



Chokyi Dronma in a 17<sup>th</sup> century mural painting at Nyemo Chekar monastery (Hildegard Diemberger)

Hindu, and the modern environmentalism that he had learnt by working with conservation biologists. These overlaid each other in the suggestive scenery. He then pulled out from his rucksack a brochure of a local environmental NGO he was part of: Kangchendzonga dominated the front cover; biodiversity was declared as a treasure of the 'Great Snow Mountain' enshrining the 'Five Treasures'. The name of the holiest mountain of Sikkim reflecting its ancient mythology had apparently acquired a 21<sup>st</sup> century dimension.

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MIKE SEARLE

## Rise and Fall of The Himalaya

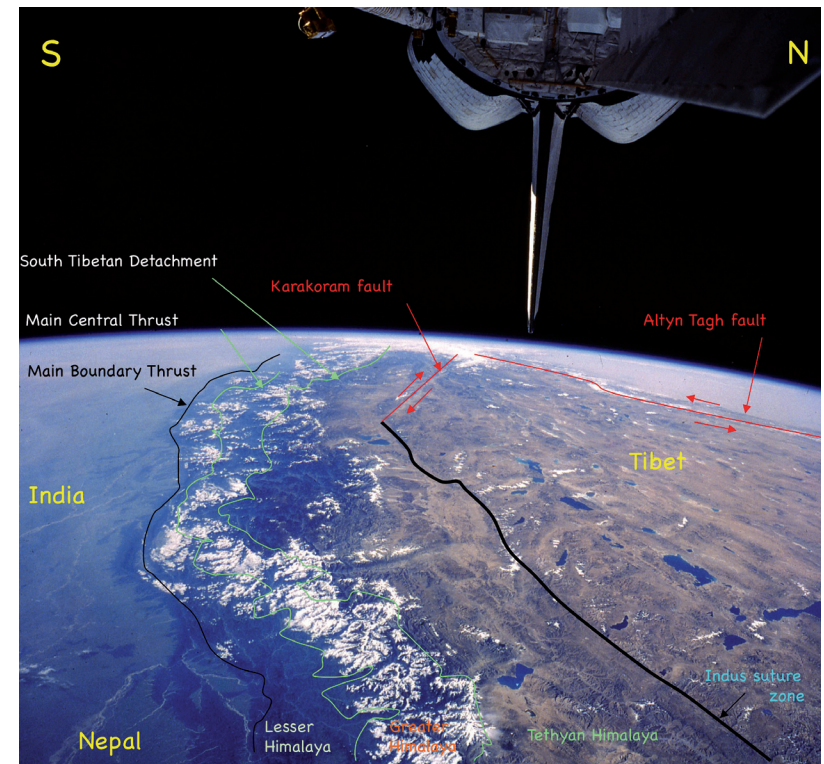


Fig. 1. The Himalaya and Tibetan Plateau looking west as viewed from the Space Shuttle. Major geological features are shown.

On 5 May 2012 a huge rockfall broke away from the summit ridge of Annapurna IV, cascading debris down some 3000 metres into the upper reaches of the Seti valley. More than 70 people died in mudflows that swept down the river. When we reached the area one week later brown muddy waters were still flowing down the Seti and into Pokhara itself. Compared to the massive catastrophic events in the geological record, the Seti khola flood was only a minor event, yet it serves as a reminder of the on-going nature of the greatest continental collision in Earth history – the rise and fall of the Himalaya. It is a story that I have been piecing together over 30 years as a field geologist. This year (2013) I set out my unravelling of the geology of the Himalaya in *Colliding Continents* (see *Reviews*, p 338); what follows is but a snapshot of a complex and awe-inspiring drama.

