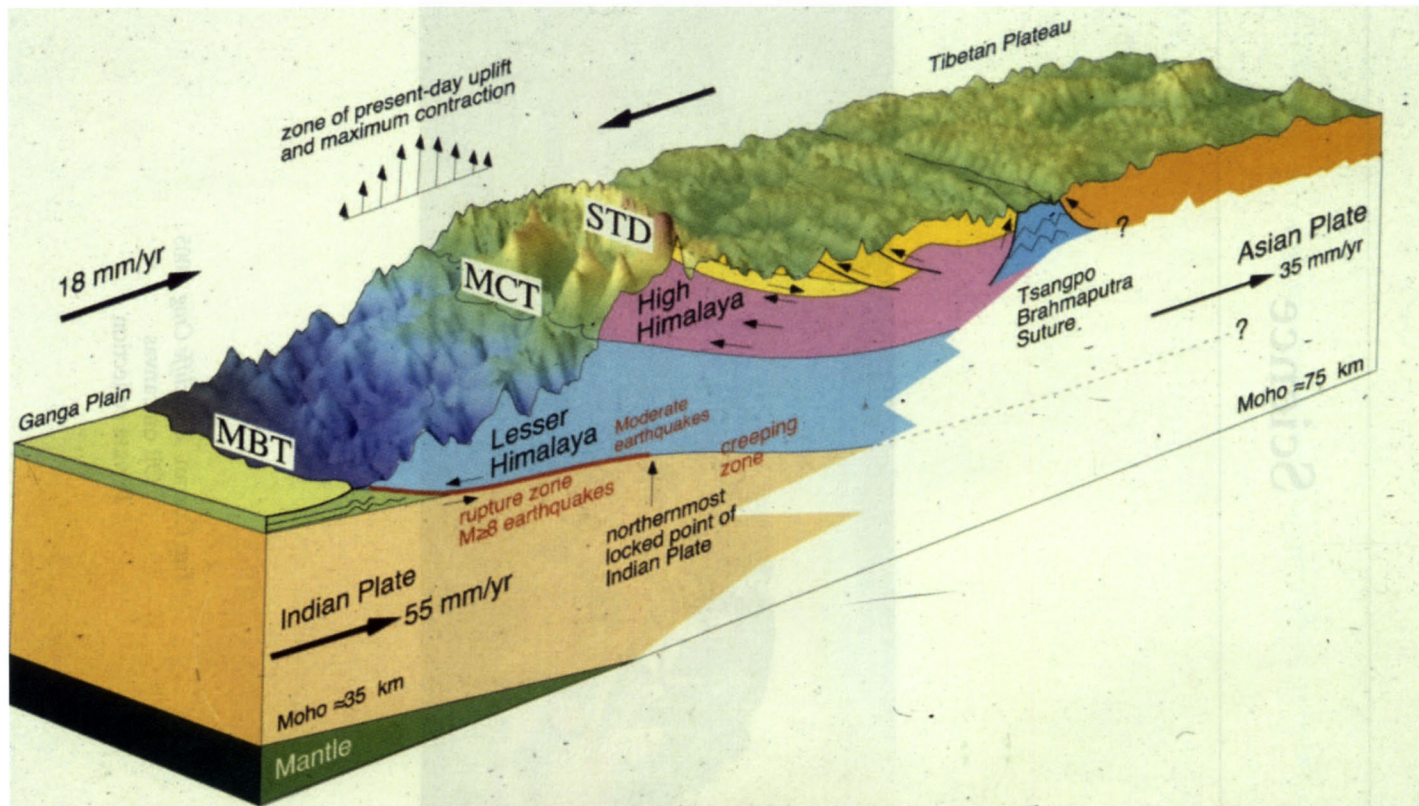

Science



Jim Curran *Almscliffe Crag* 2005
Oil on canvas
Private collection



MIKE SEARLE

Himalayan Granite

Of all the rocks that make mountains, granite has to be the most satisfying. Many of the most beautiful, spectacular, and awe-inspiring mountains are made of granite. Think of the elegant spires of the Trango Towers, the majestic shapely peaks of Shivling, Bhagirathi and Meru, the gleaming orangy granite of Makalu and Chomolongo, the massive great fortresses of Kangchenjunga, Shisha Pangma and Manaslu, to name only a few. Further afield there are of course those iconic monoliths of granite: Cerro Torre, Fitzroy, El Capitan, Half Dome, Huascarán, Huandoy, the Aiguille de Dru. Granite is a rock that crystallized from a magma, or melt, and is composed of the minerals quartz, potassium feldspar and plagioclase. Himalayan granites may also contain red garnets, black tourmalines, glistening white muscovite mica and black biotite micas, as well a whole range of other minerals in minute quantity. Most useful of all these minerals are tiny uranium and thorium-bearing minerals, zircon, monazite, xenotime, allanite that we use for dating granites. Himalayan granites are some of the most intensely radioactive rocks on the planet.

