Geology and Geography of Tibet and Western China

Pete Winn, Science Director
Earth Science Expeditions

Send comments to: peterwinn@gmail.com

(Links from this page are at the end of the page.)

You can begin reading while this file is loading. A geological background not essential.

This summary is divided into six sections:

Geoscience in China

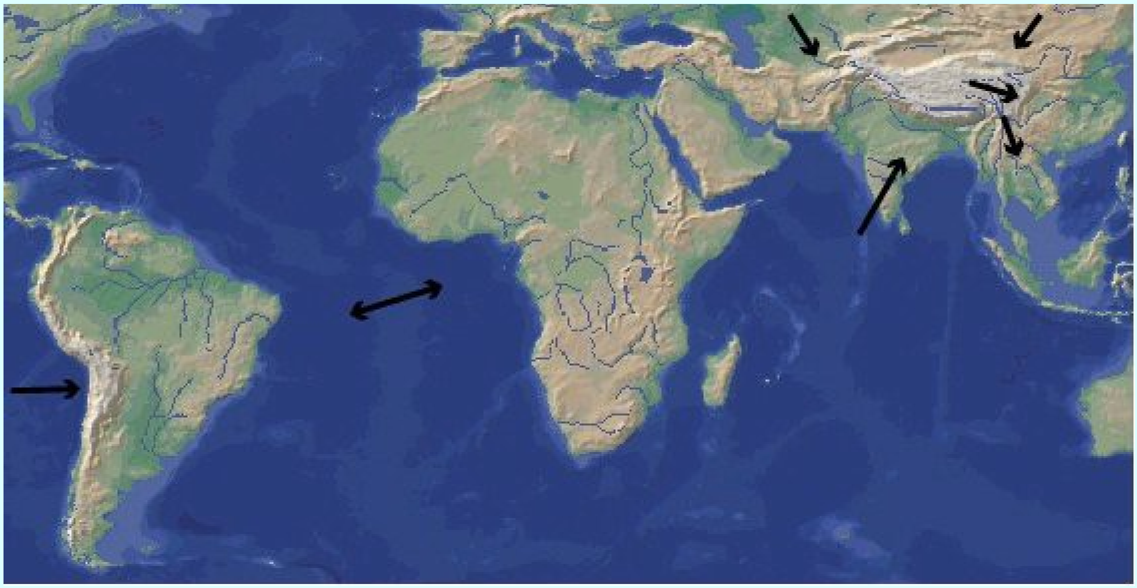
During the 1960's, the theory of plate tectonics gained world-wide acceptance - except in China. The theory proposed that large sections of the earth's crust, called plates, moved relative to each other, producing major topographic features such as the Rocky Mountains and the Andes. Earthquakes occurred at plate boundaries such as the San Andreas Fault or on zones of discontinuity within a plate as it moved.

While the plate tectonics revolution was occurring in the West, universities in China were closed. Most of the Chinese geoscientists who could apply the newly developing theory to the highly active fault systems of Tibet and western China were out of work for over a decade. Furthermore, China had been closed to foreigners since 1949, so western geoscientists were forced to evaluate their ideas about the geology of China using data from remote instruments such as satellite photographs and seismographs.

Prior to the Cultural Revolution, Chinese geoscientists, in particular paleontologists and geomorphologists, had a worldwide reputation for the high quality of their work. In the late 1800's, the works of several European geologists were translated into Chinese, and European geologists began to visit China for cooperative study. The first geology college was established in China in 1912, and their National Geological Survey was founded in 1916. In 1922 the Geological Society of China was formed. Unfortunately, from then until 1949, China was at war, both with the Japanese and with itself, so geology was a low priority.

With the exception of foreign publications by geographer, botanist and anthropologist Joseph Rock and geologists J.W. and C.J. Gregory in the 1920's and geologists Peter Misch and Arnold Heim in the 1940's, not much about the geology of China was published outside of China until the 1970's. However, as soon as Mao Zedong gained control in 1949, he realized that China badly needed raw materials for industry. Mao emphasized geology to the extent that, in spite of the dark ages during the Cultural Revolution, today there are over 50 geology colleges, over 80,000 professional geoscientists, and the Geological Society of China has 40,000 members. In the late 1970's, many of their studies became available for use by foreign scientists.