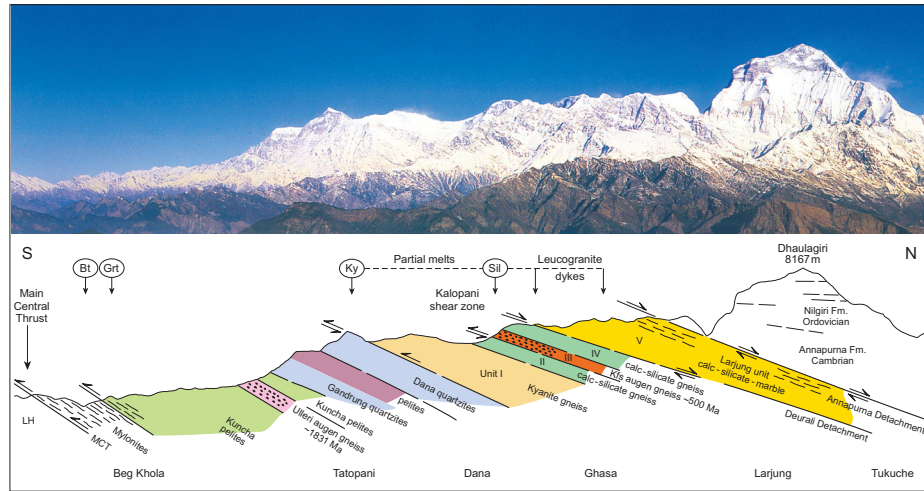


Fig. 2. Cross section of the Dhaulagiri Himal viewed from Poon Hill showing the major geological features. The main index minerals biotite (Bt), garnet (Grt), kyanite (Ky) and sillimanite (Sil) reveal the inverted metamorphism characteristic of the Himalaya. (Mike Searle)

The Himalaya result from the collision of the Indian tectonic plate with Asia some 50 million years ago, one of the largest continental collisions the Earth has experienced in the last 500 million years (Fig. 1). 130 million years ago the Indian sub-continent was attached to Madagascar, East Africa and Antarctica as part of the super-continent Gondwana. As this super-continent broke up India detached from its neighbours, pushed apart by newly formed oceanic spreading centres beneath the floor of the Indian Ocean, and began its rapid drift northwards. In just 50 million years the Tethys ocean, that once lay between India and Asia, closed as India collided with Asia. Folding and thrusting of the rocks along the colliding continental margins resulted in crustal shortening of hundreds of kilometres and a doubling of the crustal thickness to 75 km. This crustal thickening caused an increase of temperature and pressure and intense metamorphism of the rocks caught up in the collision. Shales became crystalline schists, limestones became marbles and, at the highest temperatures, the rocks even started to melt producing granites (which have been dated by uranium-lead isotopic dating techniques to between about 24 and 19 million years old – Miocene). Subsequent uplift and erosion has exposed these granites in many of the highest peaks along the Himalayan range.

In many older mountain ranges, such as the Highlands of Scotland for example, metamorphism is the right way up; in other words rocks increase in metamorphic grade with greater structural depth, as one would expect. Along the Himalaya however, the entire metamorphic sequence is upside-down. The structures all dip to the north as India under-thrusts Tibet, but the rocks show increasing metamorphic grade the further north you trek toward higher structural levels. Hotter rocks have been thrust



Fig. 3. South face of Annapurna I (8091m) composed of Cambrian-Ordovician limestones and dolomites. (Mike Searle)

south over colder rocks. Characteristic metamorphic index minerals range from low-grade biotite and garnet along the base of the thrust slab in the south through staurolite, kyanite and sillimanite grade, and eventually to migmatite (a partially molten rock) and granite as you progress upwards and northwards. The granites are pale-coloured igneous rocks composed largely of quartz and feldspar but also containing red garnet, white shiny muscovite mica and a characteristic black mineral, tourmaline.

Mapping along the Himalaya has shown that along the base of this metamorphic slab a huge shear zone or thrust fault carries all the metamorphic rocks above, and the top of the slab is marked by a low-angle, normal fault termed the South Tibetan Detachment (Fig. 2). This feature cuts across the summit region of Everest and clips the tops of many of the 8000 metre peaks (for example Manaslu, Makalu and Kangchenjunga, as well as Shivling and the Bhagirathi peaks). Above the South Tibetan Detachment unmetamorphosed sedimentary rocks show spectacular folds and thrusts. Annapurna and Dhaulagiri are two 8000m peaks composed of limestones and dolomites that form part of the unmetamorphosed Himalaya that lies above the South Tibetan Detachment (Figs. 3, 4).

