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# A Trekker's Guide to the Khumbu Himalaya: Trailside Geology Along the Everest Base Camp Trek

Brigit Anderson
*SIT Study Abroad*, banders2@bates.edu

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## Trailside Geology along the Everest Base Camp Trek


*Brigit Anderson*
*Academic Director: Isabelle Onians*
*Bates College*
*Geology*
*Asia, Nepal, Khumbu*

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## Abstract

The Himalaya is the youngest and highest mountain range in the world. It thus provides a wonderful field lab for studying the mountain building process in action. The trek in the Khumbu (northeastern Nepal) from Lukla to Everest Base Camp takes you through the Higher Himalaya and some interesting geological features. This project gives an introduction to the larger Himalaya geology and more specifically geology of the Khumbu Region. It then follows the Lukla-Everest Base Camp (EBC) trekking route pointing out interesting geologic features along the way. Some of the concepts explained in this project are somewhat technical. For this reason, a glossary has been provided and more technical terms are defined throughout the chapters.

Figure 1: Cover Photo of sign to Base Camp ()

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## 1. Geology of Greater Himalaya

Introduction

When you think of the mighty Himalaya, you're most likely thinking about climbing to great heights, seeing hairy yaks and feeling inferior to people carrying tables up mountains on their backs. You're probably not thinking about swimming in a warm, deep, salty ocean. If you were standing on top of Mt. Everest as early as 60 million years ago (M.a) , however, you would be swimming in the Tethys Ocean.

About 250 M.a., all of the continents existed as one super-continent called Pangaea, which formed approximately 470 M.a. (Upreti and Yoshida 7-9). They were shaped such that the Tethys Sea lay on the eastern coast of Pangaea. After such a long time, I imagine the continents got a little sick and tired of living in such close quarters and wanted their own space. So, in the early Mesozoic, the continents began to drift apart.

Later in the Mesozoic, rifting occurred between the smaller continental masses on Gondwana (now Africa, but at the time it held India as well). India split from Gondwana and moved northward towards the Eurasian landmass at approximately 15 cm per year. During this time, **ocean-ocean plate convergence**[1] was occurring (*Figure 2*). This closed most of the Tethys Ocean, while much of the seabed disappeared in **subduction**[2]. Simultaneously, small **microplates**[3] moved northward causing the accretion of the Tibetan land mass (at this point, not a plateau). Thus, there is a variation of **seabed and crustal blocks**[4] that make up the present-day Tibetan Plateau.

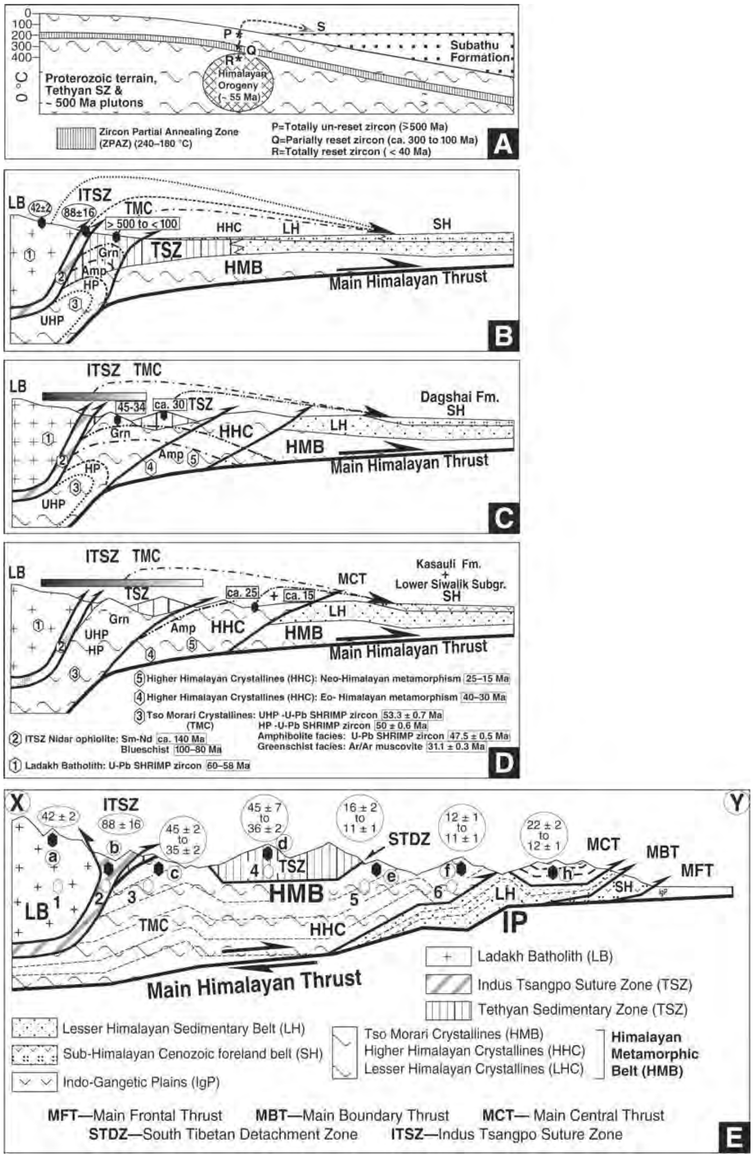


Figure 2: Himalayan Orogeny

India and Eurasia finally made contact about 50 M.a. At long last, India was reunited with Eurasia. The Tethys Ocean

[1] Based on the theory of plate tectonics, ocean-ocean plate convergence occurs as two plates both overlain with ocean are moving together

[2] when two plates converge, subduction occurs as one sinks below the other

[3] smaller plates that  become apart of larger plates with convergence

[4] seabed blocks are parts of the plates that once had ocean above them while crustal blocks have always held land

was officially closed and the Indian Ocean was opened. The sediments that were neither accreted to the Tibetan landmass nor subducted during the ocean-ocean collision were **folded**[5] and **uplifted**[6] and can be seen at the initial point of collision (just north of the Nepal-Tibet border) today.