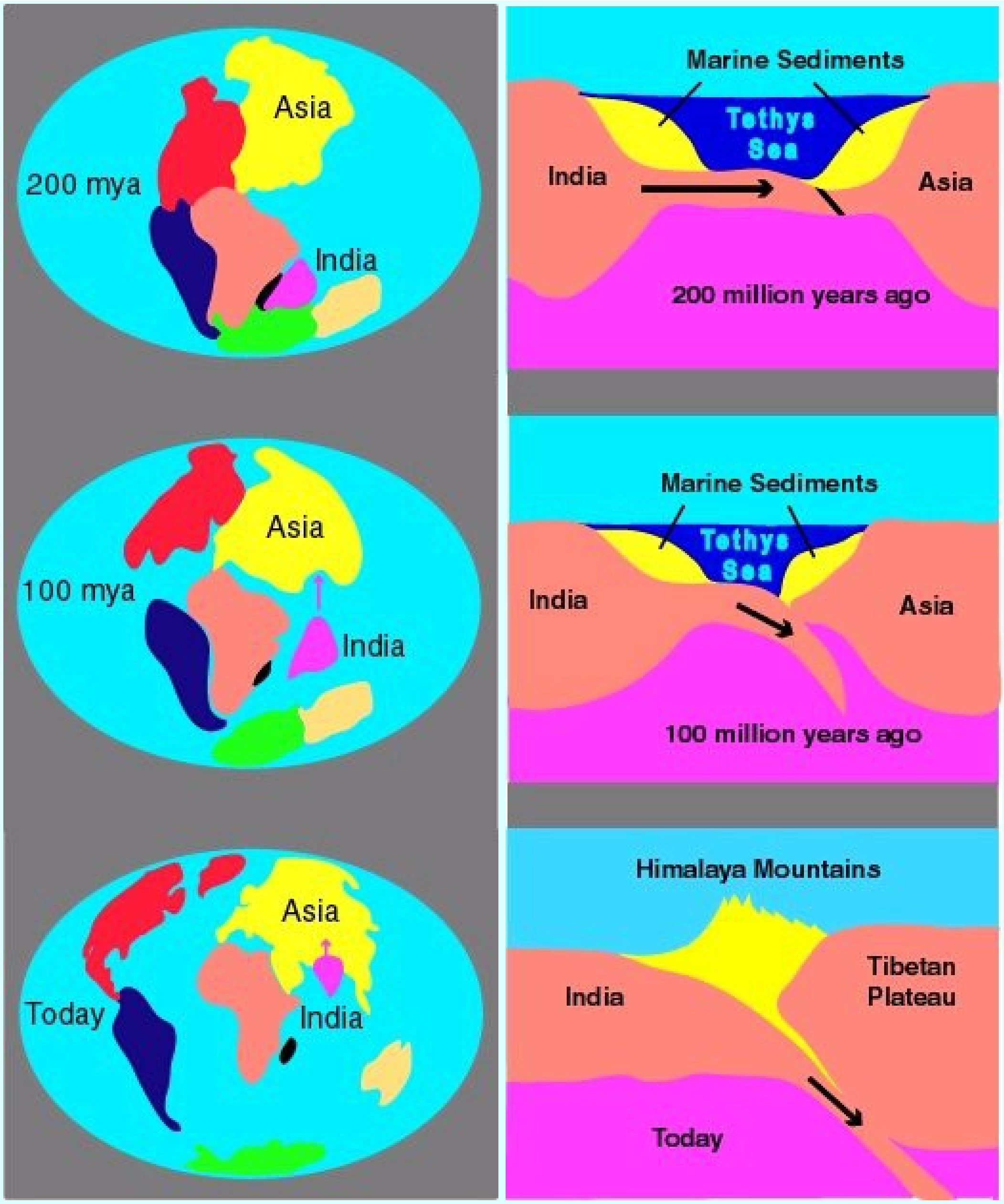
Since the Cultural Revolution ended, Chinese geoscientists have made significant progress in understanding and applying plate tectonic theory. The Chinese government has encouraged students to study at major universities in the US and Europe, and there are now more Chinese students in the US than any other foreign nationality. It has also encouraged foreign scientists to participate in cooperative studies with Chinese scientists.



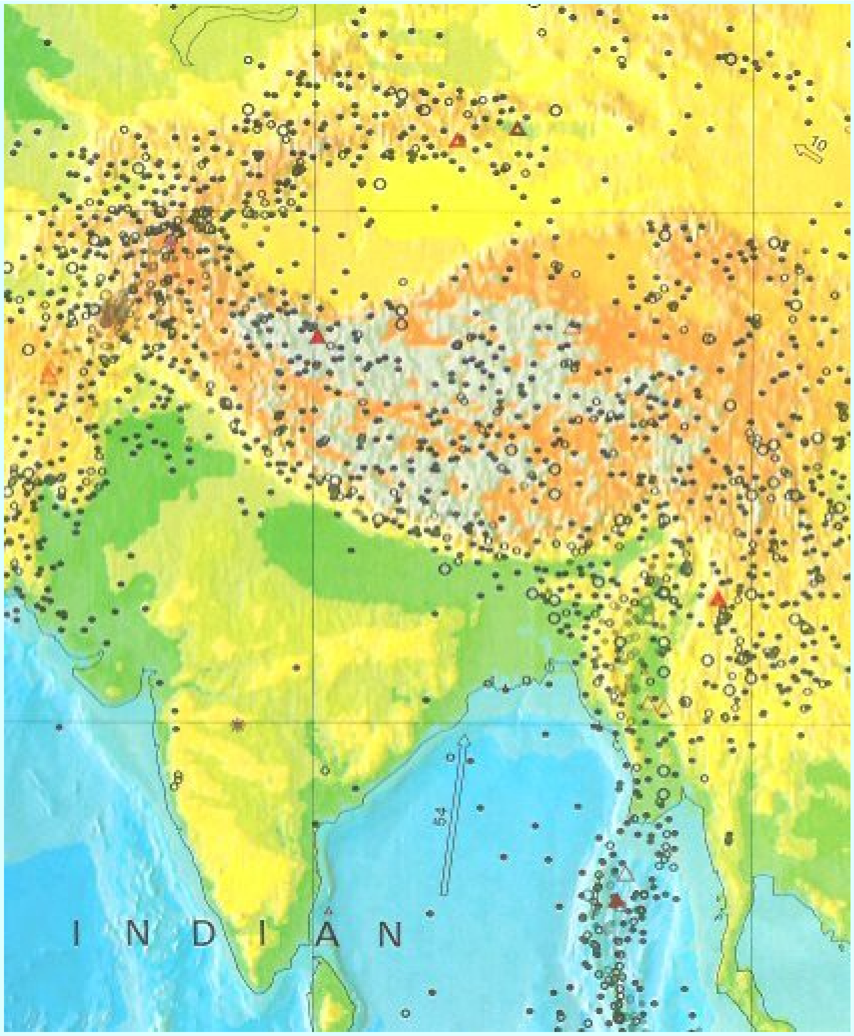
India's Collision with Asia

Almost anyone who enjoys jigsaw puzzles can look at the globe and see that South America and Africa fit together. Plate tectonics theory explains how they separated, based on data from the Atlantic Ocean floor. The ocean floor is the same age at the edge of both continents, and gets younger toward the middle. In the middle of the ocean there is a ridge where lava periodically wells up and forms new ocean floor, as the two continents slowly spread further and further apart.

Since it doesn't appear that the earth is getting larger, crustal rocks must be destroyed somewhere else at the same rate they are being produced in spreading centers. On the Pacific side of South America, this is just what appears to be happening. Pacific Ocean crust is being subducted beneath South America, causing big earthquakes, and it melts as it plunges into the hot mantle, forming the huge volcanoes characteristic of the Andes Mountains. The theory works just fine here.



