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Characteristics of seismicity patterns prior to the M ~ 5 earthquakes in the Koyna Region, Western India - application of the RTL algorithm

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We investigated the seismicity patterns associated with the M ~5 earthquakes in the artificial water reservoir triggered zone of Koyna region situated near the west coast of India by means of the Region Time Length (RTL) algorithm. The RTL algorithm, which is widely used for investigating the precursory seismicity changes before large earthquakes, is being applied for the first time to a small region where triggered earthquakes have been occurring in an area of 30 km x 20 km, and there is no other seismic source within 50 km of the Koyna region. As this method is being implemented for the first time for such a small region, the validity of the characteristic coefficients r_0, t_0 and d_0 was tested and found acceptable. We examined both the spatial and temporal characteristics of seismicity changes in the Koyna region. The RTL algorithm was applied to the earthquake catalogue of the Koyna region for the period 2006 through 2009, after removing the aftershocks of $M \geq 3.0$ earthquakes. The catalogue is complete for $M \geq 1.8$ events. We find the epicentral area showing anomalous seismic activation and quiescence before the main earthquakes. The temporal variation of the RTL values of all the four earthquakes of M 4.8 to 5.1, that occurred during 2006 through 2009, showed a seismic quiescence anomaly prior to these earthquakes. The seismicity changes inferred in this study may provide better understanding of the future M ~ 5 earthquakes and increase the probability of earthquake forecast in the Koyna region.

Introduction

The Koyna region has drawn attention of seismologists all over the world after the occurrence of the devastating earthquake of M 6.3 on 10 December 1967, that claimed over 200 human lives and caused wide spread destruction. So far this is accepted to be the largest artificial water reservoir triggered earthquake globally. The Koyna region, situated near the west coast of India started experiencing triggered earthquakes soon after the impoundment of the Shivaji Sagar Lake in 1961 (Gupta 1992, 2002). Later, impoundment of Warna reservoir, located 25 km south of Koyna, started since the late 1980s, and it was filled to a depth of 60 m, in 1993 (Rastogi et al., 1997b). This further increased the seismic activity in the region. So far 22 earthquakes of magnitude exceeding 5 and several thousand smaller earthquakes have occurred in the region. Seismic activity usually gets enhanced after filling of the reservoirs during the Monsoon period lasting from the beginning of June to end of July every year. The activity is confined to a small region of about 20 x 30 km^2 and there are no other seismic sources within 50 km radius. Near real time monitoring of seismic activity was started in the Koyna region during August 2005. Later in October 2006, real time monitoring began (Gupta et al., 2007) by connecting the 6 seismic stations (Fig.1) through V-SAT connectivity to a central seismic station situated at NGRI, Hyderabad. In the present study the region time length (RTL) algorithm has been implemented to the catalogue of earthquakes that occurred during 2006 to 2009. Four M ~ 5 earthquakes occurred during this period. We discuss the phases of seismic activation and quiescence preceding these earthquakes.

Method

The analysis of earthquake data is performed using the well established method known as RTL algorithm (Sobolev and Typukin, 1997; Huang et al., 2001) which uses the three parameters called R (region around the earthquake epicenter), T (time) and L (rupture length). The fundamental idea of RTL algorithm is to assign a weighting RTL value at a given spatiotemporal value (x, y, z, t), which comes from events that occurred in a prescribed space-time window within the characteristic distance and time. An RTL parameter is defined as the product of R, T and L describing the influence weights of location, occurrence time and magnitude as

$$R(x,y,z,t) = \sum_{i=1}^{n} \exp\left(-\frac{r_i}{r_0}\right) - R_{bk}$$

$$T(x,y,z,t) = \sum_{i=1}^{n} \exp\left(-\frac{t-t_i}{t_0}\right) - T_{bk} \qquad (1)$$

$$L(x,y,z,t) = \sum_{i=1}^{n} \exp\left(\frac{-l_i}{r_i}\right)^p - L_{bk}$$

where l_i is the rupture dimension (a function of magnitude M_i); t_i the

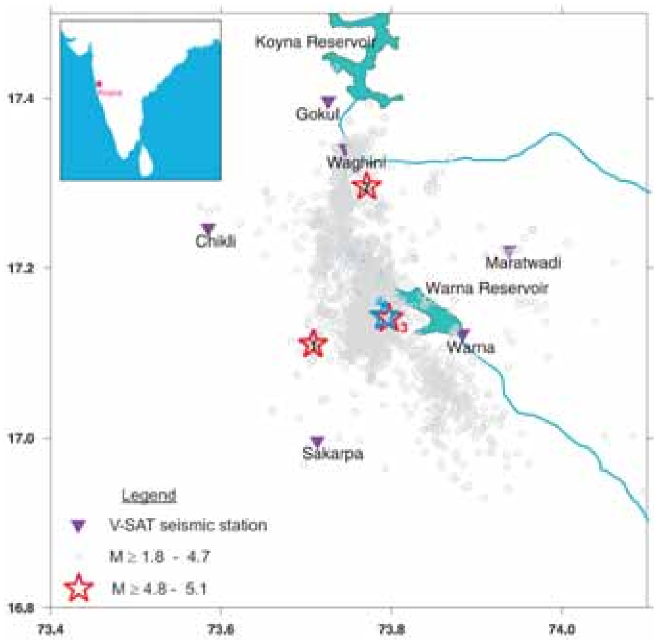

Figure 1. Seismic activity in the Koyna-Warna region from January 2006 to December 2009. Southern India map in the inset indicates the study region (pink coloured square).