### Channel Flow Model

The structural profile across the Greater Himalaya reveals a mid-crust layer of rocks which were partially melted beneath southern Tibet before being extruded out to the south during the Miocene (approximately 24-15

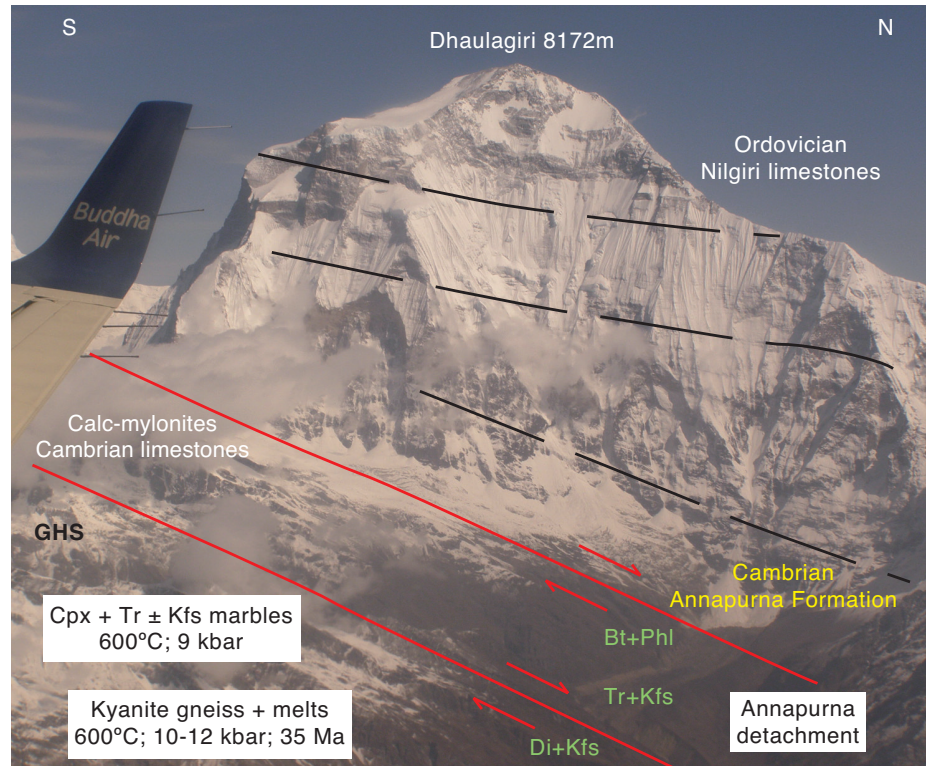


Fig. 4. Aerial view of the southeast face of Dhaulagiri (8167m) showing Cambrian limestones above mylonites of the South Tibetan Detachment, dipping gently to the north. Bt – biotite, Phl – phlogopite, Cpx – clinopyroxene, Tr – tremolite, Kfs – potassium feldspar, Di – diopside, GHS – Greater Himalayan Sequence. (Mike Searle)

million years ago). These rocks are bounded by large-scale ductile shear zones, the Main Central Thrust along the base and the low-angle normal fault, the South Tibetan Detachment along the top. This model, dubbed the 'Channel Flow model' was formulated based on the structures and the metamorphism, in particular accurate pressure and temperature determinations from the rocks across the entire mountain range (Fig. 5). It seems therefore that many of the granites that form the highest peaks along the Himalaya were formed at depths of 18–30 kilometres beneath southern Tibet from Indian plate rocks that were under-thrust to the north during the collision, metamorphosed, melted and then extruded back to the south during the Miocene. As the partially molten mid-crustal channel was extruding out to the south, the metamorphic isograds (lines of equal pressure-temperature) were folded around this hot core, such that the whole bottom limb was inverted and the top limb remained right way-up (Fig. 1).