The theory must also explain the high frequency of large earthquakes and the massive topographic features of Tibet and surrounding areas. We know there are marine fossils at the top of Mt. Everest, and the Tibetan Plateau is so large and so high it is sometimes called the Third Pole due to its affect on global climate. Several studies in the early 1970's suggested that the plate carrying India separated from Antarctica at about the same time South America and Africa separated, nearly 200 million years ago. India then moved north, closing the Tethys Sea, and about 55 million years ago it began to collide with Asia at the geologically high rate of about two inches per year, causing frequent large earthquakes between India and Tibet and throughout Tibet and surrounding areas as shown by circles and dots on the following map:



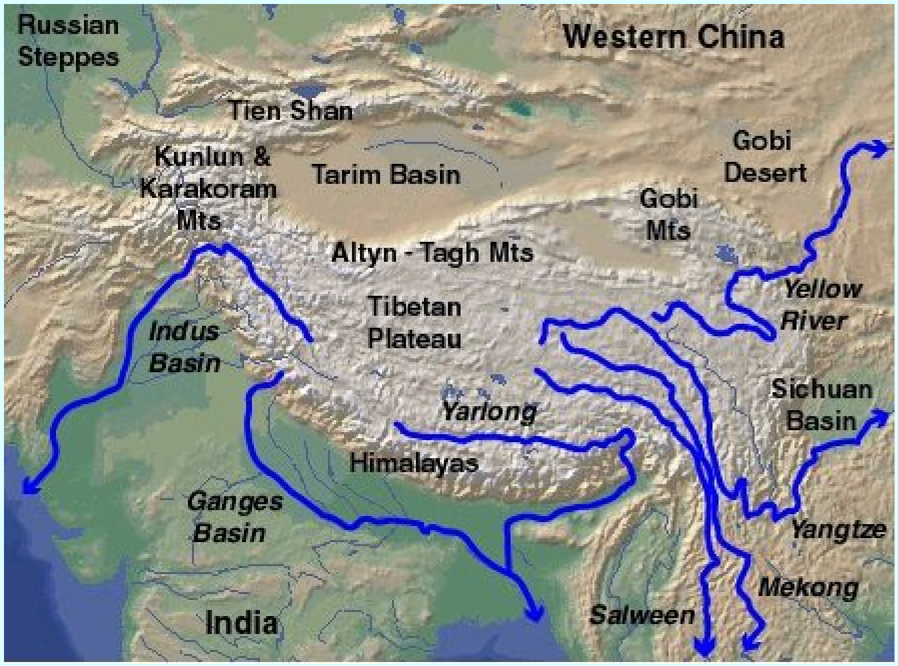
The Indian plate is too thick and its density is too low for it to be subducted beneath the Asian plate. The result is a collision, causing sea floor sediments to be pushed up about six miles, uplifting the Tibetan Plateau, a region the size of Alaska, to an average elevation of over 16,000 feet, and hundreds of miles of displacement of crustal rocks to the east and southeast.

In the early 1970's, Peter Molnar of MIT and Paul Tapponier of the University of Paris teamed up to study the Himalayas, the Tibetan Plateau and the surrounding areas of China and its neighbors using Landsat images and seismic data. They published the initial results of their research in Science magazine in 1975, and as China began to open to foreigners in the late 1970's, they were among the first to enter into cooperative research programs with Chinese geoscientists. The number of both foreign and Chinese geoscientists has increased dramatically over the past 25 years, but geology of western China is so complex that researchers will be working out the details of India's collision with China for many years to come.

It appears that India has penetrated over twelve hundred miles into Asia. What happened to the mass of rock it had displaced? Some of the lighter continental mass of the Indian subcontinent was subducted below Asian continental mass before "locking up" and transmitting India's movement to Asian crust. As a result, Asian crust has been shortened and thickened by surface folding, large scale overthrusting and plastic flow at depth.

However, these processes do not account for all of the missing mass. Molnar, Tapponier and others have postulated that as India moved northward, the regions north of the Himalayas moved east and southeast along large strike slip faults such as the Altyn Tagh, pushing into central China and Indochina. The next section discusses crustal thickening, and the following section discusses lateral displacement.

Relief Map of Tibet and Western China
showing major topographic features.

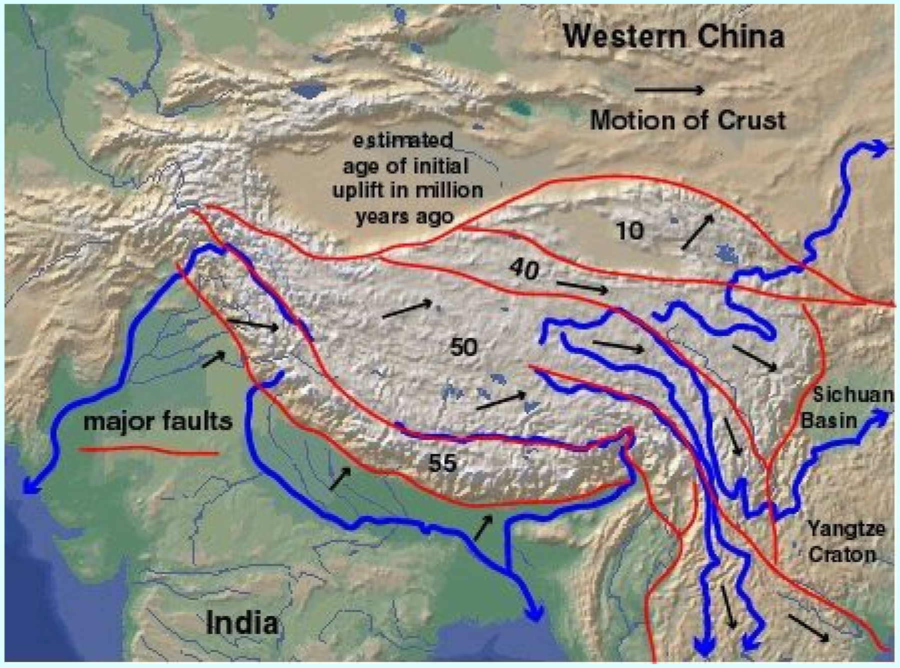


Uplift of the Tibetan Plateau

Imagine standing in a river valley at 15,000', looking at a 20,000' snow covered mountain range near the source of the Mekong River, and telling your Tibetan guide that mountains near your home in Colorado look like those mountains but the highest peaks are lower than the river you are about to float.