occurrence time of the i^{th} earthquake; r_i is the distance from the position (x, y, z) to the epicenter of the i^{th} event; r_0 and t_0 are the characteristic distance and time associated with the spatiotemporal criteria; n is the number of events satisfying the following criterion:

$M_i \geq M_{min}$ (M_i is the magnitude of i^{th} event and M_{min} is the cut-off magnitude ensuring the completeness of the earthquake catalogue); $r_i \leq R_{max} = 2r_0$, and $t\text{-}t_i \leq T_{max} = 2t_0$; R_{bk}, T_{bk} and L_{bk} are the background values of R, T and L respectively. The three dimensions less functions are further normalized by their standard deviations. The product of the above three functions is called the RTL parameter, which describes the deviation from the background level of seismicity and is in units of the standard deviation. A negative RTL value indicates a lower seismicity and a positive RTL value indicates higher seismicity compared to the background. In the present study, the temporal variation in the RTL is examined by changing the time in Eq. (1) by a step of 5 days.

Data and RTL Analysis

The network at Koyna region is being operated by the National Geophysical Research Institute (NGRI), Hyderabad, India. In the present study the earthquake catalogue for the years 2006 through 2009 of Koyna network was used (NGRI catalogue).The seismic activity at Koyna region, for the period 2006 through 2009, is shown in Fig.1. The location of epicenters has an accuracy of ± 500 m.

Aftershock Identification

The procedure given by Gardner and Knopoff (1974) is applied to eliminate the aftershocks of M ≥ 3.0 earthquakes. In this procedure of aftershock identification, the selection of time period, region and depth is adopted based on the experience of observation of the aftershock activity of the earthquakes in the region.

Let t_j, M_j be the origin time and magnitude of the j^{th} main shock in the earthquake time series. The seismic event with t_k, M_k is regarded as its aftershock and is removed from catalogue if it satisfies the criteria of $M_k < M_j$, $t_j < t_k < t_j + \tau(M_j)$ and distance ρ_{jk} between epicenters of events j and k is $\rho_{jk} < r(M_j)$. The selected range of time period and distance of the aftershock is $\tau(M) = \tau_0 \cdot 10^{a(M-M_0)}$, $r(M) = r_0 \cdot 10^{b(M-M_0)}$. Based on our experience, we used M_0=3.0, τ_0 = 2.5 days, r_0 = 4 km, a = b = 0.33. A new time series of main shocks is sorted out in the decreasing order of magnitude to remove all the aftershocks based on the incorporated algorithm. The window sizes are taken depending on the size of sources (Mandal et al., 1998; Gupta and Rambabu, 1993) and the observation for the duration time after main shock. This procedure helped us to remove 37 percent entries of the time series that were considered as aftershocks for the entire duration of the earthquake catalogue.

Verifying the completeness of earthquake catalogue

The deviation of seismic activity of the region from average numbers per area for a specified time can be better identified if the completeness of the catalogue is examined and established properly. The completeness of the data entries is basically the characteristic of the seismic network. The sensitivity and resolution of the seismic network quantify different parts of the region for judging the behavior of seismic regimes based on representation of minimum magnitude. This representation of minimum magnitude gives the completeness of the earthquake energy class that is measured using the Gutenberg-Richter relation of earthquake frequency and magnitude. We applied this relation for searching the M_{min}, representative magnitude for the present earthquake time series of the Koyana-Warna region. After eliminating the aftershocks, the time sequence is used to obtain the threshold magnitude.

The power law of Gutenberg-Richter fits the earthquake energy distribution as a linear plot of recurrence. The bending of the linear plot for the smaller magnitude earthquake gives indication of incompleteness of the catalogue below a specified magnitude. This specified magnitude is the minimum or the threshold magnitude for the study region. Therefore, the problem of identification of the representative magnitude class is statistically solved using power law of energy distribution. The evolution of this relation gives M_{min} = 1.8 for the present study. Figure 2a and 2b shows earthquake frequency-magnitude plot. It may be noted from here that the data are complete for earthquakes of M ≥ 1.8. After removal of aftershocks the remaining data set was plotted as a function of cumulative number in Fig.2c and as a function of focal depth in Fig.2d and also compared with the whole data set. The normal seismicity/ these independent earthquakes of Koyna region are then used for the present study to estimate the RTL variation with time. Sometimes, even the point above this minimum representative magnitude is located below the linear line. This indicates the missing of the entries of that magnitude in the catalogue. In this case the data points fit best in the linear power law above magnitude 1.8. While the M_{min} = 1.8 covers whole part of the Koyna-Warna region and hence the events more than this threshold are used for further analysis.

