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Development of Faults and Prediction of Earthquakes in the Himalayas

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Abstract
Recurrence period of high magnitude earthquakes in the Himalayas may be of the order of hundreds of years but a large number of smaller earthquakes occur every day. The low intensity earthquakes are not felt by human beings but recorded in sensitive instruments called seismometers. It is not possible to get rid of these earthquakes because the mountain building activity is still going on. Continuous compression and formation of faults in the region is caused by northward movement of the Indian plate. Some of the larger faults extend from Kashmir to Arunachal Pradesh. Strain build up in the region results in displacement along these faults that cause earthquakes. Types of these faults, mechanism of their formation and problems in predicting earthquakes in the region are discussed.

Keywords- Faults and faulting, Himalayan thrusts, Oil trap, Seismicity, Superimposed deformation.

1. Introduction
If we go back in the history of the Earth (~250 million years ago), India was part of a huge land mass called 'Pangaea'. The land mass was positioned in the southern hemisphere very close to the South pole (Antarctica). Because of some reason, not known to us till now, the landmass broke and India started its onward journey in a northerly direction. At around 70 million years ago India reached the Equator. The gradual shift in the position can be verified by the changing climatic conditions. The climate was cold when it was close to Antarctica but a gradual increase in temperature is revealed by rock types deposited at the subsequent stages and fossils embedded in them. The continued journey led to closure of the Tethys sea and collision with Tibet, which is a part of the Eurasian plate. The collision led to gradual rise of the Himalayas, followed by subduction of the Indian plate below the Tibetan plate. Since the Indian plate is still moving, the evolution of the mountain belt is still continuous. The process led to folding of the Himalayan rocks and formation of a large number of faults. Displacements along these faults are responsible for earthquakes in the region. The precise timing of displacement along any of these faults is not possible. The seismic prediction increases many folds because different types of faults are developing simultaneously in the region. The object of the present publication is to explain the evolution of these faults in the Himalayas and to highlight the problems related to earthquake prediction.

1.1 Types of Faults
Faults develop in all the mountain belts and vary in size from few cm to hundreds of kilometres. These can be classified into the following three types depending on the stress orientations and pattern of displacement.

- (i) Thrust fault (Figure 1a)
- (ii) Strike slip fault (Figure 1b), and
- (iii) Normal fault (Figure 1c)

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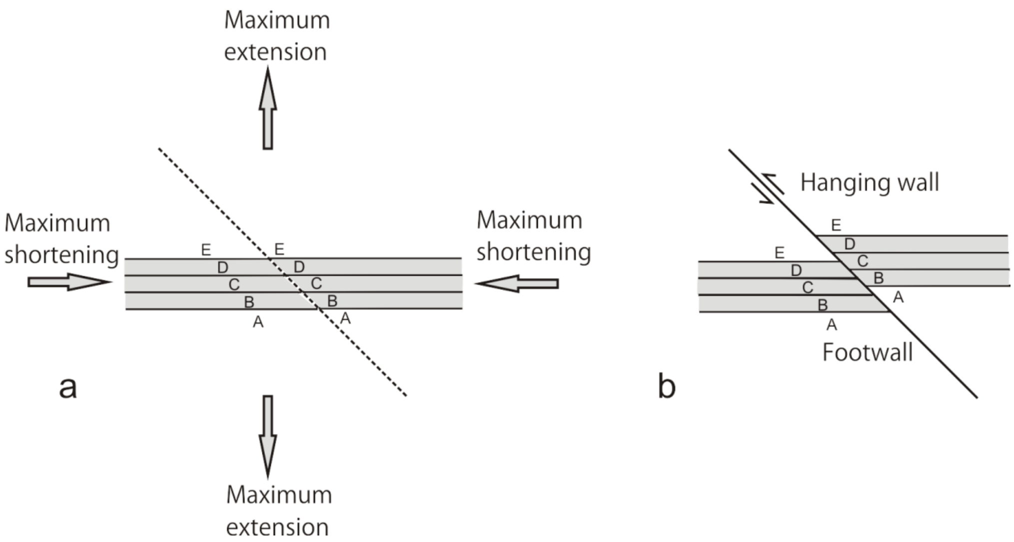

