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Study of the Potential Earthquake Risk in the Western United States by the LURR Method Based on the Seismic Catalogue, Fault Geometry and Focal Mechanisms

YONGXIAN ZHANG,[1] M. BURAK YIKILMAZ,[2] JOHN B. RUNDLE,[2,3] XIANGCHU YIN,[4] YUE LIU,[5] LANGPING ZHANG,[4] and ZIJIN WANG[6]

Abstract—Based on the load/unload response ratio (LURR) theory, spatial and temporal variation of Y/Y_c (value of LURR/critical value of LURR under 90 % confidence) in the western United States and its adjacent area (31°–44°N, −128° to −112°E) during the period from 1980 to 2011 was studied. The selected study area was zoned into 20 sub-regions, in each of which the fault geometry and the focal mechanisms were very similar such that the stress fields were almost uniform. The loading and unloading periods were determined by calculating perturbations in the Coulomb failure stress in each sub-regions induced by earth tides. Earthquakes occurring in these sub-regions were identified as a loading or unloading type, and the response rate was chosen as the Benioff strain that can be calculated from earthquake magnitude M. With a time window of 1 year, a time moving step of 1 month, a space window of a circle region with a radius of 100 km, and a space moving step of 0.5° latitudinally and longitudinally, snapshots of the evolution of Y/Y_c were generated. Scanning results show that obvious Y/Y_c anomalies can be detected near the epicenter of all big earthquakes larger than M6.5 in regions with reasonable seismic monitoring abilities. They also show Y/Y_c anomalies occurred several years prior to the big earthquakes and the lasting time of the anomaly is from one year to several years. For some LURR anomalous regions, however, no earthquakes occurred. According to the characteristics of LURR anomalies, two regions with a high risk of big earthquakes were detected. One is between the northern region of the Bay Area and the Mendocino triple junction (38°–40°N, −124° to −122°E) and the other is between Lake Tahoe and Mono Lake (37.5°–39.5°N, −120° to −118°E) along the border of California and Nevada.

[1] China Earthquake Networks Center, Beijing 100045, China. E-mail: yxzhseis@sina.com
[2] Department of Geology, University of Californian, Davis, CA 95616, USA. E-mail: mbyikilmaz@ucdavis.edu; rundlejb@gmail.com
[3] Department of Physics, University of Californian, Davis, CA 95616, USA.
[4] Institute of Earthquake Science, China Earthquake Administration, Beijing 100036, China. E-mail: xcyin@public.bta.net.cn; zhanglp@lnm.imech.ac.cn; zhanglp@lnm.imech.ac.cn
[5] State Key Laboratory of Nonlinear Mechanics, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China. E-mail: liuyue126liuyue@126.com
[6] Institute of Disaster Prevention, Beijing 101601, China. E-mail: 2605293072@qq.com

Key words: LURR, Y/Y_c, stress field, spatial and temporal scanning, western United States, earthquake potential risk.

1. Introduction

The load/unload response ratio (LURR) is an earthquake prediction method put forward by YIN (1987) based on mechanics. It is defined as

$$Y = X^{+}/X^{-} \qquad (1)$$

where X^+ and X^- are the response rates during loading and unloading measured by some method. According to LURR theory, when a seismogenic system is in a stable or linear state, $Y \sim 1$, whereas when the system lies outside the linear state, $Y > 1$.

The LURR method has been studied for more than 20 years and has been improved year by year (YIN *et al.* 1995, 2000, 2002, 2006, 2008b, 2010, 2013; YU *et al.* 2011). The LURR method has been tested by retrospective studies and applied to earthquake forecasting in some countries, such as China, USA, Japan, Australia, Iran, Sumatra, etc. (YIN *et al.* 1992, 1996, 2000, 2006, 2007, 2008a; SONG *et al.* 2000; MORA *et al.* 2000a; ZHANG *et al.* 2004, 2005a, 2006a, b, 2008a, b; YIN and MORA 2006). The results showed that LURR anomalies occurred months to years prior to most of the intra-plate and inter-plate strong earthquakes, indicating that the LURR approach is applicable to different tectonic settings. LURR has been validated by experimental and numerical simulation (MORA *et al.* 2000b, 2002; WANG *et al.* 1998, 1999a, b, 2000, 2004; YIN *et al.* 2004).