Calculation of earthquake source size

The earthquake source size is another important parameter, which

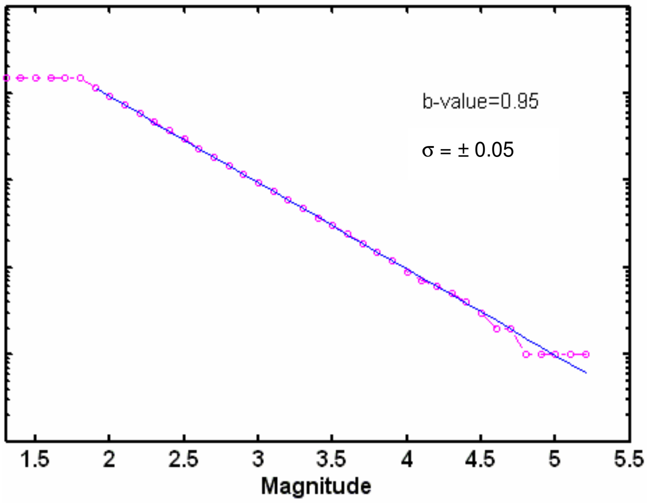

Figure 2a. b-value estimation using the earthquakes of M≥1.8 that occurred during 2006-2009 in the Koyna region.

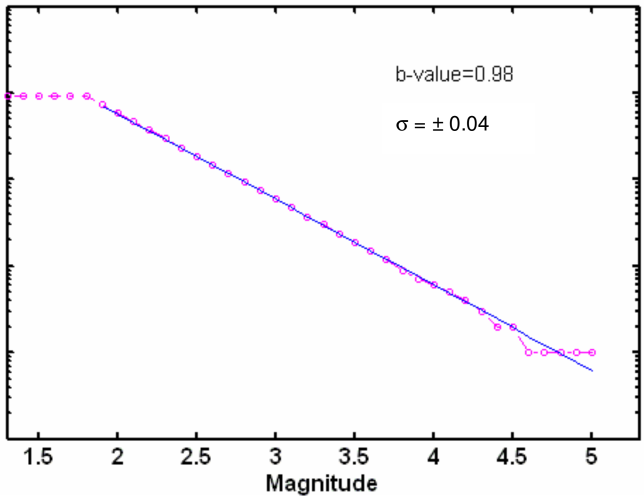

Figure 2b. b-value estimation after removing the aftershocks for M≥3.0 events from the catalogue during 2006-2009 for the Koyna region (M_{min}=1.8).

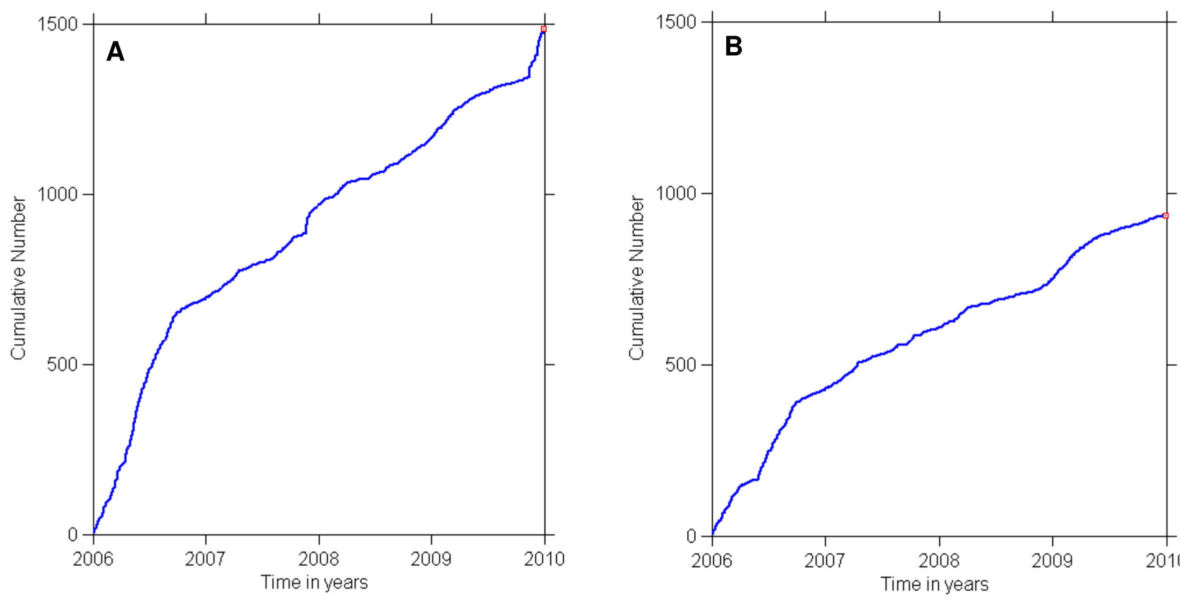

Figure 2c. Cumulative number of earthquakes during the study period from 2006 to 2009 (A) complete earthquake dataset; (B) after removing the aftershocks from the complete catalogue for estimation of RTL parameter in the Koyna region.

