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PETROLOGIC MODEL FOR GENERATION OF MEDIUM SIZE EARTHQUAKES IN DECCAN TRAP, INDIA

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The seismic activity in peninsular shield is very low in comparison to Himalayan collision zone. Ninety four years (1900-93) of seismicity data reveal that the seismicity of deccan traps (i.e. the youngest geological formation) is a separate entity as energy released in this region is four-and-a-half times more than the rest of the shield which covers sixty six percent of the total area. All the medium size earthquakes are distributed over either prominent positive or negative Bouguer gravity anomalies. These zones are associated with the dominant volcanic eruption associated with subsidence in the adjoining areas. This would produce cracks and faults in the brittle top layer providing the space for accumulation of fluid released in dehydration process generating medium size earthquakes. Latur earthquake occurred in the gravity low of -80 milligals. Presence of highly conducting fluid at a depth of 6-10km and highly elevated level of Helium in the epicentral zone of Latur earthquake suggest the validity of petrologic model as the local cause for generation of medium size earthquakes in trap covered areas.

Key Words : Petrologic Model; Earthquakes—Medium Size; Deccan Trap; Seismic Activity; Bouger Gravity; Latur Earthquake

Introduction

Indian peninsula also known as Precambrian shield is considered to be a seismic zone. However, owing to the occurrence of recent Latur earthquake of 1993 and Koyna earthquake of 1967 reassessment of seismicity of shield region and understanding its possible causes have focused the attention of geoscientists.

Indian Peninsula shows sporadic seismic activities. Its seismicity is very low in comparison to seismic activities of Himalayan collision zone. Its seismicity has been studied by different workers[1,2,3]. Western and Eastern ghats and Narmada-Son lineament have been identified as seismotectonic belts of the region. Geologically the major parts of the western peninsula is dominated by upper Cretaceous to lower Tertiary vertical Crustal movements owing to volcanic eruptions resulting in a number of deep seated faults and weak zones. These are the youngest geological formations of the region in which the tectonic activities are still continuing. The data analysis reveal the deccan trap to be seismically very active in comparison to the rest of the shield (i.e. peninsular shield excluding trap).

A number of views and models have been presented in the literature to explain continental seismicity[4-8]. Different geophysical parameters such as high heat flow[4] and gravity anomalies[5] show strong correction with seismicity. These two parameters

have been realised as the controlling agencies for seismic activities. A fault related weak zone model[6-8] and block tectonic hypothesis[9] were proposed to explain the seismic activities of Peninsular India. From the above proposed models, however, it is difficult to explain as to why medium size earthquakes are confined to shallow depth in trap covered areas. It is also difficult to explain why the eastern Peninsula does not generate medium size earthquakes. In the present article petrologic model for generation of earthquakes is advocated to explain the occurrences of earthquakes in trap covered areas.

Crustal and Lithospheric Structures

It is now established that the Moho is not a static feature but is dynamic and its configuration has been changing owing to a number of major events over geological time-scales. Such events include the thinning of the crust and up-doming of upper mantle along the west coast during Deccan volcanism. Investigations of crustal structure of Indian Peninsula have been carried out by various workers[10-13]. Deep Seismic Sounding (DSS) studies have revealed elevation of Moho along Western Ghats by 15km[14] which reduces towards east. The elevation of Moho is also confirmed by positive gravity anomalies. The investigations have revealed the average thickness of the crust in deccan volcanic province to be lower than the rest of the shield.

The Litho-asthenospheric boundary is not sharply defined. Average thickness of lithosphere for shield is 120km[15]. The South Indian and Karnataka craton show the average thickness over 200km[16]. For the Deccan trap region using gravity modelling of Lithospheric flexuring, the thickness of lithosphere is estimated to be 100km[17]. The thickness of the lithosphere of deccan trap region has also been derived by Negi *et al.*[18,19] which ranges from 38 to 100km. The above findings reveal that the thickness of crust and lithosphere in trap areas to be smaller than the rest of the shield indicating thermal sources to be still existing at shallow depths.