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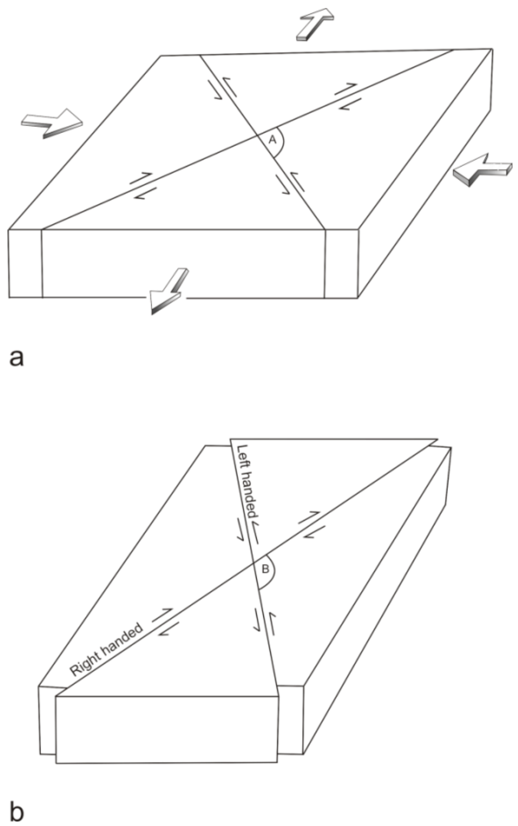

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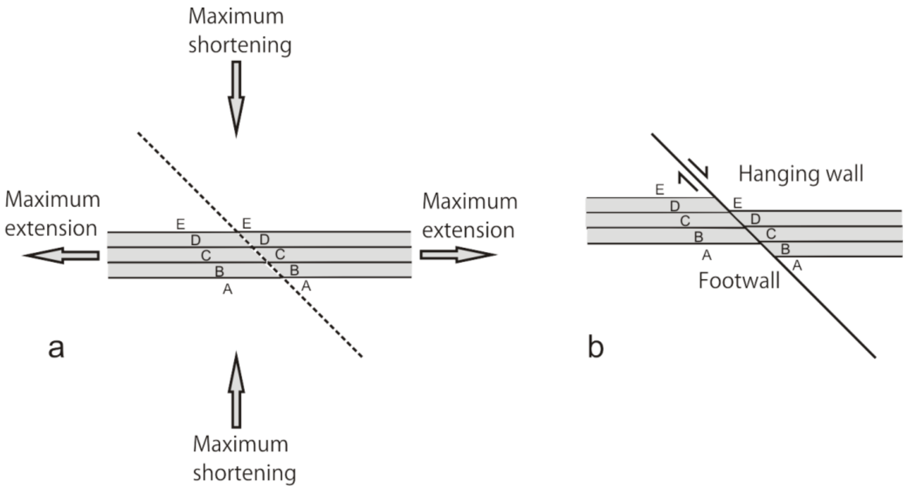

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Figure1. Stress orientations responsible for formation of three types of faults. The large arrows denote the directions of compression and extension. The relative displacements are shown by half arrows

A. Thrust fault. (a) Initial disposition of a multilayer sequence. (b) Upward displacement of the hanging wall (or downward displacement of the footwall, or displacements of both the walls).

B. Strike slip fault. (a) Conjugate set of strike slip faults. (b) A later stage of fault development. The angle between the fault and the maximum compression direction gradually increases with increase in deformation.