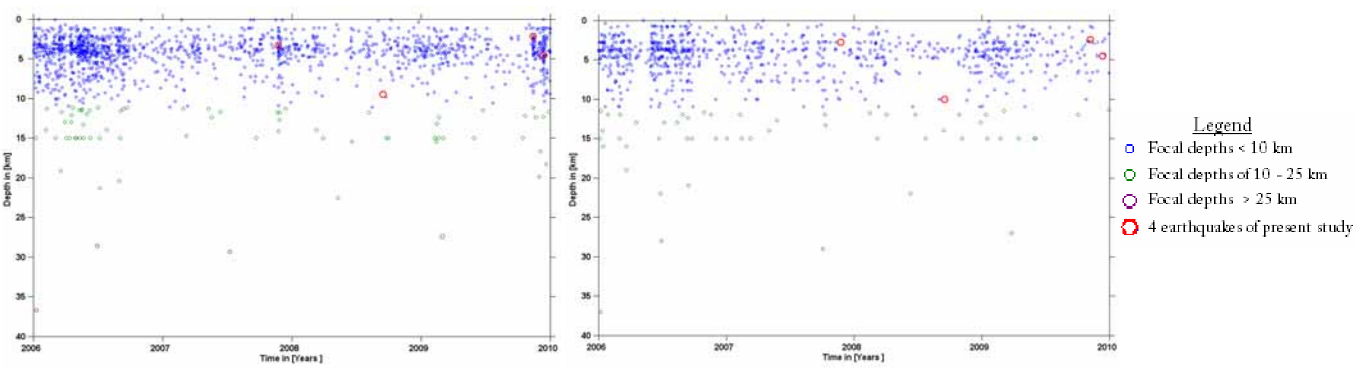

Figure 2d. Temporal variation of focal depths of earthquakes during the study period from 2006 to 2009 (A) complete earthquake dataset; (B) after removing the aftershocks from the complete catalogue for estimation of RTL parameter in the Koyna region.

is used to assign a weight for the seismic event near to the observation point. In the present study the rupture length l_i for magnitude M_i of the seismic event is calculated based on the relation obtained by Ponomarev et al. (2007) for the India region.

$$\log l_i \text{ (km)} = 0.5 M_i - 2.04 \qquad (2)$$

In the relation M denotes the seismic moment magnitude. The earthquake source parameters are obtained using the data of 6 seismic stations of the Koyna seismic network. In the routine work of source parameter calculation, local magnitude M_L and coda magnitude M_D are being evaluated. The magnitudes of the earthquake catalogue for the period 2006 to 2009 are converted to moment magnitude based on the following empirical relation (modified from Mandal et al., 1998).

$$M_w = 0.948 M_D + 0.253 \qquad (3)$$

Estimation of the characteristic RTL parameters

The characteristic parameters for the Koyna region are estimated considering the spatio-temporal distribution of earthquakes and the corresponding catalogue of earthquakes. We tried different values for the parameters, and with possible different combinations of the parameters as given in Table 1. Each time only one parameter was changed based on the criteria of Huang et al. (2001) for investigating the possible influence on the result.

On the basis of rupture dimension and the quiescence periods for the moderate magnitude earthquakes occurring, on an average, within 2 – 3 years in a small region, the following values were used : r_0 = 10 km (R_{max} = $2r_0$ = 20 km), t_0 = 25 days (T_{max} = $2t_0$ = 50 days) and d_0 = 20 km. we now consider these values as Set 1. To observe the behavior of the processing method, these parameters were assigned different values and the results are given in Table 1. The RTL values determined with the above given parameters for the time series of M ≥1.8 earthquakes for 2007 and 2008 are shown in Fig. 3a. Then in the next step d_0 value is changed to 37 km (as some of the events are falling between 20 km and 37 km) and 10 km (as most of the seismic activity is confined to a shallow depth) respectively by keeping the r_0 and t_0 as in Set 1, to observe the effect of focal depths of earthquakes on the RTL values (curves b and c in Fig.3). It was found that the correlation of the curves b & c with curve a gives highest value equal to 0.99 suggesting no effect of the focal depth for this analysis. The plots of the temporal variation of RTL value in Fig.3 also shows that the curves a, b and c are matching with each other and the activation and quiescence phases before M5.0 of 16 September 2008 is equally prominent in all the cases. Similar observations have been made by Huang et al. (2001) for the variation of characteristic depth. Therefore the choice of selecting focal depth up to 20 km is appropriate for including almost all data in depth section for investigation.

Table 1. Set 1 (a) shows the values of characteristic coefficients and the corresponding RTL computed is shown in Fig.3a. To examine the effect of changing the values of the characteristic coefficient parameters, d_o = 37 km, and d_o = 10 km are taken (case b and c), all other parameters remaining the same, and the RTL computed is shown in Fig.3b and c. Similarly, computations for r_o= 8 and 12 km (Fig.2d, and e); and t_o = 15 and 35 days (Fig 2f and g) have been made. Correlation coefficients of (b) through (g) with (a) in Fig.3 are also shown

Set 1	(a) d_0=20 km, r_0=10 km and t_0=25 days					
Cases	(b) d_0=37 km	(c) d_0=10km	(d) r_0=8 km	(e) r_0=12km	(f) t_0=15 days	(g) t_0=35 days
Correlation coefficient	0.99	0.99	0.92	0.96	0.72	0.69

