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Identification of Seismic Gap for Bhuj, Sumatra and Muzaffarabad Earthquakes

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Abstract

A seismogenic region that has historically experienced large earthquakes, but not recently, is more likely to produce a large earthquake in the next few decades than those places that have recently experienced large events. Such a geographical area is identified as a 'seismic gap', where accumulation of crustal stresses takes place, leading to a major seismic event. Space – time mapping of epicentres of the seismic events prior to such major earthquake in the area reveals that a part of it has not been frequented by seismic events for a number of years. Due to such characteristics, it has been identified as one of the long-term precursors to predict an impending earthquake.

To examine the merit of the concept of 'seismic gap', analysis of seismic events in relation to three recent major earthquakes, viz., Bhuj 7.9 M, Jan. 2001, Sumatra 9.2 M, Dec. 2004 and Muzaffarabad 7.7 M, Oct. 2005, has been carried out. For this purpose, seismic data for the period of the last 30-40 years obtained from United States Geological Survey (U.S.G.S.) and International Seismological Centre (I.S.C.) were analysed. Epicentral plots of seismic events were constructed with minimum appropriate magnitude in each case. These plots reveal a particular area, which has not been frequented by seismic events, before the major earthquake occurred. The same has been identified as a 'seismic gap'

Rikitake's (1981) equation to estimate magnitude of the impending earthquake has also been applied to the three events under consideration. The study reveals that the precursory period estimated yields the magnitude of the earthquake more or less close to observed values of the major earthquakes mentioned above.

Introduction

An earthquake is a natural phenomenon that, depending on its magnitude, causes damage of certain dimension. Study of earthquakes or seismic events deals with the following attributes:

1. Distribution of epicentres,
2. Variations in magnitude through time,
3. Distribution of foci depths,
4. Recurrence period,
5. Spatio-temporal distribution of major seismic events etc.

The study of attributes has led to the development of the science of earthquake prediction. However, this science is still in its developing stage.

Earthquake Prediction and Precursors

Iyer (1988) maintains that an earthquake prediction must specify the expected *magnitude range*, the *geographical area*, and the *time interval.* Seismologists have identified a number of precursors, which can be used for earthquake prediction. A precursor is considered as an indication, which gives signal of an earthquake before its occurrence.

No single precursor is complete in itself. An integrated approach is essential for prediction related research. All possible precursors are required to be used in combination, depending on the seismo-tectonic and physiographic characteristics of seismogenic regions. Long-term precursors should be employed to locate likely areas of accumulation of stresses. Such areas can further be closely investigated for presence of medium-term and short-term precursors. If the signals of these precursors are positive, immediate-term precursors need to be intensively monitored. Such areas should be under constant observation for all the physical and chemical changes in the lithosphere, atmosphere and biosphere.

Concept of Seismic Gap

Occurrence of earthquakes and distribution of their epicentres have led to identify two major seismogenic belts on the earth's surface. These belts, however, happen to coincide with two major convergent and divergent plate boundaries that have been identified under the concept of Plate Tectonics. It has been observed that major seismic events from the historical record and also in the recent past are confined to such plate boundaries (Bolt, 1999). A portion of plate boundary that has historically experienced large earthquakes but has remained silent in recent past (e.g. for a period of 30+ years), is more likely to experience a large earthquake in near future than those portions of the plate that have been experiencing large events in recent past. Such a geographical area is identified as a 'seismic gap' (Kelleher, 1970, 1972 and Kelleher et al. 1973). Thus, the period of quiescence that results after a major earthquake, is the one during which accumulation of crustal stresses in a 'seismic gap' takes place. As and when the tolerance limit exceeds, probability of a major seismic event increases in such gap areas (Utsu, 2002). The premises behind the concept of seismic gap is that the large earthquakes occur more or less regularly in space and time as a result of gradual stress build-up in a 'seismic gap' and sudden stress release by failure in the form of earthquakes of higher magnitude (Kanamori, 2002). Identifying and demarcating a seismic gap is a major task in the development of this precursor. This concept has been developed by Fedotov (1965), Mogi (1968) and Sykes et al. (1999).