The Tibetan Plateau, referred to by Tibetans as the "Roof of the World" is the highest and largest plateau on planet Earth. It is not a plateau in the traditional sense - it is a basin. From the map above, you can see that it is bounded on the north by the the Kunlum, Altyn Tagh and Gobi mountains, on the west by the Karakorum Range, on the south by the Himalayas, and on the east by several mountain ranges between the major rivers draining the Plateau. All of these ranges have peaks that are higher than the Tibetan Plateau, and except for the southwest and east, drainage is towards the Plateau.

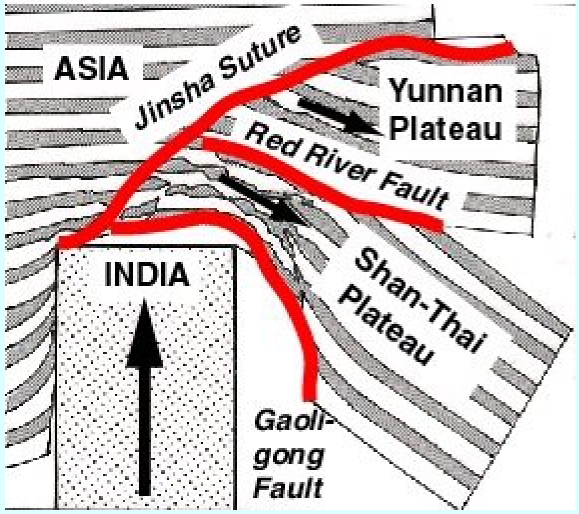
The map also shows six of the worlds largest rivers draining from the Plateau: the Indus (Gar) drains the southwest, the Bramaputra (Yarlung Tsangpo) drains the southern and southeastern area, the Salween (Nu), Mekong (Lancang) and Yangtze (Jinsha) drain the central and eastern areas, and Yellow (Huang) drains the northeastern area. The northern and northwestern areas have no external drainage and are characterized by many large lakes. The plateau is occupied by about four million Tibetans who raise yaks and sheep on tundra above the timberline, but over half of the worlds population lives in the drainage basins of these six rivers. There are numerous fault bounded ranges within the Plateau, many of which have peaks over 20,000'. Like the rivers, in the western and central plateau they trend east-west, slowly changing to a northerly trend towards the eastern edge of the Plateau near the Qinghai-Sichuan border.



The uplift of the Plateau progressed from south to north, beginning about 50 million years ago. The pressure of continued northward motion of the Indian continental mass caused large sections of Plateau crust to fold, then rise on east-west trending deep seated thrust faults. According to seismic interpretations, displacement on these faults is transferred to a zone of plastic flow at a depth of about 10 miles, where rocks are too warm to deform by brittle faulting. The depth of this zone is influenced by heat from the melting of huge sheets of Tethys oceanic crust which had been subducted below Tibetan crust over the 150 million years before the Indian continent began to collide with Asia. This material underplated, softened and thermally expanded the lower part of the overlying Tibetan continental crust.

In 2001, Tapponier and others summarized observations made over the past 25 years and identified three main fault bounded blocks in the Tibetan Plateau. The southern block is characterized by thin veneers of continental sediments up to about 50 million years old and the central block contains continental sediments up to about 40 million years old. The northeastern region is still experiencing high rates of uplift, as evident in thousands of feet of young (less than 10 mya) sediments that have been deposited in the upper Yellow River basin.

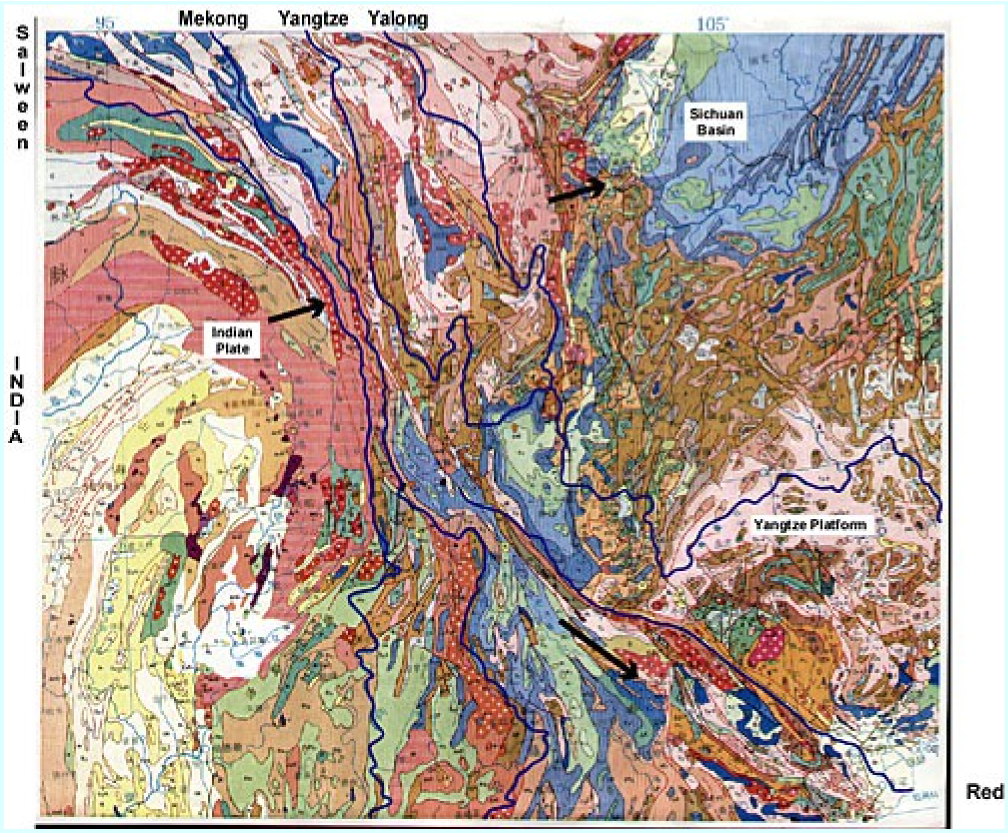
The huge mass of Asia to the west and north blocked movement of Tibetan crustal material in these directions as India pushed into Asia. As a result, northward motion on the deep seated thrust faults was transferred to east and southeast strike slip (lateral) motion. The high rate of very large earthquakes in the Himalayas, surrounding mountainous regions and on these interblock faults indicates the collision between India and Asia is still causing uplift of the Plateau.



