Probable evidence for periodicities in seismicity in Gujarat and adjoining region, India: implications on future earthquake hazard

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ABSTRACT :

The observations of temporal variation of seismic activity in Gujarat and adjoining region indicate evidence that a periodic seismicity probably exists. A complete data set from 1819 to 2006 of shallow earthquakes distributed over Gujarat and adjoining regions have been used for the first time to test the possible existence of periodicities and its implications on the future earthquake occurrences on the basis of stationary model of seismicity rates and seismic energy released in 11-years time window. The results exhibits a network of periodicities with predominant period at 1819-1848, 1898-1956 in low seismicity rate intervals followed by the 1856-1891 and 1962-2006 in high seismicity rate intervals with a period of 105 years in a harmonic variation of seismic energy release. The time interval of low seismicity rates is slightly larger than high seismicity rates. The low seismicity rate varies from 0.2 to 0.3events/year whereas the high seismicity rate varies from 0.4 to 1.0 events/year. The frequency distribution of earthquakes show that the earthquakes of small magnitude (M 4.0-5.9) follow the Poisson distribution and hence such earthquakes can not be predicted. However, the frequency distribution of large earthquakes (M 6.0-7.8) follows the nonrandom distribution (exponential distribution). The characteristics of non-randomness of earthquakes indicate that the prediction of magnitude and time of occurrences of forthcoming large earthquakes may be possible. The temporal variation of earthquake magnitude for three different magnitude ranges (4.0-4.9, 5.0-5.9 and 6.0-7.8) reflects that large earthquakes are preceded by high seismic activity in lower magnitude ranges. The seismic energy released in 11 year time windows shows a harmonic variation with a period of 105 years. The maxima of the harmonic curve coincide with the occurrence of large earthquakes. The detection of such kind of periodicities is important in earthquake study, because these patterns may lead to the prediction of large earthquakes.

KEYWORDS: harmonic variation, seismicity rates, non-randomness, Poisson distribution

1. INTRODUCTION

The word 'Seismic Cycle' was introduced by Fedotov (1968) for the tendency toward periodicity in the occurrences of large earthquakes in Kamchatka, the Kuril Islands and North-Eastern Japan. The Mexico earthquake of Central America was predicted on the basis of statistical analysis of seismicity data. Several researchers of the world statistically analyzed the seismicity data for the study of seismicity rates, seismic quiescence and seismicity fluctuations prior to the occurrences of medium to large earthquakes (Habermann and Wyss, 1984; Wyss et al., 1984; Singh and Singh, 1984; Wyss, 1986; Papadopoulos and. Voidomatis, 1987; Singh et al., 1994). For the long-term earthquake forecasting, Fedotov and Riznitchenko (1984) proposed a mathematical model of the spatial-temporal movement of the seismic processes. Seismicity data of long duration for large area shows the temporal behavior of seismic activity of the region. This study may provide the periodic nature of accumulation-relaxation of tectonic stresses in the region and used to indicate the future seismic activity. Khattri and Wyss (1978) observed the deviation of seismicity rates from normal before and after large earthquakes and also found that all earthquakes of M≥6.6 were preceded by seismic quiescence. Papadopoulos and. Voidomatis (1987) used a stationary model of seismicity rates and seismic energy released in a specific time interval to describe the seismicity time variation during 1800-1986 in the inner Aegean seismic zone. They observed that intervals of low seismicity rate (lasting for some 37 years) alternate with high rate intervals (8-12 years duration) and seismic energy released within 5-years time window approximates a harmonic curve within a period of about 50 years. Same models were used in the northeast India by Singh et al. (1994) during the period 1912 to 1977 for large earthquakes (Ms≥ 6.0) and observed that seismicity rates vary from 0.73 - 2.15 events/year and seismicity data of 66 years follows the Poisson distribution. They observed a 20 year probable periodicity of high seismic phases for northeast Indian region.

In this paper an attempt have been made to investigate the possible variation in the seismic activity of Gujarat and adjoining region using a reliable seismic data covering a time period as long as possible. This study attempts an analysis of temporal variation of seismic activity for the period 1819-2006 which shows that a periodicity probably holds.