The backbone of the Karakoram range is composed of magnificent pale coloured granite, the Baltoro granites that formed between about 24 and 15 million years ago. The peaks north of the Hispar glacier, the Ogre, the Latoks, Trango Towers, Biale, Masherbrum and the Charakusa and Hushe spires all are made of this young, solid Baltoro granite. Many of the highest peaks along the Himalaya are composed of granites that also formed around 20 million years, some 30 million years after the initial collision of India and Asia. Major episodes of crustal melting therefore occurred both along the southern part of the Asian plate (Karakoram) and along the northern part of the Indian plate (Himalaya). How then did these granite peaks along the Himalaya form?

Origins of the Himalaya

The Himalaya and the great plateau of Tibet were formed as a result of a collision between two continental plates, India and Asia, about 50 million years ago, the like of which the planet had not seen since Precambrian time, more than 480 million years ago. The Indian plate was attached to the East African continental margin and Antarctica until around 140 million

Left

Fig. 1 Block diagram showing the structure of the Himalaya. The active thrust along the southern boundary is the detachment along which India underthrusts the Himalaya and the fault along which active earthquakes occur.



Fig. 2 Himalaya viewed towards west from the space shuttle, with the Tibetan Plateau on the right. (*Photo courtesy of NASA*)

years ago when India and Madagascar rifted apart from Africa. Mid-ocean ridges in the Indian Ocean created new oceanic crust, and ocean floor spreading forced the continental plates apart. The Indian continent became an island and began its northward drift across the Indian Ocean at the enormously high plate tectonic velocity of around 5cm per year.

Roughly 50 million years ago, India collided with the southern margin of Asia somewhere near equatorial latitudes, closing the Tethyan Ocean that lay between them for some 200 million years (from Permian times to the Early Tertiary). The collision slowed India's northward flight down to about 2cm/year, but the spreading centres in the Indian Ocean continued to push India northward, relative to stable northern Eurasia, indenting into Asia as it went. GPS stations across Asia show that India continues to converge with Tibet and Asia and that the Himalaya are still rising today. Earthquakes in the historical record show that India is still underthrusting the Himalaya along the active Main Boundary Thrust, the southern margin of the Himalaya. The 8 October Kashmir earthquake of 2005 was one such event. The earthquake ruptured approximately 100km of the Himalayan

frontal thrust, releasing a huge amount of energy, and the mountains north-east of Muzaffarabad actually rose about one metre during the earthquake. It was 50 million years of earthquakes like this that made the Himalaya.

One has only to look at a satellite image of Asia to see the mountain ranges along the India-Asia collision zone swing around the plate margin, from the Chaman and Sulaiman-Kirthar ranges of western Pakistan up to the Hazara and Nanga Parbat syntaxes, where the mountains swing around along the Himalaya to the knot of mountain ranges around the eastern syntaxis centered on Namche Barwa, where they curve south again along the Indo-Burman ranges and out into the Bay of Bengal and Andaman Sea. The great 26 December 2004 earthquake off northern Sumatra occurred at about 30km depth on this plate boundary as Indian oceanic crust subducted north under the Sumatra-Java island arc. During this single earthquake, the second largest ever recorded, the Indian plate boundary ruptured 1400 km north as far as the Burmese coast. The sea floor rose up to 10 metres in places, an uplift that was responsible for the most devastating tsunami in human history.

North of the Himalaya the Tibetan Plateau is the largest area of high elevation (5023m average elevation) and thick crust (between 60-80km thick) anywhere in the world. Tibet was almost certainly elevated prior to the Indian plate collision, with southern Tibet probably looking something like the present-day Andes. Following the collision, the entire plateau, stretching from the Pamir and Karakoram in the west to the Sichuan basin in the east, from the Kun-Lun and Altyn Tagh ranges in the north to the Himalaya in the south, rose to its present height of 5km above sea-level.