Thermal Structure

Detailed heat flow studies of Indian subcontinent have been summarised by Ravishanker[20]. The Indian Peninsula has been divided in to five heat flow zones as shown in Fig. 1. Zones I to III are identified as high heat flow zones whereas IV and V as cooled regions. The region of higher heat flow zone in the shield represent areas of intense tectonisation and higher litho-asthenospheric interaction during the Phanerozoic period. Zones falling in the first category are restricted to the NW part of Himalayas and Tibet and to a narrow zone in the Sarguja distt. of eastern Madhya Pradesh along the Sonata belt. Zones II to V are well distributed over shield region. Global observations indicate that the elevation of Moho and the presence of Channels permitting up flow of geothermal fluid from deeper levels are the possible causes for high heat flow.

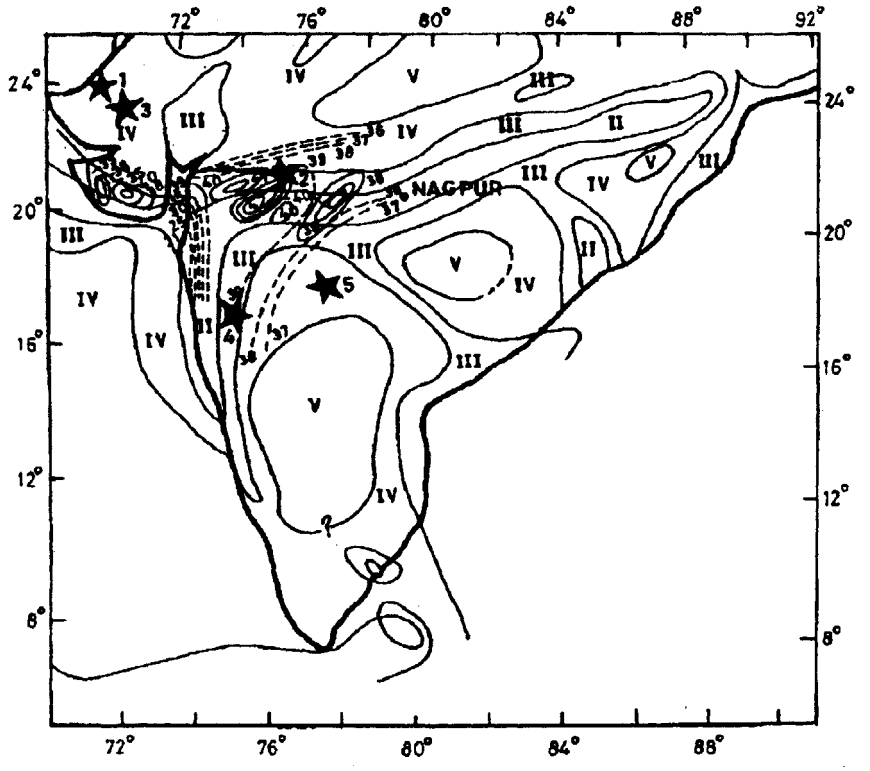

Fig 1 Different heat zones of Peninsular India with depth of Moho in covered areas. Medium size earthquakes are also marked.

About one-third of the shield region is covered by the Deccan traps[5]. The uplifting of Deccan lava started in upper Cretaceous[21]. The youngest volcanic eruption is observed in Cambay basin lying over Tertiaries showing high heat flow[22]. Another portion of the Western Ghats upto Kutch region shows high heat flow in comparison to its southern parts.[23,24]. Also most of the hot spring of traps are associated with faults of tectonic importance. In trap covered areas the elevation of Moho[14] (Fig. 1) and heat flow zones[20] are in agreement reflecting that the change in heat flow values from west to east is due to elevation of Moho (along the Western Ghats) which dips towards east. At certain places the hot springs may be associated with flow of geothermal fluids from deeper levels.

Temperature gradients in different heat flow zones have been reported to be ranging from 55°C to 20°C. Based on temperature gradients data the depth of solidus of basalt was reported to be between 22 and 60km. The trap areas are showing zones II to IV[20]. However in view of the recent findings of thinning of crust (Fig. 1) from east (38km) to west (15km)[14], and lithosphere from 100km to 38km[18,19], the liquid basalt may be assumed to be existing at shallow depths.