2. GEOLOGY AND SEISMOTECTONICS OF STUDY REGION

Gujarat is situated in the highly tectonised zone along the western margin of the Indian continental plate. According to Biswas (1987), there are four distinct tectonic regimes associated with boundaries of Gujarat: Kachchh rift zone, Cambay rift zone, Saurashtra Horst and Narmada rift zone (Figure 1).
The Kachchh rift zone was initially subjected to extension but now it is under N-S compression since 20 Ma (Talwani and Gangopadhyay, 2001). The Kachchh basin has most complete Mesozoic (135-65 Ma) record with thick accumulation (3000m) of Late Tertiary to Lower Cretaceous sediments (Biswas, 1987). From the deep seismic sounding, Kaila et al. (1980) observed seven blocks bounded by deep seated faults in the southern part of the Cambay graben. Hardas (1980) observed the fluvial sands in the northern part of the basin which was correlated with the fluvio-deltaic Lower Cretaceous formations of Kachchh and Saurashtra from the drilling data.

Gujarat and adjoining region falls in three different seismic zones according to the seismic zoning map of India. Kachchh and adjoining region along the Pakistan border falls under zone-V (highest seismic zone). A narrow fringe of the northern Kathiawar peninsula and remaining part of Kachchh falls under zone-IV. The rest part of Gujarat region falls under zone-III. Kachchh and adjoining region is seismically most active zone where high intensity but infrequent earthquakes have been occurred (Shanker et al., 2007). The most significant earthquakes of this region are May 1668 (Samaji, Delta of Indus, Intensity X), June 16, 1819 (Kachchh, Intensity XI, Magnitude 7.8), June 19, 1845 (Lakhapat, Magnitude 6.3), July 21, 1956 (Anjar, Magnitude 6.5, Intensity IX) and January 26, 2001 (Bhuj, Magnitude 7.7, intensity X). A total nine damaging earthquakes of M5.0-8.0 have been occurred during past 188 years (Rastogi, 2001, 2004). The last damaging earthquake of magnitude Mw

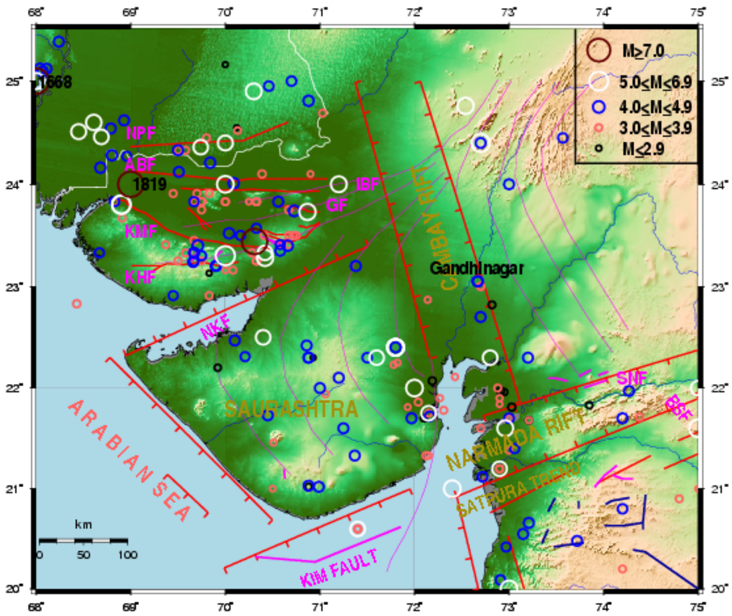

Figure 1 Topography and Seismotectonic map of Gujarat and adjoining region. Spatial distribution of events of all magnitude range which occurred from earliest time to September 2006 is shown.

origin time 03:16:40.7 UTC (08:46:42.9hrs IST) hit the Bhuj-Anjar-Bhachau region of Kachchh on the morning of 26th Jan 2001 followed by a large number of aftershocks (Gupta et al, 2001).

