2 A Note on Himalayan Seismicity

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The Himalaya has been the locus of some of the world's great earthquakes during the last 100 years. The region is a typical example of a collision type orogenic belt — a linear region that has undergone folding or other deformation during an orogenic (geotectonic) cycle. Himalayan seismicity is similar in nature to that of regions of oceanic subduction, being the result of the northward movement of the Indian plate. The absence of surface or primary ground rupture accompanying the region's great earthquakes indicates that its seismicity is related to a rupture along the Himalayan arc on a shallow north-dipping (3-5°) decollement that coincides with the top surface of the Indian shield and is encountered at a depth of 15-20 km beneath the Lesser and Higher Himalaya. This is also reflected by a belt of seismic activity in the 6-7 magnitude (M) range with a focal depth ranging from 15 to 20 km. This belt also follows the Main Central Thrust (MCT) and runs along the region of greatest uplift and a line of more than 3500m altitude. This is interpreted as the surface expression of a basement ramp where the dip of decollement changes from 5-6 degrees to 15 degrees. The region's four great (M 8+) recorded earthquakes – in 1897 (Assam), 1905 (Kangra), 1934 (Bihar-Nepal), and 1950 (Assam) – were confined to the frontal belt along the Main Boundary Thrust (MBT). These earthquakes ruptured 200-300 km of fault zone each; between these ruptures are seismic gaps, or seismically quiet zones, which are regarded as future potential sites of such great earthquakes. In addition, there have been over 650 other events of M 5-7 during the same period, which have typically occurred along transverse structures or other major thrusts or normal faults.

Introduction

Non-specialists will find introductory information on earthquakes in the appendix at the end of this paper; some definitions are provided in the glossary. The following is concerned specifically with seismicity in the Himalaya.

The Himalaya were formed by the collision of two continental plates, the Asian and the Indian. The region is a typical example of a collision type orogenic belt — a linear region that has undergone folding or other deformation during an orogenic (geotectonic) cycle. Accompanying the mountain range is a major global seismic belt where earthquakes of magnitude 4.5 to 5.5 occur every year; over 600 earthquakes of magnitude 5 (M 5) or above were recorded during the period 1950-1990. To date, four very major ('great') earthquakes of M 8 or greater have been recorded in the Himalaya or adjacent regions: the Great Assam earthquake of 1897, the 1905 Kangra earthquake, the 1934 quake near the Bihar-Nepal border, and the 1950 Assam earthquake (Figure 2.1). These earthquakes collectively killed well over 30,000 people. Other events of M 6-7, such as the Kinnaur earthquake of 1975 and the Uttarkashi earthquake of 1991, have also caused extensive damage to life and property.

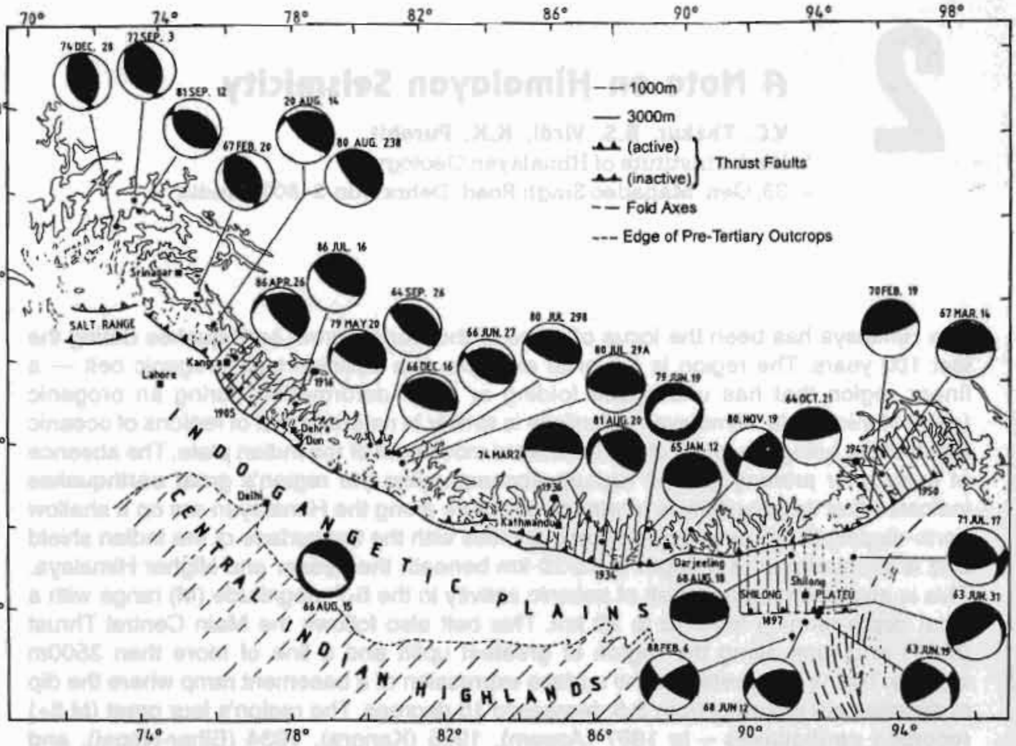

Figure 2.1: **Distribution of moderate and great earthquakes in the Himalaya and adjoining area, showing focal mechanisms ('beach ball' shapes) of moderate earthquakes (5.5≤M≤7) and rupture zones (hatched lines) of four great earthquakes: Assam, 1897; Kangra, 1905; Bihar,1934; Assam,1950** (modified after Molnar 1990). **The black area in each beach ball shape represents the fault plane of the earthquake in stereographic projection**

