Pure appl. geophys. 161 (2004) 2359–2367
0033–4553/04/122359–9
DOI 10.1007/s00024-004-2568-4

Pure and Applied Geophysics

Spatial and Temporal Variation of LURR and its Implication for the Tendency of Earthquake Occurrence in Southern California

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Abstract — Based on the theory of LURR and its recent development, spatial and temporal variation of Y/Y_c (value of LURR/critical value of LURR) in the Southern California region during the period from 1980 through March, 2001 was studied. According to the previous study on the fault system and stress field in Southern California, we zoned the Southern California region into 11 parts in each of which the stress field is almost uniform. With the time window of one year, time moving step of three months, space window of a circle region with a radius of 100 km and space moving step of 0.25 degree in latitude and longitude direction, the evolution of Y/Y_c were snapshot. The scanning results show that obvious Y/Y_c anomalies occurred before 5/6 of strong earthquakes considered with a magnitude of 6.5 or greater. The critical regions of Y/Y_c are near the epicenters of the strong earthquakes and the Y/Y_c anomalies occur months to years prior to the earthquakes. The tendency of earthquake occurrence in the California region is briefly discussed on the basis of the examination of Y/Y_c.

Key words: LURR, Y/Y_c, stress field, spatial and temporal scanning, Southern California region, tendency of earthquake occurrence.

1. Introduction

The Load-Unload Response Ratio (LURR) method, put forward by Yin (1987), has been tested in many regions in China and some regions in the United States, Japan and Australia. The method has shown considerable promise for intermediate-term earthquake prediction (Yin and Yin, 1991; Yin *et al.*, 1995, 2000, 2001).

The physical essence of an earthquake is failure or instability of the focal media. When a seismogenic system is in a stable state, its response to loading is similar to its response to unloading, whereas when the system is in an unstable state, the responses to loading and unloading become quite different (Yin, 1987; Yin and Yin, 1991; Yin, *et al.*, 1995, 2000). LURR (Load/ Unload Response Ratio) is defined as

$$Y = X^+/X^- \tag{1}$$

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where X^+ and X^- are the response rates during loading and unloading measured by some method. According to the *LURR* idea, when a seismogenic system is in a stable or linear state $Y \sim 1$ whereas when the system lies outside of the linear state $Y > 1$. In earthquake prediction practice with LURR, loading and unloading periods are determined by calculating perturbations in the Coulomb failure stress induced by earth tides. Experimental and numerical simulation have validated LURR (MORA *et al.*, 2000, 1999; WANG *et al.* 1999, 2000, 1999). In retrospective studies, high Y values have been observed months to years prior to most significant events and some successful intermediate-term earthquake predictions have been made (YIN *et al.*, 2000).

In this paper we report the results of our study on LURR variation in the Southern California region from 1980 to March, 2002 using a spatial and temporal scanning method. Frameworks of the fault system and stress field for Southern California were obtained from the SCEC (Southern California Earthquake Center) Data Center via INTERNET (http://www.data.scec.org), and the earthquake catalogue was taken from the CNSS (Council of the National Seismic System, now ANSS – Advanced National Seismic System) via INTERNET (http://www.anss.org).

2. Method to Calculate LURR

2.1 Calculation of LURR

In the LURR theory, Y is defined directly by means of seismic energy as follows:

$$Y_m = \frac{\left[\sum_{i=1}^{N^+} E_i^m\right]_+}{\left[\sum_{i=1}^{N^-} E_i^m\right]_-} \tag{2}$$

where E denotes seismic energy which can be calculated according to the Gutenberg-Richter formula (KANAMORI and ANDERSON, 1975; BULLEN and BOLT, 1985), the "+" sign means loading and "−" means unloading, $m = 0$ or 1/3 or 1/2 or 2/3 or 1. When $m = 1$, E^m is exactly the energy itself; for $m = 1/2$, E^m denotes the Benioff strain; for $m = 1/3$, 2/3, E^m represents the linear scale and area scale of the focal zone, respectively; for $m = 0$, Y is equal to N^+/N^-, and N^+ and N^- denote the number of earthquakes which occur during the loading and unloading periods.

In this paper, m is chosen as 1/2, which means that Y is determined by the ratio of Benioff strain during the loading period over the unloading period.