3. SEISMICITY DATABASE

For the statistical analysis of seismicity of Gujarat and adjoining region, various existing earthquakes catalogues and lists (historical and recent) pertaining to the region have been considered and scrutinized. Historical earthquakes of this region were taken from the catalogue prepared by Oldham (1883). For some other historical and modern earthquakes, the data have been taken from Tandon & Srivastava (1974), Chandra (1977), Quittmeyre & Jacob (1979) and Malik et al. (1999). The modern seismicity data have been taken from several agencies like India Meteorological Department (IMD), New Delhi, India; Geological Survey of India (GSI), India; USGS-NEIC; International Seismological Centre (ISC); Gujarat Engineering Research Institute (GERI), India and Institute of Seismological Research (ISR), India.

A complete seismicity database of Gujarat region bounded by 20^0-25.5^0 N and 68^0-75^0 E has been prepared from earliest time to September 2006 for all magnitude range. The analysis indicates that data is complete for the magnitude above 4.0 (Figure 2).

4. THE VARIATION OF SEISMICITY

To study the time variation of the seismicity of any region, the most commonly used tools are seismicity rates, seismic energy release with time, seismicity maps and time-distance curves. Seismicity rates and seismic energy release with time gives the quantitative evaluations of seismicity pattern which are used in this study whereas the seismicity maps and time-distance curves involves several problems such as quantitative evaluations. The time variation of seismicity in Gujarat and adjoining region is described by two independent models: a sequentially stationary model of seismicity rates and statistical model of periodic energy release.

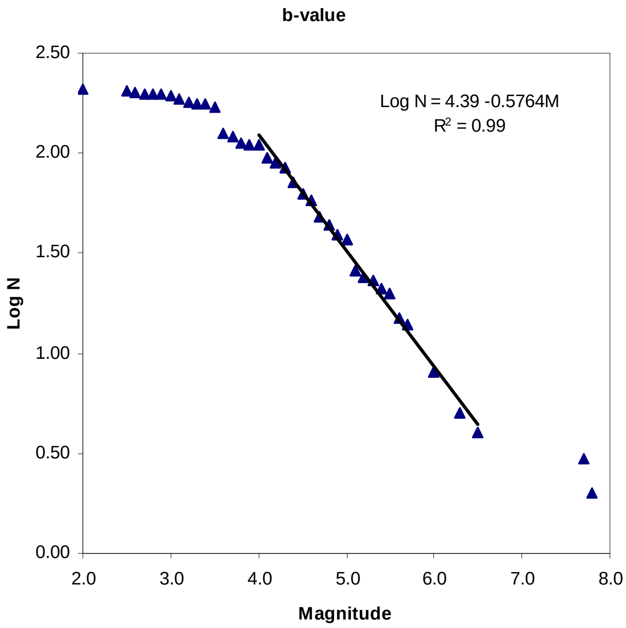

Figure 2 Plot of cumulative number of events, N, and magnitude, M, for all magnitude range from earliest time to September 2006. Cut off magnitude is observed as 4.0. A liner relation is fitted for M≥4.0 with 99% correlation coefficient.

4.1. The Seismicity Rate

Figure 3 reflects the long term seismicity rate changes as determine on the basis of the cumulative number of shallow, strong earthquakes as a function of time. For the determination of seismicity rate (the slope of the curve), r, the least-square method has been used. The mean seismicity rate, i.e. the slope of the curve for the entire period, was found to be r = 0.52 events/year. This value is in good agreement with the mean recurrence period, T_m, of 1.58 years for shallow earthquakes with magnitude M≥4.0 occurring in Gujarat and adjoining region as determine on the basis of a (= 4.39) and b (= 0.58) parameters of the earthquakes determined from the frequency-magnitude relationship for the period 1819-2006 (Figure 2). Figure 3 shows that the seismicity rate is not constant during the entire period and the intervals of low seismicity rate alternate to intervals of high seismicity rate. It is observed that the 1819-1848, 1898-1956 low seismicity rate intervals were followed by the 1856-1891 and 1962-2006 high seismicity rate intervals.