The initial collision rate was approximately 5 cm/year. This is ridiculously fast in terms of huge masses of Earth's crust. Because of the relative speed of collision, Indian crust during got pushed upwards and folded backwards and southwards, stacking Indian crust on top of Indian crust. When two plates collide, compromise is necessary. One subducts below the other in order to begin the mountain building process (*Figure3*). In this region, Eurasia won. The Indian plate was (and still is) subducting below the Eurasian plate. This process creates "**fold mountains**[7]." As the plates

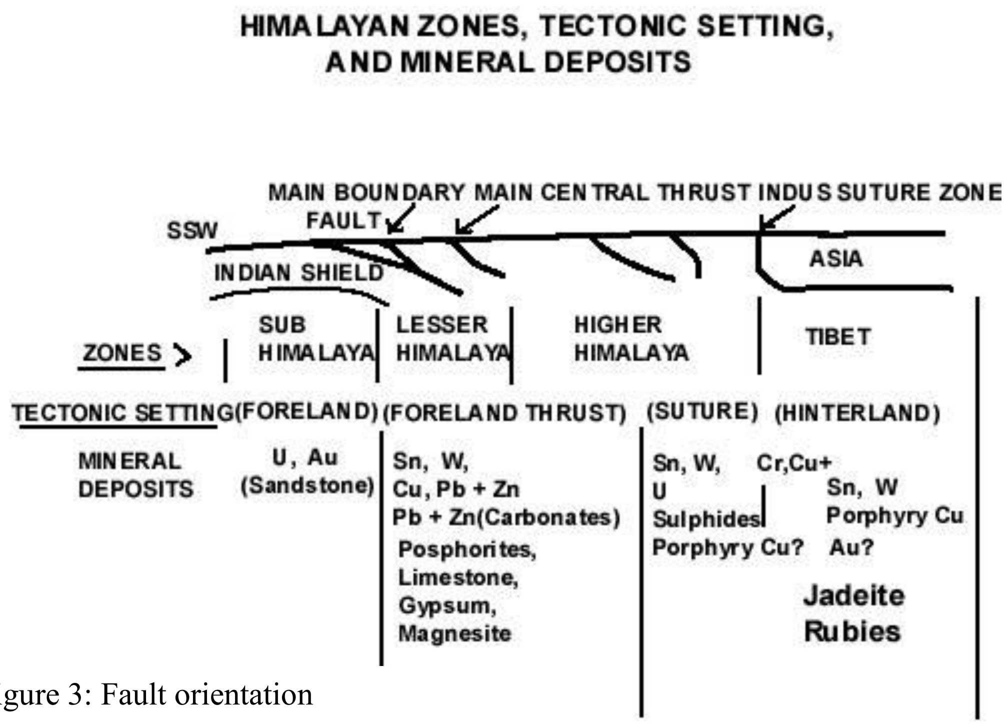


Figure 3: Fault orientation

[5] folds are created when ductile rocks are compressed to created a series of folds
[6] a rising of crust upon collision
[7] mountain type created by collision of two plates and uplift of crust

collide, a series of folds develop and form mountains. This all happens along **faults**[8]. In the case of the Himalaya, northward dipping faults were created simultaneously with the southward stacking Indian plates. As the plates continued to collide, more of these northward-**dipping**[9] faults were created (*Figure 4*).

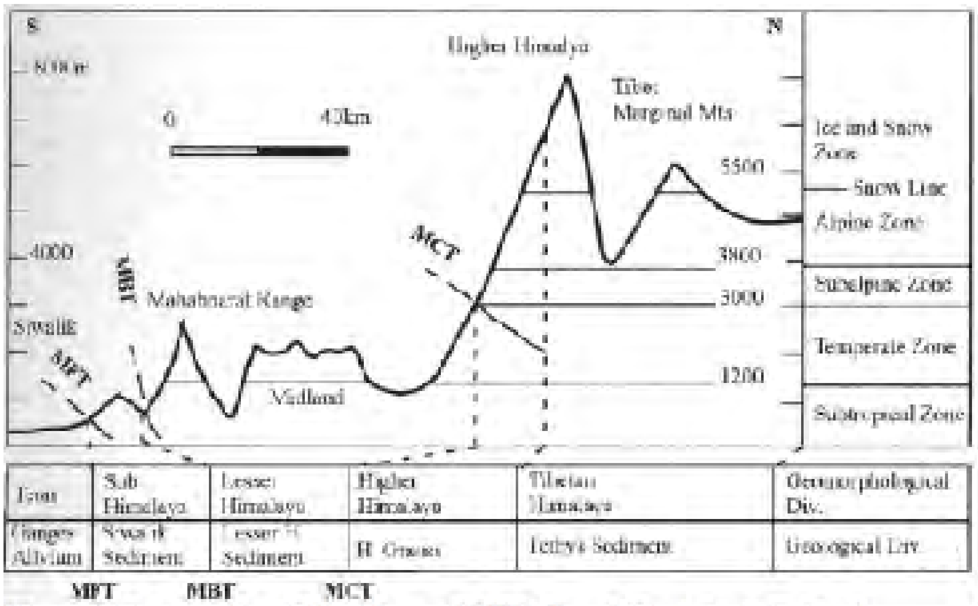


**Figure 4: Cross Section of Himalaya with Altitude and Geological Division^**

From north to south (and thus in order from oldest to youngest) are the Main Central Thrust (MCT), Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT). Another important fault that needs to be recognized is the Southern Tibetan Detachment Fault (the last of which is, unlike the aforementioned **thrust faults**[10], a **normal detachment**[11] fault) (Burchfiel *et. al., 28)*. In their studies, Upreti and Yoshida have postulated that the STD is younger than the MCT and was formed when the MCT was the most active fault (Upreti and Yoshida, 15). As the **hanging wall**[12] of the MCT was thrusted upward on the **footwall**[13], it reached a height where the vertical

[8] brittle and mobile structural boundaries of plates and crust
[9] dip is angle at which a fault or structure appears to go into the Earth
[10] fault in which the hanging wall (above plate) moves upward on the footwall (below plate)
[11] fault in which the hanging wall moves downward on the footwall
[12] above block of a fault
[13] below block of a fault

pressure was too great and underwent **gravitational collapse**[14]. The other faults were created, rather, to alleviate horizontal pressure on the most active fault of the time. As the plates continue to collide, more faults south of the MFT will be created.

The most active fault today is the MFT, which is the closest to the **foreland**[15]. As the thrusts move more inland on the **hinterland**[16], they become less and less active; the only other fault besides the MFT that is still active is the MBT (Upreti and Yoshida, 16). Eventually the MFT will become inactive and a new fault will be developed at the point of **orogen**[17].

The Himalaya's immense height is directly due to the continued collision and mountain building resulting from these faults.

[14] when crust falls because the weight and pressure reaches a unstable point and thus collapses
[15] plate in a convergent that subducts
[16] plate in a convergence that overlies the subducting plate
[17] convergence of two plates

The Formations

These faults separate the Himalayans into five main zones (again listed from north to south) in Nepal- Tibetan-Tethys Himalaya, Higher Himalaya (where Everest lies), Lesser Himalaya, Siwaliks and Terai (*Figure 4,5*) (Godin, 315).