Since the preparation and occurrence process of earthquakes are controlled not only by deterministic dynamical law but also affected by stochastic or disorder factors, ZHUANG and YIN (1999) studied the influence of random factors on LURR in order to estimate the threshold Y value, which can be regarded as an earthquake precursor within a specified confidence level. They gave the critical value of LURR

Y_c that depends on the number of earthquakes under different specified confidence levels. For instance, at the confidence level of 90%, Y_c is equal to 3.18 if the number of earthquakes in the time and space window is 20, which means that Y should be equal to or greater than 3.18 for the medium to be considered in an unstable state when the number of earthquakes is 20. For the confidence level of 99%, Y_c is 7.69 if the number of earthquakes in the specific time and space window is 20. The greater the earthquake number is, the lower the Y_c (critical value of LURR).

In this paper we give critical space-time regions of LURR by Y/Y_c instead of Y under a confidence level of 99%.

2.2 Determination of Loading and Unloading

Loading and unloading periods are determined by calculating perturbations in the Coulomb Failure Stress (CFS) (e.g., HARRIS, 1998; REASENBERG and SIMPSON, 1992) induced by earth tides.

$$CFS = \tau_n + f\sigma_n, \tag{3}$$

where σ_n stands for normal stress, τ_n denotes shear stress, f represents the coefficient of internal friction, and $\boldsymbol{n}$ is the normal direction of the fault plane on which CFS reaches its maximum. When the increment of Coulomb Failure Stress (ΔCFS) is positive, it is in a loading state; otherwise, when ΔCFS is negative, it is in an unloading state.

Stress in the crust σ_{ij} consists of tectonic stress σ_{ij}^T and the stress induced by the earth σ_{ij}^t since the level of σ_{ij}^T (on the order of 10^6–10^8 Pa) far exceeds the level of σ_{ij}^t (10^3–10^4 Pa), directions of the principle stress in the crust and the direction of n can be determined from the tectonic stress only. However, the rate of change of the tidal stress is considerably larger than that of the tectonic stress (VIDALI, *et al.*, 1998), thus ΔCFS is mainly due to stress induced by tide, which can be calculated precisely.

2.3 Tectonic Stress Field in Southern California

An outline of the stress field in Southern California can be obtained from the world stress map (ZOBACK, 1992). The stress field is supplemented by the fault system in Southern California which is provided by SCEC (Southern California Data Center). With these two sets of information, we divided the Southern California region into 11 parts, in each of which the stress field is almost uniform. The divisions of Southern California based on the stress field are shown in Figure 1.

3. Data and Scanning Parameters

The earthquake catalogue we use in this paper is from CNSS (Council of the National Seismic System).

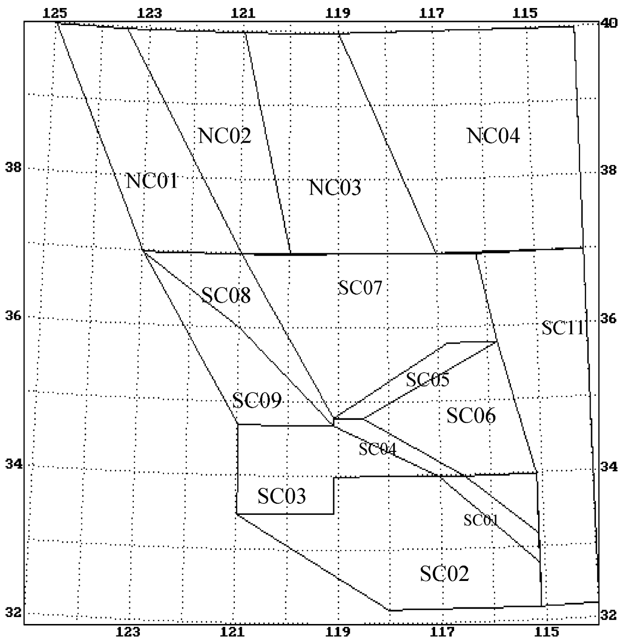

Figure 1
Divisions of Southern California based on the stress field.

In order to speed up the calculations and avoid disturbance from outstanding earthquakes, we chose magnitude thresholds according to the Gutenberg-Richter relation in each unit area.

The scanning parameters are as follows:

Time window: 1 year
Time moving step: 3 months
Space window: R = 100 km
Space moving step: 0.25° in latitude and longitude direction.