Table 1 summarized the information about seismicity rates of various phases and its time variation. The seismicity rate varies from 0.2 to 0.3 events/year and from 0.4 to 1.0 events/year for the low and high rate intervals, respectively. The duration of the low rate intervals is slightly more (47.9 to 58.3 years) than the high rate intervals (33.6 years). t-test was successfully performed with 95% confidence limit to examine the significance of the differences of low and high seismicity rates with the preceding and succeeding seismicity phases. The available data are not complete for the period prior to 1819 to determine a reliable seismicity rate.

A probabilistic approach was performed to deal with this problem under the assumptions that the entire period is a stationary Poisson process. The probability of occurrences of ‘x’ earthquakes in a time interval ‘t’ is expressed by a Poisson’s distribution:

$$P(x) = \exp(-rt)\,(rt)^x / x! \qquad (5.1)$$

where ‘r’ is the mean seismicity rate. The probability P(x) has been calculated for the four low and high rate intervals from above formula (1). Very low probabilities obtained with this approach suggest that the seismicity rates are non-accidental. Figure 4 shows the frequency distribution of the number of earthquakes for seven year time window during the period 1819-2006. This frequency distribution curve shows that the frequency distribution fits the Poisson distribution curve with 87% correlation

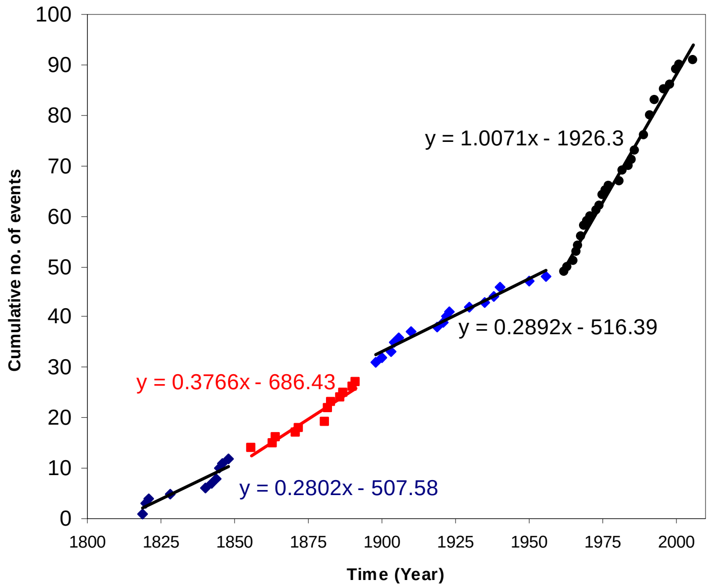

Figure 3 Topography and Seismotectonic map of Gujarat and adjoining region. Spatial distribution of events of all magnitude range which occurred from earliest time to September 2006 is shown.

Table 3.1 Data for beams under dynamic loading

Time period	r (events per year)	T(Year)	X (events)	P(x)	Rate difference (r_i - r_{i+1})	Confidence level by t-test (%)
16.06.1819-26.04.1848	0.28 ± 0.04	47.9	12	0.001800	-0.10	95
25.12.1856-27.071891	0.38 ± 0.03	33.6	15	0.085400	0.10	95
01.04.1898-21.07.1956	0.28 ± 0.02	58.3	21	0.017400	-0.72	95
01.09.1962-30.09.2006	1.00 ± 0.02	43.1	43	0.000036		

coefficient which reflects that earthquakes are randomly distributed. As the region is seismically active and has experienced some of the large events within 188 years, it is essential to study the nature of frequency distribution of larger magnitude events. To check the validity of this suggestion, the frequency distribution of earthquakes of magnitude range 4.0-4.9, 5.0-5.9 and 6.0-7.8, which were observed in 11 year time intervals overlapping by 10 years time intervals, has been examined (Figure 6). The distribution of earthquakes with magnitudes in the range 4.0-4.9 and 5.0-5.9 approximates the Poisson distribution of the form:

$$f(x) = \exp(-\lambda)(\lambda)^{x} / x! \quad (5.2)$$

where 'λ' is the average frequency of earthquakes in 11 years for the given magnitude range and 'x' is the number of earthquakes. The frequency distribution for two magnitude range is estimated to be:

$$f(x) = \exp(2.14)\,(2.14)^x / x! \qquad (\text{for } 4.0 \le M \le 4.9) \qquad (5.3)$$