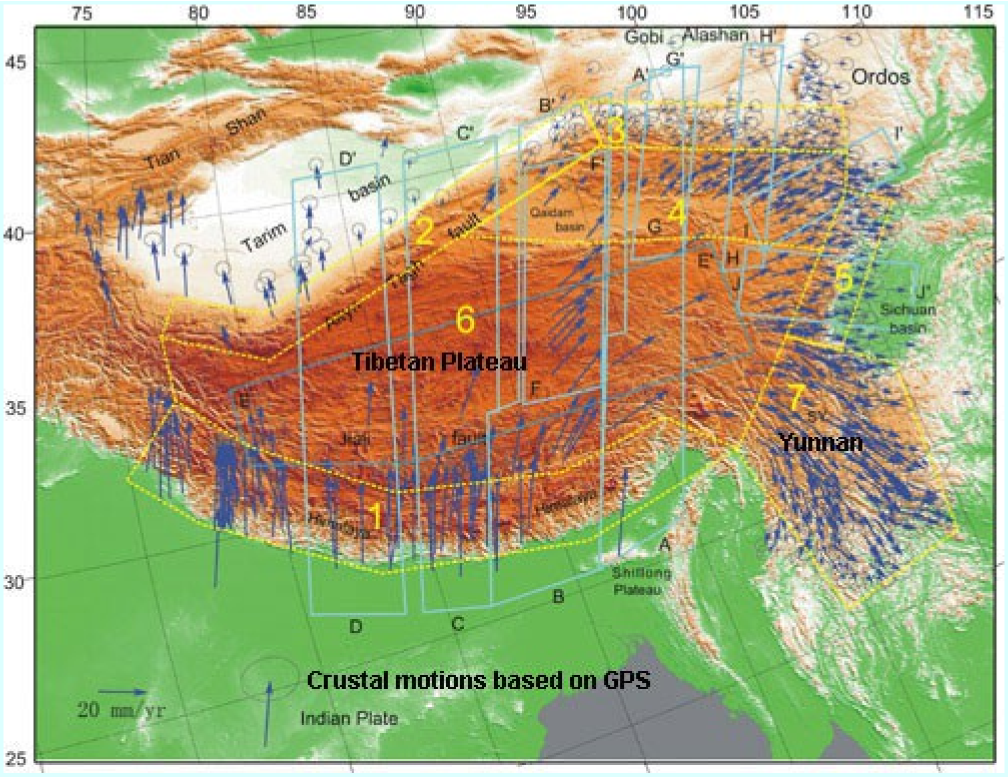
Tectonics of Lateral Displacement

If you look at a map of Asia, it's easy to imagine that the north-south trending mountains of eastern Tibet and western Sichuan and the southeast projection of Indochina into the South China Sea could have been caused by east and southeast lateral displacement of Tibetan crustal rocks. In the early 1980's, Tapponier and his colleagues modeled this concept by pushing a rigid block into a sheet of banded clay. The results of this experiment showed that eastward and southeastward extrusion of two large blocks could occur. Since then, Chinese and foreign geoscientists have measured large amounts of lateral displacement across major strike slip faults in western, central and southeast China.

This is also evident in geologic maps of the area between India and the Tibet-Sichuan-Yunnan region of China. Rock units are clearly shortened east-west and elongated north-south, and the Yangtze, Mekong and Salween drainages are compressed into a zone about one hundred miles across near the Tibet-Yunnan border. Rocks in this area are being thrust over the Sichuan Basin to the northeast and transported southeast of the Yangtze Platform along major strike slip faults.



One of the questions regarding displacement is the extent to which crustal blocks are displaced by movement on discrete strikeslip faults as suggested by the clay experiment versus the extent to which it occurs throughout the crustal blocks being displaced (distributed shear). To evaluate the relative amounts of displacement between and within blocks, Molnar and others placed GPS units at hundreds of locations on the Tibetan Plateau and Hengduan Mountains to the east and southeast, then measured their displacement over a period of years. The result was a surprise - a huge amount of displacement occurs by shear within blocks, as shown by the map below.



