement on the STD and associated detachments. Sample collected at GPS co-ordinates 27°59’15”N, 86°55’31”E.

A sample of the summit rocks of Mount Everest is described in Figure 14.4.

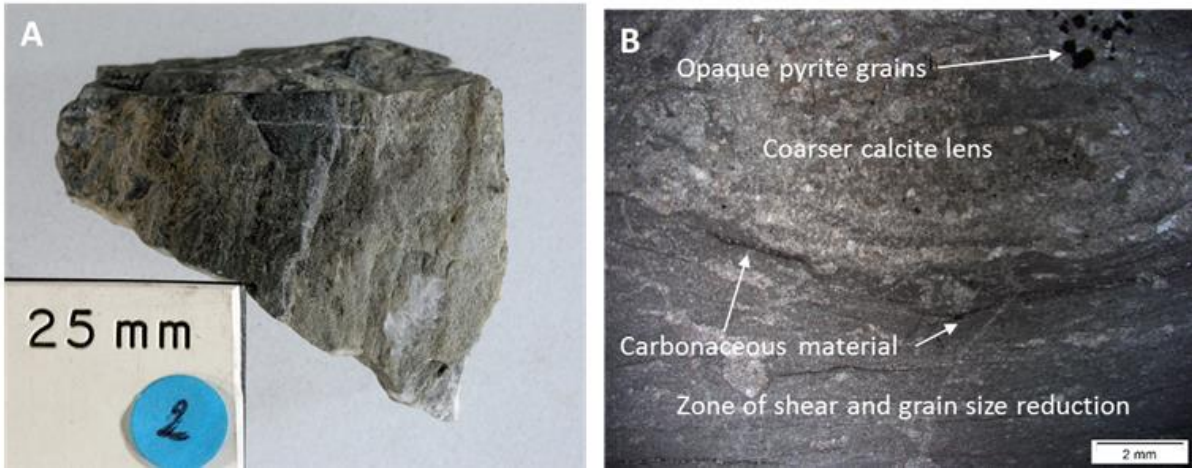


Fig. 14.4: A sample of sheared limestone from the summit of Everest, one of the highest geological samples on the planet. A - hand sample of fine-grained grey limestone. B - photomicrograph (XPL) of marble from the summit of Everest. This shows a coarse lens of calcite surrounded by finer carbonate and carbonaceous bands (stylolites) indicating that minor shear zones (related to movement on the STD and associated detachments) are present even at the summit of Everest. Sample collected at GPS co-ordinates 27°59'17"N, 86°55'31"E.

Conclusion – the end of the Geological journey through two colliding continents

The geological journey through a cross section of the Greater Himalayan Sequence and Everest Series between the town of Lukla and the summit of Mount Everest allows one to explore the evidence for recent and on-going exhumation of once-deeply buried mid-crustal material in an actively forming mountain belt.

The geology along this traverse illustrates many of the concepts of channel flow, partly driven by the high erosion rates in a zone of mountain-building. The processes of high-grade metamorphism leading to partial melting, and the segregation, ascent and accumulation of leucogranite melt are well-illustrated in the Namche migmatites and the Higher Himalayan Leucogranites intruding the sillimanite-biotite gneiss of the upper Greater Himalayan Sequence.

In the Everest Series, evidence for early invertebrate life is preserved in the highest rocks on earth. Fossils such as crinoid stems and bivalves in the Yellow Band and high carbonate and carbonaceous bearing material in the rocks near the summit of Mount Everest provide a reminder of how geological processes can bring ocean-floor sediments to high elevations.

In both the Greater Himalayan Sequence and Everest Series, the impact of the processes of burial, metamorphism and exhumation on the geological record can be clearly observed. D_1 deformation from the initial burial of the Indian crust resulted in folding, shearing, formation of an S_1 foliation and changes in the mineralogy of rocks as they were buried and heated. Subsequently, rapid exhumation gave rise to D_2 deformation with folding of the S_1 fabric and the overgrowth of new minerals on the S_2 fabric.

The geology along this traverse extends east and west along a 2500 km wide orogenic zone, which includes the entire planet's higher-than 8000 m giants with Kanchenjunga the easternmost and K2 being the westernmost summits. The active erosion and mountain building, which is on-going in the Himalayas, means that these mountains will shift and change over time and Everest may not always be the highest mountain on Earth. As with the two earthquakes on 25th April and 12th May, extensional collapse is taking place (Everest is believed to have reduced by about 1.5 m in height (DLR Earth Observation Centre Sentinel-1 satellite operated by ESA)) and erosion will eventually lead to the Himalayas reducing in altitude to that of other mountain ranges around the world. Eventually even the Tibetan plateau will be eroded to the levels of other plateaus around the world.

This tour guide has, hopefully, illustrated the principal processes and geometries visible in a mountain belt and how they can be explained through large-scale tectonic and geomorphological processes.

The most important processes explaining what can be seen in the Himalayas are those of channel flow, rapid exhumation and extrusion of a melted zone from deep within the earth's crust together with the associated metamorphism and deformation recorded in the rocks of the Greater Himalayan Sequence and the Everest Series rocks.

This guidebook has been produced with the aim of assisting the reader's understanding of the processes involved in the formation of the Himalayas, the highest mountains on Earth.

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