Seismicity Data

In 1993, India Meteorological Department (IMD) published the seismicity data of Peninsular India in the proceedings of a Workshop organised in Hyderabad[25]. Inspection of seismicity data reveals that the data before 1900 are not reliable as only a few earthquakes are reported. Also it lacks instrumentally recorded data. Therefore, the data since 1900 onwards may be considered to be reliable for seismic analysis as the magnitude for most of them has been derived from seismograms and degree of damages reported in the newspapers. Therefore, ninety four years (1900-93) of seismicity data published by IMD, New Delhi, for Peninsula lying between 80° and 25°N and 65° to 88°E. It shows a total of 54 independent earthquakes distributed all over the shield region. Events that occurred within three months of the occurrence of the main event have been considered as foreshocks or aftershocks and hence discarded from the analysis.

Seismic Morphology

The seismic morphology has been discussed by several workers[1-3, 9]. Here the seismic morphology is discussed on the basis of 94 years of seismicity data. The plot of data for the considered region for $M \geq 4$ is shown in Fig. 2. A relatively large number of symbols have been used to visualize the distribution of magnitudes in the region. It does not show any alignment of seismicity.

Only Koyana area show clustering pattern of different magnitude events. The histogram of frequency distribution for trap covers areas and the rest of shield (shield-trap) is shown in Fig. 3. It may be noted that the trap covers about thirty three percent of the Peninsular shield. If the seismicity is reduced to equal area the trap seismicity (number wise) is twice to the rest of the shield whereas in terms of energy released it is nine times more (Formula used $\log E = 12.24 + 1.44\ M$)[26]. It clearly reveals the distinct contrast in the seismicity of the trap and the rest of the shield. Comparison of seismicity of the two regions is shown in Table I. The comparison of energy released, frequency and magnitude for Western and Eastern Peninsula is shown in Table II. It reveals that all the events of $M \geq 6$ and about 66% of the total events $4 \leq M \leq 6.5$ and 84% of the total energy released are confined to Western Peninsula. The Eastern Peninsula does not show any earthquake of $M \geq 6$ in ninety four years.

Table I

Comparison of areas, frequency, magnitude and energy released

Comparative parameters	Deccan trap	Rest of the Indian Peninsula
Area	0.6 million km^2	1.2 million km^2
No. of events		
($M \geq 4.0$)	26	28
($M \geq 6.0$)	4	1
Total energy released in 94 years	3.0×10^{22} ergs.	0.68×10^{22}ergs.