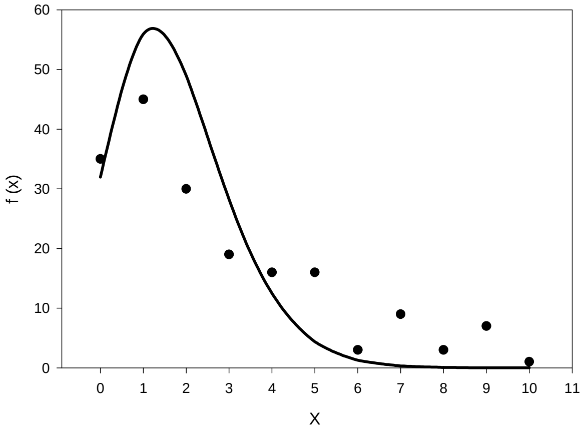

Figure 4 Frequency distribution of the number of earthquakes, x, for strong and shallow earthquakes with M≥4.0 observed in 7 year time window during 1819-2006.

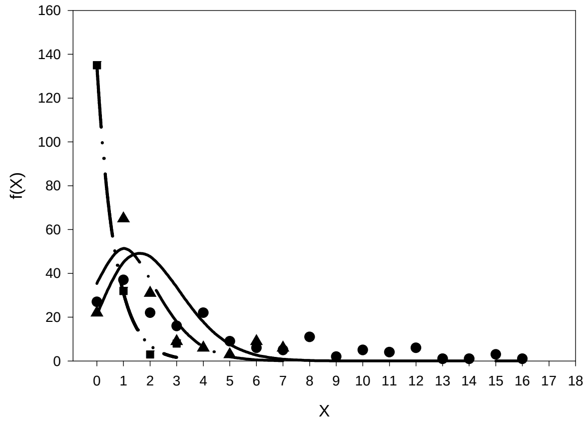

Figure 5 Graph shows the frequency distribution, x, of earthquakes which observed in 11 years time intervals overlapping by 10 years (the time shift is 1 year) for three different magnitude range 4.0-4.9 (a), 5.0-5.9 (b) and 6.0-7.0 (c). The curves (a) and (b) shows Poisson distribution while (c) shows exponential distribution.

and
$$f(x) = \exp(1.45)\,(1.45)^x / x! \qquad (\text{for } 5.0 \le M \le 5.9) \qquad (5.4)$$

On the other hand, the frequency distribution for large magnitude range 6.0-7.8 approximates exponential curve of the form:

$$f(x) = a * \exp^{(-bx)} \qquad (5.5)$$

where 'a' and 'b' parameters are calculated using least-square method and equation of curve is derived as:

$$f(x) = 135.07 * \exp(-1.47x) \qquad (5.6)$$

The frequency distribution curves (Figure 5) for above three cases show that the earthquakes occurrences in Gujarat and adjoining region consist of random and nonrandom process. The earthquakes with low magnitude range (4.0-5.9) correspond to random process while the earthquakes with large magnitude (≥6.0) correspond to nonrandom process. The time distribution of earthquakes with magnitude for three different ranges (Figure 6) shows that the stronger earthquakes with magnitude ≥6.0 are clustered in the intervals of high seismicity rates which justify the above result.

