The Geological Exploration of Tibet and the Himalaya

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(Plates 15–18)

The Great Himalaya stretches for nearly 3000km in an arc from Namcha Barwa to Nanga Parbat, forming the southern rampart of the Tibetan Plateau (figure 1). Before the second half of this century, the British Raj was the political power of the southern Himalaya, whereas to the north an independent Tibet controlled the trade routes. Today the world's highest mountain range spans the boundaries of five sovereign states, China, India, Pakistan, Nepal and Bhutan. It is the complex politics of the region during the past 40 years, as much as the forbidding terrain, that has determined the geological exploration of the region. Even today, intertribal disputes in Sikkim and Assam, the everlasting Indo-Pakistan hostilities over Kashmir, and the disputed frontiers between India and China east of Bhutan, leave very little of the Himalaya accessible to scientific expeditions.

Although the first tentative explorations of Tibet by European travellers began in the 17th century, it was not until the 19th century that systematic exploration of Tibet's geography began. By this time, interest in Tibet was precipitated by the mutual distrust between the British and Russian empires. The Survey of India recruited agents, later to become known as Pundits, from

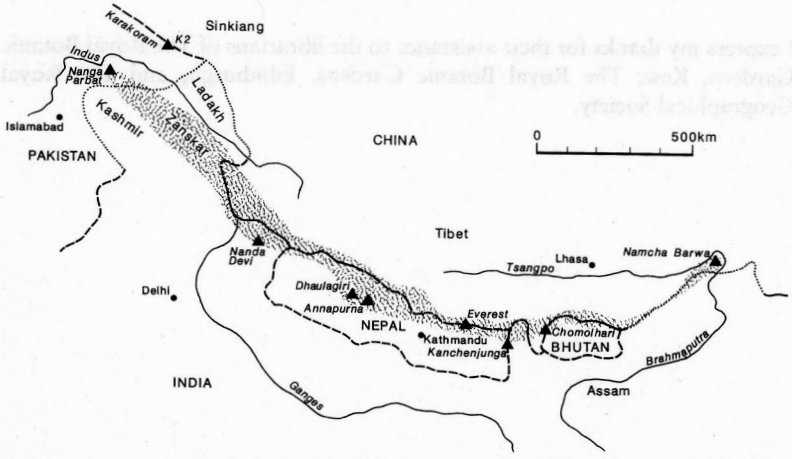


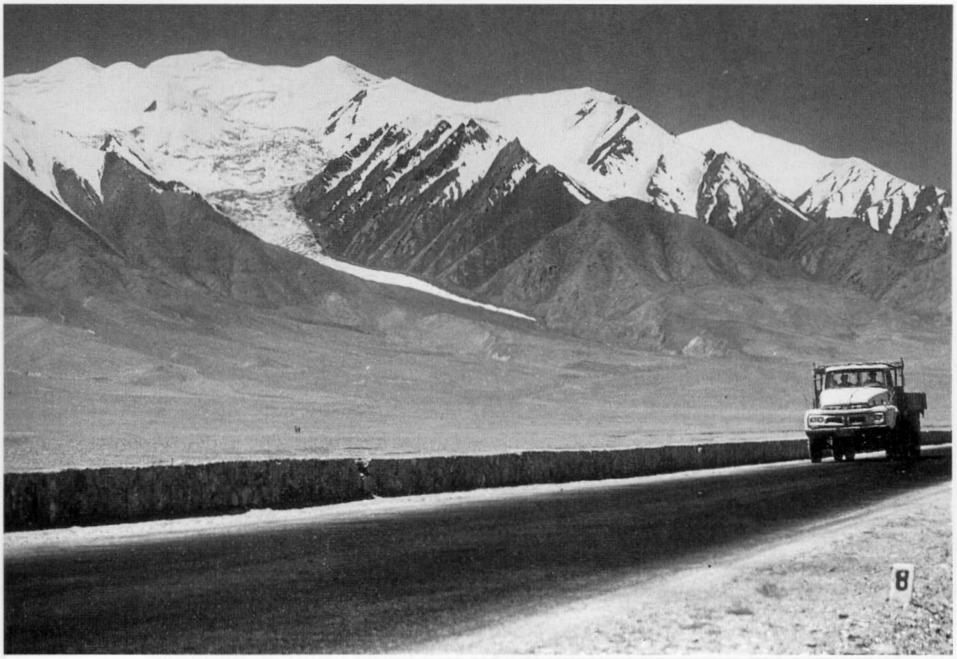
Figure 1. The geopolitics of the Himalaya (stippled). Disputed de facto *national boundaries are marked as dotted lines.*