That is, a circle region with a radius of 100 km was selected as the spatial window within which a value of Y/Y_c (LURR/critical LURR) was calculated for a specific time window (1 year), then the circle center was moved step by step in both latitude and longitude by increments of 0.25 degrees.

4. *Y/Y_c Anomalies before Strong Earthquakes and Tendency of Earthquake Occurrence in Southern California*

Eighty-six images of Y/Y_c contours during the period from 1980 to March, 2002 were obtained based on the scanning parameters listed above. The main results were listed below.

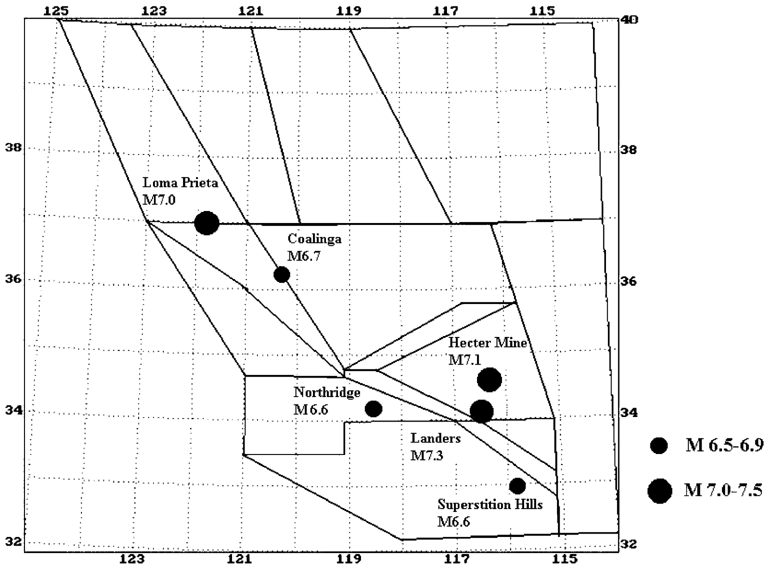

Figure 2
Six strong earthquakes ($M \geq 6.5$) in Southern California during the period from 1980 through 2001.

4.1 Y/Y_c before Six Strong Earthquakes in Southern California

Six strong earthquakes ($M \geq 6.5$) occurred in Southern California during the period from 1980 through 2001, as shown in Figure 2. These earthquakes are listed in Table 1.

Our results indicate that obvious Y/Y_c anomalies occurred 1–2 years before five of the six strong earthquakes ($M \geq 6.5$) in Southern California during the period from 1980 through 2001, as shown in Table 1.

The above results show that strong earthquakes occurred near regions of anomalous Y/Y_c. Anomalous Y/Y_c was discovered about 1–2 years before an

Table 1
Y/Y_c anomalies before six strong earthquakes in Southern California during the period from 1980 through 2001.

Date	Epicenter	Magnitude/ Δ (Km)	Max. Y/Y_c	Lasting time of anomalous Y/Y_c (month)
1983.5.2	(36.23°N, 120.32°W) Coalinga	6.7/?	?	?
1987.11.24	(33.01°N, 115.85°W) Superstition Hills	6.6/0	1.4	21
1989.10.18	(37.04°N, 121.88°W) Loma Prieta	7.0/100	1.2	24
1992.6.28	(34.20°N, 116.44°W) Landers	7.3/100	1.0	18
1994.1.17	(34.21°N, 118.54°W) Northridge	6.6/80	1.0	25
1999.10.16	(34.59°N, 116.27°W) Hector Mine	7.1/100	1.4	15

Note: Δ (km) is the distance between earthquake epicenter and the maximum Y/Y_c point.