4.2. The seismic energy release

From the previous results, it is observed that a probable cyclic variation of seismicity rates exits. Therefore, a periodicity in the relaxation of seismic energy must be expected. Temporal variation of the logarithmic of the total amount of seismic energy (in ergs), which was released by strong and shallow events in the study region within 11 year time window, Log Eq, is shown in Figure 7. The data from 1819-2006 shows the harmonic variation, which can be fitted in the form of:

$$\text{Log Eq} = \overline{LogEq} + (\log Eq)_0 \,\text{Sin}\left(\frac{360t}{T} + \phi\right) \qquad (5.2.7)$$

Where $\overline{LogEq}$ = average of the Log Eq values, $(\log Eq)_0$ = Mean of the five largest

$\left|\overline{LogEq} - LogEq\right|$ values. 'T' represent the time period. A least-square method is used for the determination of phase Φ. The best fitted equation can be written as:

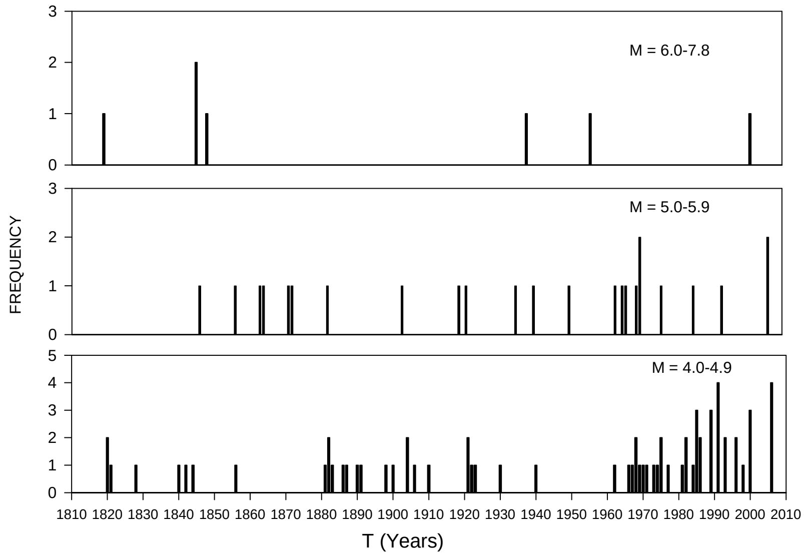

Figure 6 Earthquake frequency distribution with Time from 1819-2006 for the magnitude range 4.0-4.9, 5.0-5.9 and 6.0-7.8.

$$\text{Log Eq} = 20.51 + 1.73 \text{ Sin}\left(\frac{360t}{130} + 45\right) \qquad (5.2.8)$$

The start time't' is measured from the year 1819. The best fitted curve of equation (8) is shown in Figure 7. The fitting of the curve is generally satisfactory with allowing for the errors involved in the magnitude. This type of results was observed by Fedotov (1968), Papadopoulos and. Voidomatis, (1987) and Singh et al., (1994). The energy peaks are coinciding by the mainshocks with M≥6.0. The first peak of energy curve follows the event of 1819 (Mw 7.8) and 1845 (M 6.3), second peak follows the event of 1938 (M 5.7) and 1956 (Mw 6.5).

5. DISCUSSION AND CONCLUSION

The observations of temporal variation of seismic activity in Gujarat and adjoining region indicate evidence that a periodic seismicity probably holds. The occurrences of seismic activity of considered region has been studied statistically on the basis of two models namely stationary model of seismicity rates and energy released in 11 years time window. The analysis shows the two main subphases of low and high seismicity rates. The time interval of low seismicity rates is slightly large than high seismicity rates. The low seismicity rate varies from 0.2 to 0.3 events/year, whereas the high seismicity rate varies from 0.4 to 1.0 events/year. The frequency distribution of earthquakes (Figure 4 and Figure 6) show that the earthquakes of small magnitude (M 4.0-5.9) follow the Poisson distribution and hence such earthquakes can not be predicted. However, the frequency distribution of large earthquakes (M 6.0-7.8) follows the nonrandom distribution (exponential distribution). The characteristics of nonrandomness of earthquakes indicate that the prediction of magnitude and time of occurrences of forthcoming large