C. Normal fault. (a) Initial disposition of a multilayer sequence. (b) Downward displacement of the hanging wall.

1.1.1 Thrust Fault

These faults develop in a particular stress orientation when the maximum compression is in horizontal direction and the maximum extension (i.e. minimum compression) is in vertical direction (Figure 1a). The rock mass lying over the fault surface (i.e. hanging wall) moves upward along the fault surface and results in elevation increase. The rock mass lying below the fault (i.e. footwall) moves in the opposite direction. The movement of the Indian plate is along the horizontal direction hence the maximum compression in the Himalayan region is in horizontal direction allowing the formation of trust faults. Some of the prominent Himalayan thrusts extend throughout the length of the mountain from Kashmir to Arunachal Pradesh and are responsible for the great height of the mountain. The four prominent thrusts are as follows (Figure 2).

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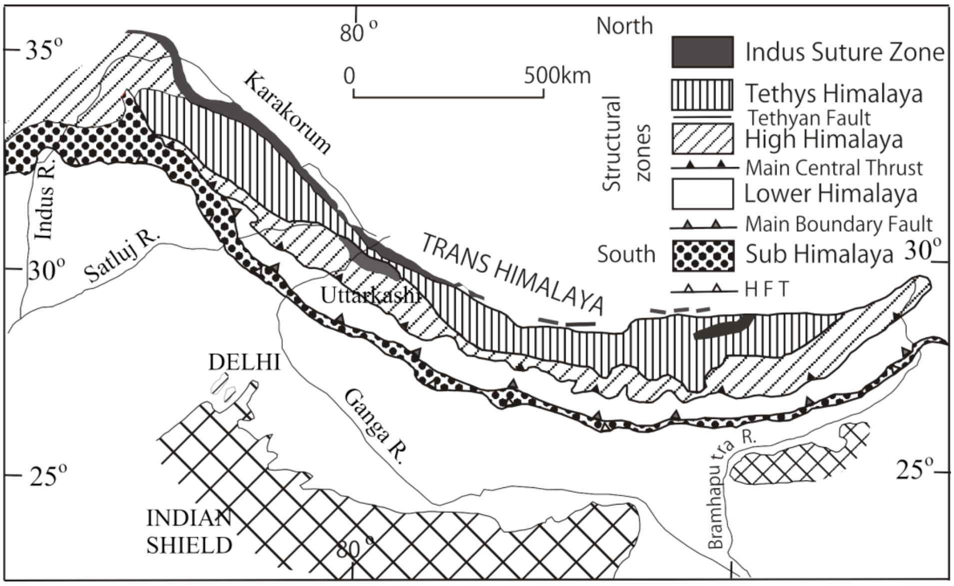

Figure 2. Tectonic subdivisions of the Himalayas (after Gansser, 1964)

Himalayan Frontal Thrust (*HFT*)

The southernmost Himalayan thrust separates the Indo-Gangetic Alluvial Plain from the Siwalik Sedimentary rocks exposed along the foothills of the Himalayas. These Siwalik rocks are fresh water sediments deposited by rivers originating from the rising mountain. Formation of the river system suggests initiation of the Indian Monsoon. A large number of vertebrate fossils indicates that the climate and vegetation were favourable for rapid growth of animals like elephant, horse, giraffe, crocodile, etc. A good exposure of the thrust can be seen at Mohand, south of Dehradun.

Main Boundary Thrust (*MBT*)

One of the exposure of this thrust can be seen north of Dehradun at Rajpur. The fault separates the young Siwalik rocks from the older Lower Himalayan rocks. These Lower Himalayan rocks have come from a deeper level because they have been subjected to higher temperature pressure conditions causing low grade metamorphism. Hence these rocks are classified as meta sedimentary rocks.

Main Central Thrust

The thrust is well exposed north of Uttarkashi in the Garhwal region. This brings into contact the Lower Himalayan rocks to the high grade metamorphic rocks of the High Himalaya. Sometimes the Main Central Thrust is divided into two; Munsiari Thrust (MT), and Vaikrita Thrust (VT). The region is described as core of the Himalayas. Most of the snow peaks are situated in this region.