In earthquake prediction utilizing LURR, loading and unloading periods are determined by incrementally calculating Coulomb failure stress (ΔCFS);

when ΔCFS is positive, it is defined as a loading period, and earthquakes occurring in this period are defined as loading earthquakes. Otherwise, when ΔCFS is negative, it is defined as an unloading period, and earthquakes occurring in this period are defined as unloading earthquakes. Because the tectonic stress (in order of 10^6–10^8Pa) is relatively stable and much higher than the tidally induced stress in the crust (in order of 10^3–10^4Pa), the directions of the principle stress of the resultant crustal stress can be determined by the tectonic stress only. However, the change rate of tide-induced stress is much larger than the change rate of tectonic stress (Vidali *et al.* 1998); as such, ΔCFS is mainly due to tide-induced stress that can be calculated precisely (Yin 1987; Yin *et al.* 1994a, b, 1995, 2000).

Based on the discussion above, determination of the directions of principle tectonic stress is a key issue to be solved for determining loading or unloading status. Only when the directions of principle tectonic stress are determined properly, can the obvious LURR anomaly be detected before strong earthquakes. Yin *et al.* (2006, 2008a, b) refer to the ideal plane at which LURR can reach its maximum value as the maximum faulting orientation (MFO). In earthquake case studies, the focal mechanisms can be utilized to determine the directions of principle tectonic stress (e.g., Yin *et al.* 1995, 2000, 2006; Song *et al.* 2000; Mora *et al.* 2000a; Zhang *et al.* 2005a, 2006a, 2008a). Fault properties can also be used to determine the directions of principle tectonic stress (e.g., Zhang *et al.* 2004, 2006b, 2008b). In fact, earthquakes do not occur everywhere, and active faults are not distributed everywhere, thus the combination of focal mechanisms and fault properties might be an effective approach for setting up the local stress field more completely than approaches only utilizing focal mechanisms or fault properties.

In this paper, we chose the western United States and its adjacent region (31°–44°N, −128° to −112°E) as our study area, and combined the focal mechanisms (from Harvard University, http://www.globalcmt.org/CMTsearch.html) and fault properties (from USGS, http://earthquake.usgs.gov/hazards/qfaults/) to study the spatial and temporal LURR variations since 1980, and explore the characteristics of LURR anomalies before large earthquakes of M6.5 or above and try to estimate the potential seismic risk indicated by LURR variation in recent years.

2. *Practical Skills of LURR Calculation*

In order to obtain the spatial and temporal variation of LURR, we first calculated LURR values at each point in the study region for a considered time window. We then moved the time window incrementally, obtaining LURR contours for any time.

2.1. *Definition of LURR in Terms of Seismic Energy*

According to LURR theory, if the response rate X in formulae (1) is chosen in terms of seismic energy, LURR value Y_m is defined directly as follows (Yin 1987; Yin *et al.* 1995):

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

where E denotes seismic energy, 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 the seismic energy; when $m = 1/2$, 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 that occur during the loading and unloading periods, respectively.

Seismic energy can be calculated from the magnitude of an earthquake according to the Gutenberg-Richter formula (Kanamori and Anderson 1975; Bullen and Bolt 1985):

$$\log_{10} E_i = 11.8 + 1.5M_i \tag{3}$$

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

From the view of statistics, the number of earthquakes N^+ and N^- will affect the reliability of Y_m. Based on the notion that seismogenic processes of earthquakes are controlled not only by deterministic dynamical law but also affected by stochastic or disorder factors, Zhuang and Yin (1999) studied the