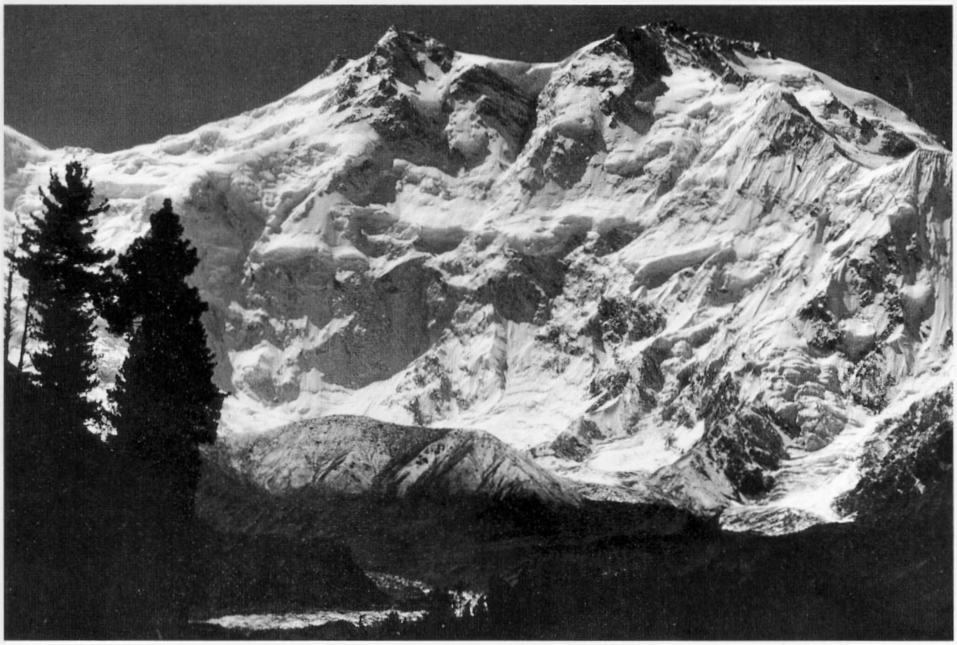
17. The Tibet Plateau. Tibet is not a northward continuation of the Himalaya but a rugged plateau that is still being uplifted, bounded by the Himalaya to the south and the Kunlun (seen in the distance) to the north. (Nigel Harris) (p 68)



18. Fans of detritus eroded from the rapidly uplifted Karakoram range. (Nigel Harris) (p 68)



15. The Kunlun Fault, northern Tibet. The Golmud-Lhasa Highway follows the line of a major strike-slip fault that allows the crust beneath Tibet to be displaced to the east. (Nigel Harris) (p 68)



16. Nanga Parbat, northern Pakistan. The western bastion and most active mountain of the Himalayan range is being uplifted by nearly 1cm each year. (Nigel Harris) (p 68)

the eastern Himalayan tribes to explore Tibet as systematically as possible, given its rugged topography and the suspicious Tibetan authorities. Pace and compass techniques were used to measure distances (the Pundits were often disguised as monks and prayer beads served to keep track of large distances), and altitudes were estimated from the boiling-point of water. Their results have proved to be remarkably accurate. In 1882 a Pundit known as AK (like all true secret agents, Pundits were identified by initials only) measured the altitude of Lhasa as 11,910ft; this compares with the correct value of 11,970ft (3650m).

The geographical exploration of the Himalaya and southern Tibet identified geological problems that remained unresolved for over a century. Tibet was established as a plateau, 2000km across from south to north, that rarely drops below 3000m above sea level (figure 2). Such a vast and high plateau is unique on this planet, although there are some similarities with the altiplano of the Andes, and it demands a geological explanation for its uplift. Another observation made by the early explorers is that the Himalaya is not a watershed; several major rivers, including the Tsangpo which emerges in Assam as the Brahmaputra, rise in Tibet and cut through the Himalaya through a spectacular series of gorges. The observation that major rivers cut through a mountain range is unusual; it is true neither of the Andes nor of the Alps, and it implies that the rivers first flowed before the mountains were there. As uplift occurred, the rivers increased in potential energy and cut through the incipient hills, forming deep gorges. This is only possible in young active mountain ranges.