Most of the earthquakes that could be clearly located in the Himalaya were found to occur within a band roughly 60-100 km north or northeast of the southern margin of the range, and 10-50 km south or southwest of the crest of the Higher Himalaya (Molnar 1990). Thus along most of the chain, the earthquakes occur south of the surface trace of the Main Central Thrust.

Fault plane solutions of most moderate earthquakes in the Himalaya (M 5-7) indicate thrust faulting, with one nodal plane dipping gently northwards or northeastwards and the other dipping steeply southward or southeastwards (Figure 2.1) (Rastogi 1974; Baranowski et al. 1984; Ni and Barazangi 1984). Nearly all measured focal depths of earthquakes in the Himalaya lie between 12 and 18 km below the earth's surface. Most of the moderately sized earthquakes occur on the top surface of the Indian plate where it slides beneath the overriding crystalline nappes comprising the Lesser Himalaya (Baranowski et al. 1984; Ni and Barazangi 1984).

The Himalaya is the locus of the world's greatest intracontinental earthquakes. Three great earthquakes – Kangra (1905), Bihar-Nepal (1934), and Assam (1950) – occurred within a 50-year span, and the seismic moments of these great earthquakes appear to have been the largest among intracontinental earthquakes in the 20th century. The rupture zone of the 1905 Kangra earthquake is estimated at 120 km long and 100 km wide, and the average displacement was 5m (Molnar 1990).

The rupture zone of the 1934 Bihar-Nepal earthquake was 200 km by 100 km and its calculated average displacement was 6.2m, while the rupture zone of the 1950 Assam earthquake was estimated to be some 400 km long and 100 km wide with an average slip of 9m on thrust faults. (For a better understanding of seismicity, general aspects concerning earthquakes are described in the appendix to this paper.)

Seismological aspects

The seismic network being managed by various organisations has provided useful data on the intensity and magnitude of Himalayan earthquakes, but focal depth estimates still differ for many events. The record of past activity shows that various sections of the Himalaya have witnessed different intensities and frequencies of earthquakes. In the Lesser and Higher Himalaya, the density of tremors is relatively high and follows a linear pattern parallel to the Himalayan arc. Moreover, there are some pockets of more concentrated activity. The seismicity north of the Higher Himalaya is rather diffuse, without any discernible linear trends.

The western sector of the Himalayan arc – the region from Kangra through Tehri-Garhwal to Kumaon – shows a linear trend of seismic activity paralleling the Himalayan arc, with pockets of high concentration around Kangra and north of Tehri (Figure 2.2). The central sector, from the Garhwal-Kumaon Himalaya in the west through Nepal to Sikkim in the east, also shows trends paralleling the Himalayan arc and pockets of concentrated activity in the Garhwal-Kumaon and Nepal area. The activity in the region east of Kathmandu is also quite high. The activity is also very high in the eastern Himalayan sector, from Darjeeling through Itanagar (not shown in Figure 2.2) up to the site of the great earthquake of 1950 in the extreme northeast. The earthquakes in this sector follow the NE-SW trend of the arc.

The earthquake parameters determined from distant recordings made at globally distributed seismological observatories (teleseismic phase data) are reasonably accurate with regard to epicentre locations, but the depth of foci are not well determined. Some broad patterns of depth-wise distribution of earthquakes have nevertheless emerged. The main Himalayan arc region comprising the three sectors (western, central, and eastern) is marked by an occurrence of shallow earthquakes (focal depths of less than 50 km). In contrast, the India-Myanmar border region is the site of a very high density of shallow to intermediate depth earthquakes.

The spatial disposition of earthquake epicentres can help to delineate the lateral extension of faults. A study of earthquake foci in depth sections can reveal the subsurface nature of these faults. The linear patterns seen on an epicentral map of the Himalayan region broadly reflect the trends of active tectonic features. These trends parallel the trends of the Main Boundary Thrust (MBT) and the Main Central Thrust (MCT). Some transverse trends are also discernible. The data on depth distribution, however, do not reflect well-defined trends.