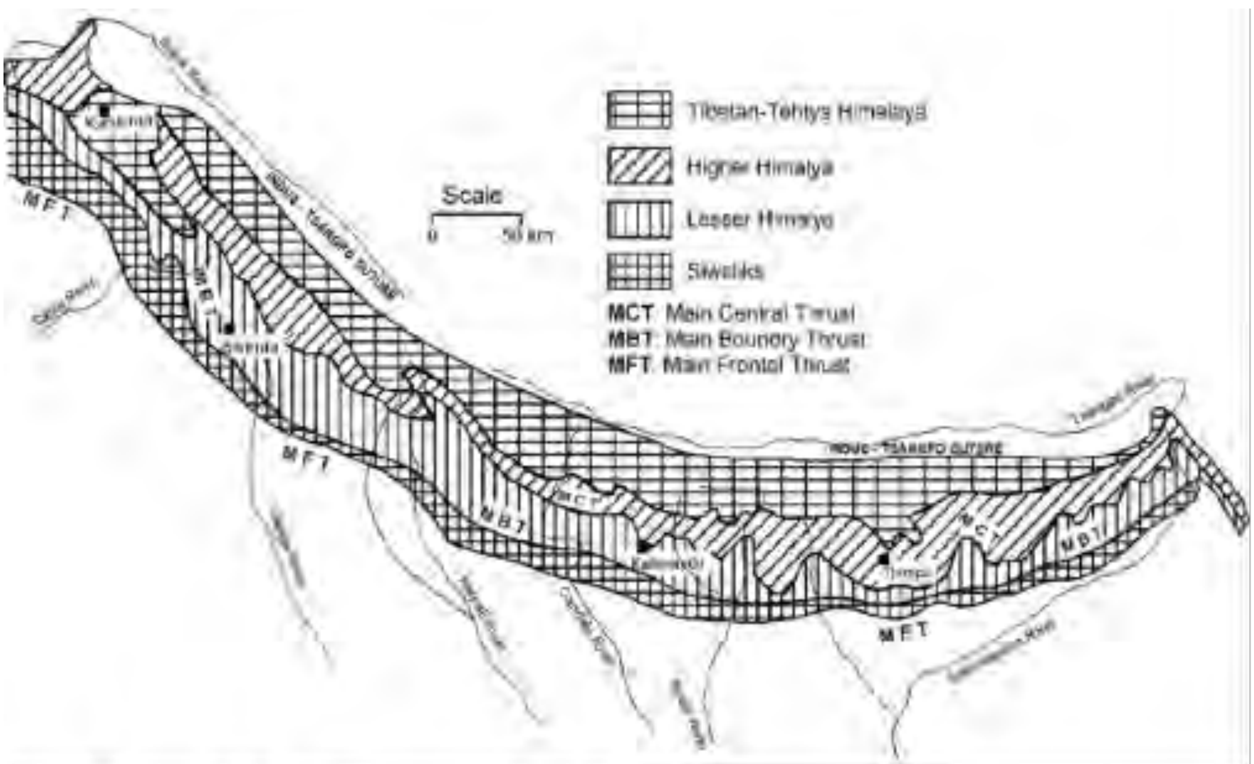


**Figure 5: Overhead Map View of Himalaya Formation Divisions^^**

*Tibetan-Tethys Himalaya*

The Tibetan-Tethys Himalaya ranges from the STDS northward into Tibet. The zone is primarily made of **sedimentary**[18] shale, limestone and sandstone. Here we see the sedimentary remnants of the un-metamorphosed Tethys bed (maybe that's where this zone got its name). This zone is riddled with **fossiliferous**[19] rocks (Godin, 312). The Tibetan Plateau[20] makes up the majority of this region; the plateau itself is a result of Indian-Eurasia collision.

*Higher Himalayan Zone*

The Higher Himalayan Zone lies between the STDS and the MCT. Its average width is only 10 km. The primary rock type seen here is highly **metamorphosed**[21] gneisses, schists and marbles (Burg *et. al.,* 394). This area spans the length of Nepal and holds all of the country's highest mountains including, yours truly, Everest. Some remnants of fossils exist here, as well, but are more difficult to distinguish due to metamorphic alterations.

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[18] rock type created by small weathered bits of rock that undergo heat and pressure to form solid rock
[19] rocks containing fossils
[20] The Indian continent reaches a certain point of subduction where the crust begins to (but does not completely) melt in the lithosphere. When it does this it is below the Eurasian plate. The increased temperature of the crust (which at this point is partially molten) begins to rise below at the base of Tibet, causing it to rise and form the Tibetan plateau.

*Lesser Himalayan Zone*

The Lesser Himalayan Zone lies between the MCT and the MBT. The main rock type here is unfossiliferous sedimentary and **metasedimentary**[22] rocks including slate, phyllite, schist, quartzite, limestone and dolomite (Le Fort, 166)). This zone is further divided into two sequences- allochthonous and autochtonous. The former is found in more Eastern Nepal and includes the highly metamorphosed gneisses and schists which have been moved southward along the faults from the Higher Himalayan Zone. The western section (mainly west of Kathmandu) of the Lesser Himalaya includes lower grade metamorphosed phyllites and slate. While this zone is divided, traces of each one can be seen throughout the region.

*Siwalik*

Between the MBT and MFT is the Siwalik, or Sub-Himalayan, Zone. This zone is divided into three sequences- lower, middle and upper Siwalik. All three sequences mainly hold sedimentary rocks. The Upper Siwalik has mostly conglomerates, siltbeds and mudstone beds. The conglomerate beds contain fragments of the Lesser Himalayan Zone, resulting from southward thrusting along the MBT (Godin *et. al.* 14). Both the lower and middle Siwalik have **interbedded**[23] sandstones and mudstones, although the lower Siwalik contains siltstone layers as

[22] rock metamorphosed from sedimentary rock
[23] alternating beds of rock type

well. The origin of these sedimentary rocks is from the **erosion** of the higher Himalaya. It is, in fact, a **foreland basin,** which predates the Terai.

*Terai*

The Terai, only 200 m above sea level extends from the MFT (this fault is still active) to the current Indian continental crust (called the Indian Shield) (Godin *et. al.* , 18). The Terai is a **foreland basin**. A foreland basin is a constant feature of continental-continental collisions. This is the point at which the plates are still colliding. As they continue to do so, the Indian Shield is moving below the Eurasian plate. This movement causes the lithosphere to bend downward, allowing sediment to erode from adjacent mountains and build up in these basins. The rocks are mainly sediments, including boulders, gravel, silt and clay.

## 2. Geology of the Khumbu

The Khumbu region lies in the Higher Himalayan Zone. It holds some of the largest mountains in the world, along with many of Nepal's glaciers and mountain rivers. It is also home to its fair share of natural hazards.

<u>The Everest Massif</u>

The Everest Massif is at the very north edge of the Higher Himalaya and actually contains rock type of the Tibetan-Tethys Himalaya. This is because part of the STDS actually lies on the massif itself. The STDS, however, is not a single fault but a series of imbricate faults, two of which separate the Everest massif into three formations. The three formations, from the base towards the summit are the Rongbul. North Col and Quomolangma.

