

# **SEISMOTECTONIC ANALYSIS OF ZIARAT, BALOCHISTAN EARTHQUAKE OF 29<sup>th</sup> OCT, 2008**



**BY**

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## **FOREWORD**

The knowledge of tectonic features, developed due to stress regimes, plays an important role to study the seismodynamic behavior of the area. Detailed analysis of location specific seismicity is of great concern to understand the geophysical behavior of earth and provides reliable foundation to determine the earthquake hazard potential in particular areas of interest. Sustainable development is directly linked to hazard potential and its mitigation. Furthermore rapid population growth even in remote parts of the country stipulates the needs for a better understanding of all kinds of natural hazard.

Quetta-Ziarat earthquake of 29<sup>th</sup> October 2008 occurred in the early morning inflicting casualties and property damage in the area. It was typically a strong jolt which resulted into severe ground shaking, experienced in the vast region around. Taking intrepid steps, a team of PMD seismologists was sent to earthquake affected areas for collection of aftershocks data. The team spent several weeks in the field, established temporary seismic monitoring stations and recorded the aftershock activities extensively. This data was then scrutinized, compiled and analyzed by a group of experienced seismic expert at Islamabad. Findings of the study would be helpful to understand the seismo-tectonics, earthquakes mechanism, faults behaviors and quaternary geology of the region.

This report may provide the guidelines to the planners who are involved in the rehabilitation & construction of Quetta-Ziarat region. It will pave the way to deeply investigate the future behavior of geodynamics, microanalysis of seismicity and to develop futuristic strategies for disaster risk assessment and management. This effort is expected to open the avenues of detailed research in other risk prone area of Pakistan where construction of infrastructure could be under-taken on solid scientific basic to reduce the economic losses and protect the lives of dwellers.

I appreciate the professional dedication of the monitoring team which completed its job in harsh weather conditions and highly volatile seismic environment. The efforts of the authors of this report are laudable who have managed nicely to complete, analyse and interpret data in the form of report. The worth of research is the strength of nations.



(Dr. Qamar-Uz-Zaman Chaudhry)  
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## ABSTRACT

A severe shock of magnitude 6.5 Mb on Richter scale occurred on 29 October 2008 in Chiltan hills Balochistan at 05:10 PST having Epicentral coordinates 30.612°N and 67.436°E, at depth of 15 km. Foreshock of Magnitude 5.0 Mb originated at 04:33 PST having Epicentral coordinates 30.51°N and 67.48°E and depth 12Km. The epicenters of these earthquakes were about 60 km North-Northeast of Quetta. Tremors of this earthquake were felt in most parts of Balochistan including some adjacent parts of Sindh Province. The intensity of main shock was VIII in and around the Ziarat-Pashin areas while Peak Ground Acceleration recorded at Quetta was 0.17m/sec<sup>2</sup> (horizontal component) and 0.06 m/sec<sup>2</sup> (vertical Component). On the same day (29<sup>th</sup> Oct) one hundred and seventy five aftershocks were recorded with the magnitude ranging between 2.2 and 4.7 Mb.

As no earthquake rupture was found on the surface of earth; only at few places some cracks were seen on the ground. The earthquake mechanism was found to be strike-slip that is one block move with respect to other. This fault movement is disagreed with the existing fault system which is thrust in nature. The trend of these aftershocks indicated that rupture inside the earth due to these earthquakes in this obscured fault is South East–North West direction.

## 1- INTRODUCTION

An earthquake of magnitude 6.5 Mb was recorded by the seismic monitoring network which struck Ziarat and surrounding areas on 29<sup>th</sup> October, 2008. The epicenter of this earthquake was 30.612°N and 67.436°E.

The earthquake was Located at a distance of,

- 40.0 kms NNW of Ziarat (Balochistan)
- 60.0 kms NE of Quetta (Balochistan)
- 124 kms NNW of Sibi (Balochistan)
- 100 kms ESE of Chaman (Balochistan)

280 people were killed and 15000 people were injured due to this devastating earthquake. Village named as “Wam” was completely destroyed and about 150 people lost their lives

in this village and thousands became homeless. Ziarat city comparatively remained safe and loss of lives and properties were not as much as found in Wam and its surrounding areas near Ziarat town.



Figure:1- Epicentral location of main shock. Courtesy United State Geological Survey.

Activity in the region have not calm down completely as aftershocks are still continuing. Another significant earthquake that struck the area merely 12 hours later at about 04:32 pm with magnitude 6.4 Mb, followed by at least four significant aftershocks including one measuring 4.5 Mb on the Richter scale. Most of the casualties were from two villages built on steep slopes in the outskirts of the Ziarat town. The victims were from outlying villages, whose mud houses were destroyed by the tremors, which triggered landslides of rocks and boulders while people slept in their beds.

The second most affected area was Tehsil Khanozai of District Pishin where more than 1000 houses were damaged. In this Tehsil, two villages like Khushab and Negandeh were badly affected. Maximum landslides were observed near Khanozai. Although the city of Ziarat was relatively safe but some nearby villages have been completely destroyed and many homes were buried in landslide triggered by the quake. The worst

affected villages in Ziarat include Waam, Khan Depo, Warchum, Speen Tangai, Gogeena, Jangian, Bar Maghzai, Ghoskai, Zargai, Ahmadoon, Mangai.

A survey team after this Ziarat earthquake of 6.5 Mb from Pakistan Meteorological Department was sent to earthquake affected areas for aftershock recording and Seismotectonic study. The survey team visited the affected area like Khanozai, Ahmadoon, Kach, Wam, Kan Depot, Kawas, Ziarat and Zandra areas. The team also installed four Digital Seismic monitoring equipments (I sec) at Kuch, Kan Depo, Gogai Village and Ziarat. These stations were around the Ziarat within the radius of 30 to 40 km and recorded aftershocks even at the micro level.

Strong aftershocks continued to rattle Ziarat, Khanozai and surrounding areas as thirty one aftershocks having magnitude more than 4.0 Mb on Richter scale were recorded up to 15 November 2008 which triggered panic among the local people. Two aftershocks with magnitudes 4.6 Mb on 5<sup>th</sup> November and another two with magnitudes 4.6 & 4.9 Mb on Richter scale at 15 November 2008 struck Quetta. The tremors also felt up to Pashin and Ziarat. At the end of January 2009, total 1185 shocks having magnitude ranging from 2.2 to 4.8 Mb on Richter scale were recorded and still this activity is continuing.

## **2- SCOPE OF THE STUDY**

The seismicity of Pakistan is characterized by important historical and recent major earthquake. The areas of Balochistan have observed many disaster earthquakes like 1945 Makran earthquake ( $M \approx 8.0$ ), the Quetta 1935 earthquake ( $M=7.4$ ), the Mach 1931 earthquake ( $M=7.3$ ) and Bam, Iran 2003 earthquake ( $M=6.6$ ) and recent 2008 Ziarat earthquake ( $M=6.5$ ). Ziarat region also observed earthquakes of magnitude 4.9, 6.1, 6.0 and 6.4 in 1983, 1984, 1985 and 1997 respectively. The study is based on the instrumental recorded data and existing fault information. The purpose of this study is to provide the geological and seismological facts and data of the study areas after Ziarat earthquakes which may provide the guidelines for the reduction of economic as well as life losses in any future earthquake if occur in this area.

The information about existing fault system of the study area is only available in fault map prepared by Geological Survey of Pakistan. The seismic investigation was done by taking following steps:

## 2.1- METHODOLOGY

- Selection of places to install the earthquake monitoring field stations.
- Establishment of temporary field monitoring stations around the earthquake affected areas to monitor the aftershocks.
- Establishment of earthquake catalogue for Quetta-Ziarat earthquakes based on data recorded by field stations and by permanent seismic monitoring network of PMD.
- Geological information was collected from Geological Survey of Pakistan, Quetta.
- This study is exclusively focused on the seismic analysis of earthquake affected areas and mechanism of the earthquakes (fig-2).