Major seismo-tectonic features

The evolution of the Himalaya is attributed to the continent-continent collision of the Indian plate with the Eurasian plate. The major tectonic features in the region are the outcome of this phenomenon. Four major tectonic features running almost the entire length of Himalaya are recognised and widely described in the literature. From north to south, these features are the Indus-Tsangpo Suture Zone (ITS), the Main Central Thrust (MCT), the Main Boundary Thrust (MBT), and the Main Frontal Thrust (MFT). Along a north-south section, these features divide

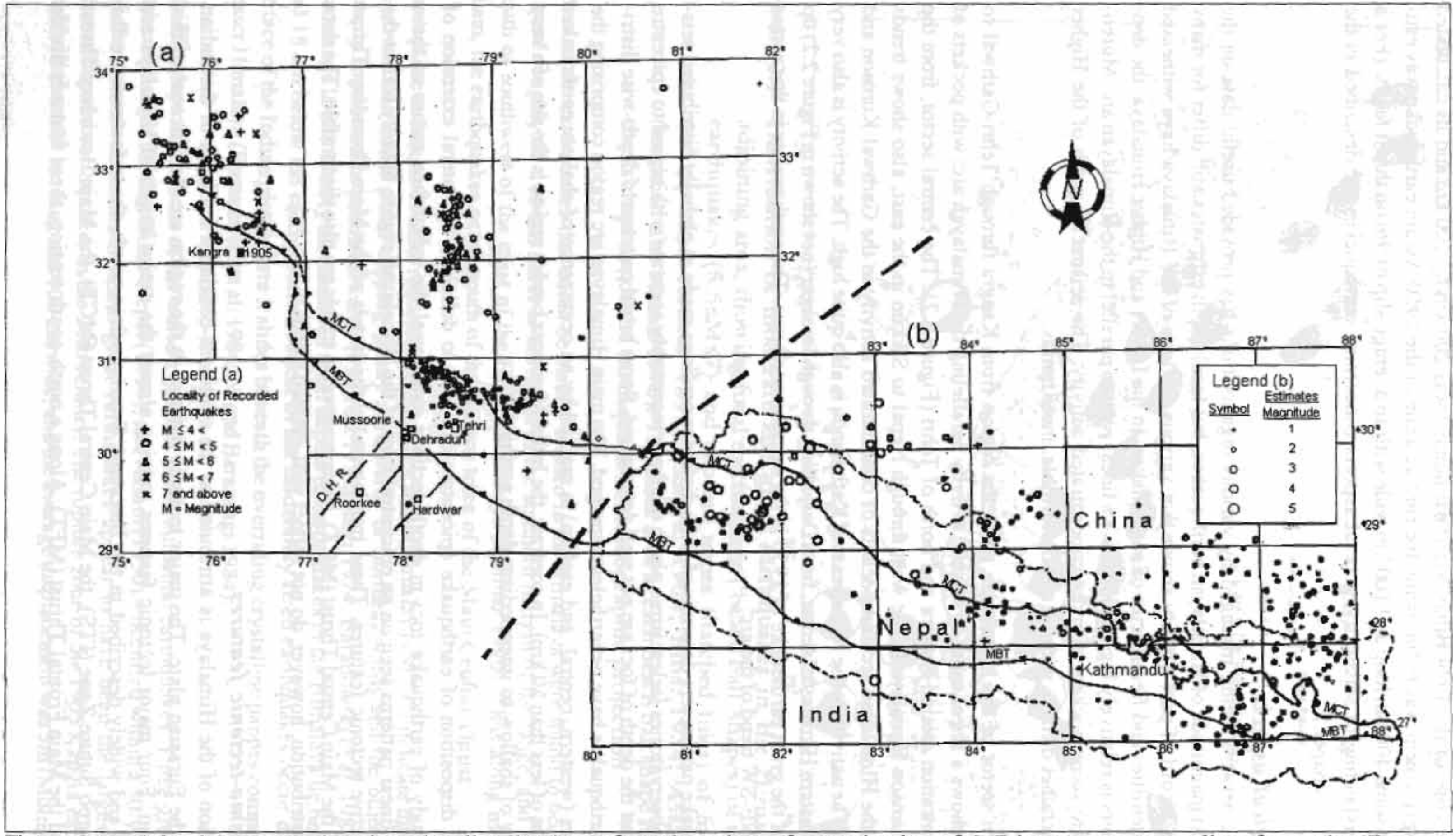

Figure 2.2: Seismicity map showing the distribution of earthquakes of magnitudes of 2-7 in an area extending from the Kangra-Chamba region to eastern Nepal in two blocks: a) Kangra-Chamba region to the Kumaon Himalaya in India, and b) the Nepal Himalaya. (a) shows earthquakes with a magngitudes of 4-7 between 1979 and 1982; (b) shows earthquakes with magnitudes of 2-5 between 1982 and 1985

the Himalaya into three geologically and tectonically distinct sectors. In addition to these, there are some localised tectonic elements either parallel to or transverse to the three major elements. Transverse features like the Delhi-Hardwar ridge or Monghyr-Sahgrsa ridge are regarded as a continuation of the tectonic fabric of the Indian Peninsular shield into the Himalayan arc (Sastri et al. 1971).