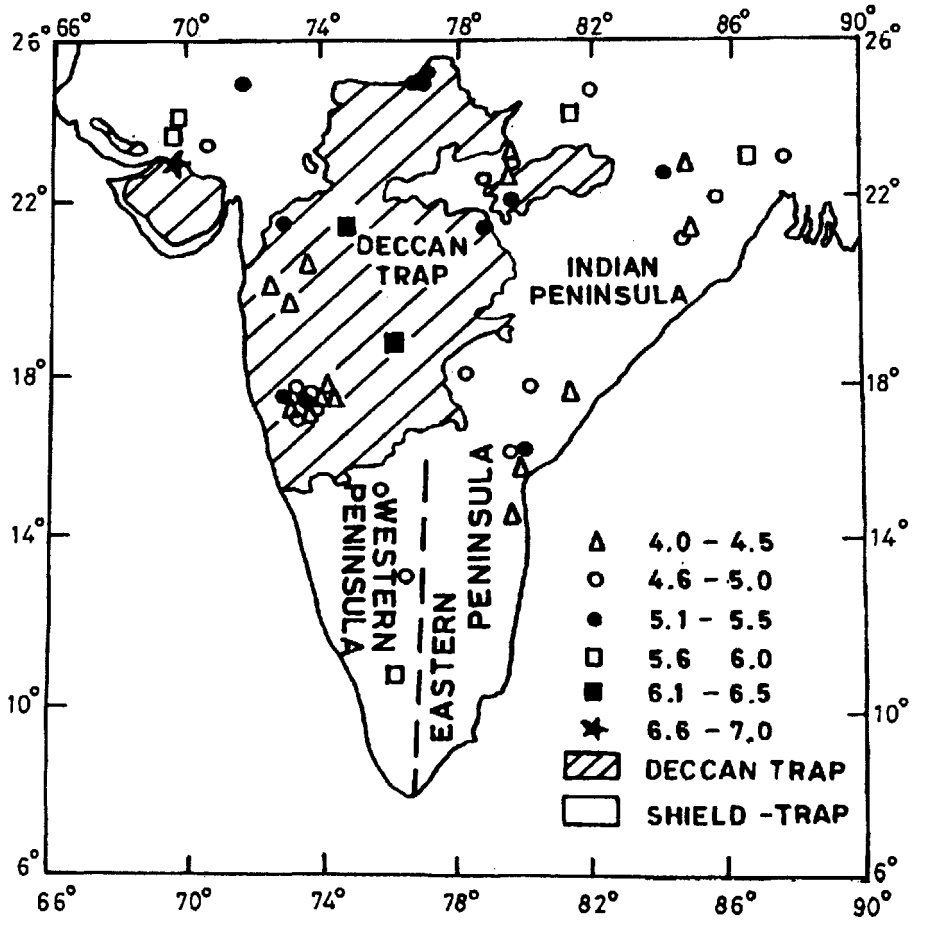

Fig 2 Seismicity of the Peninsular shield for the period 1900-93. Different symbols reflect the magnitude distribution in the shield region

Table II

Comparison of energy released, frequency and magnitude between Western and Eastern peninsula

Comparative parameters	Western Peninsula	Eastern Peninsula
No. of events		
($M \geq 4.0$)	32	22
($M \geq 6.0$)	5	–
Total energy released in 94 years	94%	16%

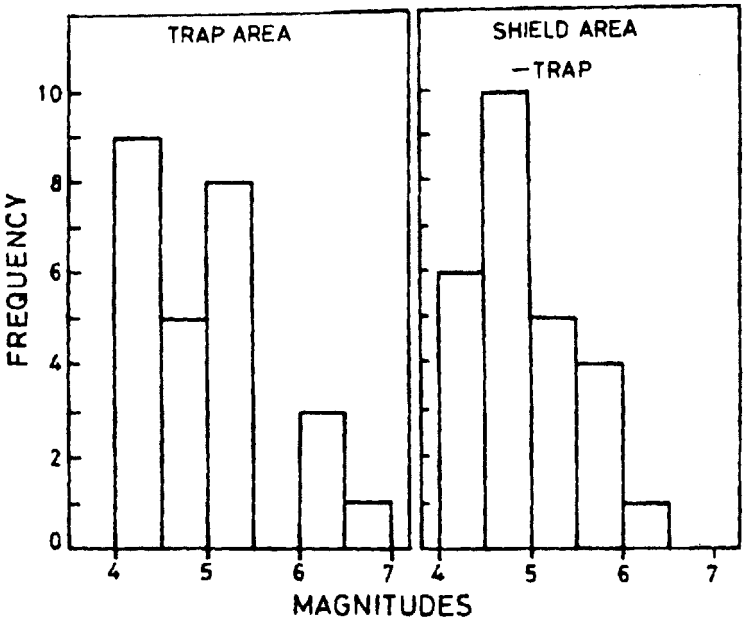

Fig 3 Histogram showing frequency distribution of different magnitude range for trap areas and the rest of the Peninsular India. It may be noted that the trap shows 4 events of $M \geq 6$ in comparison to 1 for rest of the shield