Model of Seismic Gap

Development of a seismic gap has been schematically presented in Fig. 1. All the characteristic features of seismic gap are implicit in this schematic diagram. The model shows the spatio-temporal distribution of seismic events over a geographical area. Stage 1 represents the condition immediately after the occurrence of the major earthquake event where the whole region is dotted with a number of (small/ low magnitude) seismic events. This

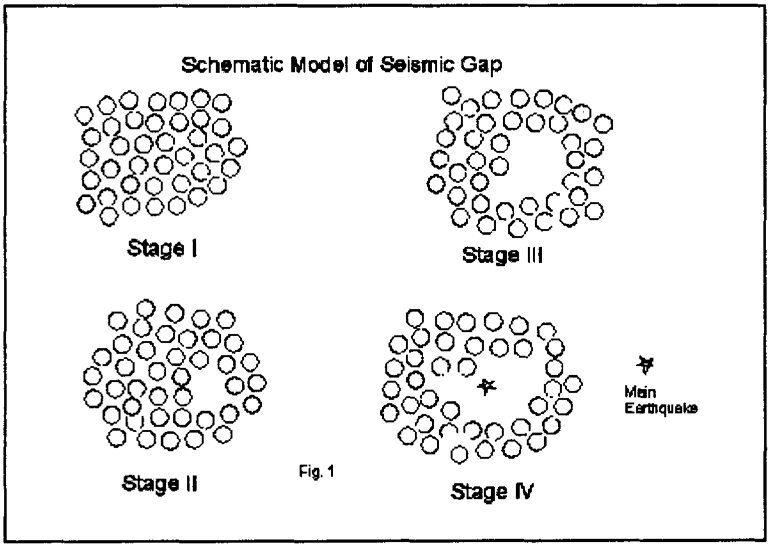

Fig. 1: **Schematic Model of Seismic Gap**

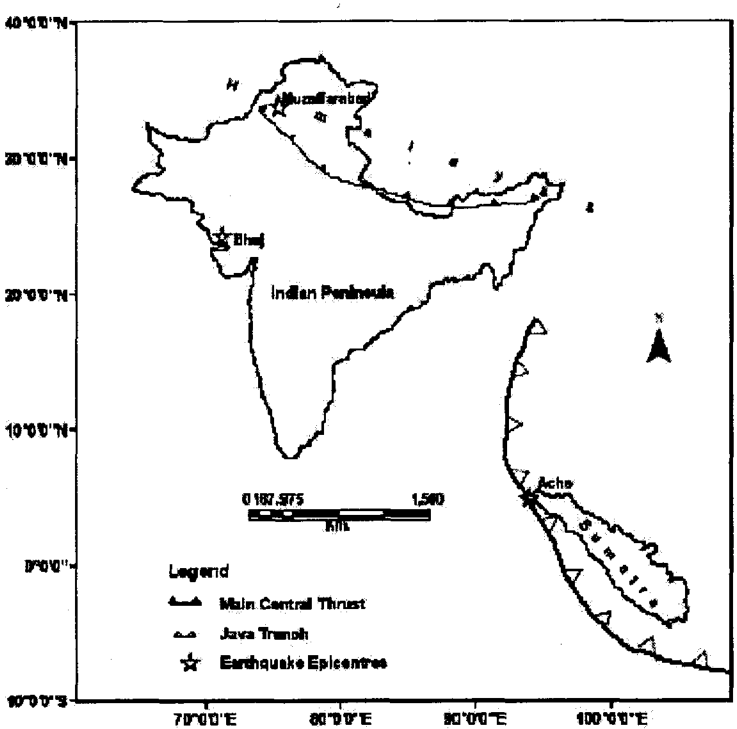

Fig. 2: **Location Map**

is an indication of the fact that the area is still releasing stress after a major event. In the subsequent stages, frequency of earthquakes decreases, indicating accumulation of stress in the region. The stage 2 shows seismic gap in embryonic stage that gets further developed in stage 3 and 4., after which a sudden release of stress in the form of an earthquake becomes a highly probable condition. .

In the present paper, an attempt has been made to identify seismic gaps for the events that have occurred in recent years, such as: Bhuj (Kutch, Gujarat, India), Ache (Sumatra, Indonesia) and Muzaffarabad (Kashmir) (Fig.2).