The collision of India with Asia and the uplift of Tibet dramatically altered the topography of Asia. As the Himalaya began to grow, the crust thickened and deeply buried rocks were metamorphosed or changed as a result of the increase in burial depth, pressure and temperature. Most of the Greater Himalayan ranges are composed of metamorphic rocks that were formed at depths between about 50km and 15km and then thrust southward along giant fault planes. Classic metamorphic minerals such as garnet, kyanite and sillimanite were formed as shales changed to schists and gneisses, and limestones changed to marble. The rocks show spectacular ductile folds and evidence of extremely high strain.

Between about 30 and 20 million years ago, the Greater Himalayan rocks reached the highest temperatures in the middle crust around 750°C, and actually started to melt, creating pockets of liquid molten magma within the gneisses. The melts began to flow under extreme strain and interconnected pockets of magma collected into feeder channels (sills and dykes). These sills and dykes transported the liquid granite magma vast distances along the strike, feeding it into larger channels. Eventually these sills reached the Earth's surface and ballooned out into giant intrusions, folding the country rocks around them as they cooled. The granite solidified and the

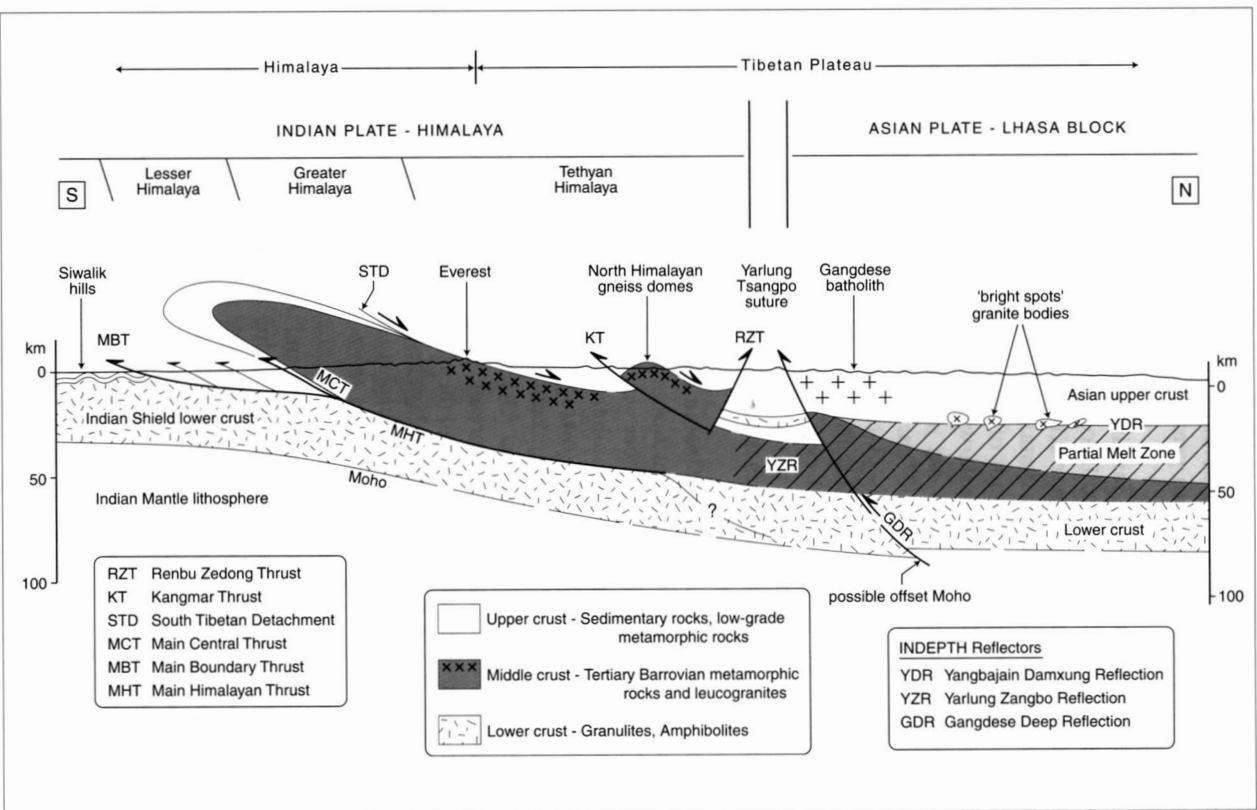


Fig. 3 Model to explain the Channel Flow hypothesis for the southward extrusion of a layer of ductile partially molten rocks from beneath southern Tibet to the Himalaya.

final puffs of gases and liquid magma were ejected out along a network of dykes emanating out from the granite. Some of the finest gems are to be found in these pegmatite dykes, black tourmaline and blue aquamarine to name a few. The south wall of Nuptse shows one of these ballooning sills in the most spectacular three-dimensional form as you walk along the Khumbu glacier towards Everest. This same granite sill can be traced westward into the Cho Oyu region and beyond and eastward to the massive pale granite forming the entire Makalu–Chomolonzo massif.