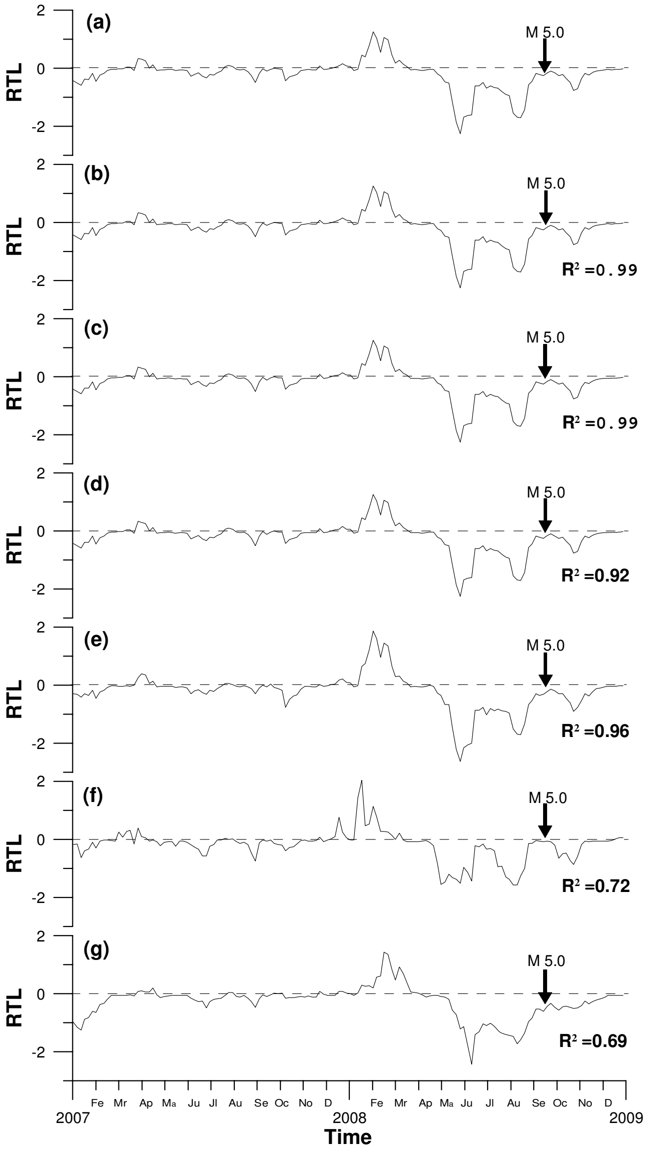

Figure 3. Estimation of characteristic parameters for the Koyna region. Temporal variation of the RTL, close to the epicenter of 16 September 2008 M 5.0 earthquake in block A (Fig.4a). The variation in RTL anomaly is obtained at this location with different values of parameters (a) r_0 = 10 km (R_{max} = 2 r_0 = 20 km), t_0 = 25 days (T_{max} = 2 t_0 = 50 days) and d_0 = 20 km; (b) d_0 = 37 km whereas r_0, t_0 remains same as in (a); (c) d_0 = 10 km whereas r_0, t_0 remains same as in (a); (d) r_0 = 8 km and t_0 = 25 days, d_0 = 20 km; (e) r_0 = 12 km and t_0 = 25 days, d_0 = 20 km ; (f) t_0 = 15 days and r_0 = 10 km, d_0 = 20 km (g) t_0 = 35 days and r_0 = 10 km, d_0 = 20 km. Right side below corner of each curve is the values of correlation coefficient with curve (a) i.e. with the selected value of parameters. Seismic activation is centered around February 2008 and quiescence has two prominent phases centered around June and August 2008.

We also tested the characteristic distance r_0 for observing the influence of the region on the RTL value. We changed r_0 from 10 to 8 and 12 km, keeping other two parameters constant as in Set 1. Correspondingly the temporal RTL variations shown in Fig.3d and e.

The influence of varying the time span of observation t_0 was also tested. The data are analyzed again by changing t_0 term and keeping the other two parameters constant as in Set 1. We changed the t_0 value to 15 days and 35 days from the initial value of 25 days. The temporal variation of RTL values has been plotted as curves f and g in Fig.3. A positive correlation of 0.72 and 0.69 were obtained for the above two curves with "a". However the seismic activation and quiescence anomaly exists in each observation prior to the M 5.0 earthquake during 2008 and it is more prominent with the initial values (Fig.3a).

Results and Discussion

During the period of present study, 4 earthquakes in the magnitude range of 4.8 to 5.1 occurred in the Koyna region (Table 2). The variation of RTL parameter from April 2006 through December 2009 is shown in Figure 4. After experimenting with several cell dimensions, the whole region has been divided into 90 cells, each cell having a dimension of about 10 x 10 km^2 to observe the variation of RTL value. In Fig.4(a) the epicenters of these 4 earthquakes are shown. The selection of the blocks from 1 – 3 to demonstrate RTL variation are based on the peak quiescence anomaly found corresponds to the blocks prior to the above mentioned 4 earthquakes in the region. Except for the 16 September 2008 M 5 earthquake, the other 3 earthquakes were preceded by a well developed quiescence which was confined only to a particular block 1 and 3, the details are as follows.