Seismic Gap Method

Being one of the long-term precursors, seismic gap can give an idea about a region, which is accumulating stress for 15 to 50 years. This can be found by plotting epicentres in a particular region with convenient time interval. In short, this is an analysis of spatio-temporal pattern of earthquakes in a seismogenic region. As the crustal stresses act over a vast region, analysis of seismic data is carried out in such a way that epicentral plots should cover, as far as possible, an entire region selected for the purpose. While selecting and delimiting a region for any type of statistical and spatio-temporal analysis of seismic data, one needs to ascertain that the region forms a seismogenic area. This is because aseismic areas may be mistaken as seismic gaps, as they may not show occurrence of major seismic events. At the same time, the region must form a fairly homogenous geotectonic unit. This is to ensure that similar stress conditions prevail in the region under consideration. This is necessary because the stress conditions differ in the different geologic and tectonic conditions. The rate at which the stress is accumulated and released differs from region to region. The release of stress during the seismic event is expressed as magnitude on Richter scale (M), which is logarithmic.

Similarly, comprehensive earthquake catalogue should be referred to for earthquake records. Some catalogues do not cover seismic events less than 4.0 M; even all the events of more than 5.0 M are not included in these catalogues, whereas some catalogues do not provide current data and lag behind the time by 4 to 5 years. Such discrepancies in data sets may lead to erroneous results.

Analysis of Seismic Events

In the present study, the merit of the concept of a 'seismic gap', as a long-term precursor, has been examined. Depending upon the geotectonic nature and the seismic history of the regions and time interval, the cut-off point for magnitude is decided for plotting the epicentres in the respective regions. In highly seismic regions like Sumatra, the seismic events only above 7.0 M are plotted to find the seismic gap, whereas for Muzaffarabad and Bhuj areas, the cut-off magnitudes are 6.0 M and 4.5 M, respectively. The epicentral plots for the seismic events from the Bhuj and Sumatra areas have been presented with the interval of 10 year period; while that for Muzaffarabad area, these have been presented with the interval of 5 five year period (Figs. 3, 4, 5). These time intervals so selected are according to seismotectonic characters of the regions. In these figures, for the three areas under consideration, a star shown represents the major seismic event in the respective area. The regional characteristics of each area are given, in brief, before discussing the development of seismic gaps.

Bhuj Area

Summary of regional characteristics:

1. Location of the Epicentre of the Bhuj earthquake (23° 42'N * 70° 20'E),
2. Depth of focus – about 16 km.
3. Areal extent for Seismic Gap analysis – 64° E to 75° E long and 18° N to 28° N. lat.
4. Geological Setting – Jurassic sedimentary rocks, equivalent to the upper division of the upper Gondwanas, interstratified with marine beds, 450 m. thick sequence (Krishnan, 1982).
5. Major Tectonic Elements – a) Island Belt Fault b) Kutch Mainland Fault c) Katrot-Bhuj Fault d) Coastal Faults (GSI, 2000). Uplifts in the area are delineated by these E-W trending major faults.
6. Physiographic Features – A rift basin with highlands due to uplift and plains – basins in the form of half grabens between uplifts. Low rolling sandy saline marshy plains, almost dry mud flat with a veneer of salt in dry winters, bare rocky hills (Singh, 1990). Elevation 0 to 15 m. above mean sea level.
7. Seismic Character – High.

It is seen from Fig. 3 – (stages 1 to 4) that there is a change in the frequency of occurrence of the seismic events. There is a slight increase in the seismic events from 1971-80 to 1981-90. However, later, there is a decrease in the frequency of seismic events in the decade of 1991-2000 and the area is marked by seismic events of lower magnitude of <5.0 M. The star in each figure represents the major seismic event of 7.9 M (2001) that rocked the Bhuj area. It may be noted that there is no major seismic event in the Bhuj area since 1981 and no seismic event exceeded 6.5 M during the period from 1971 to 2001. Such an absence of a major seismic event in the area is a clear indication of accumulation of stress, which is likely to be released in the form of a major seismic event.

Sumatra Area

Summary of regional characteristics:

1. Location of Epicentre: 5. 5° N * 95.947° East.
2. Depth of Focus: about 30 km.
3. Areal extent for seismic gap analysis: 85° E to 110° E long. and 4° S to 7° N lat.
4. Geological setting: Formations of the Precambrian to Lower Palaeozoic period, unconformably overlain by the Upper Carboniferous and the Jurassic and Cretaceous sediments and Tertiary to Pliocene with intercalated thin lignite and coal seams.
5. Major Tectonic Elements: The most active complex tectonic zone at the convergence of the Indian and Burmese plates and the oblique convergence of the Indo-Australian and Eurasian plates, marked by 300 km long Sunda volcanic arc and the Sumatran Fault system.