The ITS marks the northern boundary of the Indian plate following the closure of the Tethys ocean in the late Cretaceous-early Tertiary period (around 55-50 million years ago). The MCT, which separates the Higher Himalaya from the Lesser Himalaya, is regarded as the base slab of the Higher Himalayan Crystalline rocks and dips 30-40 degrees northwards; it appears to have developed in the mid-Miocene (20 million years ago). The MBT and the MFT were initiated around 10 and 0.2 million years ago, respectively. There has been a progressive shifting of planes of underthrusting from north to south: the MFT, which separates the foothills from the plains, is the youngest and presently tectonically active thrust.

Seeber et al. (1981) postulated that there was a detachment surface (fault) underlying the entire Himalaya and representing the upper surface of the underthrusting Indian plate (Figure 2.3). This fault was thought to be a decollement, an area with folding or faulting of sedimentary beds as a result of sliding over underlying rock. The fault was thought to dip north at a shallow angle below the Sub-Himalaya (Siwalik zone) at a depth of 2 to 7 km, and then continue into a steeper dipping Basement Thrust (BT) under the Higher Himalaya and Tethys Himalaya. The Himalayan rock formations appear in the form of thrust wedges overlying the detachment; as the Indian plate moves northward (at a rate of 1.5 to 5 cm per year depending on the location), the thrust wedges are pushed southward relative to the northward movement like a pack of cards.

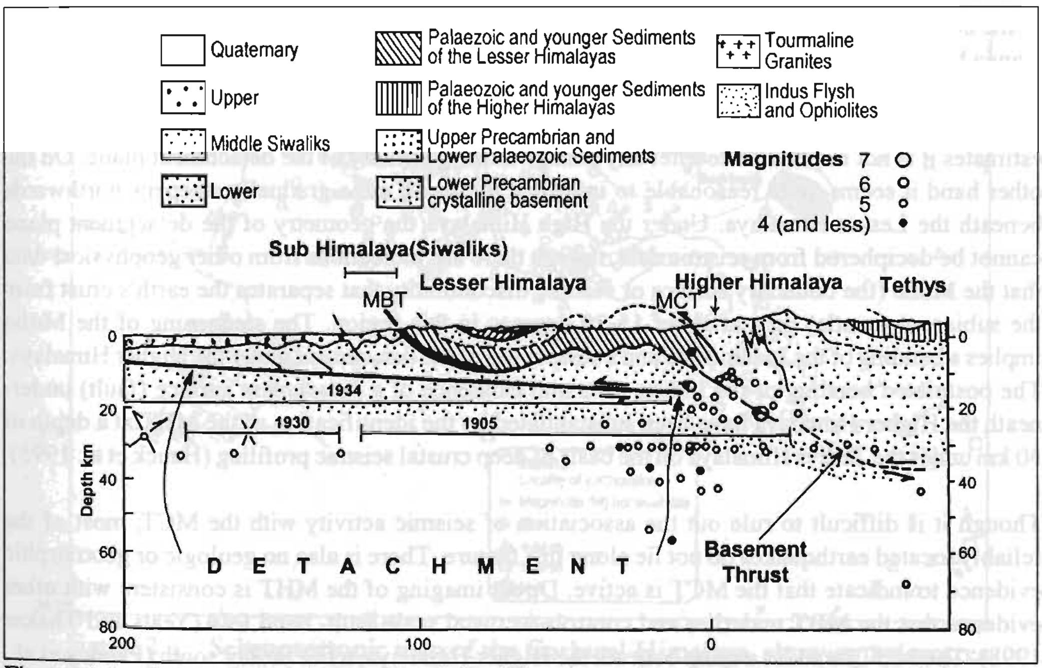

Figure 2.3: **Seismotectonic model of the Himalaya showing rupture zone of the great earthquake of 1905, 1930 and 1934, which were associated with slip along the detachment** (modified after Seeber et al. 1981)

The detachment fault was identified in the form of a deep crustal seismic profile beneath the Tethys Himalaya in southern Tibet (Hauck et al. 1995), designated the Main Himalayan Thrust (MHT) by Zhao et al. (1993). It has also been located in a seismic profile image in the Siwalik zone in the Dehradun region (Power et al. 1998), where it was found to dip at a shallow angle (5-10°C) at a depth ranging from 2 to 7 km, as postulated by Seeber et al. (1981). Seismic data indicate that in the Garhwal Himalaya the detachment fault lies at a depth of 15-20 km under the Lesser and Higher Himalaya (Khattri et al. 1988). The MCT, MBT, and MFT are splays of thrusts emerging from the detachment fault.

Most of the earthquakes in the Himalayan region are confined to shallow depths and are concentrated in a 50-100 km wide zone between the MBT and MCT. Most of the earthquakes with thrust-type focal mechanisms (i.e., resulting from compression when plates or areas of plates converge) lie within this belt. Focal mechanisms of the moderate-sized earthquakes suggest underthrusting of the Indian plate along the Himalayan arc. Some earthquakes located further south, in the Indo-Gangetic alluvial region and the Sub Himalaya, show normal fault plane solutions (arising from extension). The normal fault-type events can be considered to be of the same type as observed in oceanic trenches associated with island arcs and are perhaps due to flexing of the Indian plate as it bends and underthrusts beneath the Himalaya.