For the purpose of demonstration of the RTL algorithm to this region, from among several blocks examined, results for blocks 1, 2 and 3 only are depicted in Fig.4b. The weighted observed period of activation and quiescence lasted from a few days to months. In block 1, an enhanced seismic activity centered around April and July 2006, followed by a quiescence in December 2006 is very prominent. There were M 4.7 and M 4.2 earthquakes in the Koyna region (not shown in Fig.4a, as only M≥4.8 earthquakes are included in this figure) during April and May 2006. Later, another enhanced seismic activity is seen centered around April 2007, followed by quiescence seen centered around July, 2007. This corresponds well with M 4.8 earthquake of 24th November, 2007. Another active phase can be seen centered around March 2009 (but there is no observable quiescence) which may correspond to magnitude 5 and 5.1 earthquakes of 14th November 2009 and 12th December 2009 respectively. No pronounced

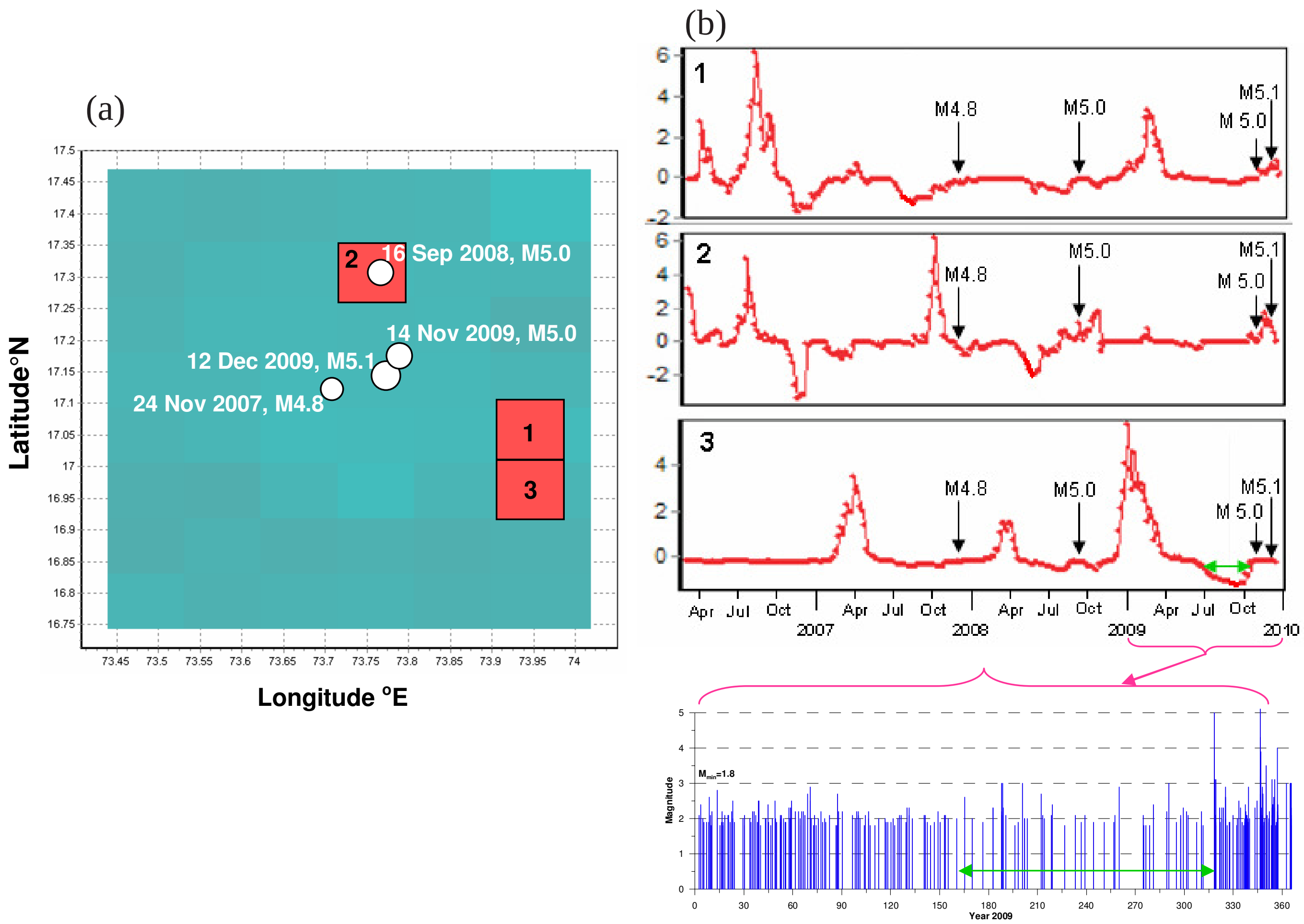

Figure 4. (a) Spatial variation of RTL and the quiescence period (red blocks) observed prior to the M~5 earthquakes in the Koyna region during the observation period from February 2006 to 2009. (b) Temporal variation of RTL, negative values in RTL (seismic quiescence) were present during (1) July to September 2007; (2) May to July 2008 and (3) July to October 2009 as indicated in Fig.4a. Below: The earthquake time series also shows the quiescence (green line) during 2009, prior to the M5 earthquakes that occurred in the months of November and December respectively.