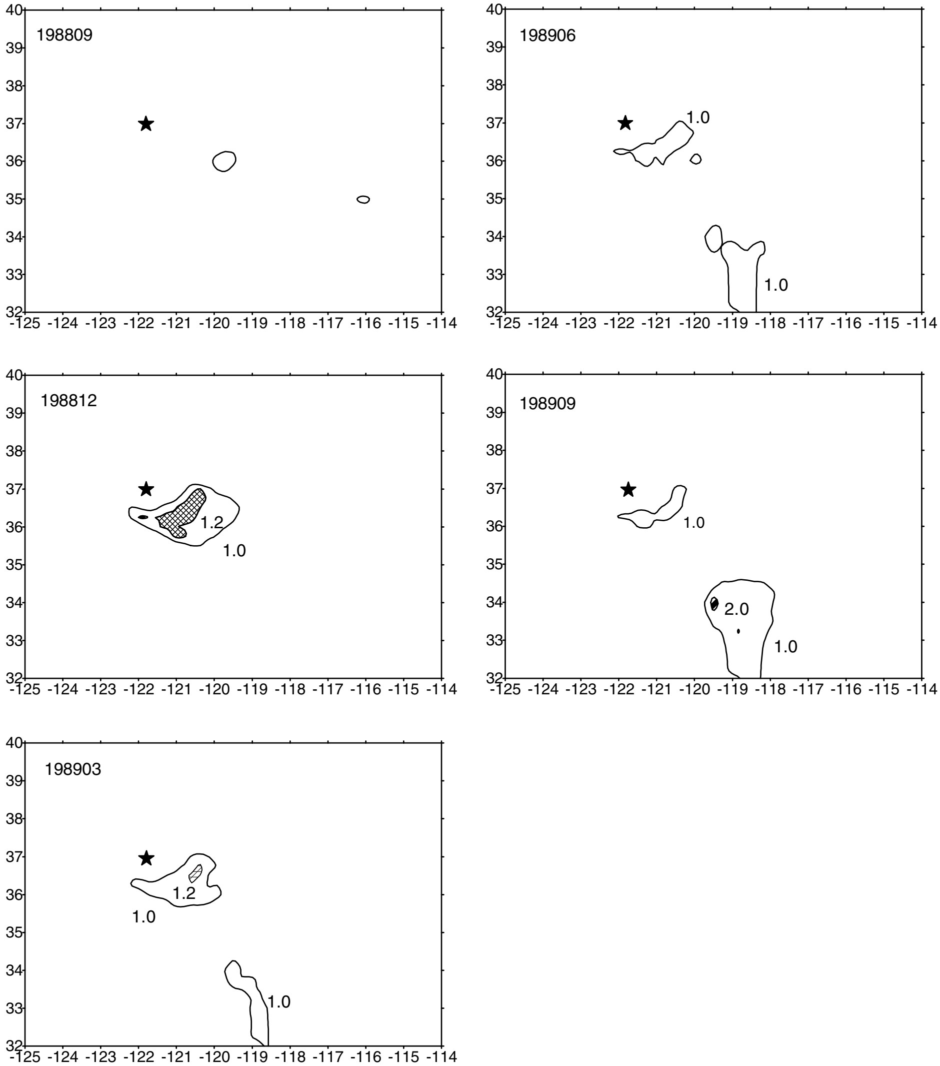

Figure 3

Y/Y_c contour from Sep. 1988 to Sep. 1989 before the Loma Prieta Earthquake. A mark of pentagon stands for the epicenter of the Loma Prieta earthquake; numeral in the upper left corner represents the time (year and month).

upcoming earthquake. For example, before the 1989 Loma Prieta $M7.0$ earthquake, the anomalous Y/Y_c region appeared from 1988. Figure 3 shows the evolution of Y/Y_c contours from Dec. 1988 to Sep. 1989. The Loma Prieta earthquake occurred at a location about 100 km to the northwest of the anomalous Y/Y_c region. We also see another anomalous region of Y/Y_c from Mar. 1989 to Sep. 1989 in Figure 3, which covered the region of 32–34.6°N, 117.7–119.7°E. This anomalous region might be

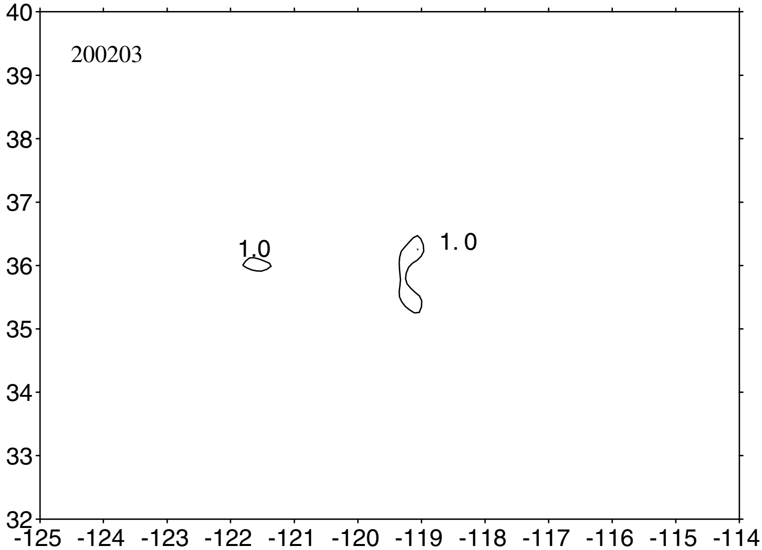

Figure 4
Y/Y_c contour in March 2002.