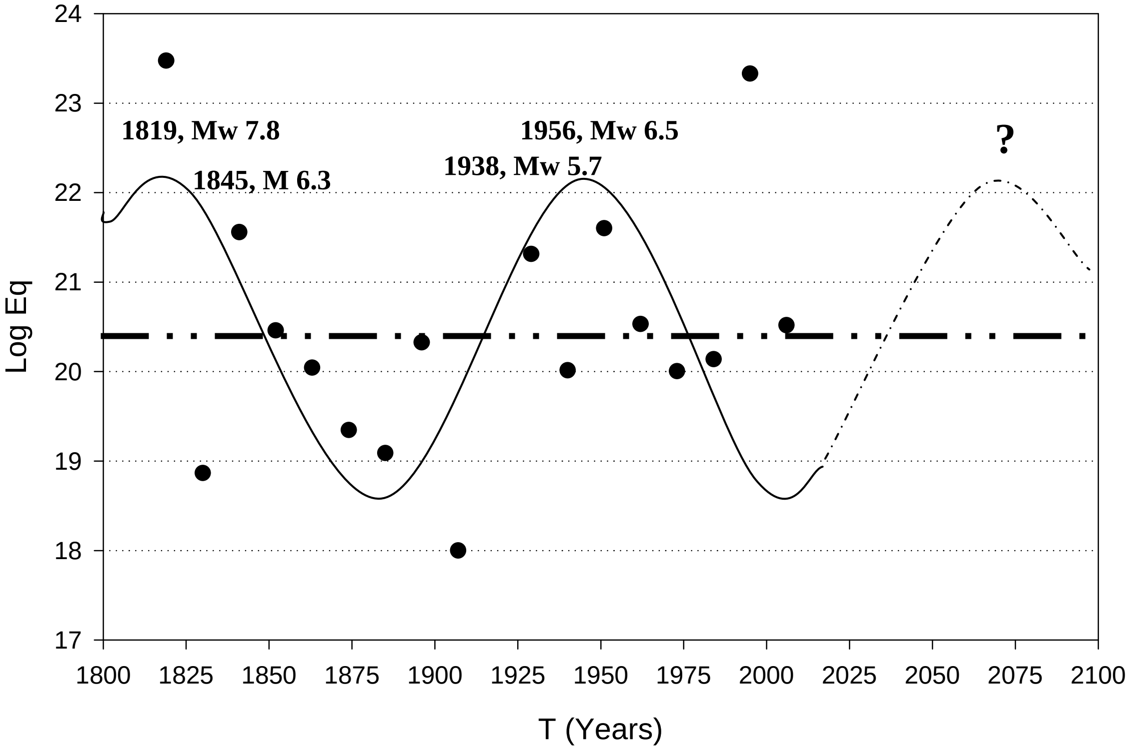

Figure 7. Temporal variation of the Log Eq, where Eq is the total seismic energy in ergs released by strong and shallow events within 11 years time window

earthquakes may be possible. The temporal variation of earthquake magnitude (Figure 5) for three different magnitude ranges (4.0-4.9, 5.0-5.9 and 6.0-7.8) reflects that large earthquakes are preceded by high seismic activity in lower magnitude ranges. The seismic energy released in 11 year time windows shows a harmonic variation with a period of 105 years. The maxima of the harmonic curve coincide with the occurrence of large earthquakes.

A reasonable explanation of two questions is required to explain the probable periodic nature of seismicity. First concerns the causes which drive the periodic seismicity and second concerns the nonrandom distribution of epicenters of large earthquakes in space i.e. concentrated along certain fracture belts. The physical explanation of above questions may be discussed on the basis of geophysical features of the region. Shanker et al. (2007) discussed the occurrences of medium to large earthquakes in Gujarat region on the basis of petrological model which was based on the release of fluid by dehydration process after injection of magma into the crust through deep seated rift faults and shear zones. They observed a conducting fluid generation mechanism on the basis of direction of stresses derived from first motion of aftershocks for 2 to 8 Km, 8 to 25 Km and 25 to 38 Km, which is responsible in triggering of medium to large earthquakes

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