Table 2. Lists the earthquakes of M4.8 – 5.1, which are preceded by seismic quiescence in the Koyna-Warna region

S. No	Date	Origin Time (UTC)	Latitude (°N)	Longitude (°E)	Depth (km)	Mw	Centre of the Quiescence block	Maximum RTL Attained on
1	24.11.2007	10:57:47	17.111	73.705	3.1	4.8	17.08;73.94	30.07.2007
2	16.09.2008	21:47:15	17.295	73.771	9.5	5.0	17.31;73.72	25.05.2008
3	14.11.2009	13:03:34	17.142	73.792	4.1	5.0	17.05;73.97	07.10.2009
4	12.12.2009	11:51:24	17.129	73.783	4.8	5.1		

signal is seen for the 16th September 2008 earthquake. The story for block 2 is more or less the same till the end of 2006. There is an enhanced activity and quiescence just before the 24th November 2007 earthquake. The 16th September 2008 earthquake is preceded by a well defined quiescence. Some activation can also be seen associated with Nov/Dec 2009 M 5 and 5.1 earthquakes. RTL values in block 3 are quite different from blocks 1 and 2 for 2006. There is a pronounced activity centered during March 2007. The 24th November 2007 earthquake is not preceded by a decipherable RTL anomaly. Another high activity phase can be seen in March/April 2008. The 16th September 2008 earthquake is preceded by some quiescence. There is another very active phase during December 2008/ January 2009. The 5.0 and 5.1 earthquakes of 14th November and 12th December 2009 are preceded by a well defined quiescence. These two epicenters are close to each other. In a nut shell, it could be said that RTL anomaly signals for the 4 earthquakes being investigated were seen in one block or the other. There were phases of enhanced activity, not followed by quiescence and that could not be correlated with significant earthquakes in the region.

We examined the RTL variations associated with the M 5.0 earthquake of 16 September 2008 in more detail. Figure 5 shows the spatial and temporal variation of RTL values calculated in the region for the period 2007 to 2008. The quiescence anomaly throughout the Koyna-Warna area is clearly visible in 5 cells (A, B, C, D, and E in Fig.5a). This quiescence was noticed (in a cell centered as 17.32°N, 73.77°E) in first week of May 2008 which attained a negative peak