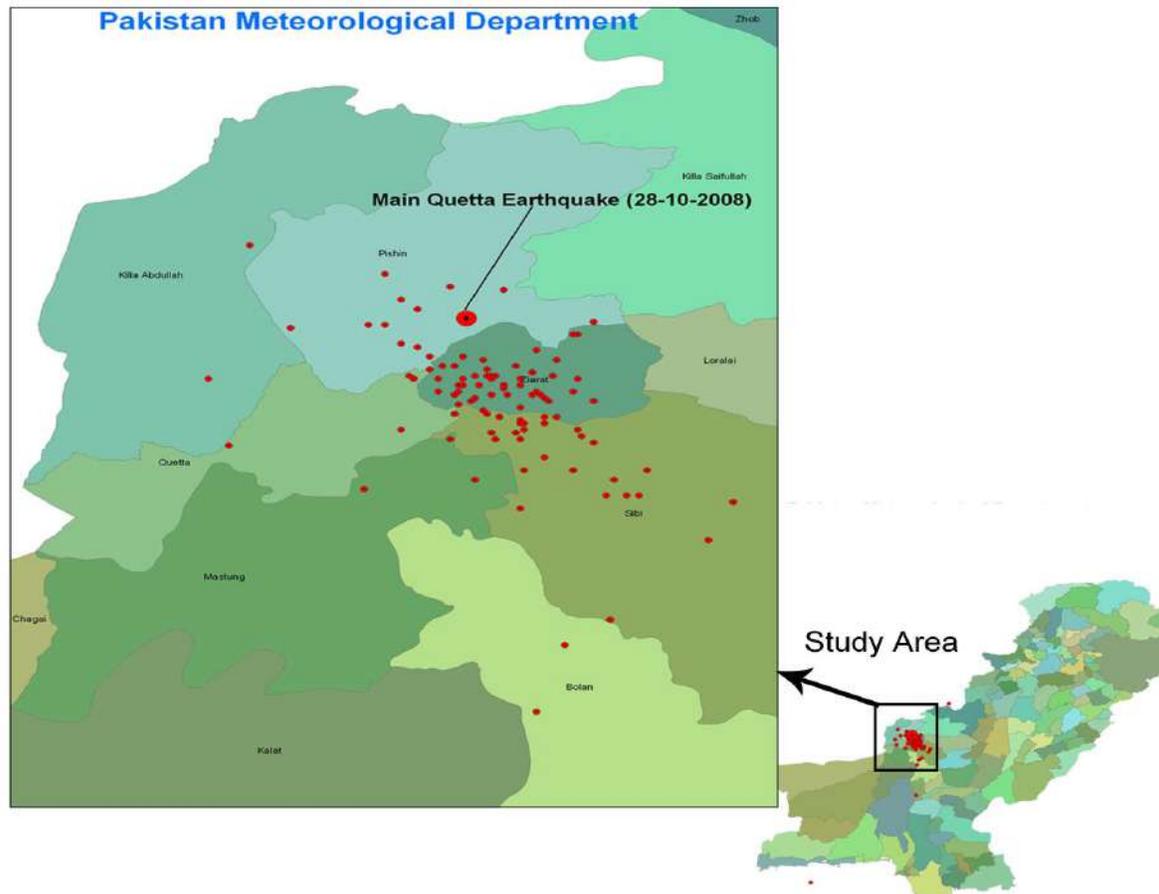


Figure: 2- Map of the study earthquake affected area.

### 3- GEOLOGY AND TECTONICS OF BALOCHISTAN

#### 3.1-TECTONICS OF BALOCHISTAN

(Courtesy geological survey of Pakistan)

The investigated area lies in seismic zone IV which has the most active regional tectonic setting. The interaction of various tectonic elements, that is, southward progressing Suleiman Lobe, Chaman Transform Fault and resistant mass at Sibbi trough were responsible for structural styles and tectonics in the region (Naimatullah, 1992). The earthquake affected area is an integrated part of the syntaxial bend of Quetta region, the whole of it falls on an over thrust sheet which forms the high ground and prominent peaks of the region, the foreland coincides with the Shahrig-Harnai low land which lies south of the investigated area and passes north of Kach (Shah, S.H.A, 1965).

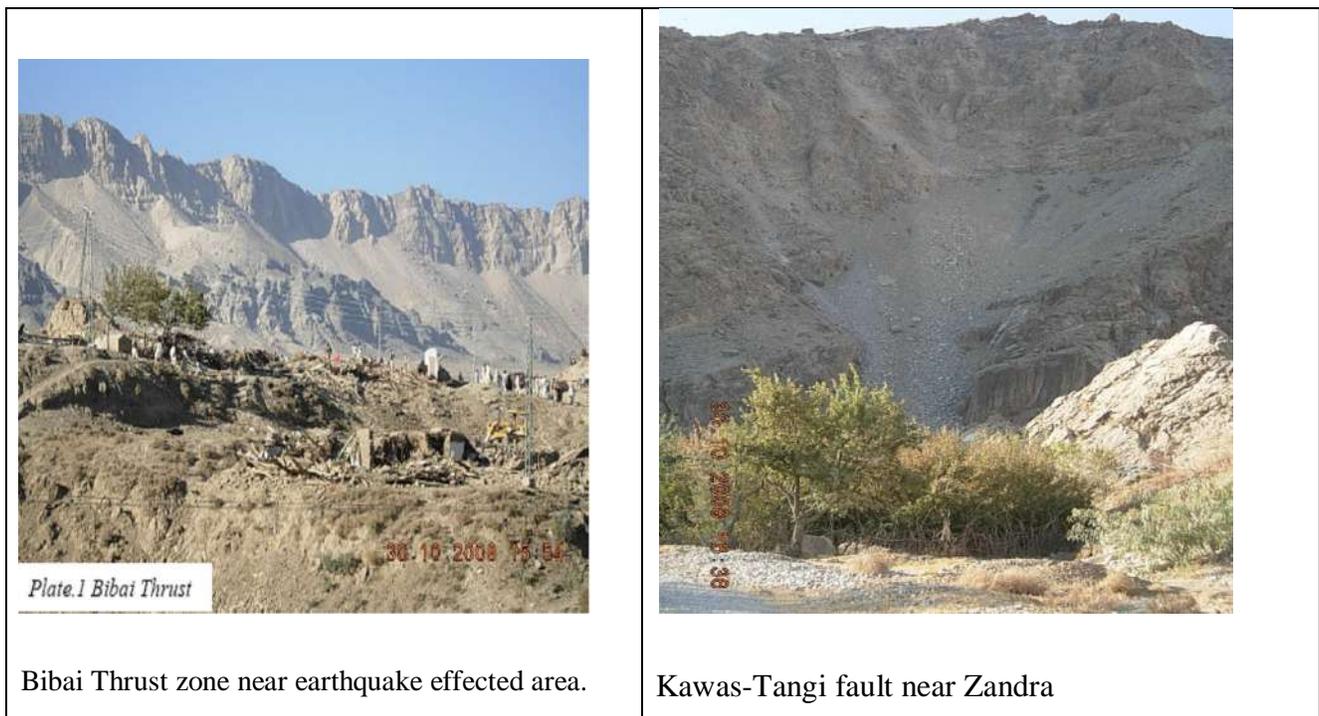


Figure: 3- Thrust zone near earthquake affected area.

In the vicinity of the devastated area two large thrust sheets i.e. the Bibai and Gogai nappes, were emplaced between middle Eocene and early Eocene epochs after the deposition of Ghazij shales but prior to the deposition of rocks of the Siwalik Group (Niamatullah et. al, 1989).

The rocks of Gogai nappe are strongly deformed and complex folding is associated with Gogai nappe whereas an imbrications zone is associated with Bibai nappe. Strike slip faults

are more common in association with Gogai nappe and at places such faults are mapped in Bibai nappe which is exposed from Kach to Ziarat area, 45 km NE of Quetta to 120 km. All the strike slip faults associated with Gogai and Bibai nappes are sinistral faults. The October 29th Gogai, Ziarat Earthquake occurred in an area with previously mapped three major active thrusts namely E-W trending Zhob valley thrust, Chinjan, Bibai and Gogai thrusts running parallel to each other in this region and splayed into several parallel fault planes, on which accumulation of strain is taking place as a result of the stresses applied by the tectonic forces which in turn stem from Chaman fault boundary. The rate of motion at this left lateral strike slip fault is reported to be 4 to 7 cm/yr. The Quetta Ziarat region lies 80 km east of 650 km long Chaman Fault that accommodates a significant amount of slip across the plate boundary. The occurrence of series of tremors suggests that other faults are present beneath the major thrust as their offshoots. Of special interest to the experts was the previously mapped Kawas -Tangi fault which on one hand acted as a barrier to safeguard the Ziarat town itself and on the other hand caused much damage between Kawas and Kach areas. There is a possibility of a blind fault running more or less parallel to this strike slip fault beneath the surface near Kan and Wam which the authors believed to be the causative fault of the recent seismic event. During the recent research on this blind fault running parallel to the Kawas-Tangi strike slip fault interpreted by various workers which trends NWSE and passes west of the Zindra village, has been identified along which most of the epicentral locations from Khanozai to Gogai and farther south lie. This is a younger fault which truncates most of the older thrusts and axis of folds. As majority of the epicenters of aftershocks > 3.5 M are located along this line so that is a clear indication of recently activated fault, which most probably is the causative fault of this event. The Ghazaband-Zhob and Gwal-Bagh Fault system in the NNW of the investigated areas are bounded by the faults from south east and west also and are in turn connected with the most active Chaman-Ornach- Nal Fault system. Along the southern limb of the Ziarat valley syncline scissor faulting within the Dungan Formation is common and has high ground potential (Thangani, et. Al, 2005).