Approximately 14 million years ago, the entire channel froze as the supply of melts ran out, and deformation propagated to the south across

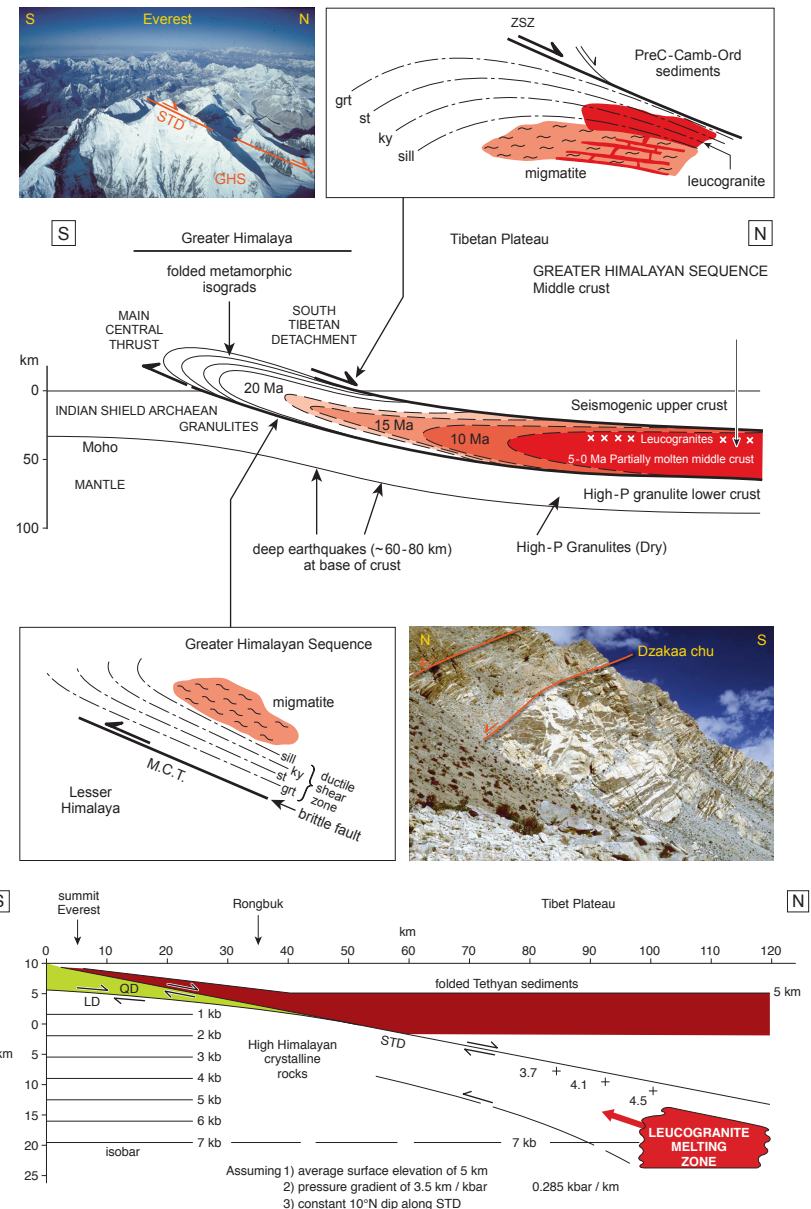


Fig. 5. The Channel Flow model for the Himalaya during the Miocene showing the mid-crustal partially molten layer (in red) extruding south beneath the South Tibetan Detachment normal fault and above the Main Central thrust with its inverted metamorphism beneath. Photo shows the normal fault clipping the summit region of Everest above the Yellow Band. Lower diagram shows the origin of the granite melts and the exhumation pathways beneath Everest. (Mike Searle)



Fig. 6. Aerial view of the south face of Machapuchare (6993m), the 'Fish Tail', west of the Seti khola with the Modi khola on the left. (*Mike Searle*)

the Lesser Himalaya. Today, all the deformation is concentrated along the active Main Boundary Thrust fault that delimits the southern margin of the Himalaya. Earthquakes are generated along this fault, where the Indian plate is subducting beneath the Himalaya and jacking up the mountain range. Thus the highest peaks of the Himalaya are all being supported by the under-thrusting of India beneath the Himalaya and Tibet.