Seeber et al. (1981) interpreted the available seismological data to determine that most of the medium-sized thrust-type earthquakes occur either along the BT or along the down-dip projection of the MCT (Figure 2.3). Molnar and Chen (1983) proposed that the medium-sized thrust events occur along the part of the detachment beneath the northern Lesser Himalaya and perhaps along the down-dip projection of the MCT and nearby subsidiary faults. The great (magnitude 8 or higher) Himalayan earthquakes, however, are believed to occur along the master detachment surface between the Sub Himalaya and the Lesser Himalaya.

Some borehole data suggest that the upper surface of the Indian plate dips 2-3 degrees beneath the Ganga basin. Most of the focal mechanisms show fault plane dipping of the order of 5-30 degrees due NW or NE (with uncertainties of 5-15 degrees). While estimated dips in the western sector are generally higher than those in the eastern sector, owing to the higher uncertainties in the western estimates it is not reasonable to infer any change in the geometry of the detachment plane. On the other hand it seems quite reasonable to infer that the thrust zone gradually steepens northwards beneath the Lesser Himalaya. Under the High Himalaya the geometry of the detachment plane cannot be deciphered from seismic data, though there are indications from other geophysical data that the Moho (the boundary surface or seismic discontinuity that separates the earth's crust from the subjacent mantle) dips at about 15-20 degrees in this region. The steepening of the Moho implies a bending of the Indian plate and a steeper dip of the detachment under the Higher Himalaya. The postulated bending of the Indian plate and existence of a detachment surface (fault) underneath the Higher Himalaya have been substantiated by the identification of the MHT at a depth of 30 km under the Tethys Himalaya on the basis of deep crustal seismic profiling (Hauck et al. 1995).

Though it is difficult to rule out the association of seismic activity with the MCT, most of the reliably located earthquakes do not lie along this feature. There is also no geologic or geomorphic evidence to indicate that the MCT is active. Direct imaging of the MHT is consistent with other evidence that the MBT underlies and controls a crustal scale fault- band fold (Yeats and Thakur 1998). The MHT includes a ramp beneath the Higher Himalaya, a flat farther south (Pandey et al., 1995), and another ramp at the Himalayan front (Power et al. 1998). The down-dipping ramp under the Higher Himalaya is characterised by a zone of earthquakes of moderate magnitude. On rare occasions, earthquakes on the down-dipping ramp have trigerred rupture across the flat to the front of the range. This has led to at least three great earthquakes on the flat in this century.

Steeply dipping faults transverse to the Himalayan arc are widely distributed in the Sub Himalaya (Siwaliks) and Lesser Himalaya. These transverse faults represent lateral ramps and have a strike-slip component, i.e. with movement parallel to the fault strike. The fault plane solution of one reliably located earthquake in the Darjeeling region (19 November 1980) shows a predominantly strike-slip mechanism. The event was located within the overthrusting Lesser Himalaya block and is representative of transverse faulting in this block. The fault plane solutions in the Tethys Himalayan region show that active tectonics are dominated by north-south-trending normal faults.

Local seismicity in the Garhwal Himalaya

During the years 1984-88, the Department of Earth Sciences, University of Roorkee operated a short-aperture local network of seismological stations in the Garhwal Himalaya in the vicinity of Tehri-Garhwal and the Uttarkashi region (Khattri et al. 1988). This has provided additional data on earthquakes of magnitudes less than 4.5. The location of these events is considered to be correct to within a few kilometres. These stations' recordings, which were done in analogue form, have led to a greater understanding of the region's tectonic features. A seismotectonic map showing seismicity and tectonic features of the Garhwal and Kumaon region is shown in Figure 2.4.

No reliable focal mechanism based on teleseismic (distant) observations for the Garhwal Himalaya. The nearest available focal mechanism indicates thrust-type solutions. The dip of the composite

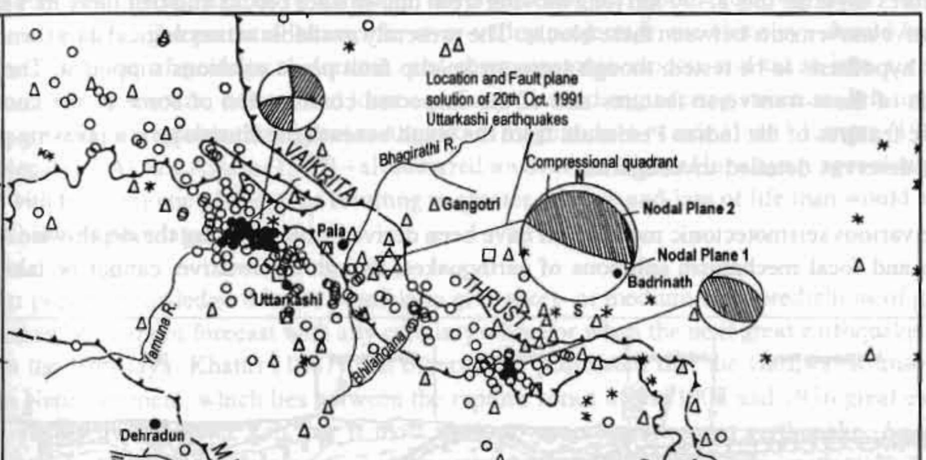

Figure 2.4: **Seismotectonic map of the Garhwal Himalaya, showing epicentres of earthquakes with magnitudes of 4-6** (modified after Thakur and Kumar 1994). **The shaded area in the beach ball shapes represents the fault plane of the earthquake in stereographic projection**