Epicentres of Earthquakes of M = 4.5
Bhuj Area

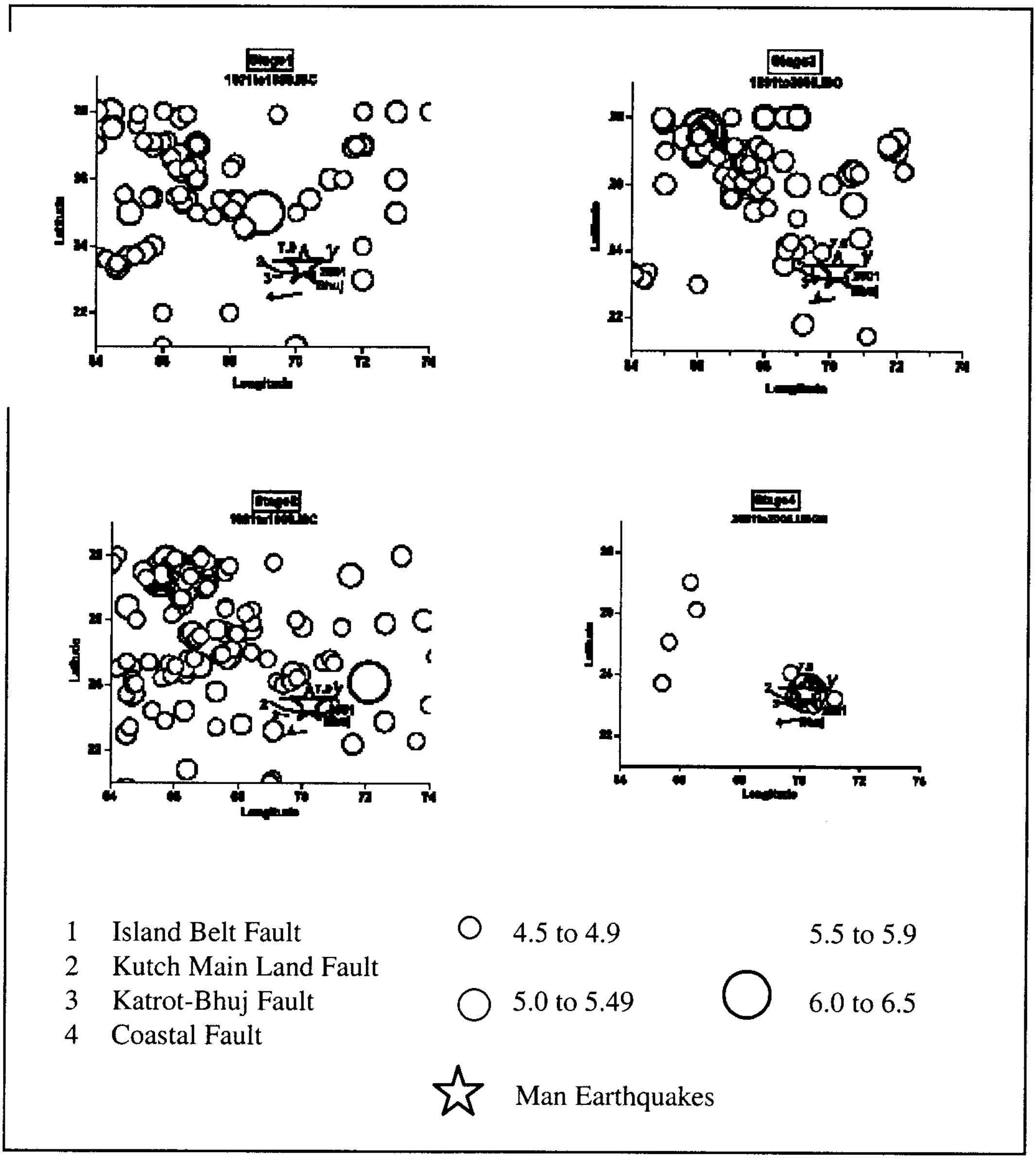

Fig.3: **Seismic Gap – Bhuj Earthquake, 7.9 M (26th Jan., 2001)**

Epicentres of Earthquakes of M = 7.0
Sumatra Area

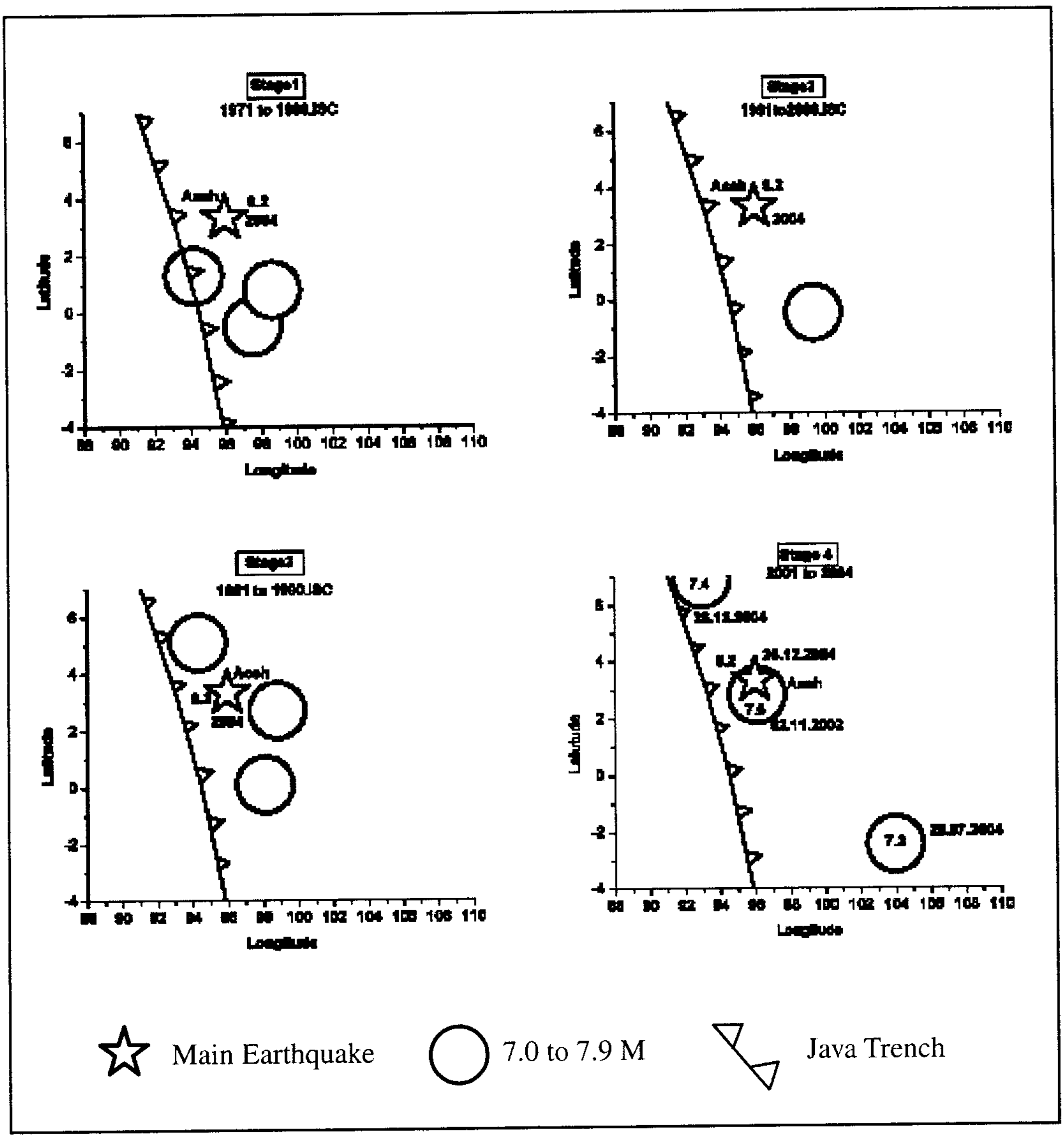

Fig. 4: **Seismic Gap – Sumatra Earthquake 9.2 M, (26th Dec., 2004)**

6. Physiographic Features: Volcanic island with indented coast line, elevation of about 0 to 10 m above mean sea level.
7. Seismic Character: High