Geophysical surveys across Tibet

Mapping geological structures across mountain ranges like the Himalaya is painstaking and difficult. Geologists can usually access the valleys and occasionally climb high on some peaks, but much of the terrain remains difficult to access. However, it is only possible to make geological maps and determine the structure of the parts that are exposed. The only way to determine the deep structure of mountain ranges and plateaux is remotely, using geophysical methods, notably seismology. Earthquakes occur when rocks deep in the crust move along faults and spontaneously release energy. Earthquakes release shock waves, which travel along the surface of the earth (surface waves) and cause the ground to vibrate. Shorter period vibrations move through the Earth (body waves) and can be detected by seismometers. The fastest primary waves (P waves) travel at about 6km per second through the crust and somewhat faster between about 8km and 14km per second through the mantle. Secondary waves (S waves) vibrate at right angles to the direction of motion and can only pass through solid material.

Seismic surveys rely on a network of receivers laid out to pick up seismic waves from an energy source on the Earth's surface, usually an explosion of some sort. Various deep crustal seismic surveys have been carried out by Chinese, French, British and US scientists across parts of Tibet, but in the summers of 1994 and 1995 a major survey was initiated called the INDEPTH project (International Deep Profiling of Tibet and the Himalaya).¹ Continental deep seismic surveys are juggernauts of geophysical experimentation. They require large trucks of recording equipment and relatively flat, uninhabited terrain suitable for setting off explosions, both of which are rather hard to find in the Himalaya and south Tibet. The INDEPTH profile found the flattest part of south Tibet to be the large rift valley called the Yadong-Gulu rift, which runs due north of Bhutan, and this is where they laid out the first of a series of north-south seismic lines.

The most prominent feature found on the profile was a large reflector corresponding to the thrust fault called the Main Himalayan Thrust, along which the Indian plate is presently underthrusting the Himalaya and south Tibet. This fault dips gently to the north and runs from the southern margin of the Himalaya, where it reaches the surface. Most of the recent earthquakes in northern India, Nepal and Bhutan have occurred along this fault zone, including the 8 October 2005 Kashmir earthquake. This fault is now the

current plate boundary and earthquakes occur down to depths of 80km as it plunges north beneath the Himalaya.

Another fascinating discovery on the INDEPTH profile was the presence of a mid-crustal zone of high electrical conductivity, determined from magnetotelluric studies. These data indicate the presence of pockets of hot fluids at relatively shallow depths in the crust beneath southern Tibet. Together with the seismic data and the high heat flow measured in lakes of southern Tibet, this seemed to fit the picture emerging of a layer between the depths of about 15 to 20km where the crust was extremely hot, had interconnected pockets of fluid-like material, and was partially molten. Fluids at these temperatures, above 600°C, in this sort of tectonic environment are most likely to be granite melts, similar to the granites seen today along many of the high peaks of the Himalaya. The whole of Tibet is known to have high heat flow, with numerous powerful geysers and hot springs erupting all across the plateau.

The results of the INDEPTH project appeared at first to be a real conundrum. How could the vast plateau of Tibet, the highest elevated mass on Earth, support itself above a layer of partially molten crust with pockets of magma at such shallow depth? The seismic evidence seemed to suggest that the crust was almost layered, so instead of buoyantly rising granite magmas, the only place for this partially molten layer to go was sideways, extruding south to hit the Earth's surface at the High Himalaya, precisely the position where the 20 million-year granites were found.

The reflectors on the seismic profiles could be directly linked to the major faults along the Sikkim-Darjeeling profile and the pockets of magma forming today beneath southern Tibet were on a direct link to the granites that form the high peaks of Kangchenjunga and Jannu.² Maybe the 20-17 million-year-old granites on Kangchenjunga were the older cooled equivalents of the pockets of liquid melt inferred today beneath southern Tibet. It was rather like a honey sandwich, where the upper crust and lower crust were relatively rigid, and a narrow layer of 'mush' in the middle was flowing as a fluid, rather like thick honey or oil. Gravity acting on the sandwich (Tibet) forced the honey to flow out to the side between the buttered sides of the sandwich – the shear zones either side of the High Himalaya range. Surprisingly, the INDEPTH profile showed that the lower crust beneath the partially melted layer was more solid, and therefore interpreted as the old, gneissic and granitic crust of the underthrusting Indian plate.