The base of Everest is made up of the Rongbul Formation, starting at the base and reaching up to 7000 m. The primary rock type found here are schist and gneiss. Intrusions of leucogranite **sills** and **dikes**[24] of varying thicknesses (1cm to 1500 m) dominate this formation (Searle *et. al.,* 345).

The Lhotse fault separates the Ronbul Formation from the North Col Formation, which ranges from 7000 m to 8600 m. The North Col Formation is further divided into two sections. The top 4000 m, between 8200 and 8600 m is the distinctive Yellow Band, whose name is derived from the weathered yellow-brown color of marble rich in diopside and epidote minerals. Also making

[24] Intrusions of igneous rocks; sills lie horizontally relative to the crust, while dikes intrude perpendicularly

up the Yellow Band is a collection of semischisht and phyllite (both metamorphic rocks). The upper 5 m of the Yellow Band can be as highly deformed as it meets the QD, which can be seen as a 5-40 cm fault breccia, which is very brittle broken rock. Below the Yellow Band is the rest of the North Col Formation, ranging from 7000 to 8200 m on Everest. It mainly consists of a series of metamorphic rocks from the Middle Cambrian beds of mudstone, shale, sandstone and limestone. Today, post-metamorphism, they are phyllite, schist and marble. Between 7000 and 7600 m, schist and marble dominate the formation. Between 7600 and 8200 m phyllite and small amounts of schist are most abundant (Searle *et. al.,* 352).

Above the North Col formation, separated by the Qomolangma detachment fault, is the Quomolangma Formation. The summit rocks (approximately 8600 m and above, although the exact location of the contact is debated), the Qomolangma formation, consist of Ordovician limestone and minor traces of siltstone. There is evidence of conodonts fossils and coral fossils still visible in the impure limestone. Marble rich in calcite and quartz was collected is also close to the summit. The bottom 5 m of this formation are highly deformed and consist of many high angle faults ending at the Qomolangma detachment fault.

The three Everest formations are divided by the aforementioned Qomolangma detachment (QD) and Lhotse detachment (LD), both low-angle detachment faults. The QD appears on the upper slopes of Everest and the fault line itself, seen as a contact of sedimentary limestone rock and the Yellow Band (or the contact between the upper two formations) can be viewed on the north face of Everest with a dip of approximately 10-12 degrees N. Its dip decreases towards the north, as it meets with the shallower dipping LD approximately 40 km north of Everest. Together, these two faults make up the South Tibetan detachment series (STD), which is a system of low-angle normal faults (Upreti and Yoshida, 34). The STD, including the QD and LD, was formed in the Oligocene, approximately 20 M.a. after the initial collision of India with Asia. The LD reached its peak activity in the early Miocene and it currently extinct. Studies suggest that the QD remains slightly active, having reached its peak activity only 16 M.a.  Everest itself stopped "morphing" around this time.

Please bare with me as explaining the massif's extreme altitude gets a bit complicated and technical (it took me a few weeks to grasp what was going on, myself). According to Searle *et. al.'s* 2003 study, Everest's great height can be partially explained by the existence of these faults and the regional morphology (Searle *et al.,* 346-366). The majority of the regional metamorphism, horizontal compression and crustal thickening occurred approximately 23-16 M.a. Early studies attributed this to gravitational collapse and alternating periods of N-S extension and compression. These forces, however, would have resulted in a decreased elevation at some point of the greater Himalayan slab- an event that is not supported by any evidence. The STD hanging wall rocks were apparently stationary, while the footwall moved in a southward direction. No horizontal extension, however, was concluded. Something must have been happening, then, to account for the lack of stretching that an expanding active normal fault, like the STD at the time, is expected to create.

It was not just the STD in action. South of the STD is the Main Central Thrust Zone (MCTZ) is a high strain area of 3-5 km wide dipping at an angle of 10-30 degrees N. The shearing, however, of the MCTZ was in a southward dipping direction. This combination of pure and simple shear was acting on a mid-crustal ductile layer. The ductility at this time accounts for the extreme metamorphism of the Everest region. Ductile zones are only possible at high temperatures, thus melting was simultaneously occurring. As the STD surfaced material to the south, southward shearing along the MCTZ acted faster to thrust the propagating slab from the STD vertically rather than horizontally. As the then-ductile leucogranite intruded along these faults, it pushed rock further upwards. Upon cooling, it had a somewhat ballooning effect on the massif, raising it higher than any other mountain in the world. Thus, the STD shear zone was set above the rest of the Greater Himalayan slab, explaining the massif's altitude.

During this time, the **top-down**[25] order or rocks as seen on Everest today were also established. The brittle structures came after this, approximately 16 M.a. ago, when temperatures fell and ductile activity ceased. After that, brittle structures as we see them today at the QD and LD boundaries cut the rock.

After that, the story is not as complicated. Having cooled, the entire Greater Himalayan slab became susceptible to other regional thrusts, including the Main Boundary Thrust. Since 16 M.a. ago, the Greater Himalayan slab has been uplifted and carried by younger thrusts developing in the Lesser Himalaya and Main Boundary Thrusts systems to the south.

[25] the youngest rocks lie on top and age increases downward

## Ice and Water

### *Glaciations: Past and Present*

The Khumbu has experienced three recent major periods of the glaciations (not directly associated with the regional mountain glaciers). The first was the Periche Stage, which occurred 18-25 thousand years ago, followed by the Chhukung Stage, 10 thousand years ago. The most recent was the Lobuche Stage, which was only 1-2 thousand years ago (Flint, 192). This last stage preceded the **Little Ice Age**[26], which was the most recent cooling period in Earth's history. All three of these glaciations have left **moraines**[27] throughout the Khumbu Himalaya. The glaciers present in the Khumbu during these periods differ from the glaciers seen there now (which are created from the mountains). The origin of these glaciers is ice caps that **accreted** southward over Nepal.

The more recent and currently prevalent glacier types in the Khumbu are mountain valley glaciers. These originate at the top of mountains. Here, it snows all year long and is always below freezing. While this isn't the ideal environment for animals and plants to prosper, it provides the perfect condition for glaciers. The ice that is generated by the snow and freezing temperatures builds up over time until eventually it becomes so think and heavy that the pressure causes a layer on the bottom to start melting. This layer mixes with soil and dirt to create a nice sloshy base layer that makes the glacier mobile as gravity pulls it down the mountain.  This

[26] most recent period of cooling
[27] deposits of rocks left by moving glacier

process repeats itself as new snow is constantly falling and accumulating to birth a growing glacier.

While it descends, it makes contact with the valley created during mountain building. During this time, it picks up boulders, **clasts**[28] and sediments, changing the shape of the valley floor. As it seasonally grows and retreats, moraines are created. Terminal moraines exist at the downward end of the glacier, where the front edge pushes rocks and debris as gravity pulls the glacier down the mountain. Lateral moraines exist on the sides of the valley making contact with the valley edge. Ground moraines lie in front of a retreating glacier and are strongly indicative of a retreating glacier.