The distribution of medium size earthquakes over heat flow zones and gravity anomalies[27] of trap covered areas are shown, respectively, in Figs. 1 & 4. Fig. 1 demonstrates that the occurrence of medium size earthquakes are not confined to high heat flow belt. The Kutch earthquakes of 1819 (EC 24°N, 70°E; M 7.8) and 1956 (EC 23.3°N, 70.2°E, M 7) lie in zone IV. The epicentral zones of the above two events are characterised by high gravity anomalies i.e. 50 and 10 milligals[28]. The Tapal earthquake of 1938 (EC 21.6°N, 75°E; M 6.3) lies in heat flow zone III where the gravity contour is of -20 milligal orienting in almost E-W direction. Besides this the epicentre of the event is very close to a hot spring of 35°- 55°C. Koyna earthquake of 1967 (EC 17.5°N, 73.8°E; M 6.5) occurred in high heat flow zone III. The earthquake is located over the gravity gradient of 3 milligal km[29] and the gravity contour of -100 milligal[27]. Latur earthquake of 1993 (EC 18.7°N, 76.6°E; M 6.3) occurred in heat flow zone IV. In this area the gravity value is of the order of -80 milligal. The earthquake of 1900 (EC 10.7°N, 76.6°E;M 6) occurred in South India where the gravity is of the order of -100 milligal. Fig. 2 demonstrates that the frequency of earthquake over M 5.5 are more in Deccan trap than the other areas of peninsular India. The data reveals the focal depth of medium size earthquake to be less than 15km whereas in other areas of the shield region the average depth is 23km. It may also be noted