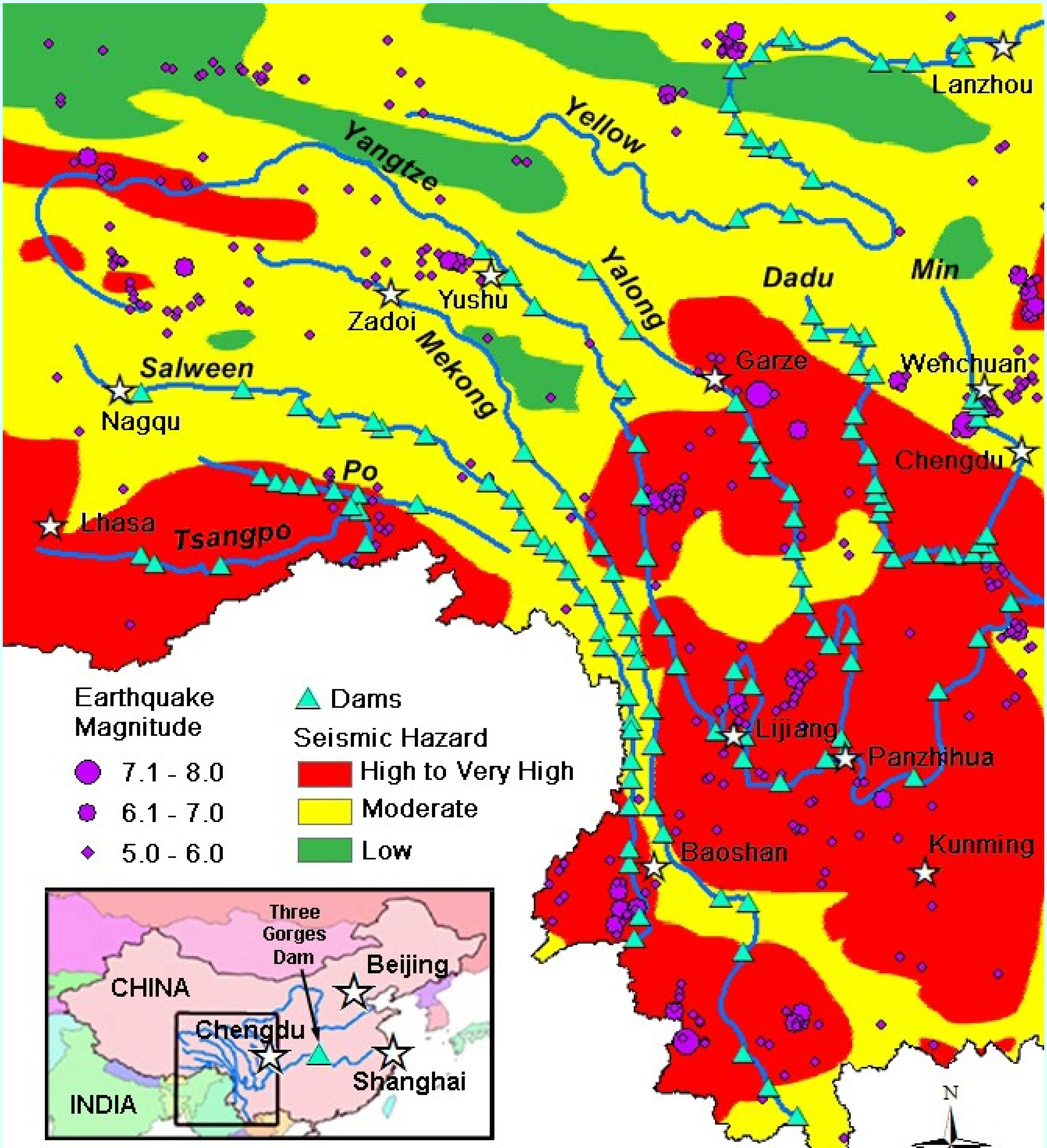
In November, 1994, Peter Molnar joined Earth Science Expeditions on a first descent and geological reconnaissance of the Yangbi River. For hundreds of miles before its confluence with the Yangbi, the Mekong is sandwiched in between the Salween (Nu) River on the west and the Yangtze (Jinsha) River on the east. In western Yunnan, the three rivers diverge - the Yangtze turns north, then east, the Mekong turns southeast, then south, and the Salween continues to the south. The Yangbi River drains the area between the Yangtze and the Mekong; Lake Erhai south of the Great Bend of the Yangtze drains into the Yangbi. Tapponier and other researchers believe one of the great strike slip faults along which Indochina was extruded southeastward as India pushed northward passes though this area. As the northeast corner of India passed by western Yunnan, this fault should have had left lateral displacement - if you stand on one side, the other side moves left, relatively speaking. Based on the clay experiment, at some point, as India continued its northward penetration into Asia, the displacement would stop and eventually reverse. The older fault is called the Ailao Shan Fault, which is thought to represent the southwest continental margin of the Yangtze craton. It could have as much as several hundred miles of left lateral displacement across it. The younger, right lateral strike slip fault is called the Red River Fault. The Red River flows in a nearly straight line from near the headwaters of the Yangbi to Hanoi, Vietnam.

In a 1990 article in Nature magazine, Tapponier and his colleagues, including several from the Chinese Academy of Sciences, concluded that left lateral strike slip activity on the Ailao Shan Fault occurred from about 50 to 20 million years ago. At that time the current level of exposure of the fault was as much as ten miles below the surface, and the zone of deformation was about five miles wide. On the way to the Yangbi River, the 1994 expedition members crossed the northwestern extension of the Ailao Shan Fault just southwest of Dali. Here, in a steep, narrow gorge through the Diancang Mountains, 400 million year old marble and gneiss nearly a billion years old have been severely deformed. The rocks have a near vertical foliation with a sub horizontal lineation trending northwest. Picture a tablet of lined paper standing on its bottom edge, with the lines horizontal. The sheets represent foliation, the lines represent lineation. These are characteristics of deeply buried rocks subject to large amounts of horizontal shear. They have recrystallized under high temperatures and pressures. Microscopic textures indicate the shear is left lateral.

One of the problems geoscientists face in figuring out what happened millions of years ago is that younger tectonic events frequently alter the geologic record of older events. This is clearly happening in western Yunnan. Most likely, the Ailao Shan Fault continues northwestward beyond the Diancang Mountains near Dali and the Jiali Fault in southeast Tibet is its northwest extension. Changes in the regional stress field as India penetrates further into Asia, however, have resulted in a change in the nature of deformation, which has disrupted the continuity of the older faults.

The Red River Fault was first described by Chinese geologists in 1913; the Gregorys and Misch also mention it. According to geoscientists from the Seismological Bureau of Yunnan, MIT and Cal Tech, the Red River Fault has about three miles of right-lateral displacement. The displacement is quite recent - certainly in the last two to three million years. Like the Ailao Shan Fault, the Red River Fault is not obvious northwest of the Yangbi drainage area. Here, displacement has been transferred faults with greater dip slip (vertical) displacement than strike slip displacement, resulting in young basin and range topography, much like that of Nevada. There are numerous warm springs on these faults - the Yangbi River expedition members and local farmers used them for bathing, and sometimes they are religious or tourist sites. This area also has numerous mineral deposits, which are frequently associated with warm springs. Warm water slowly circulates along fractures in large volumes of rock, including the buried hot rocks which warm the water, dissolving soluble minerals. As the warm water rises and cools, it loses its ability to hold the minerals and deposits them, often along fault zones. Eventually the concentration of minerals becomes great enough to justify economic extraction, and when the deposit is exposed on the surface by erosion, the chances are that an observant person will find it.

Many of the large earthquakes that have occurred in the past seventy five years were located on the Red River and related dip slip faults. The high seismicity and recent displacements on these faults is almost certainly related to India's continued penetration into China.