Glaciers played a significant role in the formation of the original Himalayan topography. When I was in kindergarten I had a very difficult time telling the letters “u” and “v” apart. I’ve found in studying mountains that my old frustrations about their differences arise again. Two types of valleys exist within mountain ranges- “u-shaped” and “v-shaped” valleys; the difference (as suspected) is the roundness of valley’s base. When glaciers gravitate and form a valley, their vastness and large surface base causes a “u-shaped” valley. A river, contrarily, cuts a steeper-walled and angular-based “v-shaped” valley.

[28] small chunks of rock

*Khumbu Glacier*

Along this trek, you will become extremely familiar with the Khumbu Glacier, Nepal's biggest glacier. Khumbu is 12 km long, draining form the West Cwm of Everest and running between Mt. Everest and the Lhutse-Nuptse Ridge (Bajracharya *et. al*.). Like most of the glaciers of the Himalaya, Khumbu is a mountain valley glacier. It is a heavily debris-covered glacier with the lower 10 km of the glacier mainly covered in clasts. The debris itself comes mainly from avalanches (which melt, exposing the rock). Its altitude ranges from 8000 m to 4900 m. The accumulation zone starts at 5600. The transition between the **accumulation zone** and the **ablation zone**[29] changes seasonally with an alternating climate.

The Khumbu Valley, cut by the Khumbu glacier is a perfect example of a u-shaped valley. Before the Khumbu glacier's descent, the valley would have existed only as a syncline formed in the mountain building process of the Everest massif.

This is one of the signs of recession that the Khumbu glacier is exhibiting. Studies have suggested that the glacier is retreating at 20 m per year. The area covered by the ground moraine has thus increased, further evidence that the glacier has been receding. When a debris-covered glacier recedes, the ice that was holding up the debris disappears and the debris falls to create a large ground moraine (Bajracharya *et. al*.).

[29] zones of a glacier where ice build-up dominates (accumulation) and melt dominates (ablation)

Another indication of climate change's effect on the Kumbu Glacier is its deceleration. Everest Base Camp itself has actually fell 40 m in the past 55 years. This suggests that the glacier is thinning. The thinning further up mountain is greater than at the glacier's terminus, which means that the glacier's slope is reducing. Because of these two factors (reduced slope and thinning overall) the glacier's speed is decelerating (Bajracharya *et. al*.).

The Khumbu glacier experiences great season changes. In the warmer months, melting exceeds accumulation, thus the glacier is in a retreating stage. In the colder months, accumulation exceeds melting, thus the glacier accretes downward.

One of the most dangerous and volatile places along the Khumbu glacier is the Khumbu Icefall. (Don't worry! You won't have to experience this part of the Everest climb on the trek to base camp). The Khumbu Icefall is the point at which the glacier suddenly has to go over a point in which its path greatly narrows or steepens. Because of this, its movement accelerates. With increasing speed, the ice cannot flow smoothly down and once it reaches its point of elasticity, starts to break. The Icefall, home to many deaths on the path up Everest, is seen as a series of tall, jagged glacial fragments. Between these large blocks of ice are massive crevasses. Climbers hoping to make it up Mt. Everest have to use strong ladder structures in order to safely make it across these crevasses.

*Mountain River Valleys*

As mountain rivers flow down from the peaks, they cut V-shaped valleys. The Khumbu is home to many rivers, all tributaries to the greater Kosi River System. Much of the trek from Lukla to EBC follows the Dudh Kosi River. The Dudh Koshi is one of the seven tributaries to the Kosi River, which is (in turn) a tributary of the Ganga River. The Koshi is one of the largest tributaries to the Ganga, draining 69,300 square kilometers. It drains from the Everest massif and flows down through the Gokyo Lakes.

## Natural Hazards in the Solu Khumbu

### *Glacial Lake Outburst Floods (GLOF)*

Glacial lakes are formed when glaciers are in the process of melting. The water from the melting glacier is trapped between the already-made terminal and lateral moraines of the retreating glacier. When these moraine dams fail, water overflows, causing flooding. These moraines can fail in a number of ways, including (but not limited to) erosion, excessive water pressure, earthquakes and glacial breakoff displacing the water.

Erosion is a very slow, but ever-present, process. As soon as rock is deposited it begins to be eroded away. Eventually, the rocks that make up any moraine (either terminal or lateral) will erode away, below the water level of the glacial lake. When this happens, water will spill over the edge. And thus, another GLOF, occurs.

While the glacier retreats, the lateral moraines creating side-dams for the glacial lakes increase. The already created terminal moraine, however, remains constant. There reaches a point where it can no longer sustain the volume of water melted from the glacier. In this case, the terminal moraine dam will break due to water pressure build up.

Earthquakes are another immediate cause of GLOF. In an earthquake-prone area (such as the Himalaya), the ground is very unstable. Many small earthquakes (although most are too minor for human detection) occur annually. While humans cannot feel their effects, any subsurface movement can shake the ground enough to deform the moraine dams and cause flooding.

Associated with gradual glacial melt are sudden breaks of large chunks of ice from the glacial. When this happens above solid ground, icefalls and crevasses are created. When this occurs above a glacial lake, however, mass displacement of water can occur.

In the past three decades, the Nepal Himalaya has seen a substantial increase in GLOF. GLOFs are particularly dangerous, rendering discharges 7 to 60 times greater than normal floods (resulting from snowmelt runoff or monsoon precipitation). In 1985, Namche suffered from a large GLOF, known as the Dig Tsho GLOF. The Langmoche glacier had created a lake 1,500 m long, 300 m wide and 18 m deep (with a water volume of 5 million cubic meters) (Bajracharya *et. al*.). An "ice avalanche' from the Langmoche glacier fell into the lake and displaced the water (creating a 5 m wave) over the moraine. Since 1960, GLOF have occurred in eastern Nepal ever three or four years. In 2000, the International Center for Integrated Mountain Development surveyed 2,315 glacial lakes, deeming 26 potentially dangerous lakes in Eastern Nepal (ICIMOD).

*Earthquakes*

Earthquakes occur along active faults. When one block is moving against another friction builds up until it reaches its points where elasticity is broken. This causes a sudden shock movement to occur- the original point of broken friction is called the epicenter. When this happens, two sets of waves are set off. First are Primary (P) waves, followed by secondary (S) waves. The more friction that builds up, the greater the elastic break is, the stronger the waves are and (finally) the stronger the earthquake is felt.

Because the Himalaya is so tectonically active, the region is very susceptible to earthquakes. Most of the recent seismological activity in the Khumbu region has occurred along shallow faults, which do not create as strong Earthquakes, and thus cannot be detected by humans. Major Earthquakes are felt in Nepal every 75 years (approximately). The last major earthquake occurred in 1934 and destroyed much of the village of Tengboche.