With recent advances in dating techniques it is now possible to constrain the geological history of the Himalaya with increasingly greater precision. We can use palaeomagnetic and stratigraphic data to constrain the timing of India-Asia collision (50 million years ago). We can use uranium-lead isotopes to date the timing of peak Himalayan metamorphism (maximum pressures and depth at 35-29 million years ago; peak temperature and partial melting to produce granites 24-18 million years ago). We can use low-temperature thermochronometers ( $^{40}\text{Ar}/^{39}\text{Ar}$ ; fission tracks) to date the cooling and exhumation history of rocks. We can use cosmogenic isotopes ( $^{10}\text{Be}$ ;  $^{36}\text{Al}$ ) to date geomorphic features such as river terraces, glacial moraines, etc and we can use the record preserved in cores taken from ocean floor sediments to interpret the chemical weathering of Himalayan granites and climate history.

#### Antecedent Rivers

As the Himalaya rose during the Oligocene (34 to 23 million years ago) and the Early – mid-Miocene (23 to 12 million years ago), rivers were initiated that flowed both south towards India and north towards Tibet. Some rivers (like the Indus, Sutlej, Yarlung Tsangpo and Brahmaputra) are ante-



Fig. 7. South face of Annapurna IV (7525m) taken before the landslide with the Seti khola on the left. (*Mike Searle*)



Fig. 8. Aerial view of the west face of Annapurna IV taken after the landslide showing the scar in the summit ridge and pale coloured rock debris extending west to the Seti khola. (*Photo courtesy of Avia Club, Pokhara*)

cedent, in other words were formed before the rise of the Himalaya, and now cut through the high mountains. All of these antecedent rivers rise around the Mount Kailash region of south-west Tibet. The Indus cuts through the Ladakh, Karakoram, Kohistan and Himalayan ranges flowing through some of the deepest gorges known, between Nanga Parbat (8123m) and Haramosh (7409m) to deposit its erosional load onto the plains of Pakistan and finally into the Arabian Sea. The Yarlung Tsangpo river rises from Kailash and flows for 1700 kilometres east across southern Tibet before plunging through a series of incredible gorges between the Namche Barwa (7756m) and Gyal Peri (7150m) massifs in south-east Tibet. Only 21km separates these two peaks as the lammergeier flies and the river has carved a chasm more than 4km deep between the two.

The third great antecedent river is the Sutlej, which rises from Lake Raksas, south of Kailash, and trickles gently through the barren, dry badlands of Tsaparang in the ancient Kingdom of Guge before abruptly cutting through the Kumaon Himalaya in India.

As the Himalaya began to rise during the Oligocene – Miocene, the mountains effectively dammed many of the early rivers. A huge lake some 300km long and 40km wide was formed around the Tsaparang region. At some point the Sutlej river burst through the Himalaya draining the entire lake into the plains of Punjab. The scattered remains of this great lake can still be seen all around the Tsaparang basin of south-west Tibet.

The Kali Gandaki river carves a gorge more than 5km deep between the peaks of Nilgiri and the Annapurna (8091m) massif and Dhaulagiri (8167m). The Kali Gandaki was dammed by the rising Himalaya to form a lake that backed up all the way north to Mustang and southern Tibet. At some stage this lake also burst, flooding down into the valleys and plains of Nepal. On the trek north from Jomson to Lo Mantang, into Mustang, the flat-lying lake sediments can be seen plastered onto the canyon walls. Similar great floods continue to this day along the Himalaya.

### Seti khola Landslide and Flood, 5 May 2012

In the upper Seti khola, the river that flows between Machapuchare (6993m) and Annapurna IV (7525m), another smaller version of the Kali Gandaki ancient lake is preserved as a 300m thick section of lacustrine sediments sitting above the metamorphosed limestones and marbles of Machapuchare (Fig. 6). These old lake sediments record the former presence of a connecting ridge of rock between Machapuchare and Annapurna IV that dammed the river. The present-day watershed lies north along the connecting ridge between Annapurna III (7555m) and Annapurna IV, the lowest point along which lies at 5400m. At some point, probably thousands of years ago, the lake burst through this rock wall and flowed catastrophically down the Seti valley to flood into the intermontane valley of Pokhara. The Seti river cuts through older flood debris, as the 100m high cliffs of barely consolidated conglomerates on both banks testify. The Pokhara valley shows up to 2000m thickness of flat-lying lake sediments, built up



Fig. 9. Aerial view of the Seti khola in Pokhara, showing the brown mud and debris from the floods after the landslide. (Photo courtesy Avia Club, Pokhara)

over hundreds of thousands of years by floods draining south from the Annapurna massif.