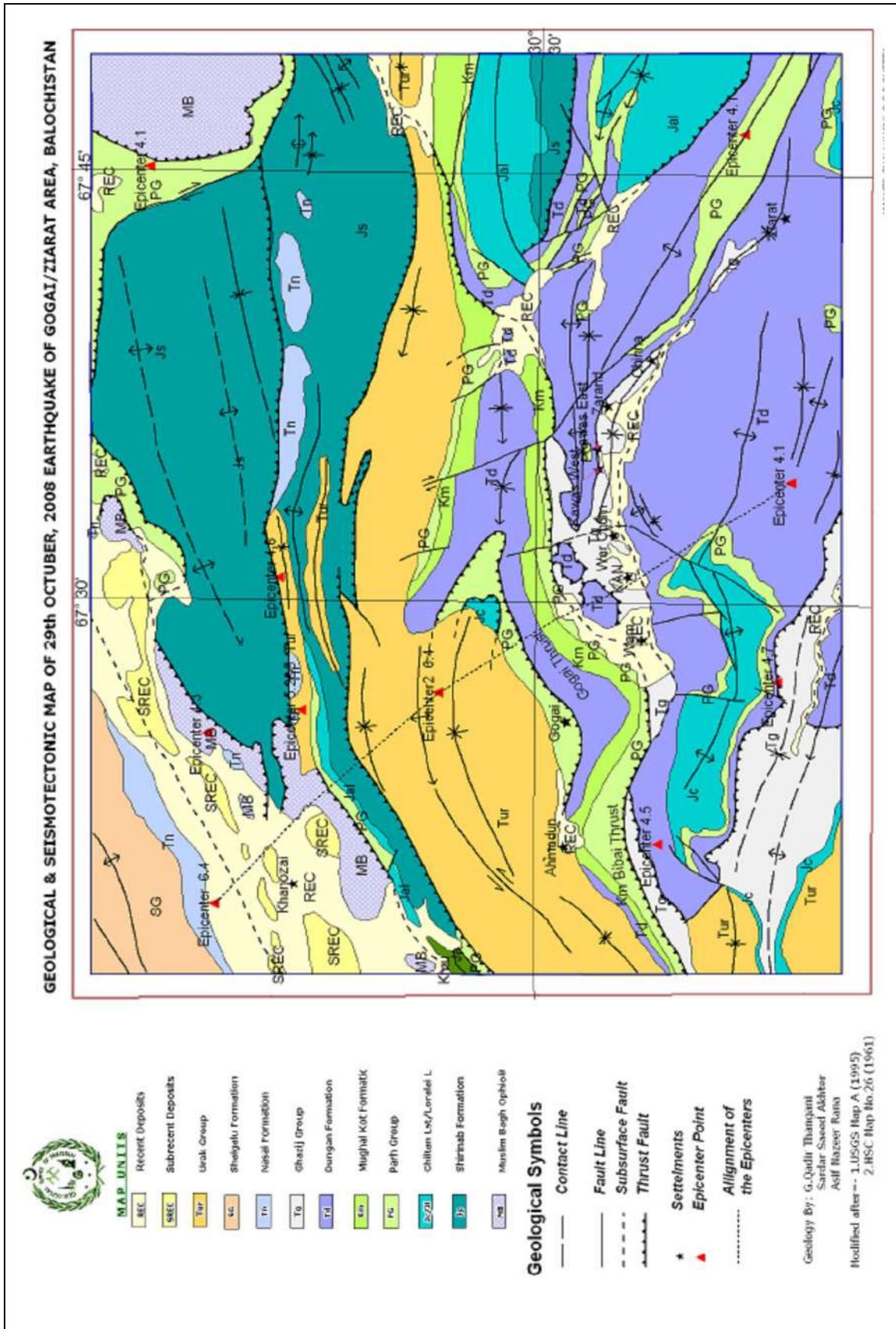


Figure: 4- Geological and Seismotectonic map of Ziarat/Gogai areas. (Courtesy GSP)

### **3.2-Quetta Transverse Zone**

This zone extends eastward from Quetta to the South of the Sulaiman range and is a part of the fold and fault belt relating to the Indian/Eurasian Plate boundary. This zone exhibits the highest level of seismic activity with moderate to large earthquakes occurring during 1930 and 1960. Besides famous Quetta earthquake of 31 May, 1935, this transverse zone had the following significant earthquakes: (i) Shahrigh earthquake of 25 August 1931 occurred at 30.30°N, 67.80°E and its magnitude was 7.0. It was felt over an area of 3 1000 sq. miles. At Shahrigh, particularly, every building was damaged to some extent. (ii) Mach earthquake of 27 August 1931 occurred at 29.30°N, 67.80°E and its magnitude was 7.4. It was felt over an estimated area of 3, 70,000 sq. miles. Old and new Mach, Kirta, Dadhar, Mushkaf Naoshera, Sanni, Shoran, Gandava and Kotra were severely damaged. Bridges were also damaged.

### **3.3-Geology of Ziarat and surrounding areas**

The Upper Cretaceous Bibai Formation is exposed in Kach-Ziarat and Spera Ragma-Chinjun valleys and near Muslimbagh, within the western part of the Sulaiman Thrust-Fold Belt east of the Quetta Syntaxis. The formation generally comprises basic volcanic rocks, volcanic conglomerate and breccia, sandstone, mudstone and ash beds. Within the Kach-Ziarat valley it is dominantly composed of volcanoclastic sediments and rarely lava flows, while, within the Spera Ragma-Chinjun valley dominantly the in-situ basaltic volcanic rocks. The volcanoclastic succession may be categorized into various facies viz volcanic conglomerate (VC), volcanic breccia (VB), sandstone (SS), sandstone interbedded with mudstone (SSMS), mudstone (MS), limestone (LS) and lava flows (VOL), which are comparable with the facies classes A, B, C, D, E, and F of Mutti & Ricci Lucchi (1972, 1975) and Pickring et al. (1986a), indicating deposition by sediment gravity flows and slumping / soft sediment deformation. The volcanic conglomerate, VCP-VCC-SS association of the facies, their stacking pattern, erosive bases and fining-upward trend suggest deposition within a channelized complex anastomosing on a submarine fan system. The SSMS facies of sandstone interbedded with mudstone, characterized by Bouma (1962) Tabcde, Tbcde, Tcde and Tde sequences, sole marks, soft sediment deformation, pinch-and-swell and general thinning- and fining-upward trends of 2nd-order cycles, indicate deposition by turbidity currents in over bank (-levee) complex

between channels. The mudstone (MS) facies, possessing occasional thin sandstone beds in lower part and profusion of shallow marine fauna in upper part, indicate deposition in lower fan / basin plane conditions and shows an overall shallowing-up of the succession. Limestone (LS) facies, interbedded with volcaniclastic facies in lower part of the formation, is very finely crystalline (Bio-Micritic) possessing micro-foraminifera of the globotruncana family suggest deposition during calm periods when volcanic activity had been suspended intermittently. The general south-southwestward flow of the pale current pattern and litho- facies distribution in various studied sections suggests that source area was north of the Bibai Peak. Texture, composition and whole rock geochemistry of rock fragments of the volcanic conglomerate indicate that sediments were derived from a hotspot related volcanic terrain where detritus of the alkaline acidic igneous rocks was also available, from time to time, along with the major proportion of basic volcanic rocks, also of alkaline nature. The October 28 and 29 earthquakes occurred in the Suleiman fold-and-thrust belt, a region where geologically young (Tertiary) sedimentary rocks have been folded and squeezed by forces associated with the Indian-Eurasian collision. The earthquakes are located approximately 80 km east of the 650-km-long Chaman fault, which is a major left-lateral strike-slip fault that accommodates a significant amount of the slip across the plate boundary. The occurrence of the earthquakes suggests that other left-lateral strike-slip faults are present beneath the fold-and-thrust belt and that they accommodate some of the relative motion of the Indian and Eurasian plates.

#### **4- Seismic Investigation and Analysis of the after shocks**

The after shocks analysis was done by using IASPEI softwares library for the better understanding of the after shocks algorithm and activity pattern of aftershocks.

PMD survey team installed four portable seismic recorders at Kuch, Kan Depo, Gogai Village and Ziarat for the monitoring of after shocks (Fig-5). The list of after shocks has been shown in Appendix-2 and plotting in Fig-6. The equipments were installed within the radius of about 40 km. The map of temporary field stations is shown in Fig-5.



Figure-5: Map of temporary field stations: Ziarat, Gogai, Kan Depot and Kach are the names of the field stations which established in the affected areas.

Trend of the aftershocks (Fig-6) helped to draw the possible rupture line created by these earthquakes. The region of Ziarat earthquake is marked by Quetta syntaxes which bifurcates the region of thrust faults. The marking of possible rupture line due to these earthquakes is based on aftershocks analysis, fig-6. It is comparable with the existing fault system, mapped by GSP, of this area; only the right wings of the fault system moved and generated earthquakes which are clearly evident from the figures 6 and 9. The epicenter, the point where the maximum energy released, lies in the region of strike slip movement and the direction of fault movement is in North East-South West. Based on aftershock activity analysis the fault rupture will be estimated 40 Km to 50 km in north east to south west direction.