The area is highly seismic and the seismic events of about 7.0 M are very common. Thus, for seismic gap analysis, seismic events of = 7.0 M are considered. It may be noted that Java trench being the controlling factor, the epicentres are more or less aligned linearly along the same (Fig.4 – stages 1 to 4). Since 1971, there is no major seismic event of the order of 8.0 M or above. There are only three seismic events of = 7.0 M in the decades of 1971-1980 and 1981-1990. In the following decade, i.e. 1991-2000, the frequency of the seismic events of = 7.0 M came down to one and this seismic event of = 7.0 M is far from the epicentre of the major seismic event of 9.2 M (2004), clearly indicating the building-up of stress in the area culminated into the major event.

Muzaffarabad Area

Summary of regional characteristics:

1. Location of Epicentre: 34° 30' N* 73°30' E
2. Depth of focus: about 26 km.
3. Areal extent for seismic gap analysis: 68°E to 79°E long. and 29°N to 40°N lat.
4. Geological setting: Metamorphosed Central Tethyan sediments with granitic plutons and basic intrusives of the Precambrian; unconformably overlain by sedimentaries of the Cretaceous to Tertiary to Pliocene (Pascoe, 1965).
5. Major tectonic elements: E-W trending – i. Main Mantle Thrust, ii. Main Boundary Thrust and iii. Main Central Thrust. Major neotectonic faults are: Jhelum, Mangla, Tarbela, Shinkiari, Peshawar and Attock (GSI, 2000); located at the plate margin between Indian and Eurasian plates.
6. Physiographic Features: Rugged mountainous region forms a part of the western Himalayas (Singh, 1990), Elevation > 5500 m. above mean sea level.
7. Seismic character: High

Being located at the plate margin between the Indo-Australian and the Eurasian plates, the area is seismically very active. Here the seismic events of =6.0 M are considered for the analysis. It may be noted that since 1991, the frequency of occurrence of seismic events has been reduced in the area around Muzaffarabad (Fig.5 – stages 1 to 4). Also there are only three events of 7.0 to 7.5 M from 1986 to 2001. They are 7.3 M (July, 1991), 7.2 M (Aug, 1993) and 7.4 M (March, 2002). Overall decrease in the frequency of seismic events in the area and limited number of seismic events of 7.0 M to 7.5 M, can be taken as an indication of impending major earthquake of magnitude more than 7.5 M. This assumption is clearly supported by the Muzaffarabad earthquake (7.9 M, October, 2005).

Precursory Period and Magnitude Estimation using Rikitake's Equation

The time from which a particular precursory condition begins to appear before a major earthquake is called Precursory period (Tp).