Geological mapping of Everest

A major geological mapping was initiated in the Everest region both on the Nepal and Tibetan sides in order to constrain the structure of the Himalaya in more detail. During this work many samples were collected for radiometric dating, geochemical and isotopic analysis and thermobarometric analysis in order to constrain the pressure, time and time of

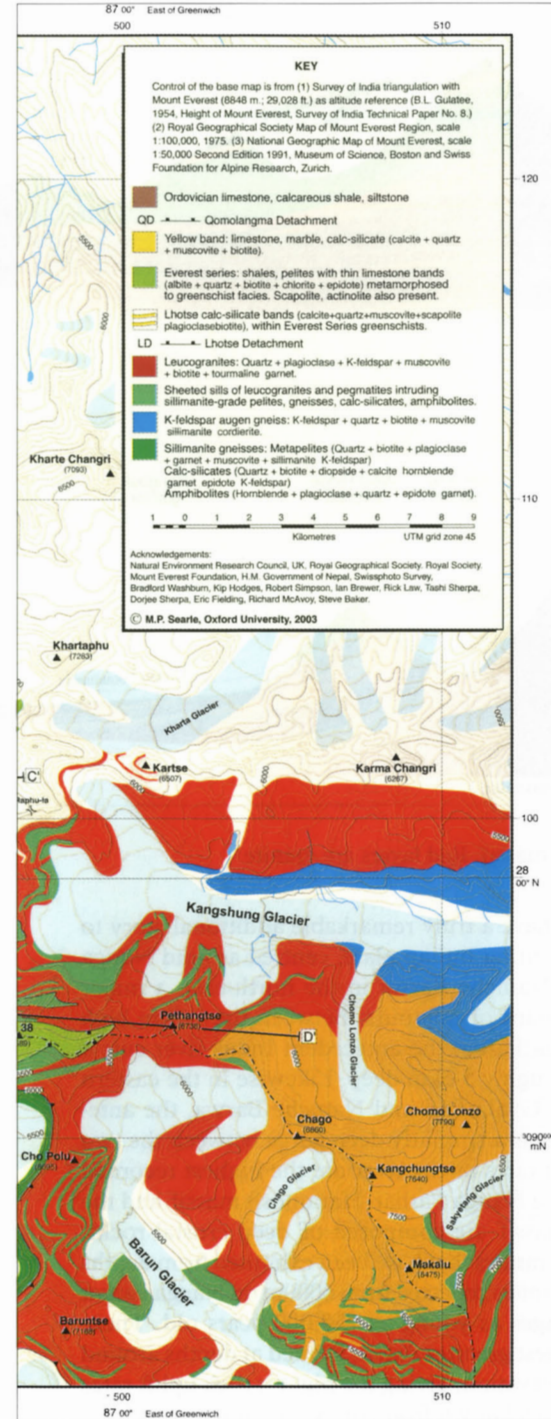
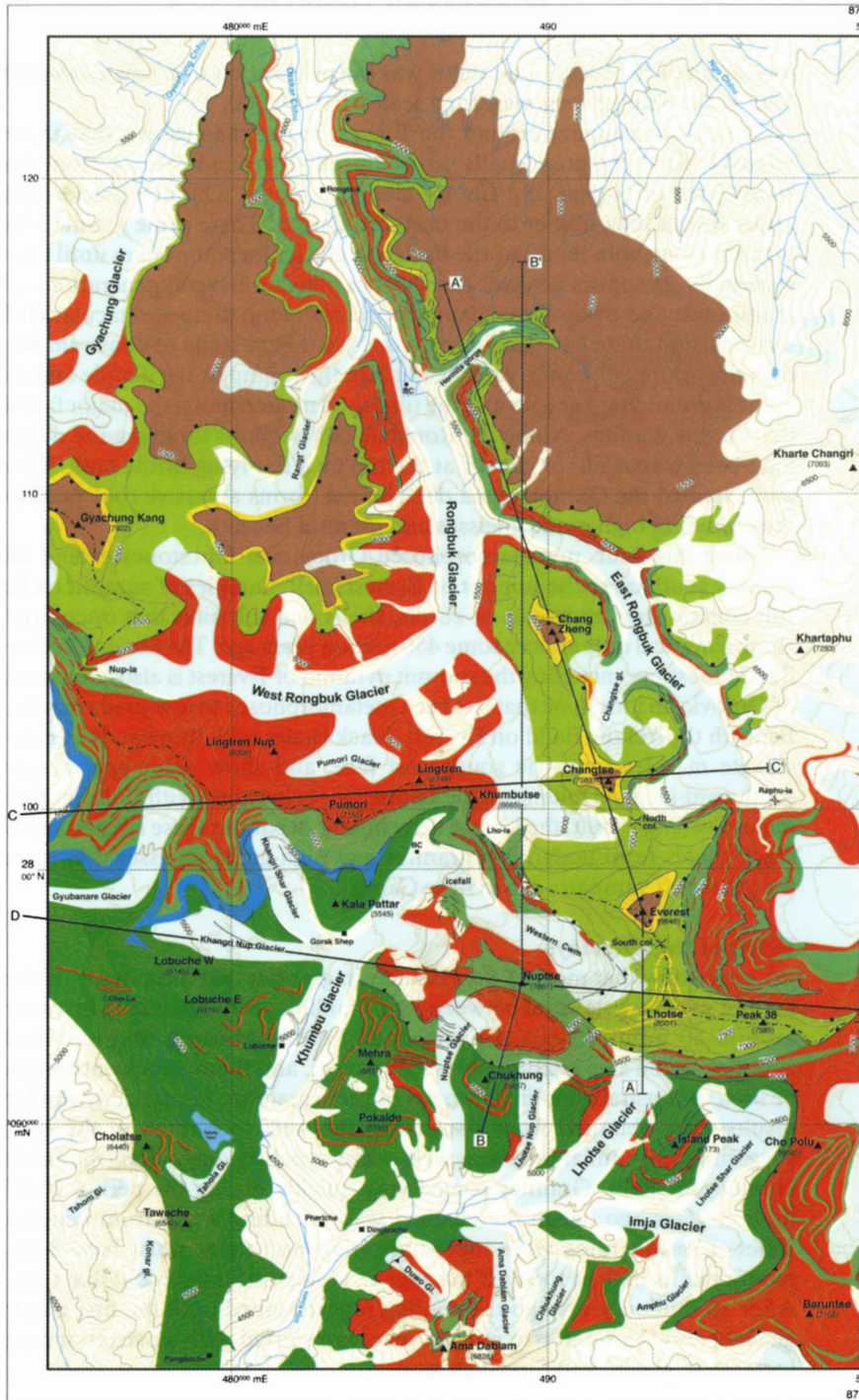
formation of the rocks. One result was the publication of a new *Geological Map of the Mount Everest massif* at a scale of 1:100,000.^{3,4}