Earthquakes are one of the major causes of large-scale avalanches and landslides. Rocks and snow are more sensitive to movements of the Earth's crust. Even when slight movements are undetected by humans, avalanches and landslides can occur. Both of these natural hazards can be hugely detrimental to human-build structures and safety of the region.

Both landslides and avalanches are not simply the cause of earthquakes. Both can result from a large build-up of snow or rocks and can happen seemingly spontaneously.

## 3. The Trek

The trek from Lukla to Everest Base Camp and return to Lukla takes approximately two weeks (*Figure 7*). The path takes you from an altitude of 2840 m to 5545 m (if you choose to climb Gorak Shep). On the ascent, you follow the Dudh Kosi River, climb above tree line and hike on the Khumbu Glacier. Because of the variation in altitude and long distance you'll walk, you'll get to see some important features of the Higher Himalaya geological zone. This next section points out certain stops of geologic interest along the trekking route.


Figure 6: Trekking Route %%%

*Conglomerate*

Location: Conglomerates make up a large part of the sedimentary Himalaya. On the way from Pakhding to Monjo (along the Dudh Kosi), there are many series of exposed conglomerates.

**Figure 7: Conglomerate Layering**

Description: The conglomerate here is mainly clast-supported with small pebble to cobble clast sizes. It source is a past rockslide. The bedding of the sand shows the direction of the slide, as it slopes (in the picture form right to left) downward.

*Leucogranite*

Location: After checking into Sagamartha National Park just past Monjo, you have to descend a steep set of stairs. To the left of these steps is a large granite bluff, probably the best exposure of the Khumbu leucogranite along the trek.

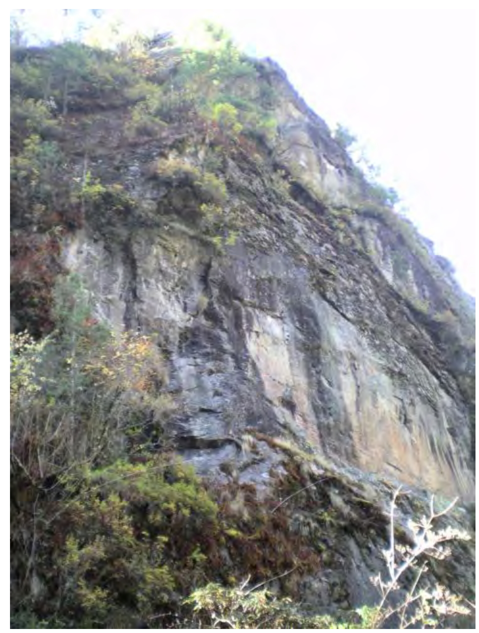

**Figure 8: Leucogranite Bluff**

Description: The fresh rock color of the granite is not exposed. The weathered rock doesn't allow for an easy identification of the rock, but that's why we have things like guidebooks to tell us what to look for. The granite is light in color with large grain size (these leucogranites are, in fact, pegmatites). The main mineral composition is quartz, plagioclase and K-feldspar. Most of the leucrogranites in the region intruded as sills or dikes along faults during the Cenozoic.

*Dudh Kosi Confluence*

Location: For the first day and a half of the trek, you follow the Dudh Kosi River alone. Right before you begin the tiring climb to Namche Bazaar, you will see the confluence of the Dudh Kosi River and the Bhote Kosi River. The climb follows the spur between the two rivers, although is closer to the Dudh Kosi.

**Figure 9: Dudh Kosi River right before confluence point**

Description: The Dudh Kosi drains from the Everest massif, while the Bhote Kosi drains from Tibet. The two converge and continue southward to drain into the Sun Kosi river system, which finally flows to the Gangetic plain. *GLOF on Ama Dablam*

Location: The best views of Ama Dablam appear on the long ridge running from Namche Bazaar to Tengboche (each turn your make, in fact, brings better and better views). This view gives you the most famous view of Ama Dablam, but perhaps not

**Figure 10: Ama Dablam Debris Flow**

the most geologically interesting (of course, this a personal opinion). Once you reach Pheriche, the view of Ama Dablam changes and you can see a large debris slide that runs down the side.

Descriptions: Evidences of floods and landslides riddle this trek- so why is this one of particular interest? Prior to 1977, a glacial lake lay on the side of Ama Dablam from the Nara Glacier. A GLOF in 1977, however, caused mass flooding on the side of the mountain destroying homes and bridges in the water's path. Rock debris remnants from the flood dominate the face of the mountain now. The flood was caused when a smaller glacier lake drained into a larger one on the west face of the mountain, releasing 4.9 million cubic meters of water.

*Yellow Band*

Location: Coming from Orsho, you much climb over a pass before descending to Pheriche. At the top of this pass, you will get some of the best Everest views of the trek. If you are lucky enough to reach this pass on a clear day, you can make out the Yellow Band near the top of Everest.

**Figure 11: Yellow Band on Everest Massif**

Description: The name "Yellow Band" is a bit misleading. If you are looking for a bright yellow strip of rock that obviously sticks out on the massif, you will be disappointed and lost. The Yellow Band, rather, appears as a slightly lighter (yellow-brown) colored band of rock. The top of the yellow band marks the boundary between the two formations on Everest (separated by the Qomolangmo Fault). It is mainly composed of marble and phyllite that have traces of fossils from the initial beds of limestone it was metamorphosed from.

*Moraine*

Location: Walking from Duglah to Lobuche you first ascend over the steep section of the Khumbu terminal moraine. The rest of the walk to Lobuche follows the rest of the terminal and lateral moraine.

**Figure 12: Subglacial Moraine of the Khumbu Glacier**

Description: The terminal moraine marks the furthest extent of Khumbu glacial accretion. As the glacier moves down the valley, it pushes rocks forward. The initial climb marks the further point of accretion and the final pile up of migrated clasts. As you continue up the valley, you walk between the sides of the U-shaped glacial valley. On either side of your, the walls are marked by the lateral moraine of the glacier. What you are walking on is the morphed subglacial moraine, which consists of rocks altered by the movement of the glacier over them. The rock types of the moraines vary greatly, because they are a collection of rocks moved from their original location.

*Fold on Mountain*

Location: On the walk from Lobuche to Gorak Shep, you really feel (more than ever) that you are in the mountains. Keep at eye out for some great outcrops of folds- particularly this one layering of an upright fold that appears on the left side of the trail about halfway through the two villages.

**Figure 13: Upright Fold**

Description: There are two very easily distinguishable layers on the side of this mountain. Folds are a result of a compressional force upon rocks in the ductile stage. During the orogeny, these folds would have been created as the mountains were being uplifted. The fold seen here is a syncline. Anticlines can be seen partially on either side of it. The fold set is a series of anticlines and synclines that are aligned parallel with the direction of impact. This fold is an open, upright and parallel fold.