Of the 137 proposed, under construction and constructed large dams on the Yellow, Yangtze, Yalong, Dadu, Min, Mekong, Po Salween and Tsangpo Rivers, 48% are located in zones of very high to high seismic hazard (peak ground acceleration or PGA = 2.4 to 5.6), 51% are located in zones of moderate seismic hazard (PGA = 0.8 to 2.4) and only 1% are located in zones of low seismic hazard (PGA = 0 to 0.8). Dams in the very high to high zones have a 10% risk of damage and possible failure within the next 50 years. Base map from ESRI; earthquake data from the USGS, dam locations from HydroChina, and seismic hazard zones from GSHAP (1999). Probe International, 2012.

Figure 1

Seismic Hazard Map for Western China's Dams

Source:Earthquake Hazards and Large Dams in Western China 2012

Earthquakes in Yunnan

A disproportionate number of large earthquakes have occurred in western Yunnan. In November 1988, an M=7.6 earthquake was followed 13 minutes later by an M=7.2 earthquake on faults in the Nanding River fault system southwest of the Mekong, killing over 700 people, injuring several thousand, leaving tens of thousands homeless, and forming Dragon's Teeth rapids, the largest on the Mekong above the Man Wan Reservoir. In October 1995, while Earth Science Expeditions was rafting Dragon's Teeth, an M=6.5 earthquake occurred about 80 miles northwest of Kunming (about 200 miles northeast of the rapid), killing 44, injuring hundreds, and leaving about 20,000 homeless.

Chinese people who have lost relatives in one of these quakes would probably say that China has had more than its fair share of earthquakes. More Chinese people have died in earthquakes than anywhere else on earth. The most deadly earthquakes in China include the Hua Xian earthquake in Shaanxi in 1556 which killed 830,000, the 1920 Haiyuan earthquake (estimated M=8.5) which killed about 200,000, and the Tangshan earthquake in 1976 which killed 242,000. In the US, it's a major disaster when tens or hundreds die. North America, including the San Andreas Fault system, is seismically quiet relative to China, where there have been over 100 major earthquakes in this century alone.

Large earthquakes must have occurred in western China for tens of millions of years in order to produce the extreme relief in this area. Certainly there were some in the years immediately prior to AD 132, because Zhang Heng invented what is probably the first seismograph that year. He placed eight carved dragons in an octagonal pattern and put a ball in each of their mouths. When an earthquake occurred, the ball would fall out of the mouth of the dragon whose back was facing the epicenter. Today, the State Seismology Bureau operates nearly a thousand seismograph stations, and one of its highest priorities is development of a reliable means of earthquake prediction.

Western Yunnan has experienced at least ten earthquakes greater than M=7.0 during the past 75 years, second only to Tibet. In addition to the two 1988 and the 1995 earthquakes, one in 1925 near Dali, on the shore of Lake Erhai, caused a famous 150' high pagoda built several centuries ago to lean like the Tower of Pisa. In 1970, a 7.7 quake south of the Jihong Bridge killed over 10,000 people. On February 3, 1996, an M=7 earthquake hit Lijiang, killing at least 210 and causing over 3700 serious injuries. In 1515, an M=8 (estimated) struck near Chenghai, one of the largest to occur in China. An M=8 earthquake has thirty times the destructive energy of an M=7!

The Chinese completed the Man Wan dam in 1993 and expect to complete another 8 hydroelectric dams on the Mekong in western Yunnan before 2017. These dams will flood about 400 miles of river, from the southern part of Great Rivers National Park to the Yunnan - Myanmar border. This is a high risk source of energy considering the frequency of large earthquakes in western Yunnan.

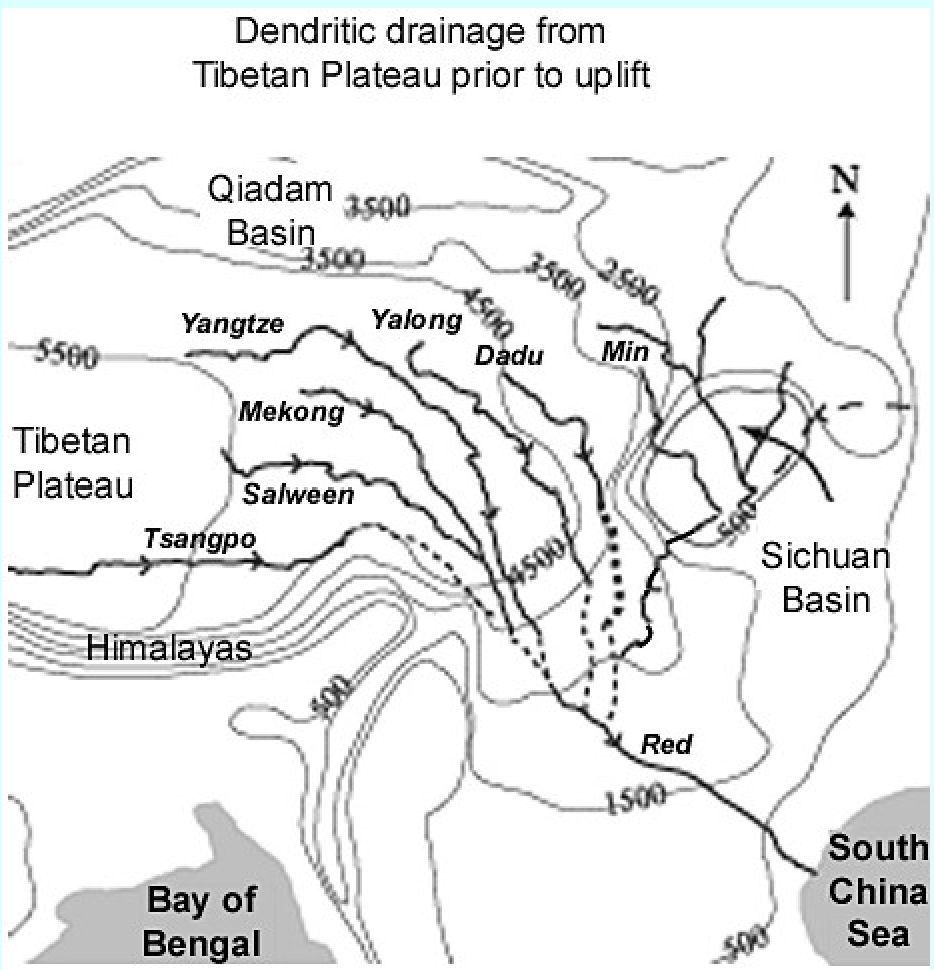
Western Yunnan has been designated an international earthquake prediction experimental test site. Three Chinese agencies - the State Seismology Bureau, the Ministry of Geology and the Institute of the Geology of the Chinese Academy of Sciences, are working with US Geological Survey to establish a seismic net in northwestern Yunnan. Their goal is to relate regional and local fault zone geology and seismicity to over a thousand parameters, such as changes in groundwater flow, chemistry and temperature. While the US approach to earthquake prediction has historically been theoretical, the Chinese are more practical. They even monitor the behavior of several animals which sometimes changes in characteristic ways prior to earthquakes.