Tethyan Fault

This fault has a complicated history of extension and compression revealed by upward and downward displacements along the fault. The recent displacement along the fault is that of

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gravity gliding. The hanging wall rocks show a thick sequence ranging from sedimentary to high grade metamorphic rocks. The fault can be observed at Malari, close to Badrinath.

Main Himalayan Thrust
The HFT, MBT, MCT and the Tethyan Fault are not planar surfaces but curved surfaces whose geometry is characterized by steep inclination (i.e. dip) near the surface and gradual decrease in dip with increase in depth. The geometry is described as listric fault. All the five faults joins at depth along a broad shear zone termed as the Main Himalayan Thrust (Figure 3).

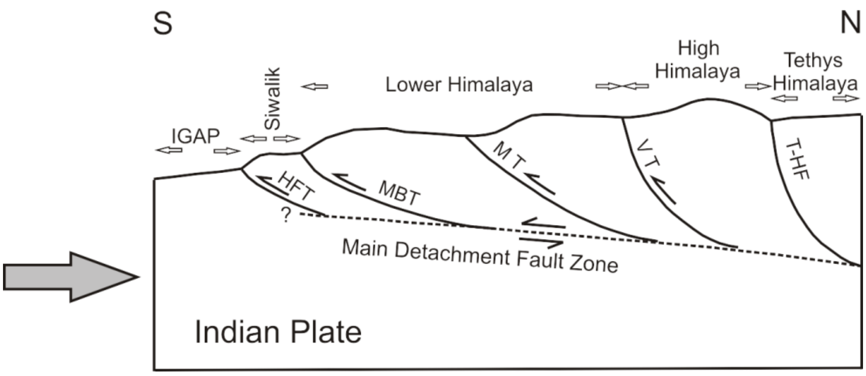

Figure 3. A cross-section of the Himalayas from south to north

1.1.2 Strike Slip Fault
These faults initiate when the maximum and the minimum axes of compression are horizontal. These faults are vertical, oriented at acute angle to the maximum compression direction and are marked by horizontal displacements (Figure 1b). Karakoram fault in Ladakh Himalaya is one of the largest strike slip fault as it extends for a distance of ~800 km.

1.1.3 Normal Fault
Normal fault is formed when the axis of maximum compression is vertical and the maximum extension takes place along a horizontal direction (Figure 1c). Most of the normal faults are minor structures in the Himalayas with the exception of a few, e.g. Leopargial Horst (Himachal Pradesh). The Tethyan fault is also reactivated as a normal fault but no seismic activity has been reported along the fault.

The above three types of faults represent the ideal conditions. When fault displacement is oblique to true dip of the fault surface (i.e. combination of any of the two type of faults), the fault is described as oblique fault or oblique slip fault. When a number of faults are present, the displacement can be transferred from one fault to the other in a way that decrease in slip along one fault is compensated by increase in slip on the other fault. The transfer can take place along a transfer fault zone (Davis et al., 2011).

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2. Problems in Prediction of Earthquakes

All earthquakes are related to displacement along one of the above faults or because of volcanic activity in the region. The molten magma pushes the overlying rocks with great force and the volcanic eruption is accompanied by earthquakes. There is no volcanic activity in the Himalayas but earthquakes in Iceland are good example of this kind of earthquake. The country is positioned above the Mid Atlantic Ridge, which is a long volcanic chain extending from south to north across the earth. Since the movement of subsurface magma is comparatively easy to monitor using geophysical methods, this type of earthquake can be predicted with satisfactory precision. In most parts of the world, earthquakes are related to a particular fault type. For example earthquakes in Turkey, Iran and western coast of America are related to displacement along strike slip faults. Earthquakes in Japan and Sumatra regions are related to thrust faulting. However, earthquakes in the Himalayas are related to all the three types of faults that are developed throughout the vast region.