*Lake bed of Gorak Shep*

Location: Your last sleeping stop is Gorak Shep. The village is located on a dried up lake bed. The lake is not completely drained; there is still a small lake to the side of the village.

**Figure 14: Gorak Shep Lake Bed**

Description: Right below the lodges, there is a huge flat plane of sand that was once a glacial lake. The remnants of water in the area suggest that the lake did not dry an excessively long time ago. There are a few explanations for why a glacial lake dries up- the first could be a GLOF that depleted the bed of all of its water. Another explanation is decreased precipitation and increased temperature- when the latter causes the rate of evaporation to exceed the rate of precipitation, lakes can dry up. There has been no evidence of a GLOF around Gorak Shep, so I personally hypothesize the second option caused the lake to dry.

*Khumbu Icefall*

Location: Everest Base Camp! If you're at Everest Base Camp in the fall, it might not be as exciting from a "Trekking cultural" standpoint, but there is still some pretty god Earth-fun to be had. From EBC you can see the Khumbu Icefall, which is apparently one of the most technically dangerous parts of the Everest climb (excluding dangers from altitude).

**Figure 15: Khumbu Icefall**

Description: The icefall occurs when the valley the glacier is descending into narrows or steepens. The Khumbu glacier is a particularly steep section of the valley, explaining the Icefall's location. This causes the ice's movement to speed up and deformed more rapidly than the structure can accommodate. Thus, crevasses are created. At the bottom of the icefall, the valley widens again allowing the ice to flow more slowly and have time to morph smoothly.

*Everest Massif*

Location: Although you might be tired from a sleepless night in Gorak Shep after a long day to Base Camp, the trip up Kala Pattar to get the best view of Everest is apparently a must-do (altitude related problems caused me

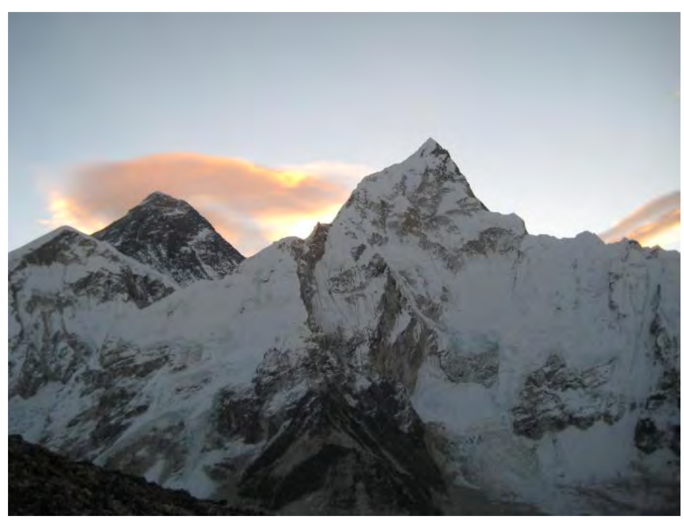

**Figure 16: Everest Massif from Kala Pattar**

to have to descend rapidly in the morning, having to miss out on Kala Pattar, but I hear that it is very worth the climb).

Description: From the top of Kala Pattar, the whole Everest massif is visible. The massif is composed of three peaks- Everest, Lhotse and Nuptse. At this point, we know why the Himalaya are the highest mountains, but what is it about this massif that allows it to hold two of the world's highest mountains. As previously discussed, the leucogranite is the answer! There is a large sill of garnet, muscovite and tourmaline rich leucogranite that, upon cooling, actually had a balloon-like effect on the massif, elevating it so extremely.

## Appendix

## Appendix A: Glossary[30]

### A

Anticline: A large fold whose limbs are lower than its center; a fold with the oldest strata in the center.

### B

Bedding: A characteristic of sedimentary rocks in which parallel planar surfaces separating different grain sizes or compositions indicate successive depositional surfaces that existed at the time of sedimentation.

### D

Deposition: A general term for the accumulation of sediments by either physical or chemical sedimentation.

Dip: The angle by which a stratum or other planar feature deviates from the horizontal. The angle is measured in a plane perpendicular to the strike.

Drift (glacial): A collective term for all the rock, sand, and clay that is transported and deposited by a glacier either as till or as outwash.

Drumlin: A smooth, streamlined hill composed of till.

### E

Earthquake: The violent oscillatory motion of the ground caused by the passage of seismic waves radiating from a fault along which sudden movement has taken place.

Elastic limit: The maximum stress that can be applied to a body without resulting in permanent strain.

Epicenter: The point on the Earth's surface directly above the focus or hypocenter of an Earthquake.

Erosion: The set of all processes by which soil and rock are loosened and moved downhill or downwind.

[30] All term definitions come from Glossary of Geological Terms (Geotech)

## F

Fault: A planar or gently curved fracture in the Earth's crust across which there has been relative displacement.

Fault-block mountain: A mountain or range formed as a horst when it was elevated between parallel normal faults.

Fault plane: The plane that best approximates the fracture surface of a fault.

Focus (earthquake): The point at which the rupture occurs; synonymous with hypocenter.

Fold: A planar feature, such as a bedding plane, that has been strongly warped, presumably by deformation.

Formation: The basic unit for the naming of rocks in stratigraphy: a set of rocks that are or once were horizontally continuous, that share some distinctive feature of lithology, and are large enough to be mapped.

Fossil: An impression, cast, outline, or track of any animal or plant that is preserved in rock after the original organic material is transformed or removed

## G

Glacial valley: A valley occupied or formerly occupied by a glacier, typically with a U-shaped profile.

Glacier: A mass of ice and surficial snow that persists throughout the year and flows downhill under its own weight. The size range is from 100 meters to 10,000 kilometers.

Gneiss: A coarse-grained regional metamorphic rock that shows compositional banding and parallel alignment of minerals.

Granite: A coarse-grained, intrusive igneous rock composed of quartz, orthoclase feldspar, sodic plagioclase feldspar, and micas. Also sometimes a metamorphic product.

Gravel: The coarsest of alluvial sediments, containing mostly particles larger than 2 mm in size and including cobbles and boulders.

Ground moraine: A glacial deposit of till with no marked relief, interpreted as having been transported at the base of the ice.

## I

Igneous rock: A rock formed by congealing rapidly or slowly from a molten state.

## L

Landslide: The rapid downslope movement of soil and rock material, often lubricated by groundwater, over a basal shear zone; also the tongue of stationary material deposited by such an event.

Lateral moraine: A moraine formed along the side of a valley glacier and composed of rock scraped off or fallen from the valley sides.

Limb (fold): The relatively planar part of a fold or of two adjacent folds (for example, the steeply dipping part of a stratum between an anticline and syncline).

Lithification: The processes that convert a sediment into a sedimentary rock.