On 5 May 2012 history repeated itself when a huge rockfall broke away from a 300-metre wide section of the summit ridge of Annapurna IV (Fig. 7,8). The debris fell some 3000 metres into the upper reaches of the Seti, falling on top of old, barely consolidated lake sediments and acting as a bulldozer, temporarily damming the gorge. The river outlet was probably only blocked for a matter of 30 minutes, enough time for water to build up to flood. When the blockage was breached, seven or eight waves of fast-flowing mud and water cascaded 20km down the gorge and reached the village of Kharapani at approximately 10.15 am. Twenty minutes later the mudflows reached Pokhara itself (Fig. 9). Several houses in Kharapani were buried under 15m of mud and debris that also reached up to the swing bridge.

The rock avalanche was actually witnessed by Capt. Alexander Maximov of the Avia Club, Pokhara, who was flying over the region at 9am that morning. He was able to alert the air traffic controller in Pokhara,

who then spread the warning on local radio. However, the news failed to reach the remote villages in the Seti. Approximately 72 people died in a series of catastrophic mud flows that swept down the Seti. One week after the disaster brown muddy waters were still flowing down the Seti and into Pokhara. However, compared to the massive catastrophic events in the past geological record, such as the draining of the Tsaparang lake down the Suttlej or the draining of the Mustang lake down the Kali Gandaki, the Seti khola flood was only a minor event.

#### River Incision and Capture

A glance at the topographic map of the Himalaya shows that several major rivers are incising northward through the Himalayan watershed divide. The Arun river in Nepal is now within 10km of breaching through all the way north to the Yarlung Tsangpo river in Tibet. When this breach does occur, in thousands or hundreds of thousands of years' time, an immediate and catastrophic new drainage pattern will suddenly emerge. The Yarlung Tsangpo drainage will cascade south through Nepal and the great gorges of south-eastern Tibet in the Namche Barwa region will be left with a greatly reduced load.

This kind of river capture has occurred in the past on a huge scale. The Yangtze, Mekong and Salween rivers all rise in eastern Tibet. The Yarlung Tsangpo river originally flowed eastward into the Yangtze and drained east into the Yellow Sea. This river was first captured by the Red River, flowing south through North Vietnam into the South China Sea, then by the Mekong, possibly also the Salween flowing into the Andaman Sea, until finally being captured by the Brahmaputra river, flowing south into the Bay of Bengal. The Annapurna IV landslide and the Seti khola flood was just one of thousands or millions of geological events that result eventually in large-scale reorganisation of the Himalayan landscape. Mountains rise and fall. Tectonic forces control the rise of mountains; climate, monsoons, rivers and floods demolish them and remove the debris. Offshore Calcutta, the Bay of Bengal is underlain by approximately 20km thickness of sediment, all of which has been eroded off the central and eastern Himalaya and transported down the Ganges to be dumped in the Bengal Fan. Sediments on the floor of the Indian Ocean as far south as Sri Lanka were derived initially from the high peaks along the Himalaya. In the great Buddhist *thangka* showing the cosmic mandala, the inscription 'impermanence of all existing things' seems particularly appropriate.

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& SILVIO MONDINELLI

## Critical Factors For Himalayan Avalanches

An investigation prompted by the 2012 Manaslu tragedy



Looking up the track of the big Manaslu avalanche of 23 September 2012. Photo taken from the site of where most of camp III was deposited by the avalanche. (*Christian Gobbi*)

**Science allied to experience...** *by Giulio Caresio*

Passion is our great motivator, the irresistible drive that determines most of our steps. I'm thinking of the commitment of alpinists undertaking the most arduous climbs, as well as of my work as editor-in-chief of the Italian magazine *ALP*, and of the strength of all the many people I meet in the mountains whose dedication to their chosen activity stems from loving what they do.

The choice to live and the choice to love are the same thing. This applies to our being in the mountains as well as to the rest of life. Any other choice is to die ahead of our time, to kill our dreams and passions – to give in to one of the worst evils of life: the fear of death.

To love is the way to go further. Surely many of the victims of avalanches,