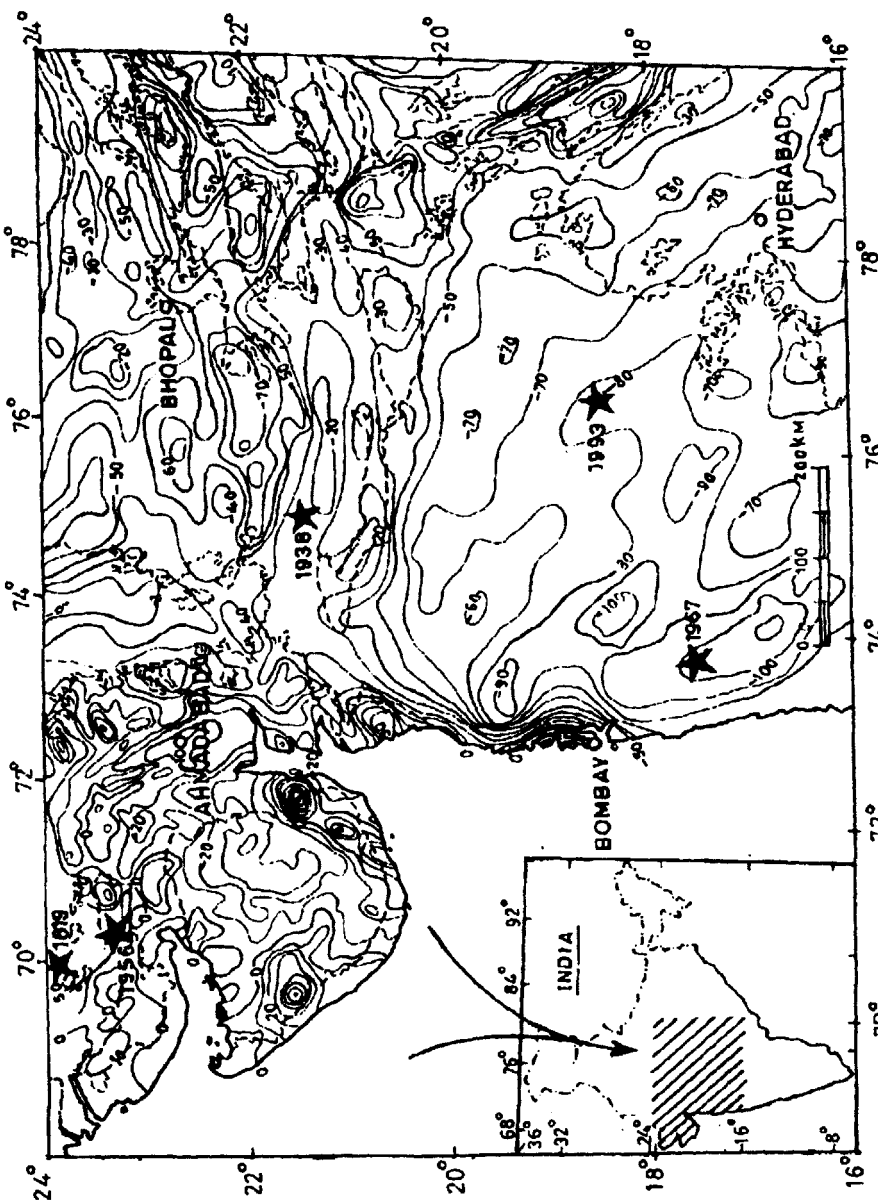

Fig 4 The distribution of medium size earthquakes over gravity anomalies. It may be observed that all earthquakes are located at either positive or negative gravity anomalies indicating elevations and depression in Moho. Hence, such zone may be identified as fractured zone favourable for accumulation of fluids for generation of medium size earthquakes

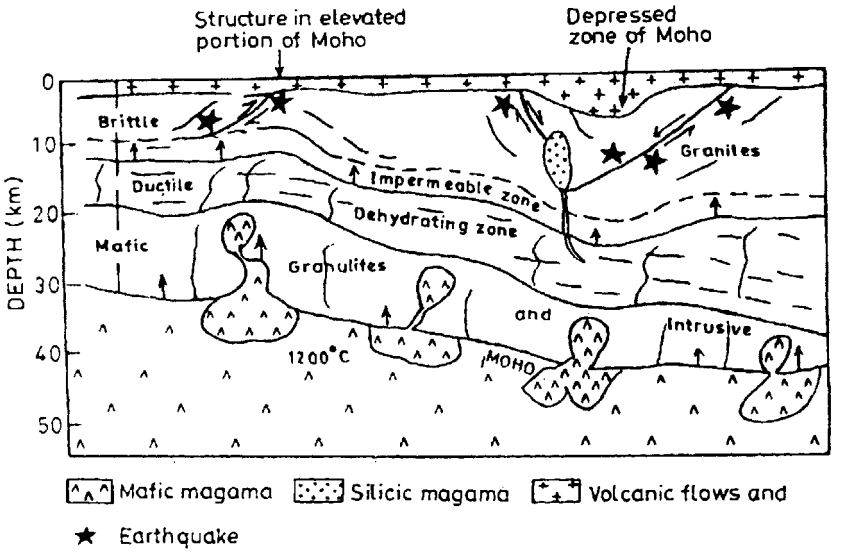

Fig 5 Schematic petrologic model of crustal structure of trap areas. The base of the crust is interpreted to be approximately at the dry basalt solidus. Fluids produced as a result of dehydration of the mid crustal and lower crustal rocks are inferred to rise to an impermeable zone at the top of the midcrust. The zone of fluids and partial melt is interpreted to poduce high conductivities

that all the medium size earthquakes are distributed over prominent positive or negative gravity anomalies.

Petrologic Model for Earthquakes

Petrological model for crustal structure of continental magmatic arc of cascade region was proposed to explain the seismic activities of this region[30]. In the above region the earthquakes are occurring within the top 15km thick crustal layer. It provides the convincing explanation for the occurrences of shallow earthquakes. In view of the presence of highly conducting fluids at depth of 6-10km in the epicentral region of Latur earthquakes, the focal depth of medium size earthquake (<15km), elevation of Moho and Shallow thickness of lithosphere a petrologic model is proposed as the local cause of seismic activities.

Schematic petrologic model of the crustal structure is shown in Fig. 5. In view of less Lithospheric thickness and high temperature gradient[20], the depth of solidus of basalt may be ranging from 22km to 60km from west to east. Correspondingly the thickness of brittle top crust, the middle crust (dehydration zone) and the zone

of partial melting would change. In this model the brittle to ductile transition in crustal rocks is produced due to the effect of temperature and pressure the base of the crust and below is interpreted to be approximately at the dry basalt solidus. The anhydrous basalt in the lower crust is heated up by presence of lava below. The lava alongwith gases may also rise towards surface because of high pressure. Fluid produced as a result of dehydration in the middle and lower crustal rocks which rises into the impermeable zone (through faults and joints) at the top of the mid crust. A high stress field would be developed at the base of the brittle top layer. If the cracks or faults of the weak zones are extending to the dehydration zone the fluid may be injected through these to the brittle crust. As the process continues for a long time high pressure stress zone may be developed in the fault zone resulting in earthquakes. The fluids would also reduce friction to promote sliding.