Some of the recent earthquakes in the Lower Himalayas were generated by thrust faulting (e.g. Kangra, 4 April 1905; Uttarkashi, 20 October 1991, magnitude 6.5; Chamoli, 29 March 1999, magnitude 6.3). The Kinnaur earthquake (19 January 1975, magnitude 6.5) of the Himachal Himalayas was caused by normal faulting. The central Nepal earthquake (25 April, 2015, magnitude 7.8) was caused by predominant thrust faulting with a component of strike slip faulting (i.e. oblique fault slip). As mentioned in the preceding section, each type of fault develop in a specific stress condition. Then how the different type of faults are developing simultaneously in the region?

One of the models for simultaneous development of thrust and normal faults is discussed here.

2.1 Simultaneous Development of Thrust and Normal Faults.

A schematic model for the simultaneous development is shown in Figure 4. The first stage of deformation (Figure 4a) shows compressive stress using the pistons and displacement along a gently dipping thrust fault with maximum extension in vertical direction. Progressive deformation leads to rotation of the listric fault surface in a clockwise direction thereby resulting in increase in thrust dip (Figure 4b). The deforming rock mass gradually reaches to the height of the pistons. Displacement along the thrust leads to initiation of a fault propagation fold (Figure 4c). The degree of fold asymmetry depends upon the thrust dip. A gentle dip results in a greater asymmetry. The upward extension of the model, after surpassing the height of the pistons, leads to overflow of the upper part in horizontal directions. The overflow results in extensional regime at the higher levels creating conditions suitable for formation of normal faults (Figure 4d). Thus thrust and normal faults develop simultaneously at different levels. The described mechanism may be responsible for development of recent shallow normal faults in several parts of the Himalayas where similar deformation conditions exists (Valdiya et al., 1984; Rautela and Sati, 1996; Srivastava and John, 1999; Kandpal et al., 2006;).

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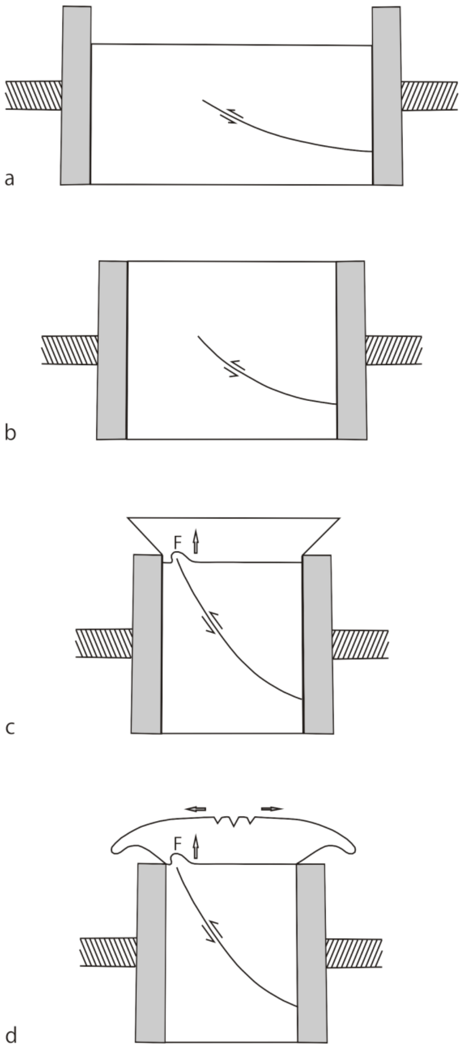

Figure 4. Schematic diagram showing simultaneous development of thrust and normal faults (details in text)

The model explains the absence of young thrusts at the surface. The active blind thrust cannot propagate in the upward direction because of prevalence of extensional strains near the surface. Thus the proposed model brings a tiding for the regional habitats. The contrasting stress conditions at the upper level can reduce or confine the displacement along an active thrust fault thereby lowering the intensity of a possible earthquake.

The following four major earthquakes have occurred in the recent history.