Epicentres of Earthquakes of M = 6.0
Muzaffarabad Area

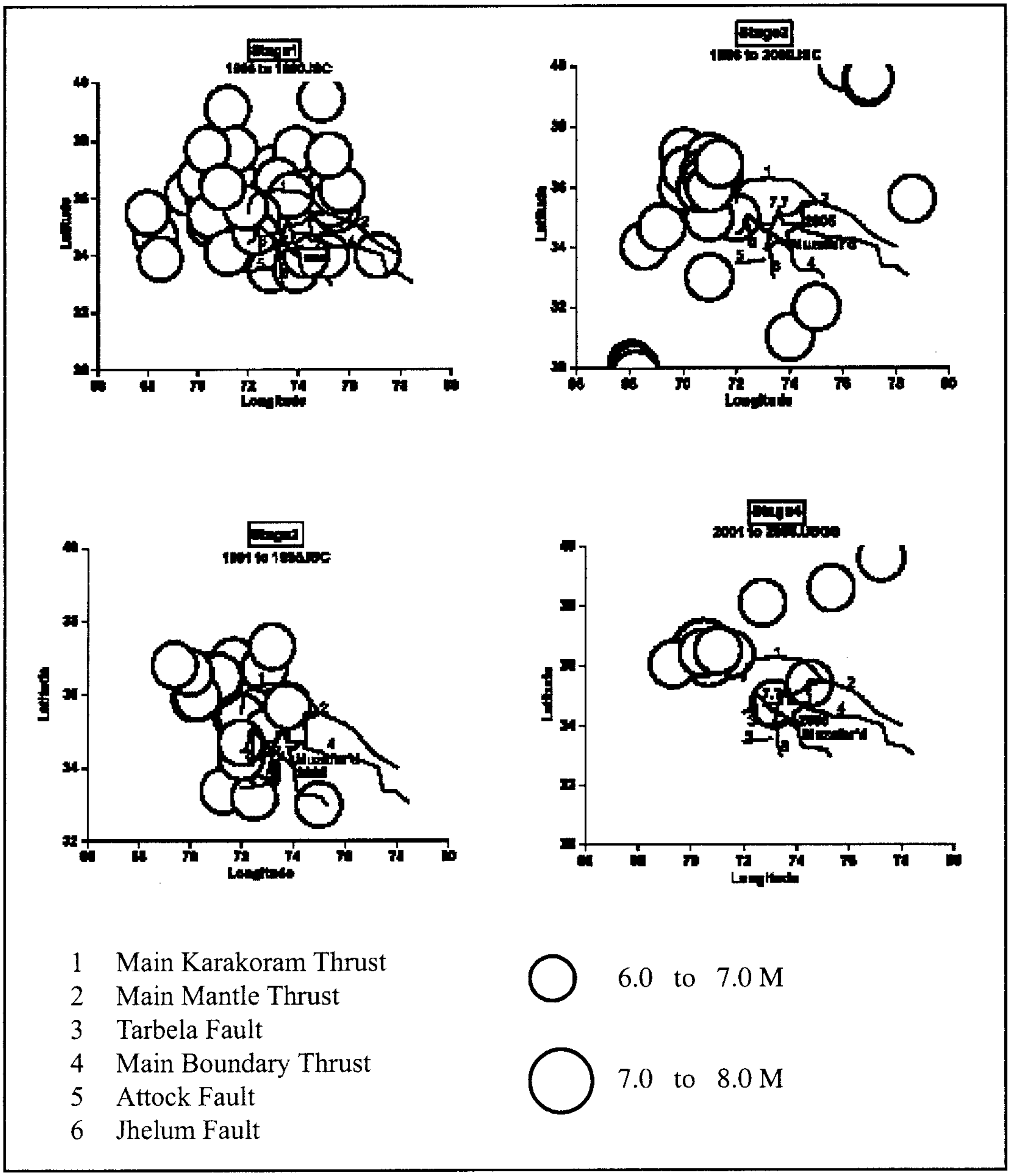

Fig. 5: **Seismic Gap – Muzaffarabad Earthquake, 7.7 M (8th Oct., 2005)**

This varies with the type of precursor. For long-term precursors, like seismic gap, Tp may range from 15 to 50 years. Rikitake (1981) has used such long-term precursory period in his equation for estimation of magnitude of the earthquake, which is likely to occur in the gap area. In the analysis of the three seismic events from Bhuj, Sumatra and Muzaffarabad areas, it was found that the precursory period starts from stage 1, wherein the area is dotted with only low magnitude earthquakes. Gradual development of seismic gap takes place within which subsequently a major seismic event can be expected. The precursory period should be counted till the seismic gap develops fully as shown in the stage 4 of Fig. 3 and also in Figures 4 to 5. Rikitake (1981) has suggested the following equation,

$$\text{Log } Tp = 0.60M - 1.01$$

where: Tp: - Precursory period (No. of days) and

M: - Expected magnitude.

This equation has been employed in all the three events for comparing the observed and estimated magnitudes by taking precursory period from the respective seismic gaps. The results are given in Table. 1.

Conclusions

In brief, it can be stated that the post event analysis of the three major seismic events, viz; Bhuj, Sumatra and Muzaffarabad has brought out the significance of seismic gap as a long-term precursor for identifying the most probable geographic area, where major seismic events could take place in future. At the same, the validity of Rikitake's equation in estimating the magnitude of future earthquake also gets established.

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Table 1: **Estimation of Magnitude**

**based on Rikitake's Equation*

Seismic Event	Seismic Gap Initiation since	Precursory Period (in days)	Observed Magnitude	Estimated Magnitude*
Bhuj (Jan 26, 2001)	1986	5474	7.9M	7.9M
Sumatra (Dec 26, 2004)	1971	12410	9.2M	8.5M
Muzaffarabad (Oct 8,2005)	1991	5474	7.7M	7.9M

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