Geological mapping around the Everest massif has shown that these relatively flat-lying granite sills can be traced all around Everest, from the south faces of Nuptse and Lhotse along the upper Khumbu glacier and upper Kangshung glacier to the northern flanks.⁴ These same granite sills outcrop along both flanks of the Rongbuk glacier for some 60km until they eventually disappear beneath the Tibetan plateau. Several generations of granite sills and dykes have been mapped out along these spectacular cliff sections, and these have now been dated, so it is possible to constrain not only the timing of granite melting but also the timing of the ductile fabrics in the surrounding gneisses and the timing of motion along the major faults that cut the granites. Along the Rongbuk cliff sections these granite dykes have been truncated, or cut off at the top by a flat-lying brittle fault. This fault, termed the Qomolangma detachment, forms a passive roof fault to the extruding high-grade gneisses and granites beneath.

Above this fault, unmetamorphosed Ordovician limestones extend all the way south up to the summit of Everest itself. Samples of summit rocks still contain tiny fragments of corals, shells and trilobites that once lived along a tropical ocean shore some 450 million years ago. The famous Yellow Band limestone encircling the summit pyramid of Everest is also composed of Ordovician limestone that has been metamorphosed to low-grade marble. Beneath the Yellow Band on Everest, black shales with thin bands of calc-silicate marbles form the south-west face, and show some spectacular southward-inclined folding on the Lhotse face below the South Col. Another major low-angle fault, the Lhotse detachment, separates these Everest series black shales from underlying granites and high-grade gneisses that form the great cliff ramparts above Base Camp.