(i) Shillong earthquake (12 June 1897, M 8.1)
(ii) Kangra earthquake (4 April 1905, M 7.8)
(iii) Bihar-Nepal earthquake (15 January 1934, M 8.1)
(iv) Assam earthquake (15 August 1950, M 8.6)

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However, except the Assam earthquake, the other events have not produced coseismic ruptures (Yeats and Thakur, 1998). The above model can explain the termination of thrust faults beneath the surface because of prevalence of extensional strains at the upper levels.

2.2 Simultaneous Development of Thrust and Strike Slip Faults

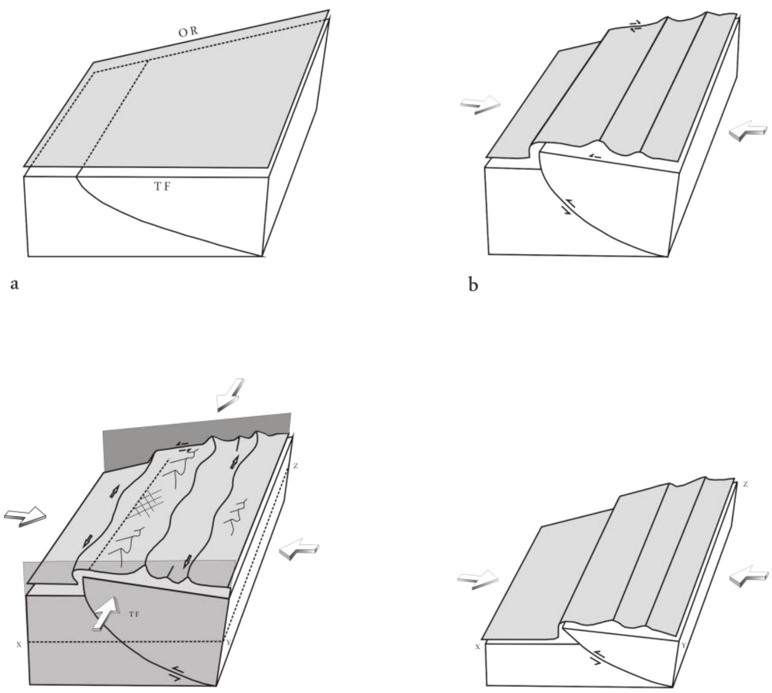

Figure 5. Schematic diagram showing simultaneous development of cross folds, thrust and strike slip faults at different structural levels (details in text)

The model for the simultaneous development is shown in Figure 5. A listric fault is shown in the basement. The fault may have formed prior to deposition of some of the younger formations. The fault is bounded by a transfer fault zone (TF) at the front face and an oblique fault at the back face. An overlying undeformed layer is shown in gray. The compressive stress led to thrust displacement along the fault and development of an asymmetric propagation fold at the propagating thrust tip. Upright buckle folds form at some distance from the thrust (Figure 5b). The fold hinge lines are parallel to strike of the thrust. The thrust surface rotates with increase in deformation thereby increasing the amount of dip. The thrust locks at steep dips and the folds acquire rotation hardening at low interlimb angles (Figure 5c). After locking the thrust can extend only parallel to its strike. The fold surfaces also extend parallel to the hinge lines after the rotation hardening. Thus the stress orientation in the system changes. The maximum compression direction remains horizontal and the extension direction changes from vertical to horizontal direction (details in Dubey, 2014). This condition is favourable for formation of strike slip faults that are formed in conjugate set oblique to the fold surface (Figure 5c). The horizontal extension is prohibited by the boundary condition imposed by the transfer fault and the oblique fault. The restrain at the two ends results in curvature of the fold hinge lines and formation of folds whose hinge lines are parallel to the axis of maximum compression. These folds may be termed as superposed folds though they have formed in the same phase of deformation. The simultaneous development of folds and strike slip faults can be observed only at upper levels. At the lower structural levels, the listric thrust does not lock because of gentle dips (because of listric fault geometry) and can undergo thrust displacement. Figure 5d shows the predominant structure at depth along the X - Y section shown in Figure 5c.