fault plane solutions referred to earlier are of the order of 60 degrees, which conforms with the geological observation that the thrust faults in the Himalaya have steeper dips at shallow depths

Local seismicity in the Nepal Himalaya

Geoscientists from His Majesty's Government of Nepal and a team of geophysicists from France have been monitoring microseismicity in Nepal for more than 10 years. Out of the 4,000 local events recorded between 1985 and 1992, 1,200 occurred within the Kathmandu network. Most of these microseismic events were shallow with local magnitudes of less than 4 (one notable exception was a tremor of magnitude 6.5 on 21 August 1988). Pandey et al. (1995) noted a clustering of microseismic events in an east-west belt along the front of the Higher Himalaya and following the trace of the Main Central Thrust (MCT). Most of the seismic events were clustered at a shallow depth of 5-20 km in the vicinity of the midcrustal ramp beneath the Higher Himalaya (Figure 2.5). Based on this model, Pandey and his co-workers proposed that the microseismicity recorded at the front of the Higher Himalaya over the last decade has resulted from stress accumulation over the midcrustal ramp.

Some significant problems of Himalayan seismicity

The present seismological data do not enable an understanding of the seismic nature of features transverse to the Himalayan arc, nor of strike-slip movements. The gaps in fault plane solution data are quite prominent over wide spans. In the framework of plate tectonics, the entire Himalayan arc is considered to be the result of the northeasterly-moving Indian plate and its underthrusting beneath the Tibetan plateau. However, it would appear most probable that there are transverse features dividing this 2,400 km long moving front into smaller blocks and that there may be some relative movements between these blocks. The presently available seismological data do not allow this hypothesis to be tested, though some strike-slip fault plane solutions support it. The delineation of these transverse features and of the suspected continuation of some of the known tectonic features of the Indian Peninsula from the south beneath the Himalaya is a pressing problem that deserves detailed investigation.

The various seismotectonic models that have been derived from studying the depth-wise distribution and focal mechanism solutions of earthquakes, though informative, cannot be taken to be

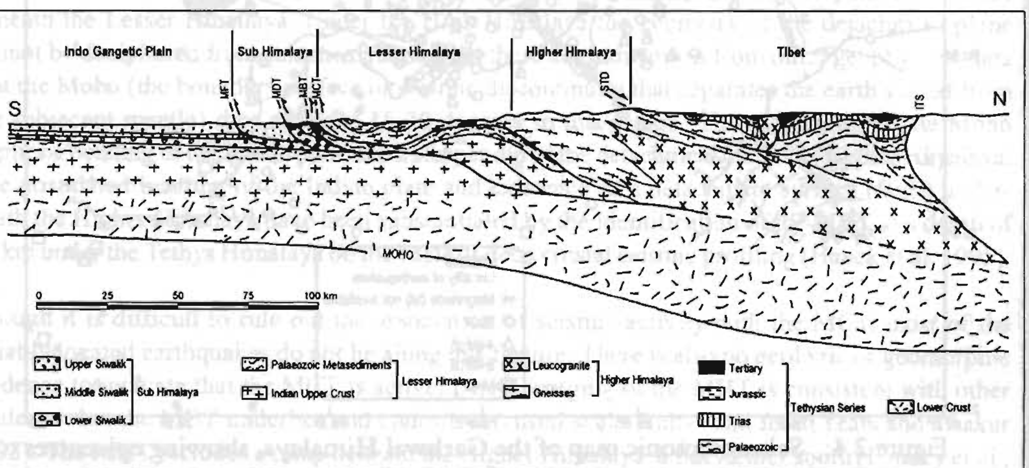

Figure 2.5: **Seismotectonic model of the Central Nepal Himalaya, showing detachment and ramp structures** (modified after Pandey et al. 1995)

conclusive, as they are based on preliminary and inadequate data. Because of a paucity of data, depth sections are often prepared by projecting events lying in a rather wide zone of a few hundred kilometres onto a single vertical plane, without regard to changes in tectonic and seismic trends. Such sections have resulted in potentially questionable features.