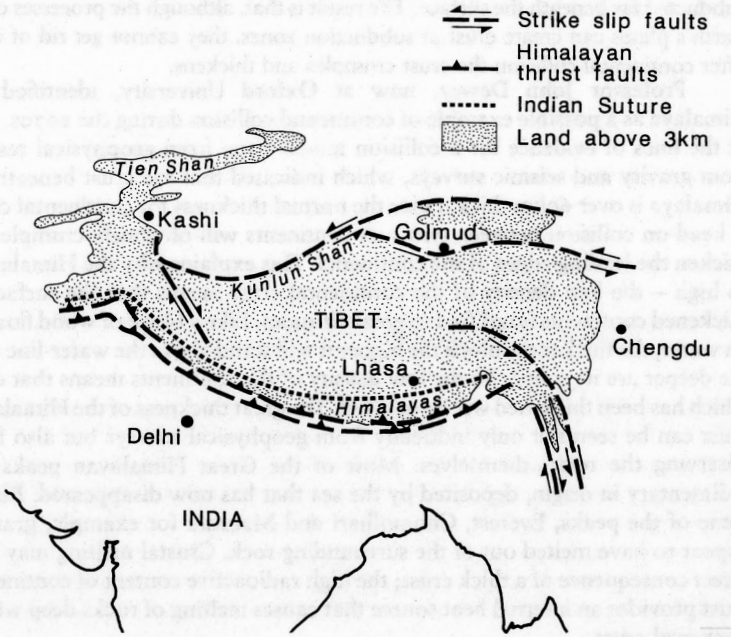


Figure 2. The structure of the Tibetan Plateau.

In some ways the geological exploration of Central Asia during the second half of this century has mirrored the geographical exploration of the last century. Although most of the Himalaya and Tibet have been inaccessible to scientific study until recently, select regions of the southern Himalayan slopes have been surveyed by geologists for much longer. The most detailed area of geological study has been in the western Himalaya of northern Pakistan, the same region that had been surveyed by Colonel Alexander Gardiner in the first half of the 19th century. It was here that in 1964 Augusto Gansser, the distinguished Swiss geologist and Himalayan explorer, discovered fragments of oceanic crust near the Indus river. But like the European explorers of the previous century, western scientists had to stay on the southern Himalayan slopes. Tibet was off-limits until about a decade ago.

Modern understanding of the geology of the highest mountains on Earth really began with the exploration of the ocean floor and the formulation of the theory of plate tectonics about a century after the early expeditions of the Pundits. Since the early 1960s, earth scientists have realized that oceans were transient features, growing from sinuous volcanic ridges such as the mid-Atlantic ridge; these are largely submarine but occasionally form spectacular volcanic islands, such as Iceland today. Oceans not only grow but also shrink, due to a process called subduction, and in the contraction of ocean basins the continents on their opposing sides converge. The final stage of this process is collision between two continents. Continental crust is less dense than oceanic crust, and much less dense than the mantle beneath it. The low density means that continents cannot be subducted far beneath the surface. The result is that, although the processes of the Earth's plates can create crust at subduction zones, they cannot get rid of it. So after continental collision the crust crumples and thickens.

Professor John Dewey, now at Oxford University, identified the Himalaya as a possible example of continental collision during the 1970s. One of the lines of evidence for a collision model came from geophysical results, from gravity and seismic surveys, which indicated that the crust beneath the Himalaya is over 60km thick, twice the normal thickness for continental crust. A head-on collision between two vast continents will obviously crumple and thicken the leading edges of the continents. This explains why the Himalaya is so high – the low density of the continental crust means that the surface of thickened continents is uplifted to great altitudes. Like a block of wood floating on water, the thicker the block the higher it will stand above the water-line (and the deeper are its roots). So the low density of the continents means that crust which has been thickened will be uplifted. The great thickness of the Himalayan crust can be seen not only indirectly from geophysical surveys but also from observing the rocks themselves. Most of the Great Himalayan peaks are sedimentary in origin, deposited by the sea that has now disappeared. But on some of the peaks, Everest, Chomolhari and Manaslu for example, granites appear to have melted out of the surrounding rock. Crustal melting may be a direct consequence of a thick crust; the high radioactive content of continental crust provides an internal heat source that causes melting of rocks deep within thickened crust.