Earthquake prediction is still in its infancy. The State Seismological Bureau has probably had greater success than most other organizations since they began their studies in the late 1960's, estimated to be 20% -30%. They predicted a M=7.3 earthquake near Haichen and Yinkow in 1975, saving thousands of lives, and another one in western Yunnan in 1976. However, they were surprised by the Tangshan earthquake which killed 242,000. One of the problems with predicting earthquakes is that people might panic, and if no earthquake happens, more injuries might occur than if no prediction were made.

The Development of Major River Drainages

The geologic record may preserve evidence of ancient river drainages. For instance, about 100 million years ago, the ancestral Sierra Nevada mountains (now on the California-Nevada border) were part of the North American continental divide. Evidence of the rivers draining the ancestral Sierra Nevada is visible in the canyon walls of drainages produced by the current mountain range. These ancient rivers deposited characteristic sediments as they flowed east across the region of the current continental divide in Colorado to an ocean that covered eastern North America. Sixty million years ago, the Rocky Mountains began to uplift, eventually becoming the new continental divide. Thirty million years ago, the San Juan Mountains formed one of the highest ranges in the Rockies, and today the sources of five major rivers are found there: the Gunnison, Delores, San Juan, Rio Grande, and Arkansas.

Similarly, the Tibetan Plateau is the source of numerous major rivers because it is the largest and highest region of eastern Asia. If you put your hand (India) on a table cloth (Asia) and push it, the table cloth folds around your hand. The troughs in the folds near your fingertips represent the headwaters of these rivers, while folds on the sides of your hand represent faults followed by rivers as they flow off the Plateau towards surrounding lowlands.



Geomorphologists believe that the dendritic drainage pattern illustrated above developed in the area north and east of the Himalayas prior to uplift of the Plateau.

As the elevation of the Plateau area increased, it collected greater and greater precipitation. This water was initially ponded in basins due to irregular uplift, like the current Chang Tang region of the Plateau, but eventually drainages became integrated. All the today's major drainages were probably once tributaries to the Red River, which today flows into the South China Sea at Hanoi, Vietnam. As India penetrated further into Asia, large faults began to form as illustrated in maps above. Faults represent breaks in the crust, where otherwise solid rock is broken and more easily eroded. A good example is the Yarlung Tsangpo, which drains much of the north side of the Himalayas. It largely follows the Indus-Tsangpo suture, which represents the original boundary between India and Asia, before turning south to join the Bay of Bengal.

Due to irregular rates of uplift, particularly in eastern Tibet (Namchabarwa is over 25,000'), Sichuan (Gonga Shan is about 25,000') and western Yunnan (there are multiple mountains over 20,000'), smaller stream were able to capture the flow of the Red River Tributaries through rapid headward erosion. The lower Yangtze captured the Min, Dadu, Yalong and upper Yangzte. The lower Mekong captured the upper Mekong, the lower Salween captured the upper Salween, and the Bramaputra captured the Tsangpo, resulting in the drainage pattern we have today.

The upper Yangtze follows the Jinsha Suture, which separates the southern and central blocks of Tibetan crust, then is controlled by a complicated system of faults in northwest Yunnan before meandering east across the Sichuan and East China Basins to the East China Sea. The upper Yellow initially follows the eastern Kunlun Fault, which parallels the boundary between the central and northern blocks of Tibetan crust, before turning northwest and exiting the Plateau on the Haiyuan Fault on its convoluted way to the Yellow Sea. Apparently its eastward path along the Kunlun Fault was blocked by the uplift of the northeastern margin of the Plateau along the northwest margin of the Sichuan Basin.

In the Three Gorges area east of the Himalayas, the Salween follows the Gaoligong Fault before meandering across the Shan-Thai Plateau of Myanmar to the Andaman Sea. The Mekong follows a segment of the Jiali fault, the northwest extension of the Ailao Shan Fault, before turning south and meandering across the Shan-Thai Plateau and Indochina lowlands to the South China Sea. Although the southern, western and central parts of the Plateau reached their current (and probably maximum) elevation about eight million years ago, these drainages have been developing over tens of millions of years as uplift of the Plateau progressed.

About two million years ago, the earth entered a major ice age. Polar ice caps grew, reaching as far south as the northern US and covering the entire Tibetan Plateau and Himalayas. Ice sheets advanced and retreated four times, most recently retreating only 10,000 years ago - a few minutes in geologic time. The effect of these ice sheets on topography was dramatic. Mountain tops were eroded to form jagged peaks and ridges while valleys were filled with glacial sediment. Strong winds winnowed out the fine silt (called loess), depositing thick layers of it across the entire upper Yellow River basin (hence its name), and leaving behind coarser sand and gravel which today chokes the river beds.

As a result, the headwaters of all of the major rivers on the Tibetan Plateau are braided streams flowing over glacial gravels in broad valleys, characterized by constant moderate gradients and few significant rapids. By the time they begin to flow off the Plateau, the rivers have gained the volume necessary to erode these gravels and renew the process of cutting deep, narrow canyons in underlying bedrock. Where they flow over hard layers and giant boulders, there are huge rapids such as Tibetan Terminator and Dragon's Teeth on the Mekong, Leaping Tiger Rapids on the Salween, Tiger Leap Gorge on the

Yangtze, and waterfalls such as Rainbow and Hidden Falls in the Great Bend of the Yarlung Tsangpo.