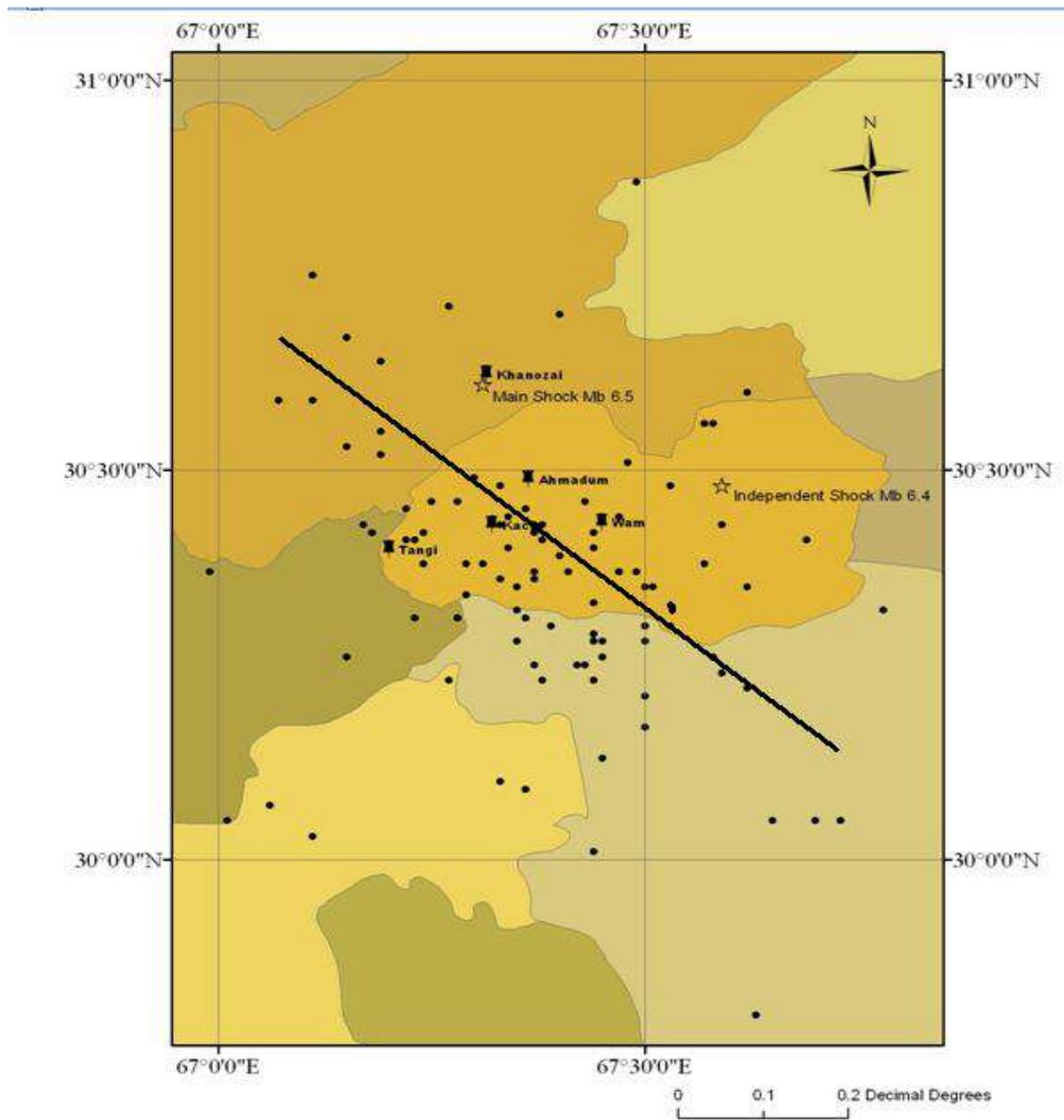


Figure: 6- Trend of aftershocks, NW–SE direction and possible rupture line. Fault ruptures (bold line). The major concentration of the aftershocks is along the possible rupture line with few events are located far away from the rupture line. These may be due to the triggering of local faults. The maximum damaged villages/towns like Khanozai, Tangi, Ahmadoon, Wam and Kan depot are situated along the fault line.

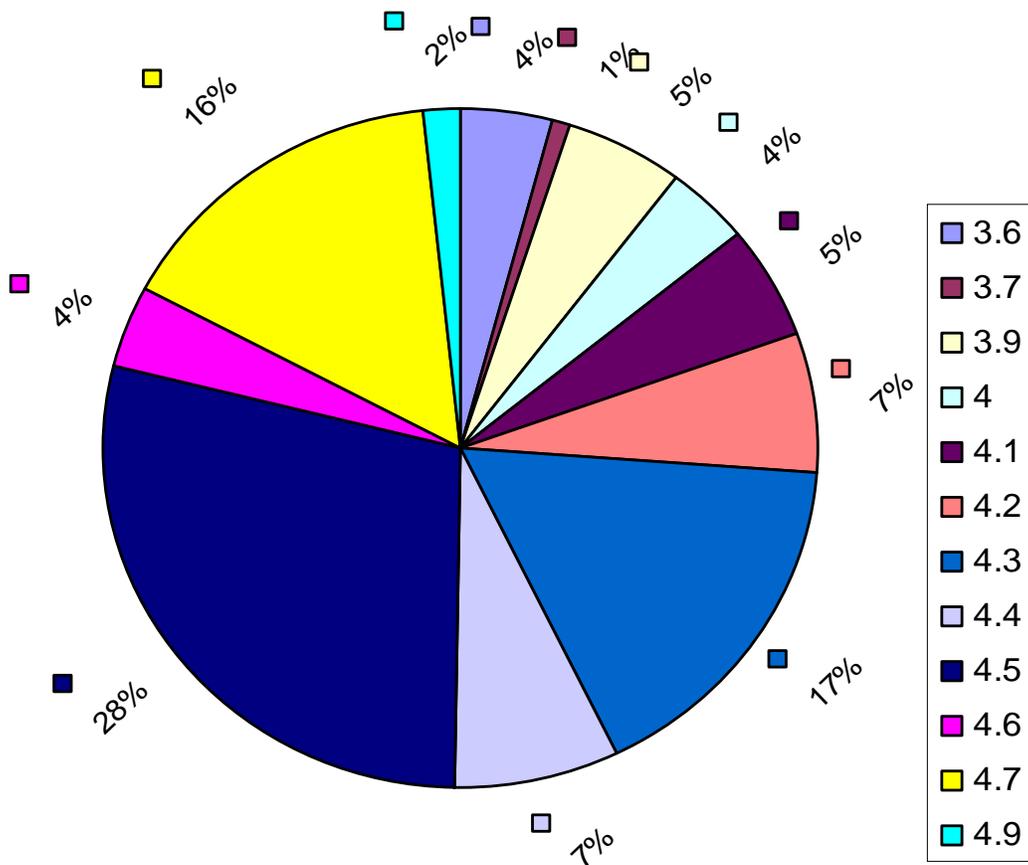


Figure-7: Occurrence of earthquakes in percentage with different magnitudes for the period 29 Oct 2008 to 30 Jan 2009, indicating frequency – magnitude relationships of aftershocks.

Maximum events with magnitude 4.9 which is the 28 % of aftershocks, recoded up to 30 January 2009 (Fig-7). Aftershock data also indicated that the majority of the aftershocks have magnitudes more than 4.0. All these events were shallow which generated ground shaking in earthquake affected areas. Aftershocks of magnitude 4.5 Mb are almost one fourth of total number of aftershocks recorded i.e. 325 out of 1201 till 30<sup>th</sup> January 2009, as blatant from fig-7. This also indicates that during settlement of the activity major portion of strain energy was released due to aftershock ranging between 4.0 Mb to 4.9 Mb. One aftershocks of this magnitude can trigger another aftershock during settlement along fault causing a variation in decay pattern of aftershock (fig-8).

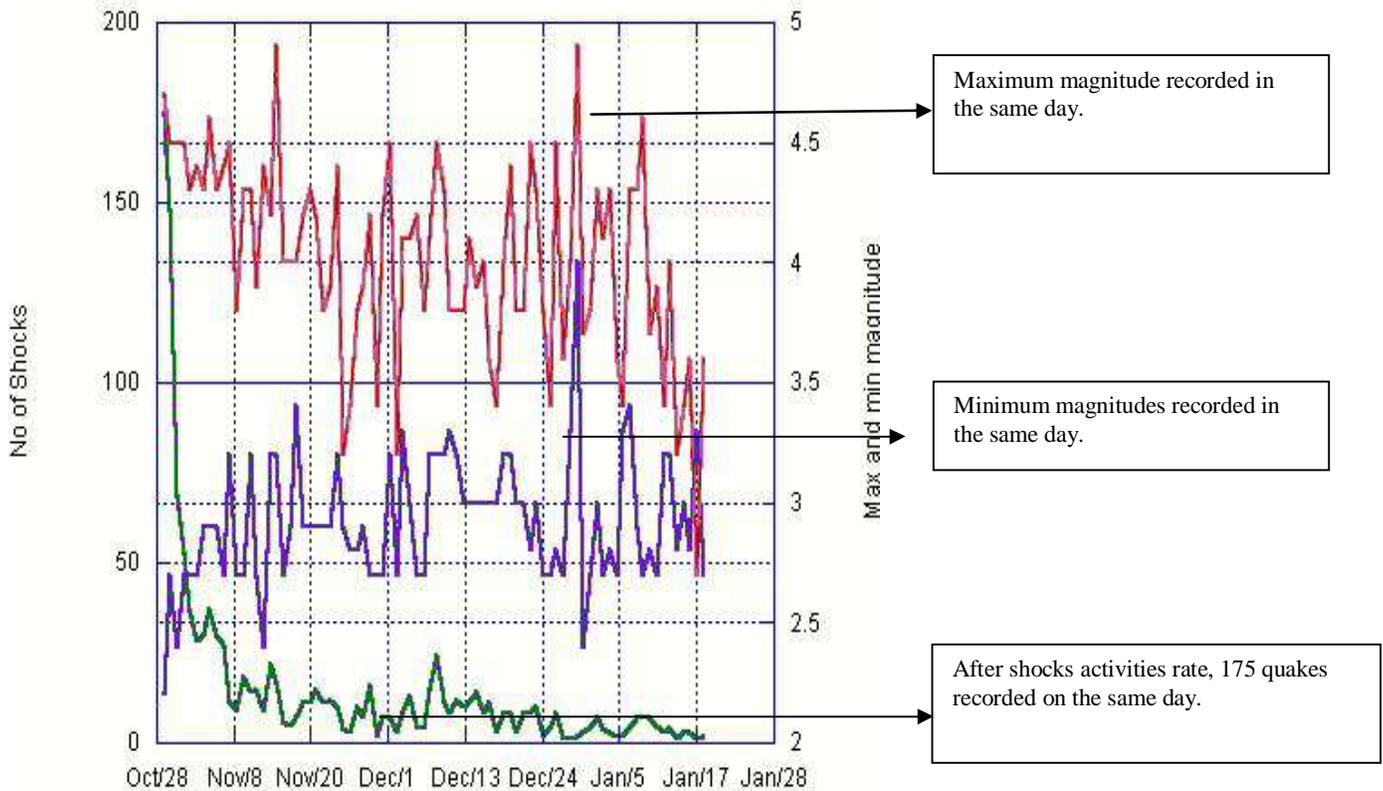


Figure-8: Rapid fall of aftershocks is observed with some abnormal rise of earthquake frequency. The comparison of minimum and maximum magnitudes with frequency of occurrence of earthquakes which shows how the magnitude and frequencies changed with the time. The size, strength, and frequency diminished with time.