Earth scientists have also traced the movement of India before its impact

with the rest of Asia. About 100 million years ago, India lay in the southern hemisphere where it fragmented from a vast southern landmass, rifting from Madagascar along its western coast and from Antarctica along its eastern coast. India drifted north at a velocity of about 20cm per year. Impact with the rest of Asia occurred 50 million years ago. The fragments of oceanic crust found by Augusto Gansser in the Indus valley are the remains of a vast ocean floor which was folded and crumpled within the suture zone that now separates the former continental masses.

This simple model of collision between two continents explains the formation of a narrow high mountain range such as the Himalaya, but does not obviously explain the Tibetan Plateau. Like the Himalaya, Tibet is supported by an unusually thick crust. A related problem is the continued northern movement of India. Since the initial collision the two continents have not simply fused into a single supercontinent. India and the rest of Asia have continued to converge at an average rate of 5cm a year, amounting to over 2000km since the ocean was first closed by subduction. Three models have been proposed to account for such a staggering convergence between continents in the absence of an intervening ocean.

Firstly, the crust can be squeezed out sideways. The idea was first put forward in 1975 by Peter Molnar of MIT and Paul Tapponier of the University of Paris. On satellite images they spotted long faults dissecting the Earth's crust in northern, eastern and western Tibet. From analysing the seismic waves associated with earthquake activity that result from movement along the faults they determined that the Earth's crust is moving sideways across them. Such faults are called strike-slip faults (figure 2). The Molnar–Tapponier model for crustal deformation in Tibet predicts that movement across these strike-slip faults allows wedges of continent to move out sideways, particularly to the east, clearing the path of the converging continents.

Secondly, the Indian crust may be thrust under Tibet by a series of faults which dip towards the north; such faults which result from compression of the crust are known as thrust-faults (figure 2). Field-work in the Himalaya has identified a series of such faults. The devastating earthquakes that plague the lives of inhabitants along the southern slopes of the Himalaya result from movement along these thrust-faults. Although no single fault carries a slice of continental crust more than a few tens of kilometres beneath another, their combined effect is to thicken up the crust. Some mountains owe their altitude to movement on such faults. Nanga Parbat, for example, is an extraordinary mountain in that it is a long way from any other 8000-metre Himalayan peak and stands proud of its neighbours by several thousand metres. This is partly because it lies on a finger of the Indian plate which points north into the Asian landmass, and is riding upwards on thrust-faults to the north, east and west.

A third theory for the mechanism of India's northward movement suggests that the crust may shorten by stretching vertically, as a piece of plasticine is lengthened when squashed from the side. The vertical stretching model is not needed in the Himalaya because much of the convergence can be explained by the major thrust-faults, but it could account for crustal shortening across the Tibetan Plateau.

By the beginning of the 1980s the broad-brush geology of the Himalaya was known from geological exploration, but Tibet itself was known to the West only from satellite images, and from occasional samples retrieved by 19th-century explorers (John Dewey's early papers on continental collision in the Himalaya cited evidence for recent volcanic activity within Tibet from samples collected in 1916 by the Swedish explorer Sven Hedin). The reasons for Tibet's inaccessibility have changed through time. Until this century the Himalaya was largely successful in protecting Tibet from visitors from the south, and the hostile plateau protected it from visitors from the north. Tibet's geography, however, could not maintain its isolation for ever. A brief incursion to Lhasa by a British military expedition in 1903 marked the beginning of Tibet's brutal acquaintance with modern life. The British mission did not stay long, partly because the fears of Russian influence in Tibet proved to be groundless, but in 1951 Lhasa was again occupied, this time by the Chinese. Since then Tibet has been incorporated into China and governed from Beijing as an Autonomous Region of the People's Republic of China. Over the past 40 years, entry to Tibet for scientists and mountaineers alike has depended on international relations between China and the West.