Since the Himalayan belt is very large in its lateral extent, any attempt to acquire data of the type mentioned above would have to be carried out at a few key locations where tectonic elements are well mapped on the surface. These locations then should be covered with a network of seismological observatories that enable the acquisition of earthquake data in digital form. The network might be operated in one location for about a year and then shifted to another key area. One could plan to have five such networks operating simultaneously, each covering an area of 100 km radius. To start with, these five locations could be the Kangra area, Tehri-Garhwal, the Kumaon Himalaya, the Nepal-Bihar border (site of major earthquakes in1934 and 1988), and the area centred at 27°N and 93°E in the eastern Himalaya.

In addition to seismological experiments, it would also be very useful to launch simultaneously other geophysical experiments, such as detailed gravity and magnetic and geodetic investigation, in these selected key areas. Such an approach would also permit tomographic modelling of subsurface features and boundaries, which in turn would help in delineating the continuity of tectonic features at depth.

Seismic hazards

Earthquakes pose great hazards to all major developmental activities, including dams, canals, roads, and bridges. The potential hazard for river-valley projects in the Himalaya should be assessed on the basis of geological, seismic, and seismotectonic aspects and taken into account when determining the size, design, and location of any planned engineering structure. It is important to note that the region's three great earthquakes (magnitude>8) since 1900 – Kangra (1905), Bihar-Nepal (1934), and Assam (1950) – all occurred south of the Higher Himalaya ranges along the border with the Gangetic plains, thus resulting in greater damage and loss of life than would have occurred in less populated regions.

With our present knowledge it is not possible to give short- or medium-term predictions of great earthquakes. We cannot forecast with any certainty where or when the next great earthquake will strike in the Himalaya. Khattri (1987) and others have postulated that the Garhwal-Kumaon—Western Nepal segment, which lies between the rupture zones of the 1905 and 1936 great earthquakes, represents a seismic gap that is most likely to experience a great earthquake. Another seismic gap is indicated in the region west of the rupture zone of the 1905 Kangra earthquake, since there is no historical evidence for any great earthquake in Jammu and Kashmir between the Taxila earthquake of AD 25 and the 1905 event, although smaller magnitude earthquakes did occur in 1828 and 1885 in Kashmir (Yeats and Thakur 1998). There is little basis for estimating the return period of great earthquakes in the Himalaya, it could be anywhere between 100 and 1000 years. Kathmandu in Nepal was destroyed by an earthquake in AD 1255 and again damaged in 1934, an interval of 679 years, with intervening smaller earthquakes in 1408 and 1681 (Bilham et al. 1995). Paleoseismological observations north of the Shillong Plateau, within the rupture zone of the 1897 earthquake, document earthquakes around 500, 1,100, and 1,500 years ago, a recurrence interval of 500 years (Sukhija et al. 1996). But much more needs to be done

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Appendix

Earthquakes - some general aspects

An earthquake is the oscillatory, sometimes violent movement of the earth's surface that follows a release of energy in the earth's crust. The energy can be generated by a sudden displacement and dislocation of segments of the crust, volcanic eruptions, or even manmade explosions. Most of the destructive earthquakes in the world are caused by dislocations in the earth's crust.

Seismology (from the Greek word 'seismos', meaning earthquake) is the science and study of earthquakes and seismic waves. **Seismographs** are instruments for detecting and recording earthquakes, while seismograms are records produced by these instruments. The seismicity of a region is the degree of susceptibility of a region to earthquake activity

The outer shell of the earth (the **crust**) consists of a several pieces called **plates**, which move relative to each other and to the interior of the earth (the **mantle**). These plates bump into, pull away from, or move past each other, creating strains. The plate movement also leads to the development of so-called **faults**, cracks in the earth that develop because sections of a plate, or two plates, are moving in different directions. Faults are more common, but not confined to, areas near the edges of plates.

The common types of faults are

- **normal fault**: a dipping fault plane with the top dropping down. This arises from extension when two plates diverge
- **thrust fault** (or **reverse fault**): dipping fault plane with the top riding over the bottom. This arises from compression, when two plates converge
- **strike slip** (or **transform fault**): no vertical motion, one side sliding horizontally relative to the other.

The plate movement (tectonic forces) causes blocks of rock on both sides of a fault or plate boundary to move past each other, but the movement isn't smooth. The rocks 'catch' on each other — they are still pushing against each other but not moving. After a while the rocks break because of the pressure that has built up – and an earthquake occurs.

Earthquake locations, when worked out with enough precision, are almost always along active faults. At the global scale, they define the plate boundaries. At the regional scale, the distribution of earthquakes defines the multiple faults that frequently characterise a plate boundary. In other words, plate boundaries and faults are major seismic zones. In general, major mountain belts, mid-oceanic ridges, faults, and trenches are zones of high seismicity; major shield regions are less seismic. However, no part of the earth's surface can be regarded as aseismic (free from earthquakes).