The above analysis revealed that two peaks of maximum magnitudes observed in mid of November and in last week of December, 2008. Although magnitude 6.5Mb released significant amount of stress still the touching edges needed to adjust the new position and this additional realignment created the aftershocks.

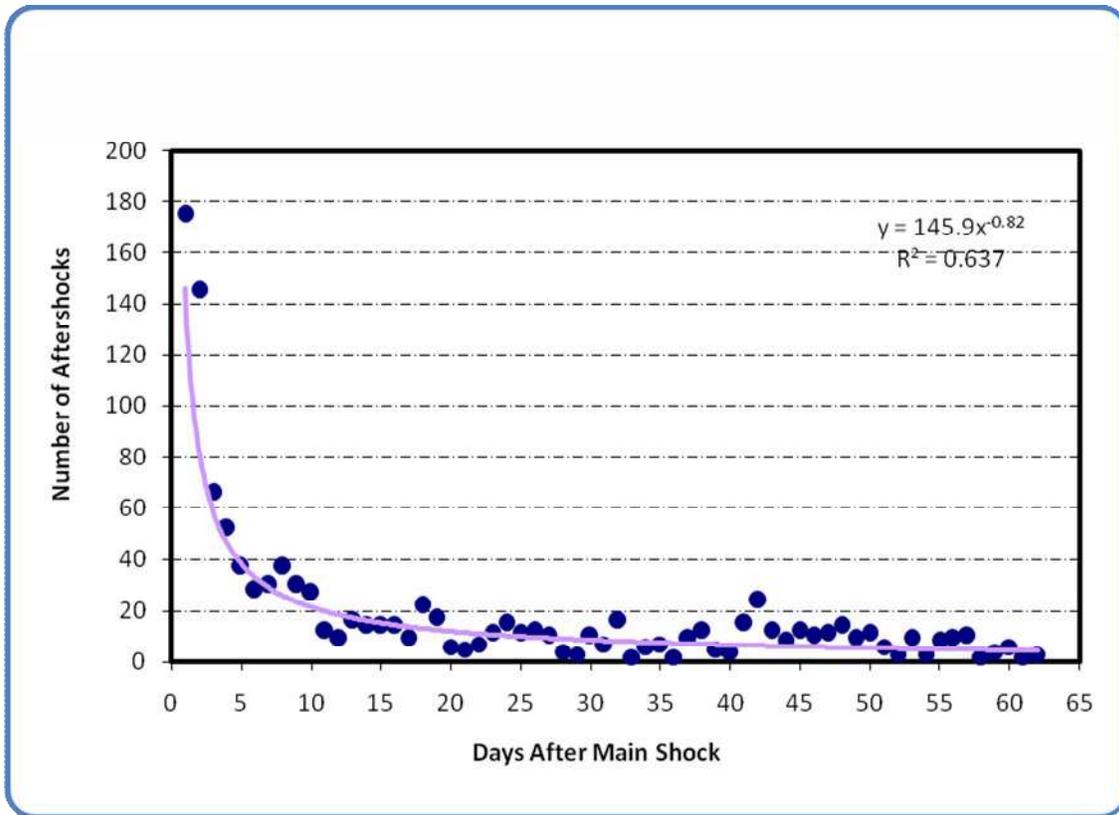


Figure-9: Decay pattern of the aftershocks. At first day (29 Oct 2008), 175 and on second day 146 quakes were recorded by PMD seismic monitoring network.

#### 4.1-The Mechanism of Earthquake

The focal mechanism of the two earthquakes shows the strike slip behavior which needs further investigation. A focal mechanism solution (FMS) is the result of analysis of wave forms generated by earthquake and recorded by a number of seismographs (Appendix 3). By using moment tensor, we ultimately resolved the orientation and sense of slip of the fault which is north west-south east direction. This wealth of information about an earthquake is plainly for the interest of a structural geologist working on active structures. FMS beach ball diagrams shown in Fig-9 are stereographic projections that show two black compression quadrants and two white dilatation quadrants.

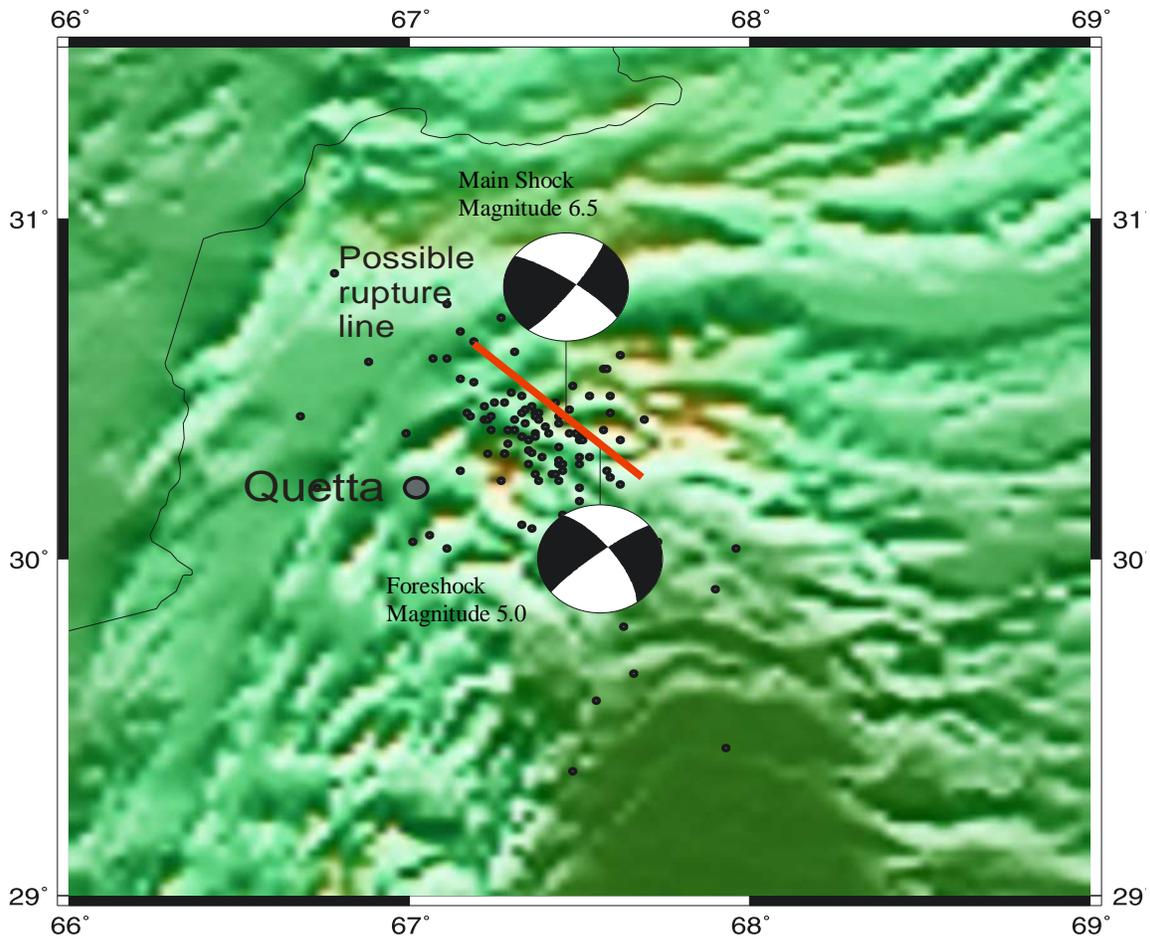


Figure-10: Mechanism of the fault movement during the earthquakes of Magnitudes of 5.0 & 6.5 on 29<sup>th</sup> October 2008.

The great-circle arcs are the nodal planes, one of which coincides with the fault surface that generated the earthquake. The analysis of fault system and local area geology show that the fault moved in the direction of NW-SE. The aftershocks analysis fig-6 confirmed that fault movement direction. The two figures 6 & 9 are correspond to each other and supported by the geological structure of study area. The strike of the fault is indicated by a line connecting the two points where the great circle corresponding to the fault and strikes in the west-southwest direction.