Discussions

A number of hypotheses such as high heat flow[4], weak zone fault[6-8] and block tectonics[9] have been proposed to explain the seismicity of Peninsular India. The weak zone fault model can not explain the occurrences of 80% of the earthquakes of $M \geq 6$ confined to trap covered areas. It is unable to explain as to why a number of weak zones or faults of the Eastern Peninsula do not show seismic activities. High heat flow shows good correlation with the seismicity. However, it does not explain the occurrences of Latur and Kutch earthquakes in zone IV. Recently block tectonic hypothesis[9] was proposed to explain the seismicity of Peninsular India. It is based on strain rebound developed by Indian plate movement and its collision along the Himalayas with the Eurasian land mass. It is difficult to explain why the northern block of Peninsular India does not show any earthquake of $M \geq 6$ and why the focal depth of medium size earthquakes is confined to 15km only while the thickness of lithosphere in trap region is 38 to 100m.

Deccan trap is the youngest and largest geological formation of Peninsular India. The duration of volcanic lava eruption is 4my[21]. the large eruptive zones of the flood basalt are associated with the subsidence of neighboring crustal rocks into the upper mantle. These are well reflected by prominent positive and negative gravity anomalies. The rises and depressions in Moho would develop cracks and faults extending to deeper crust in the surrounding areas of gravity anomalies. Such zones may be the proper place for accumulation of fluid released in dehydration process. Probably this could be reason why medium size events are confined to such areas. In high heat flow zone (i.e., zones II and III) the fluid injection from the dehydration zone into the top crustal layer may be more because of its shallow depth. Perhaps this may be reason for more number of events along the western ghats and Narmada-Son-Lineaments. For subsidence zones the depth of solidus basalt is at larger depths. In such an area an earthquake may occur if opening of cracks or faults extends

to deeper level allowing the fluids to come to the top brittle layer. The Latur earthquake may be the result of this happening.

The detailed geophysical investigations of the epicentral regions of medium size earthquakes which occurred in high heat flow belt to trap zones are not available. For these zones the solidus of basalt lies at 22 to 36km. The epicentre of Latur earthquake lies in the cooled region (zone IV). If the Petrologic model explains the geophysical observations of the epicentral zone for this event a similar analogy may be drawn for other events as well. Magnetotelluric studies in the epicentral region of Latur earthquake reveal high conducting fluid to be at 6-10 km depth[31]. The investigations have also revealed highly elevated levels of helium in the epicentral zone[32]. Their presence can be explained by this model. Krishna Bramham and Negi[33] and Valdiya[34] have suggested that the event was related to the Kurudvadi graben as inferred on the basis of gravity anomaly. Deep seismic sounding studied have not shown any evidence for the existence of graben[35].

Crustal and Lithospheric thickness for the rest of the Peninsular India is relatively large in comparison to Deccan trap because of old geological formations. Correspondingly the depth of the solidus basalt, would be relatively at greater depth in the rest of the shield and as such less number of events with smaller magnitude should occur. This is revealed by Figs. 2 and 3. Some of the events may be occurring due to local geological causes. Focal mechanism studies of medium size earthquakes of Peninsular India have been reported by different scientists which show the direction of P-axis to be oriented towards north to north-east. The direction of stresses may be explained in the light of drifting of Indian plate towards north. Owing to its northward drifting the Indian subcontinent is under compression and hence it would develop cracks in the weak zones striking East-West. According to this model the injection of fluid in to the upper crust through faults would accumulate in cracks causing their widening and lengthening to long distances. As the process continues for a long time the fluid would generate stress perpendicular to the cracks or fault surfaces resulting an earthquakes. The presence of fluid would also act as a lubricant reducing friction to promote sliding. The above model may also explain the seismic activities along the Son and Tapti rift Zones and other hot springs belts of Peninsular India. The variations in average focal depths in trap and rest of the shield can also be explained by this model.

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