Origin and description

The most widely accepted theory of the origin of earthquakes postulates a process known as elastic rebound (the elastic rebound theory). According to this theory, when subjected to deep-seated forces (whose origins and natures are largely unknown), the crust may first bend but then, when the stress exceeds the strength of the rocks, it breaks and 'snaps' back to a new position. In the process of breaking, vibrations, or waves of energy, called **seismic waves** are generated. These waves travel from the source of the earthquake (referred to as the **focus**, or hypocentre) and travel through the earth and along its surface at varying speeds depending upon the media through which they travel. The point on the surface of the earth directly above the focus is called the **epicentre**. The location of an earthquake is commonly described by the geographic position of its epicentre and its focal depth. Seismologists refer to the direction of slip in an earthquake and the orientation of the fault on which it occurs as the **focal mechanism**. The focal mechanism can be calculated from measurements of the radiation pattern (direction of seismic waves) from an earthquake made at a number of distant seismic stations (**teleseismic phase data**; the results of the calculation may be called the '**fault plane solution**'). This pattern may be represented by a '**beach ball'** diagram, the '**focal sphere**', which shows both the orientation of the fault and the sense of motion on it. The area of the fault along which a slip occurs is called the **dislocation**. A dislocation can measure from a few to more than 100 km, whereas the actual slip is more likely to be in the range of a few centimetres to a few metres. The overall geological area affected by the earthquake, where the stresses produced exceeded the ultimate strength of the rocks, as shown by crushing and fracturing, is called the **rupture zone**.

Earthquakes with a focal depth of less than 60 km are termed shallow. Those with depths of 60-300 km are referred to as intermediate, while those with focal depths greater than 300 km are termed deep. The foci of deep earthquakes may reach depths of 700 km. Most earthquakes occur in the brittle rock of the lithosphere, (the uppermost 80-100 km of the crust and upper mantle), and shallow earthquakes are responsible for most seismic-related destruction on the earth's surface.

Elastic Rebound theory explains shallow earthquakes. But for intermediate and deep focal earthquakes, the earth is too 'fluid like' for elastic rebound theory to work. The best explanation for deep earthquakes is a sudden change in phase from one crystal form to another.

Most of the earthquakes with thrust-type focal mechanisms (i.e., resulting from compression when plates converge) are shallow. Focal mechanisms of moderate-sized earthquakes in the Himalayan region suggest underthrusting of the Indian plate along the Himalayan arc. Some earthquakes located further south, in the Indo-Gangetic alluvial region and the Sub Himalaya, show normal fault plane solutions, in other words they are the result of parts of the plate moving away from each other, not of pushing together.

Magnitude and destructiveness

The **magnitude** of an earthquake is usually expressed in terms of the **Richter Scale**. This is a measure of the amplitude of seismic waves and is related to the amount of energy released, an amount that can be estimated from seismographic recordings. The Richter scale, named after Charles Richter of the California Institute of Technology, is logarithmic: thus a recording of 7 indicates disturbance with ground motion 10 times larger than a recording of 6. An earthquake of magnitude 2 is the smallest that can be felt by humans. Earthquakes with Richter values of 6 or more are commonly considered major earthquakes.

The **Modified Mercalli Scale** (MM scale) is a subjective measure that describes the intensity of a shock felt at a particular place. It is based on the extent of damage to property and loss of life by an earthquake, and ultimately gives the measure of an earthquake's effects in a given locality in values ranging from I to XII. The evaluation of intensity is made from intensive ground surveys, eyewitness records, and the like.

The destructiveness of an earthquake depends on many factors. In addition to magnitude, these include focal depth distance from the epicentre, local geological conditions, and the design of buildings and other man-made structures, population density, and construction patterns in the affected area.

Earthquakes of large magnitude do not necessarily cause the most intense surface effects. The effects in a given region depend on local surface and sub-surface geological conditions. An area underlain by unstable ground (sand, clay, or other unconsolidated material) is likely to experience more noticeable effects than an area equally distant from an earthquake's epicentre but underlain by firm ground such as granite.

Prediction

The prediction of earthquakes is a subject that has occupied the minds of men since ancient times. Modern methods require large inputs of instrumentation and observations over long stretches of time. These include the following.

- Study and analysis of past activity, or palaeoseismology, which can help in estimating the repeat times of major earthquakes. However, such estimates can only be approximate.
- Frequent measurement of ground-elevation changes (geodetic measurements) in areas of known seismicity can be used to forecast seismicity.
- Emission of radon gas along weak zones, and water-level changes in wells and springs, can also be used as precursors.

However, the most reliable indicators of future seismicity are the results of a close network of sensitive seismographs that continuously record tremors. These measurements provide the basis for identifying seismically active areas and evaluating the depth, intensity, and magnitude of earthquakes. Seismologists can further analyse these data to estimate the extent of the rupture zone and determine the type or nature of movement (**focal mechanisms** or **fault plane solutions**).

Despite the creation of a global network of seismic stations, to date only a few earthquakes have been successfully predicted. Long-term predictions, made by analysing historic seismic gaps – extended periods of seismic quiescence – to estimate the repeat times of large earthquakes, can provide general guidance on probabilities and risks. However, short-term predictions (within a few hours or days of an event) have proved to be more challenging as a result of difficulties in establishing the magnitude and timing of fore-shocks or precursor events.