In the earthquake of magnitude 5.0, fault strike at  $229^{\circ}$  and dipping of fault was found at  $63^{\circ}$  as well as fault slipped in the direction of  $220^{\circ}$ . Similarly the second earthquake which was of 6.4 magnitudes, its active fault strikes at  $304^{\circ}$  its dipping was in the direction of  $73^{\circ}$  and it slipped at  $171^{\circ}$ . The source mechanism solutions of both earthquakes are same with some minor variation of strike, dip and slip angles but the

direction of fault movement is more or less in the same direction. The second result is that both earthquakes were due to the movement of same fault.

## **Conclusions**

- The epicentral distribution (locations) of aftershocks is North West to South East direction which is in agreement with geological evidences of the study area.
- The mechanism of the earthquakes shows strike slip movement of the fault i.e. one block move with respect to other which is contrary to the existing fault system i.e. thrust nature.
- Earthquakes generated due to the existing fault system but mechanisms of earthquakes heading us to think otherwise. There could be two possibilities, one is that only the right wing of the fault system which is thrust in nature, moved and released seismic energy or there may be hidden strike slip fault and could not be mapped before.

## **Recommendations:**

Some serious measures must be taken to minimize the future death toll, by implementing Building Code Regulations and by law strictly in earthquake affected areas. The fault mapping of affected areas must be revised. A micro seismic hazard analysis of earthquakes affected areas may be conducted profoundly which may help to strengthen the by laws.

## **Acknowledgement**

Authors are thankful to Director General Met Services for supporting this work. Without the encouragement and the stimulus given by Director General Met services the report might never have been completed. We also appreciate the efforts of Mr. Tahir Azeem for providing technical assistance in completion of this report.

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[www.ndma.gov.pk](http://www.ndma.gov.pk)

## Appendix-1

### Aftershocks recorded on 29<sup>th</sup> October 2009

Phase		Origin Time (UTC)	Magnitude
Ep	Es		
00:32:06	00:32:16	00:31:58	4.6
00:01:02	00:01:11	00:00:50	4.0
00:04:20	00:04:27	00:04:11	3.8
00:09:03	00:09:15	00:08:47	4.1
00:12:34	00:12:41	00:12:25	4.2
00:17:53	00:17:59	00:17:45	3.8
00:20:40	00:20:48	00:20:29	4.3
00:32:05	00:32:15	00:31:52	4.6
00:55:06	00:55:14	00:54:55	3.9
00:59:47	00:59:55	00:59:39	3.8
01:01:15	01:01:24	01:01:13	3.8
01:12:33	01:12:42	01:12:21	4.1
01:22:32	01:32:38	01:22:24	3.8
01:27:54	01:28:03	01:27:42	4.0
01:38:09	01:38:18	01:37:57	3.7
01:42:47	01:42:55	01:42:36	4.1
01:47:01	01:47:10	01:46:49	3.8
01:54:28	01:54:37	01:54:16	4.2
02:01:01	02:01:11	02:00:48	3.9
02:20:47	02:20:53	02:20:39	4.0
02:23:17	02:23:26	02:23:09	3.7
02:41:19	02:41:37	02:40:56	3.9
02:58:58	02:59:05	02:58:49	4.5
03:02:30	03:02:37	03:02:21	3.8
03:15:18	03:15:27	03:15:06	3.9
03:17:43	03:17:57	03:17:24	3.8
03:28:22	03:28:37	03:28:01	3.8
03:50:22	03:50:31	03:50:10	3.9
04:04:00	04:04:09	04:03:48	4.0
04:08:23	04:08:33	04:08:10	3.9
04:18:48	04:18:59	04:18:33	4.1
04:29:27	04:29:32	04:29:16	3.8
04:39:16	04:39:22	04:39:08	3.8
04:48:10	04:48:17	04:47:57	4.5
04:57:56	04:58:02	04:57:45	3.9
05:07:15	05:07:22	05:07:07	3.6
05:17:30	05:17:36	05:17:22	3.6
05:38:05	05:38:10	05:37:58	3.8
05:59:48	05:59:54	05:59:40	3.6
06:13:22	06:13:28	06:13:14	3.4
06:15:36	06:15:41	06:15:27	4.6
06:29:48	06:29:54	06:29:37	3.8

06:32:52	06:32:58	06:32:44	4.0
06:37:32	06:37:39	06:37:23	3.6
06:43:37	06:43:43	06:43:29	4.5
06:50:01	06:50:09	06:49:50	3.5
06:52:24	06:52:30	06:52:16	3.8
06:59:19	06:59:25	06:59:11	3.9
07:08:02	07:08:08	07:07:54	4.5
07:10:55	07:11:21	07:10:46	4.5
07:19:57	07:20:03	07:19:46	3.6
07:25:35	07:25:41	07:25:24	3.6
07:28:21	07:28:26	07:28:14	3.9
07:37:06	07:37:15	07:37:54	4.2
07:41:30	07:41:39	07:41:18	3.8
07:50:58	07:51:04	07:50:50	3.2
07:59:09	07:59:19	07:58:56	4.5
08:11:00	08:11:04	08:10:55	3.8
08:35:35	08:35:41	08:35:27	4.1
08:51:38	08:51:43	08:51:31	3.3
09:01:10	09:01:16	09:01:02	3.9
09:22:43	09:22:53	09:22:35	3.4
09:29:07	09:29:13	09:28:59	4.1
09:40:28	09:40:37	09:40:16	4.6
09:52:08	09:52:17	09:51:56	3.8
10:38:54	10:39:03	10:38:12	3.4
10:42:01	10:42:10	10:41:49	3.8
10:55:24	10:55:33	10:55:12	3.9
11:18:08	11:18:14	11:18:00	3.8
11:20:56	11:21:04	11:20:47	3.6
11:39:40	11:39:47	11:39:31	4.2
11:46:34	11:46:41	11:46:25	3.7
11:56:32	11:56:38	11:56:23	4.2
12:03:31	12:03:39	12:03:20	4.0
12:11:58	12:12:06	12:11:47	4.4
12:30:27	12:30:36	12:30:15	4.2
12:45:46	12:45:53	12:45:24	3.8
12:47:51	12:47:57	12:47:43	4.2
13:03:05	13:03:12	13:02:56	3.9
13:16:58	13:17:01	13:16:53	3.4
13:24:58	13:25:04	13:24:50	4.0
13:28:58	13:29:05	13:28:49	3.6
13:32:35	13:32:41	13:32:27	4.3
13:38:15	13:38:20	13:38:08	3.4
13:39:05	13:39:13	13:38:54	4.0
13:43:17	13:43:20	13:43:12	4.0
13:52:02	13:52:08	13:52:54	3.5
13:53:20	13:53:23	13:53:15	4.3
13:58:57	13:59:03	13:58:49	3.4
14:03:45	14:03:47	14:03:40	4.0
14:12:41	14:12:48	14:12:32	4.1

14:16:41	14:16:43	14:16:36	3.6
14:19:28	13:19:33	14:19:21	3.4
14:21:38	14:21:40	14:21:33	3.6
14:31:24	14:31:31	14:31:15	3.4
14:35:13	14:35:16	14:35:08	2.2
14:37:53	14:37:56	14:37:48	3.5
14:52:15	14:52:21	14:52:06	3.4
14:52:16	14:52:22	14:52:07	4.2
15:00:36	15:00:41	15:00:29	3.0
15:05:17	15:05:26	15:05:06	3.2
15:10:41	15:10:48	15:10:30	4.1
15:15:51	15:16:00	15:15:39	3.9
15:20:49	15:20:55	15:20:41	3.6
15:22:18	15:22:25	15:22:09	3.8
15:24:56	15:25:03	15:24:37	3.4
15:32:58	15:33:05	15:32:49	4.1
15:38:32	15:38:40	15:38:21	3.3
15:45:35	15:45:37	15:45:30	3.2
15:47:33	15:47:39	15:47:25	3.4
15:49:40	15:49:43	15:49:35	4.2
15:57:02	15:57:10	15:56:51	4.3
16:10:10	16:10:20	16:09:57	3.4
16:12:08	16:12:18	16:11:55	3.8
16:29:26	16:29:33	16:29:17	4.3
16:37:30	16:23:39	16:45:19	4.4
16:57:56	16:58:04	16:57:45	3.8
17:06:04	17:06:49	17:06:33	3.4
17:08:28	17:08:35	17:08:19	3.2
17:09:25	17:09:30	17:09:18	4.7
17:20:56	17:21:05	17:20:44	4.0
17:28:58	17:29:06	17:28:47	3.8
17:32:40	17:32:47	17:32:29	3.9
17:34:52	17:35:02	17:34:39	4.0
17:45:48	17:45:56	17:45:37	4.0
17:49:00	17:49:052	17:48:53	4.3
18:00:36	18:00:41	17:59:59	4.2
18:02:38	18:02:45	18:02:29	3.6
18:05:16	18:05:19	18:05:11	4.0
18:06:36	18:06:40	18:06:31	4.4
18:20:22	18:20:26	18:20:17	3.6
18:28:12	18:28:23	18:27:57	3.8
18:29:24	18:29:30	18:29:16	4.0
18:42:47	18:42:56	18:42:35	4.2
18:58:32	18:58:38	18:58:24	3.6
19:02:37	19:02:46	19:02:22	3.6
19:05:03	19:05:12	19:04:51	3.6
19:10:03	19:10:08	19:09:56	4.1
19:18:52	19:19:00	19:18:41	4.1
19:22:40	19:22:47	19:22:31	4.0