Uplift of the Himalaya

We now know that most of the Himalayan granites that form many of the highest peaks crystallized between 24-17 million years ago with a hiatus at around 20 million years. Several dating methods using uranium-lead isotopes, argon step heating (⁴⁰Ar/³⁹Ar ratios), and fission track dating can be used to constrain cooling histories of these granites. Remarkably similar results were obtained from Zaskar in the west to Bhutan in the east, suggesting that similar processes were acting synchronously along the entire Himalayan chain. Granites cooled very quickly during the period 20-17 million years ago, when the channel was extruding south from beneath Tibet. Erosion rates were incredibly high and there must have been mountains as high as today, if not higher, along the Himalaya at that time. After 16 million years ago the cooling rates declined until the first major glacial periods around two million years ago started with a corresponding increase in glacial and fluvial erosion.



KEY

Control of the base map is from (1) Survey of India triangulation with Mount Everest (8848 m : 29,028 ft.) as altitude reference (B.L. Gulatte, 1954, Height of Mount Everest, Survey of India Technical Paper No. 8.) (2) Royal Geographical Society Map of Mount Everest Region, scale 1:100,000, 1975. (3) National Geographic Map of Mount Everest, scale 1:50,000 Second Edition 1991, Museum of Science, Boston and Swiss Foundation for Alpine Research, Zurich.

- Ordovician limestone, calcareous shale, siltstone
- Gomolangma Detachment
- Yellow band: limestone, marble, calc-silicate (calcite + quartz + muscovite + biotite)
- Everest series: shales, pelites with thin limestone bands (calcite + quartz + biotite + chlorite + epidote) metamorphosed to greenschist facies. Scapolite, actinolite also present.
- Lhotse calc-silicate bands (calcite+quartz+muscovite+scapolite plagioclase/biotite), within Everest Series greenschists.
- Lhotse Detachment
- Leucogranites: Quartz + plagioclase + K-feldspar + muscovite + biotite + tourmaline garnet.
- Sheeted sills of leucogranites and pegmatites intruding sillimanite-grade pelites, gneisses, calc-silicates, amphibolites.
- K-feldspar augen gneiss: K-feldspar + quartz + biotite + muscovite sillimanite cordierite.
- Sillimanite gneisses: Metapelites (Quartz + biotite + plagioclase + garnet + muscovite + sillimanite, K-feldspar)
- Calc-silicates (Quartz + biotite + diopside + calcite hornblende garnet epidote K-feldspar)
- Amphibolites (Hornblende + plagioclase + quartz + epidote garnet).

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Kilometres UTM grid zone 45

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Fig. 4 Geological Map of the Mount Everest area.