The first major international geological expedition to Tibet was a Sino-French study of southern Tibet from 1980 to 1983. This established the details of the northern boundary of the Indian plate which follows the Tsangpo (Brahmaputra) river along much of its length. A trail of oceanic fragments has now been traced over 2000km from northern Pakistan to south-east Tibet which marks the suture between India and Eurasia (figure 2). At about the same time an expedition across Tibet was conceived, jointly funded by Academia Sinica in Beijing and the Royal Society and led by Professor Robert Shackleton of the Open University and Professor Chang Chenfa of Academia Sinica. The geotraverse team was made up of 22 Chinese and western earth scientists. During 1985 they surveyed over 1700km of the plateau from Lhasa to the town of Golmud on the edge of the deserts of Central Asia. Results from this study draw together evidence from palaeomagnetism, palaeontology, sedimentology and geochronology for the movement of the tectonic plates that make up Tibet. They indicate that there was no single collision 50 million years ago, and several earlier collisions have now been identified. The Kunlun mountains of northern Tibet, for example, saw a continental collision 300 million years ago, and since that time at least two distinct collisions have occurred before the final convergence of India. Because of inclement weather and minor accidents one of these possible collision zones was never visited by the geotraverse team, but two years later a group of second-year geological students from Cambridge found their way to this remote spot in central Tibet and returned with both samples and a geological map. The age of amateur scientific exploration is not quite dead.

Results from the geotraverse expedition also help to unravel the way in which the Tibetan crust has been uplifted and thickened. The expedition found little sign of active or recent thrusting across the Tibetan Plateau, in strong contrast to the Himalaya. An erosion surface that planes off the peaks of many of the mountain ranges of central Tibet was found to be at least 10 million years

old and yet virtually undeformed; this rules out strong folding in the recent history of the Tibetan crust. Field evidence therefore argued against internal shortening of the Tibetan crust by folding or faulting.

Geologists have also been able to make some deductions about the timing of uplift of the plateau. Measuring uplift is not easy; there are three principal methods, none without its problems. Firstly, fossil plants can indicate the approximate surface altitude at which they grew. Chinese palaeontologists working in Tibet have identified a switch from sub-tropical to alpine flora about 25 million years ago. Secondly, geomorphology can provide evidence for rapid uplift periods, particularly from deeply eroded river terraces. Thirdly, a recently developed technique called fission-track dating allows an estimate to be made of the rate at which rocks have reached the surface of the crust based on the preservation of microscopic tracks left by nuclear fission. Fission-track data indicate that in the Himalaya Nanga Parbat is being uplifted very rapidly, about 7mm a year, almost double the uplift rate for most of the Himalaya. Combination of results from all three techniques indicates that Tibet has been uplifted in two distinct phases. Initially it was uplifted relatively slowly to an altitude of about 3000m, reached earlier than about 25 million years ago. Subsequently it was uplifted to its present average altitude (5000m) during a period of very rapid uplift over the past five million years. Interestingly, the period of most rapid uplift is a period of little internal deformation of the plateau.

This two-stage uplift history fits what is now known about the geophysics of colliding continents. Collision will thicken up both the crust and part of the upper mantle beneath, known together as the lithosphere, but this process cannot go on indefinitely. The thermal structure of the underlying mantle places an upper limit on how thick the lithosphere can become. In time the base of the thickened lithosphere will heat up and will effectively be absorbed by the convecting layer underneath it. In other words, the lower and denser part of the lithosphere will be removed through thermal processes. The result is rapid uplift, known as isostatic rebound. Application of this model to Tibet shows that crustal thickening more than 25 million years ago was largely from vertical stretching of the lithosphere, and the more recent period of rapid uplift results from the rebound caused by dropping off the lower, denser part of the lithosphere.

In retrospect it appears that the international scientific expeditions to Tibet during the first half of the 1980s were made possible by a brief rapprochement between China and the West, and by an easing of Chinese military rule in Tibet. Even before the Beijing massacre in 1989, martial law in Lhasa had been reimposed by the Chinese military to control civil unrest. Most of what western geologists know about the geology of central and northern Tibet results from a single north-south traverse, coupled with interpretation of satellite imagery. There is much work still to be done in understanding the best example of continental collision on Earth, and although the construction of major roads across both central Tibet (the Lhasa–Golmud Highway) and the western Himalaya (the Karakoram Highway) has simplified the logistics of geological exploration, the geopolitical problems of Central Asia are probably more intractable now than they were in the 19th century.

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