19:28:03	19:28:12	19:27:51	4.3
19:35:35	19:35:44	19:35:23	3.7
19:38:41	19:38:49	19:38:30	3.9
19:48:26	19:48:31	19:48:19	4.0
19:51:11	19:51:19	19:51:00	4.3
20:08:54	20:08:59	20:08:47	4.1
20:13:45	20:13:52	20:13:36	3.3
20:16:26	20:16:35	20:16:14	3.8
20:22:37	20:22:42	20:22:28	3.7
20:43:38	20:43:55	20:43:15	3.7
20:46:55	20:47:04	20:46:43	4.0
21:13:57	21:14:04	21:13:48	3.3
21:20:31	21:20:39	21:20:20	3.8
21:25:38	21:25:46	21:25:30	3.3
21:37:48	21:37:54	21:37:40	3.8
21:41:57	21:42:04	21:41:48	3.5
21:43:44	21:43:53	21:43:32	4.3
21:48:26	21:48:32	21:48:18	4.2
21:49:50	21:49:55	21:49:43	4.4
21:52:48	21:52:53	21:52:41	4.0
21:56:28	21:56:37	21:56:16	3.8
21:58:38	21:59:45	21:59:29	3.9
22:06:58	22:07:07	22:06:46	3.8
22:12:50	22:12:55	22:12:43	3.4
22:15:18	22:15:22	22:15:13	3.3
22:10:42	22:10:44	22:10:37	3.2
22:39:44	22:39:52	22:39:33	3.3
22:41:05	22:41:12	22:40:56	3.9
22:46:40	22:46:45	22:46:33	2.7
22:47:47	22:47:57	22:47:34	3.7
22:52:18	22:52:27	22:52:06	3.9
23:11:20	23:11:55	23:10:34	3.4
23:31:38	23:31:59	23:31:10	3.4
23:37:13	23:37:20	23:37:04	3.0

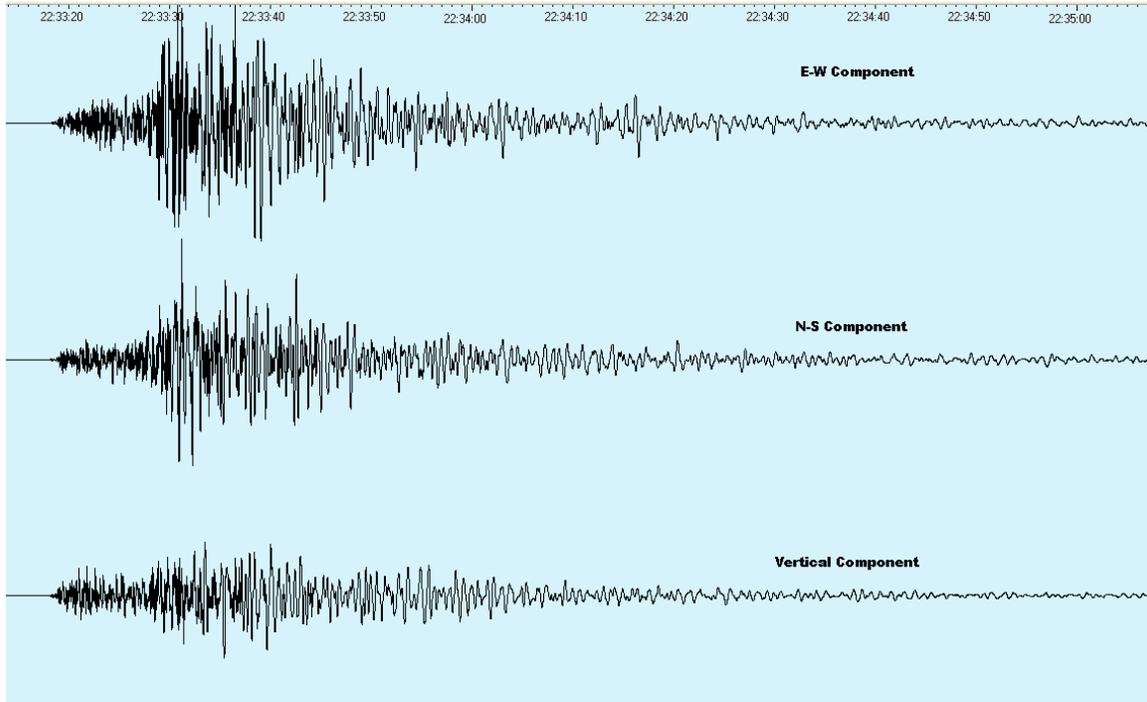
## Appendix-2

### Total number of aftershocks on daily basis

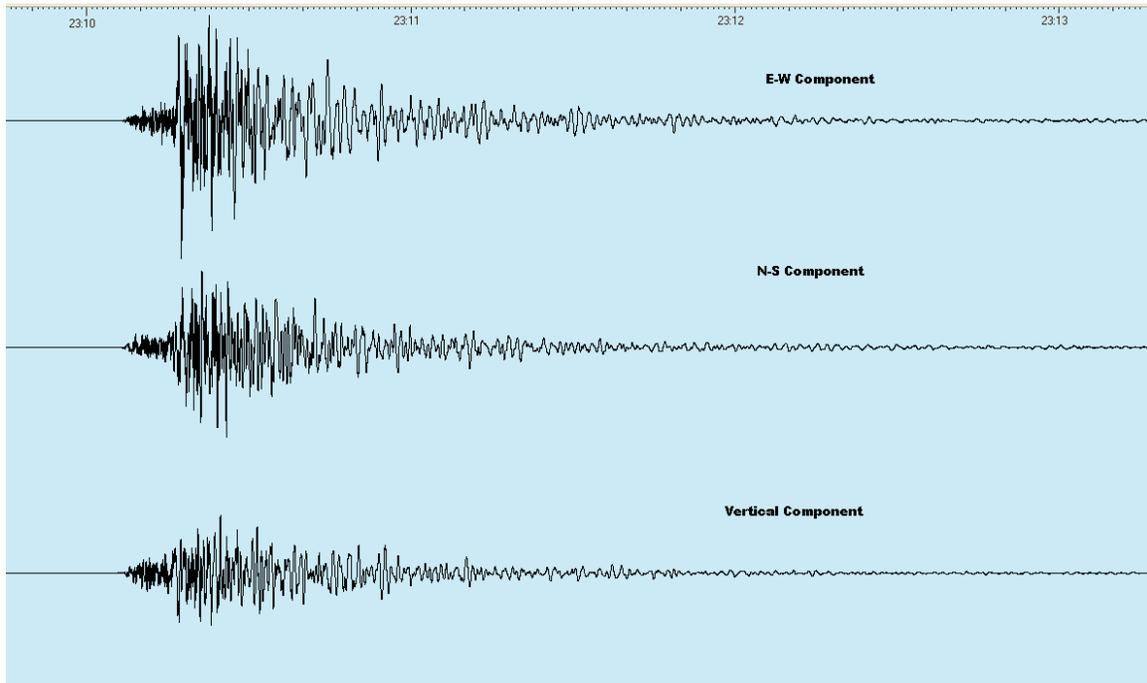
Date	No. of After shocks	Minimum Magnitude	Maximum Magnitude
29-10-2008	175	2.2	4.7
30-10-2008	146	2.7	4.5
31-10-2008	66	2.4	4.5
01-11-2008	53	2.7	4.5
02-11-2008	37	2.7	4.3
03-11-2008	28	2.7	4.4
04-11-2008	30	2.9	4.3
05-11-2008	37	2.9	4.6
06-11-2008	30	2.9	4.3
07-11-2008	27	2.7	4.4
08-11-2008	12	3.2	4.5
09-11-2008	9	2.7	3.8
10-11-2008	16	2.7	4.3
11-11-2008	14	3.2	4.3
12-11-2008	15	2.7	3.9
13-11-2008	9	2.4	4.4
14-11-2008	22	3.2	4.2
15-11-2008	17	3.2	4.9
16-11-2008	6	2.7	4.0
17-11-2008	5	2.9	4.0
18-11-2008	7	3.4	4.0
19-11-2008	11	2.9	4.2
20-11-2008	11	2.9	4.3
21-11-2008	15	2.9	4.2
22-11-2008	11	2.9	3.8
23-11-2008	12	2.9	3.9
24-11-2008	10	3.2	4.4
25-11-2008	4	2.9	3.2
26-11-2008	3	2.9	3.4
27-11-2008	10	2.9	3.8
28-11-2008	7	2.7	3.9
29-11-2008	16	2.7	4.2
30-11-2008	2	2.7	3.4
01-12-2008	7	3.2	4.2
02-12-2008	7	2.7	4.5
03-12-2008	3	3.3	3.6
04-12-2008	9	3.0	4.1
05-12-2008	13	2.7	4.1
06-12-2008	5	2.7	4.2
07-12-2008	4	3.2	3.8
08-12-2008	15	3.2	4.1
09-12-2008	24	3.2	4.5
10-12-2008	12	3.3	4.3
11-12-2008	8	3.2	3.6
12-12-2008	12	3.0	3.6
13-12-2008	10	3.0	3.8
14-12-2008	11	3.0	4.1
15-12-2008	14	3.0	3.9