Lithosphere: The outer, rigid shell of the Earth, situated above the asthenosphere and containing the crust, continents, and plates.

## M

Magma: Molten rock material that forms igneous rocks upon cooling. Magma that reaches the surface is referred to as lava.

Metamorphism: The changes of mineralogy and texture imposed on a rock by pressure and temperature in the Earth's interior. Meteoric water: Rainwater, snow, hail, and sleet.

Moraine: A glacial deposit of till left at the margin of an ice sheet. See specifically by name, ground moraine, longitudinal moraine, medial moraine, and terminal moraine.

Mountain: A steep-sided topographic elevation larger than a hill; also a single prominence forming part of a ridge or mountain range.

Mudflow: A mass movement of material finer than sand, lubricated with large amounts of water.

## N

Normal fault: A dip-slip fault in which the block above the fault has moved downward relative to the block below.

## O

Orogeny: The tectonic process in which large areas are folded, thrust-faulted, metamorphosed, and subjected to plutonism. The cycle ends with uplift and the formation of mountains.

Outcrop: A segment of bedrock exposed to the atmosphere.

## P

Pangaea: According to some theories, a great proto-continent from which all present continents have broken off by the mechanism of sea-floor spreading and continental drift.

Pegmatite: An igneous rock with extremely large grains, more than a centimeter in diameter. It may be of any composition but most frequently is granitic.

P-wave: The primary or fastest wave traveling away from a seismic event through the solid rock, and consisting of a train of compressions and dilations of the material.

## R

Ridge (mid-ocean): A major linear elevated landform of the ocean floor, from 200 to 20,000 kilometers in extent. It is not a single ridge, but resembles a mountain range and may have a central rift valley.

Rockslide: A landslide involving mainly large blocks of detached bedrock with little or no soil or sand. Rounding: The degree to which the edges and corners of a particle become worn and rounded as a result of abrasion during transportation. Expressed as angular, subrounded, well-rounded, etc.

## S

Sandstone: A detrital sedimentary rock composed of grains from 1/16 to 2 millimeters in diameter, dominated in most sandstones by quartz, feldspar, and rock fragments, bound together by a cement of silica, carbonate, or other minerals or a matrix of clay minerals.

Schist: A metamorphic rock characterized by strong foliation or schistosity.

Sea-floor spreading: The mechanism by which new sea floor crust is created at ridges in divergence zones and adjacent plates are moved apart to make room. This process may continue at 0.5 to 10 centimeters/year through many geologic periods.

Seismicity: The world-wide or local distribution of earthquakes in space and time; a general term for the number of earthquakes in a unit of time.

Subduction zone: A dipping planar zone descending away from a trench and defined by high seismicity, interpreted as the shear zone between a sinking oceanic plate and an overriding plate.

S-wave: The secondary seismic wave, traveling slower than the P-wave, and consisting of elastic vibrations transverse to the direction of travel. It cannot penetrate a liquid.

Syncline: A large fold whose limbs are higher than its center; a fold with the youngest strata in the center.

## T

Tectonics: The study of the movements and deformation of the crust on a large scale, including epeirogeny, metamorphism, folding, faulting, and plate tectonics.

Terminal moraine: A sinuous ridge of unsorted glacial till deposited by a glacier at the line of its farthest advance.

Thrust fault: A dip-slip fault in which the upper block above the fault plane moves up and over the lower block, so that older strata are placed over younger.

Till: An unconsolidated sediment containing all sizes of fragments from clay to boulders deposited by glacial action, usually unbedded.

Time scale: The division of geologic history into eras, periods, and epochs accomplished through stratigraphy and paleontology.

## U

Uplift: A broad and gentle epeirogenic increase in the elevation of a region without a eustatic change of sea level.

U-shaped valley: A deep valley with steep upper walls that grade into a flat floor, usually eroded by a glacier.

## V

Valley glacier: A glacier that is smaller than a continental glacier or an icecap, and which flows mainly along well-defined valleys, many with tributaries.

V-shaped valley: A valley whose walls have a more-or-less uniform slope from top to bottom, usually formed by stream erosion.

## W

Weathering: The set of all processes that decay and break up bedrock, by a combination of physically fracturing or chemical decomposition.

## Appendix B: Geo Time Scale [$]

**Geologic Time Scale**

| Era | System & Period | Series & Epoch | Some Distinctive Features | Years Before Present |
|---|---|---|---|---|
| CENOZOIC | Quaternary | Recent | Modern man. | 11,000 |
| | | Pleistocene | Early man; northern glaciation. | 1/2 to 2 million |
| | Tertiary | Pliocene | Large carnivores. | 13 + 1 million |
| | | Miocene | First abundant grazing mammals. | 25 + 1 million |
| | | Oligocene | Large running mammals. | 36 + 2 million |
| | | Eocene | Many modern types of mammals. | 58 + 2 million |
| | | Paleocene | First placental mammals. | 63 + 2 million |
| MESOZOIC | Cretaceous | | First flowering plants; climax of dinosaurs and ammonites, followed by Cretaceous-Tertiary extinction. | 135 + 5 million |
| | Jurassic | | First birds, first mammals dinosaurs and ammonites abundant. | 181 + 5 million |
| | Triassic | | First dinosaurs. Abundant cycads and conifers. | 230 + 10 million |
| PALEOZOIC | Permian | | Extinction of most kinds of marine animals, including trilobites. Southern glaciation. | 280 + 10 million |
| | Carboniferous | Pennsylvanian | Great coal forests, conifers. First reptiles. | 310 + 10 million |
| | | Mississippian | Sharks and amphibians abundant. Large and numerous scale trees and seed ferns. | 345 + 10 million |
| | Devonian | | First amphibians; ammonites; fishes abundant. | 405 + 10 million |
| | Silurian | | First terrestrial plants and animals. | 425 + 10 million |
| | Ordovician | | First fishes; invertebrates dominant. | 500 + 10 million |
| | Cambrian | | First abundant record of marine life; trilobites dominant. | 600 + 50 million |
| | Precambrian | | Fossils extremely rare, consisting of primitive aquatic plants. Evidence of glaciation. Oldest dated algae, over 2,600 million years; oldest dated meteorites 4,500 million years. | |

## Suggestions for Further Research

It would be interesting to carry out a similar project of making a geologic trekking guidebook in other parts of the Nepal or Indian Himalaya (for instance, the Annapurna Circuit or the Mustang Area). There are also many other routes that can be taken in the Khumbu that probably present many other interesting geo-stops that can be made into a similar project. It would be more interesting, though, to possibly study some of the subjects presenting in this project more in depth. For instance, GLOF are becoming much more prominent and a study of their causes and effects would probably make for some good research.

*Methodology*

The main resources for information on this project are research-base. I spent two weeks in the field doing the Everest Base Camp trek in order to determine stops along the route that highlight the geologic history of the region.

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