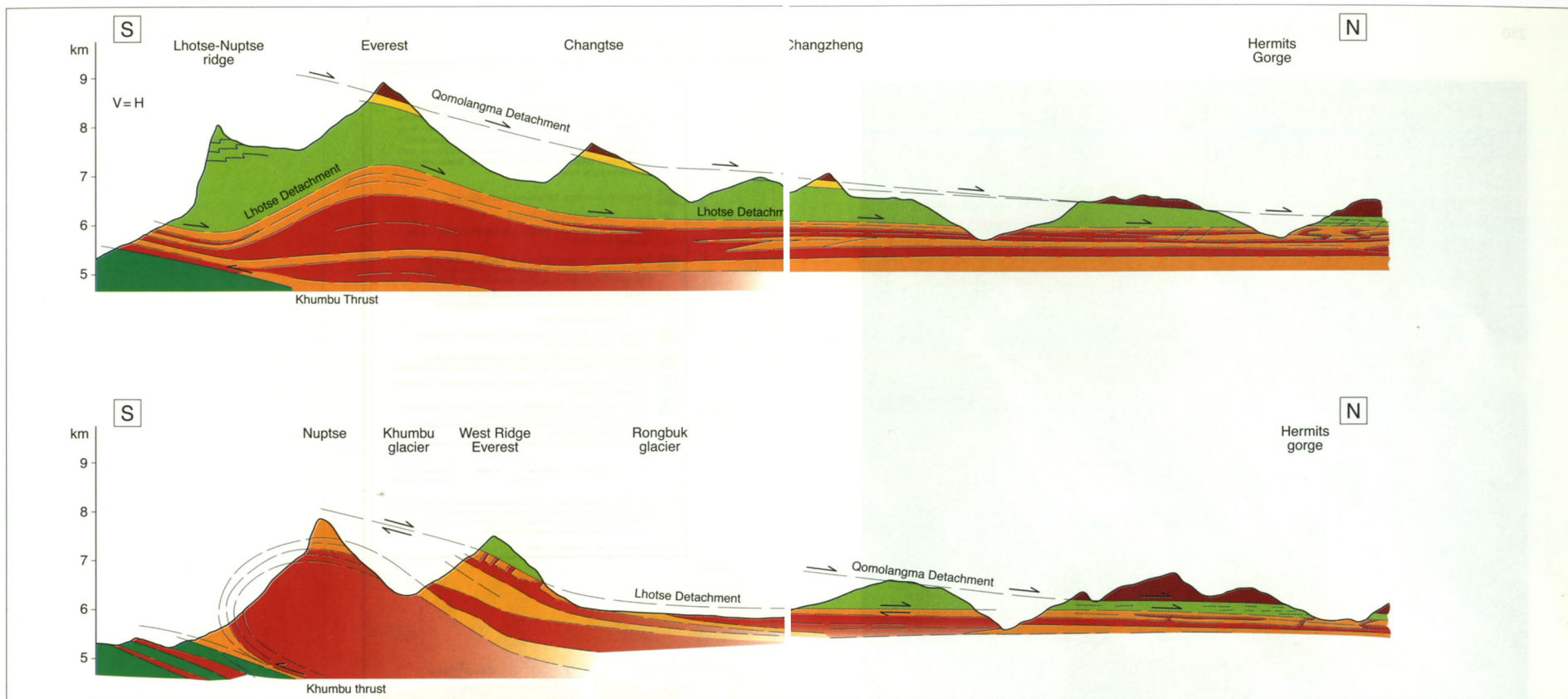


Fig. 5 Cross-sections of the Everest massif. Red layers are granite.

Two areas of the Himalaya have a truly remarkable additional story to tell. At each corner of the indenting Indian plate, centred around Nanga Parbat in the north-west and Namche Barwa in the north-east, a major knot of mountains creates a chaos of contours. Between the 7-8km high peaks of Haramosh and Nanga Parbat the antecedent Indus river cuts a gorge through the Himalaya roughly 5-6km deep. Likewise in the eastern syntaxis between the peaks of Gyala Peri and Namche Barwa, the antecedent Yarlung Tsangpo river cuts a similarly deep gorge between the two mountains. Uplift and incision rates of the river are the highest recorded anywhere in the world. Both the Nanga Parbat-Haramosh massif and the Namche Barwa-Gyala Peri massif are composed of deep crustal rocks, gneisses, migmatites and leucogranites that have been exhumed from depths of 30km or more. Samples of granites collected from 6000m on Nanga Parbat have been precisely dated at ages as young as 750,000 years old. These Quaternary granites, the youngest granites dated, formed at depths around 25-30km and are now at 6km elevation, giving the highest rock uplift rates and the highest exhumation rates known from anywhere in the world.

Climatic consequences of Himalaya-Tibet uplift

The uplift of the Himalaya and particularly Tibet affected not only the topography of Asia but also the climate of the northern hemisphere if not the entire world. Due to the Coriolis affect, or the spin of the Earth, the northern hemisphere has a dominant wind flow direction of west to east. The Tibetan plateau was suddenly thrust up into the troposphere, blocking the easterly flowing jet stream. A large high-pressure system sits over the high plateau during the summer months with lows sitting over northern India. This has the effect of sucking in the warm, moist air over the Indian Ocean which is drawn north across the sub-continent. As soon as these moisture-laden clouds reach land they dump their load over India giving the life-giving monsoon rains to India. The ground-hugging monsoon rains lash the southern slopes of the Himalaya but rarely rise over the highest peaks to the dry, arid landscape of Tibet. Heavy monsoon rains result in increased erosion. The Greater Himalaya suffers extreme erosion whereas erosion rates on the arid and relatively flat Tibet plateau are very low. It is clear that tectonic forces created the Himalaya and Tibet, climatic



144. The Rakhiot face of Nanga Parbat (8125m). (*Mike Searle*)



145. The gleaming granite of Makalu (8463m), one of the most stunning, scenically beautiful mountains on the planet. (Mike Searle)

consequences followed and now each process feeds off each other to keep the whole tectonic-climate cycle going. The high granite peaks of the Himalaya however, provide not only a geophysical-geological link from Tibet to the Himalaya, but they also provide us with some of best climbing in the world, and certainly some of the most stunning, scenically beautiful mountains on the planet.

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