16-12-2008	9	3.0	4.0
17-12-2008	11	3.0	3.6
18-12-2008	3	3.2	3.4
19-12-2008	9	3.2	4.0
20-12-2008	9	3.0	4.4
21-12-2008	3	3.0	3.6
22-12-2008	6	2.9	3.8
23-12-2008	9	3.0	4.5
24-12-2008	10	2.7	4.3
25-12-2008	2	2.7	3.6
26-12-2008	4	2.9	3.4
27-12-2008	6	2.7	4.1
28-12-2008	2	3.3	3.6
29-12-2008	1	4.0	4.0
30-12-2008	2	2.4	2.9
31-12-2008	3	2.7	3.7
01-01-2009	4	3.0	3.8
02-01-2009	7	2.7	4.3
03-01-2009	4	2.9	4.1
04-01-2009	3	2.7	4.3
05-01-2009	2	3.3	3.5
06-01-2009	2	3.4	3.4
07-01-2009	4	2.9	4.3
08-01-2009	7	2.7	4.3
09-01-2009	7	2.9	4.6
10-01-2009	7	2.7	3.7
11-01-2009	5	3.2	3.9
12-01-2009	3	3.2	3.4
13-01-2009	4	2.9	4.0
14-01-2009	1	3.0	3.0
15-01-2009	3	2.9	3.4
16-01-2009	3	3.3	3.6
17-01-2009	1	2.7	2.7
18-01-2009	2	3.3	3.6
19-01-2009	1	3.2	3.2
20-01-2009	3	3.0	3.3
21-01-2009	0	0	0
22-01-2009	1	3.4	3.4
23-01-2009	0	0	0
24-01-2009	3	4	4.3
25-01-2009	1	2.9	2.9
26-01-2009	5	3.5	3.8
27-01-2009	1	3.4	3.4
28-01-2009	0	0	0
29-01-2009	0	0	0
30-01-2009	1	4.0	4.0
<b>Total No. of Aftershocks</b>	<b>1201</b>		

**Wave form data of Foreshock and Main shock**



**Foreshock of magnitude 5.0 at 04:33 PST**



**Main shock of magnitude 6.5 at 05:09 PST**

## Glossary

**Accelerogram** - Time history of accelerations.

**Active fault** - (1) A fault that has had sufficiently recent displacements so that, in the opinion of the user of the term, further displacements in the foreseeable future are considered likely. (2) A fault that on the basis of historical, seismological, or geological evidence has a high probability of producing an earthquake. (3) A fault that may produce an earthquake within a specified exposure time, given the assumptions adopted for a specific seismic-risk analysis.

**Crust** - The outer major layer of the earth, separated from the underlying mantle by the Moho discontinuity, and characterized by P-wave velocity less than 8 km/s. The thickness of the crust in the Norwegian Continental Shelf in the range 15-25 km.

**Dip** - The *dip* gives the angle below the horizontal of a tilted bed or feature, and is given by the number ( $0^{\circ}$ - $90^{\circ}$ ) as well as a letter (N,S,E,W) with rough direction in which the bed is dipping

**Duration** - A qualitative or quantitative description of the length of time during which ground motion at a site shows certain characteristics (perceptibility, violent shaking, etc.).

**Earthquake** - A sudden motion or vibration in the earth caused by the abrupt release of energy in the earth's lithosphere; shaking of the ground by different types of waves generated by tectonic movements or volcanic activity. By far the largest number of destructive earthquakes are caused by tectonic movements. An earthquake is initiated when the accumulated tectonic stresses at any one point in the ground become greater than the strength at this point. Release of stress at one point may increase the stresses nearby, and result in a progressive rupture which may propagate for several hundred kilometres. The rupture will almost invariably occur along old zones of weakness (faults), and the wave motion may range from violent at some locations to imperceptible at others.

**Epicentre** - The point on the earth's surface that is directly above the focus (hypocenter) of an earthquake.

**Fault** - A fracture or a zone of fractures along which displacement has occurred parallel to the fracture. Earthquakes are caused by a sudden rupture along a fault or fault

system; the ruptured area may be up to several thousand square kilometres. Relative movements across a fault may typically be tens of centimetres for magnitude 6.0-6.5 earthquakes, several meters for magnitude 7-8 earthquakes.

**Focal Mechanism** - The focal mechanism of an earthquake describes the inelastic deformation in the source region that generates the seismic waves. In the case of a fault-related event it refers to the orientation of the fault plane that slipped and the slip vector and is also known as a fault-plane solution. Focal mechanisms are derived from a solution of the moment tensor for the earthquake, which itself is estimated by an analysis of observed seismic waveforms

**Hypocenter** - The point where the earthquake started, also called focus. Hypocenter depths are typically 30 km and less for shallow earthquakes, several hundreds of kilometres for earthquakes occurring in subduction zones. Most earthquakes in Fennoscandia originate at depths between 10 and 30 km.

**Intensity (of an earthquake)** - A qualitative or quantitative measure of the severity of ground shaking at a given site (e.g., MSK intensity, Modified Mercalli intensity, Rossi-Forel intensity, Housner Spectral intensity, Arias intensity, peak acceleration, etc.) based on effects of the earthquake such as how the earthquake was felt, damage to structures, how people reacted, soil or rock slides, etc.

**Interplate earthquake** - An earthquake along a tectonic plate boundary. Most earthquakes are caused by the relative plate movements along plate margins, i.e., between plates.

**Intraplate earthquake** - An earthquake within a tectonic plate. Scandinavia belongs to the Eurasian plate and is well removed from the nearest plate boundary.

**Isoseismal** - Contour lines drawn to separate one level of seismic intensity from another.

**Magnitude** - A measure of earthquake size at its source. Magnitude was defined by C. Richter in 1935 as: "The logarithm to the trace amplitude in 0.001 mm on a standard

Wood-Anderson seismometer located 100 km from the epicentre" The Wood-Anderson instrument measures the responses in the period range near 1 sec. Other magnitude scales have later been devised based on the responses measured in other period ranges, and on maximum amplitudes of specific wave forms Some of the more commonly used magnitude scales are:

1.  $M_L$ = local magnitude, similar to the original Richter magnitude. Usually determined from shear wave response in the period range near 1 sec. at relatively close distances from the epicentre (< 600 km).
2.  $m_b$ = body wave magnitude is based on the largest amplitude of body waves, usually the compressional component with period near 1 sec.
3.  $M_s$ = surface wave magnitude is measured in the period range near 20 sec.
4.  $M_w$ =moment magnitude is based on the seismic moment and be computed directly from source parameters or from long period components in the earthquake record. Symbol M is also used for this magnitude.

Magnitude scales are also based on other earthquake parameters such as felt area, length of rupture and surface displacement, and area within different intensity zones.

A large number of empiric relations between magnitude and other earthquake parameters such as energy, fault movement, fault area, intensity, maximum acceleration, etc., are available. Such relations may differ considerably from one seismic region to another.

**Moment tensor solution** - The moment tensor solution is typically displayed graphically using a so-called beachball diagram. The pattern of energy radiated during an earthquake with a single direction of motion on a single fault plane may be modeled as a double couple, which is described mathematically as a special case of a second order tensor.

**Nappe** - large body or sheet of rock that has been moved a distance of about 2 km (1.2 miles) or more from its original position by faulting or folding. A nappe may be the hanging wall of a low-angle thrust fault

**Peak ground acceleration (PGA)** - It is the maximum acceleration generated by an earthquake at a site.

**Seismic event** - The abrupt release of energy in the earth's lithosphere, causing an earthquake.

**Seismic hazard** - Any physical phenomenon or effect (e.g., ground shaking, ground failure, landsliding, liquefaction) associated with an earthquake that may produce adverse effects on human activities, representing the earthquake's potential danger. Specifically, the probability of occurrence over a given time period in a given location of an earthquake with a given level of severity. Seismic exposure may be used synonymously with seismic hazard.

**Seismic zone** - A generally large area within which seismic design requirements for structures are constant. Some times used synonymously with **Seismogenic zone**.

**Seismic zoning (zonation)** - The process of determining seismic hazard at many sites for the purpose of delineating seismic zones. Some times used synonymously with **Seismotectonic zoning**.

**Seismicity** - The occurrence of earthquakes in space and time.

**Seismotectonic** - The study of the tectonic component represented by seismic activity a subfield of active tectonics concentrating on the seismicity, both instrumental and historical, and dealing with geological and other geophysical aspects of seismicity.

**Strain** - Change in the shape or volume of a body as a result of stress.

**Stress** - Force per unit area.

**Strike** - The *strike* of a bed, fault, or other planar feature is a line representing the intersection of that feature with a horizontal plane

**Strike Slip Fault** - A geologic fault in which the blocks of rock on either side of the fault slide horizontally, parallel to the strike of the fault. The types include left lateral or sinistral and right lateral or dextral strike slip faults

**Tectonics** - A branch of geology dealing with the broad architecture of the outer part of the earth, that is, the regional assembling of structural or deformational features, a study of their mutual relations, origin, and historical evolution.

**Thrust Fault** - A fault in which the hanging wall has moved upward relative to the footwall.



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