The described variation of the stress state with depth is significant for understanding the seismicity in the Himalayan region. The inference also has implication for GPS studies where the data are collected from surface displacements alone. The deep earthquakes are related to thrust faulting mainly along the Main Himalayan thrust where the listric geometry plays a crucial role. The thrusting takes place at deeper levels where the dips are gentle and not at upper levels where the dips are steep. The middle level earthquakes are related to strike slip faulting that has taken place after locking of the listric thrust at this level. The shallow earthquakes are likely to be caused by normal faulting.

3. Discussion

The seismic prediction still remains enigmatic despite years of research by a large number of eminent scientists on different aspects of Earth sciences. The main obstacle lies in complexity of structures that are responsible for an earthquake. The story is similar to patient- doctor relationship. If the patient is suffering from a single disease the treatment is simple. But if he is suffering from a large number of diseases at the same time, then the treatment becomes complex. The doctor must prescribe a large number of medicines, which may interfere with one another and produce several side effects. In orogenic belts like the Himalayas, there is simultaneous development of thrust, normal, and strike slip faults along with oblique faults and displacement out of the tectonic transport plane. The region has also suffered superimposed deformation resulting in reactivation of thrust and normal faults. Some of the strike slip faults are related to early deformation (resulting from ~N-S maximum compression) whereas the others are related to superposed deformation (resulting from ~E-W maximum compression). High strain regions are known to earth scientists but the present knowledge does not allow them to determine the precise time for strain release in form of displacement along a fault. Suggestions have been made but they are approximate and not very reliable. For example, the Central Nepal earthquake (25 April, 2015) had happened about 100 years ahead of the scheduled time postulated by seismologists.

Precise geometry of the subsurface structures is also not known. This is mainly because of lack of drilling data from the region. The geophysical investigations and drilling are costly affairs hence these are not attempted on a large scale because of lack of petroleum reserves. There are a large number of faults in the area and they have inhibited the formation of suitable oil traps. There are a few gas shows, e.g. at Jwalapur in Himachal Pradesh. A continuous flame can be observed in the temple of Jwaladevi. The historical records shows that the Mogul emperor Akbar (1556-1605) visited the temple, observed the flame and donated a large bell (*Ghanta*), which is still preserved in the temple. However no oil or gas reserve could be located despite drilling by the ONGC. This could be because of two reasons; (i) the oil bearing formation is at a great depth, and (ii) presence of faulting has prevented gas accumulation.

Efforts have been made but we fail to understand as to how some animals can predict an incoming earthquake. Their natural warning system provides them enough time to come out of their holes or shelters and reach to a comparatively open and safer place. However, the advanced specie of human has failed in all attempts on the prediction. Perhaps the answer lies in the evolution history. For example, whale was initially an amphibian with a much smaller body but after passing through different stages of evolution, it has now grown enormous in size and is totally aquatic. The monkeys and chimpanzees can easily climb on trees and can perform acrobatics but their descendents lack in this quality. Hence the evolution results in increase of certain capabilities of organs and decrease of some. The humans have increased the size of their brains but they appear have lost some of their vital sensory organs including the one which could provide an earthquake warning. We may have lost this sense but are not in a position to know what we have lost. This can be compared to a situation where a visually handicapped person cannot visualize the seven colours of a rainbow. Be hopeful because one day science may let us know what we are looking for and the technical advancement will somehow recoup the lost sense. Anyway, in the mean time we have to satisfy ourselves with the present seismic warning system that provides us a couple of seconds for all the preparations before an earthquake.

4. Conclusions

Precise timing for an earthquake is not possible anywhere in the world but it is more complicated in the Himalayan region because all the three types of faults are developing at the same time at different levels. The three dimensional geometry of these faults also varies and dip amounts show a considerable variation with depth and in the horizontal direction. Theoretical and experimental models suggest thrust faulting at deeper levels, strike slip faulting at intermediate levels, and normal faulting at shallower levels. However, at the moment these results are only suggestive.

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