related to the $M5.4$ earthquake (34.14°N, 117.70°E) on Feb. 28, 1990 and the $M5.8$ earthquake (34.27°N, 117.99°E) on June 28, 1991, which were the only two mid-strong earthquakes in this region during the period from 1990 to 1991.

4.2 Y/Y_c in periods and regions without strong earthquakes ($M \geq 6.5$) in Southern California

Few anomalous Y/Y_c regions occurred during the investigated periods without strong earthquakes ($M \geq 6.5$). For example, no earthquakes greater than $M6.5$ occurred after the Hector Mine $M7.1$ earthquake, and there was no obvious Y/Y_c anomaly during the period from 2000 through 2001. A few anomalous Y/Y_c regions appeared without succeeding strong earthquakes, which might indicate that the earthquake preparation process is very complex.

4.3 Tendency of Earthquake Occurrence in Southern California

Our results show that there were no obvious Y/Y_c anomalies from 2000 to 2001, which implies that hazardous earthquakes are not likely to occur in Southern California in the near future. Two small anomalous Y/Y_c regions in Southern California in March 2002 (Fig. 4) may indicate an occurrence of a moderate earthquake of about magnitude 5 around (36°N, 119°W) and (36°N, 121.6°W) within about 1 year. If the Y/Y_c anomalous region grows larger and lasts for half to one year or more, there might be a stronger earthquake in these regions.

5. Conclusions and Discussion

In this paper, the variation of Y/Y_c in Southern California during the period from 1980 through March, 2002 was studied by a spatial and temporal scanning method based on the stress field in Southern California. The calculating results covering 22 years within which 6 strong earthquakes with $M6.5$ or greater occurred in Southern California. According to the results above, the following conclusions could be drawn:

1. Obvious Y/Y_c (value of LURR/critical value of LURR) anomalies occurred near the epicenters of upcoming 5 strong earthquakes out of 6 with $M6.5$ or greater during the period from 1980 through 2001 in Southern California. The amplitude of Y/Y_c is within 1.0 to 1.4 and the nearest distance from the epicenter to the Y/Y_c anomalous region is from 0 km to 100 km.
2. The size of the anomalous region of Y/Y_c is 100–300 km, which might imply the scale of the seismogenic region of the upcoming strong earthquake.
3. The anomaly of Y/Y_c began about 1 to 2 years prior to the upcoming strong earthquake and underwent a process of development firstly and weakening subsequently. Most of the strong earthquakes occurred in the weakening stage of Y/Y_c.
4. According to the above results, LURR is a promising approach to intermediate-term earthquake prediction before strong earthquakes with $M6.5$ or greater in Southern California.

In comparison with the previous study of LURR in China Mainland (e.g., YIN *et al.*, 1995), the lasting time of LURR anomaly in Southern California is shorter than that in China, which might reflect the difference of earthquake cycle between Southern California and China Mainland under different tectonic fields.

The above results depend on the details of stress field, earthquake catalogue and scanning parameters, consequently we might heighten the credibility of LURR and improve the accuracy of earthquake prediction if detailed knowledge of the stress field in Southern California and a higher quality of earthquake catalogues could be accessed. Meanwhile, suitable scanning parameter might improve the results.

Acknowledgements

Funding support is gratefully acknowledged by NSFC under grant No. 10232050. Special Funds for Major State Basic Research Project under grant No. 2002 CB412706 and Supercomputing Center of Computer Network Information Center, Chinese Academy of Science (INF105–SCE-2-02). We also express our thanks to QUAKES and CNSS. The reviews of Akio Yoshida and an unknown reviewer assisted our improvment of the manuscript.

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(Received September 27, 2002, revised April 25, 2003, accepted May 5, 2003)