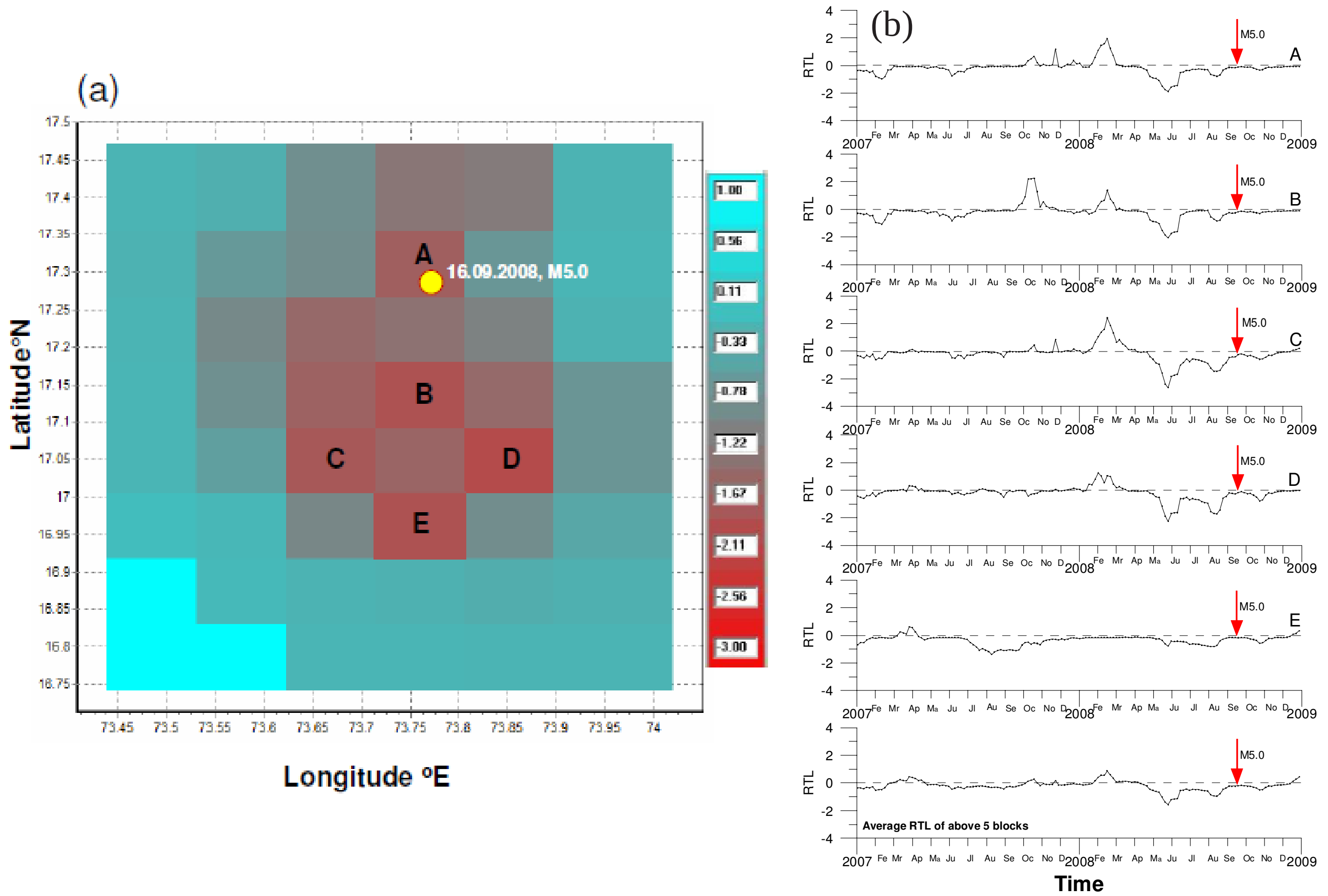

Figure 5. (a) spatial variation of RTL as on 25th May 2008 in the Koyna-Warna region during the observation period from 2007 to 2008. The scale on the right corresponds to the RTL value in the units of the standard deviation. (b) Temporal variation of RTL of the cells A, B, C, D and E shown in Fig.5a. The last curve is the average RTL value of cells A, B, C, D and E. The arrow indicates the occurrence time of the M 5.0 earthquake on 16 September 2008.

RTL on 26 May 2008, this time the anomaly was observed extending towards south as the time progresses from the initial location and present up to July 2008 where the region experienced an earthquake of M 5.0 on 16 September 2008 (Cell A). An M 4.3 earthquake occurred on 29 July 2008, which is close to the location of 16 September 2008 M 5.0 earthquake. Probably the quiescence anomaly found in block 2 from May to July 2008 corresponds to these two earthquakes. It was found from the temporal variation of RTL values for this period that an enhancement in the seismic activity during January to March 2008, followed by a seismic quiescence period from May 2008 to middle of the July 2008 (Fig.5b). We have also plotted the variation in RTL parameter for other 4 cells and are able to see the quiescence period before the M 5.0 earthquake on 16 September 2008. The average RTL plot using data of above 5 cells shows quiescence before the M 5.0 earthquake (bottom of Fig.5b).

In many parts of the world, the RTL method has been used for larger regions and longer seismic catalogues. It is found, most of the times, suitable to observe the quiescence phenomenon prior to large earthquakes (Keilis-Borok and Kossobokov, 1990; Huang and Sobolev, 2001; Sobolev et al., 2002; Huang et al., 2001, 2002; Huang and Nagao, 2002; Sobolev, 2004). However, the work so far is mostly confined to regions of high seismicity. The earthquake catalogues used are for larger regions and longer durations. In the present study, the algorithm is tested for the first time for the reservoir triggered seismic activity, where the seismicity is mainly confined within a small region of 20 x 30 km^2 area in the Koyna-Warna region near the west coast of India. The application of RTL method to pin point the seismic quiescence in space and time seems to be working for this region for the moderate sized earthquakes in the magnitude range of 4.8 to 5.1. The phases of seismic activation and quiescence throughout the Koyna-Warna area are visible for the catalogue used in the present study.

From the above observations it is noticed that the quiescence anomalies occurred prior to M ~ 5 earthquakes in the years 2007 and 2009 were confined to a particular cell, whereas the quiescence anomaly for 16 September 2008 earthquake was observed for a larger area. This variation in the spatial behavior of RTL in this region may be related to the location of the earthquake of 2008, which is quite different than that of 2007 and 2009 earthquake locations, revealing the variable characteristic of the region.

Conclusions

For the first time the RTL algorithm has been implemented to a triggered earthquake time series occurring in a small region at Koyna-Warna near west coast of India. The results obtained are interesting and reveal the patterns/phases of seismic activation and quiescence before the moderate sized earthquakes in the reservoir triggered zone. The duration of the quiescence period varies from two weeks to about 3 months prior to M ~ 5 earthquakes in this region. As Koyna-Warna region continues to be seismically active, we intend to observe RTL values on near real time basis to further develop the RTL approach to see whether it could be used to forecast earthquakes.

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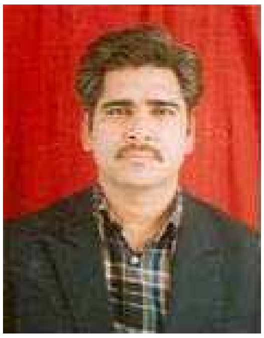

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Gupta, Harsh, President, Geological Society of India, is involved with the mitigation of natural hazards, particularly earthquakes. He is well known for his work on artificial water reservoir triggered earthquakes. He has authored over 150 scientific papers and four pioneering books (all published by Elsevier).