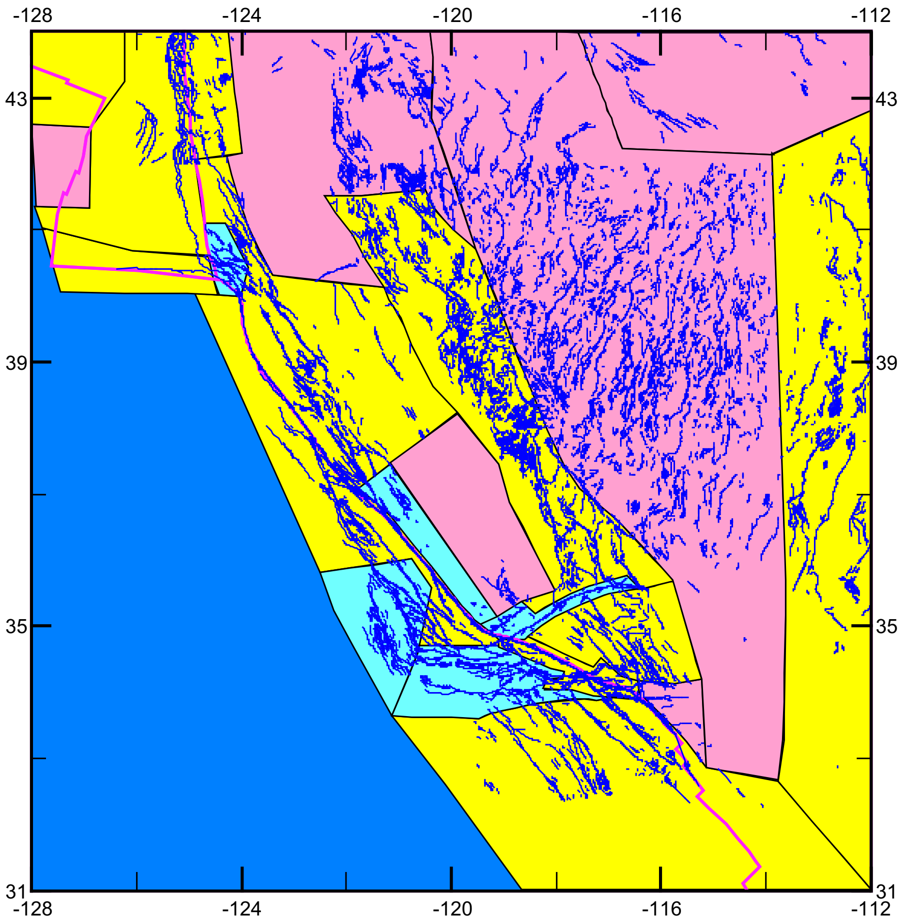

Figure 1
Twenty divisions of the study region with USGS fault system information (*X* west longitude, *Y* north latitude. units in degrees, *Yellow regions* denote the strike slip fault regions, *pink regions* denote normal fault regions, *pale blue regions* denote thrust fault regions, the *blue region* indicates the Pacific Ocean)

influence of random factors on the LURR in order to estimate the threshold *Y* value that can be regarded as an earthquake precursor within a specified confidence level. Additionally, Zhuang and Yin (1999) studied the influence of random factors on the LURR using a large number of synthetic earthquake catalogues, incorporating the assumptions of a Poisson model and the Guterburg-Richter law. They estimated the threshold *Y* value that can be regarded as an earthquake precursor within a specified confidence level. They provided the critical value of LURR, Y_c that depends on the number of earthquakes under different specified confidence levels. For instance, at the 90 % confidence level, 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 a 99 % confidence level, Y_c is 7.69 if the number of earthquakes in the specific time and space window is 20 (Zhuang and Yin 1999). The greater the earthquake number is, the lower the Y_c (critical value of LURR) is. In this paper, we give critical LURR space–time regions by Y/Y_c instead of *Y* under a confidence level of 90 %. When we take the value $Y/Y_c > 1$ as the credible LURR anomaly, we can remove most of the incredible results and decrease the false LURR anomalies. When we take the value $Y/Y_c > 1$ instead of $Y > 1$ as the LURR anomaly prior to a strong earthquake, we can avoid some unstable LURR anomalies caused by a small number of earthquakes in the time window and improve the confidence of the results.

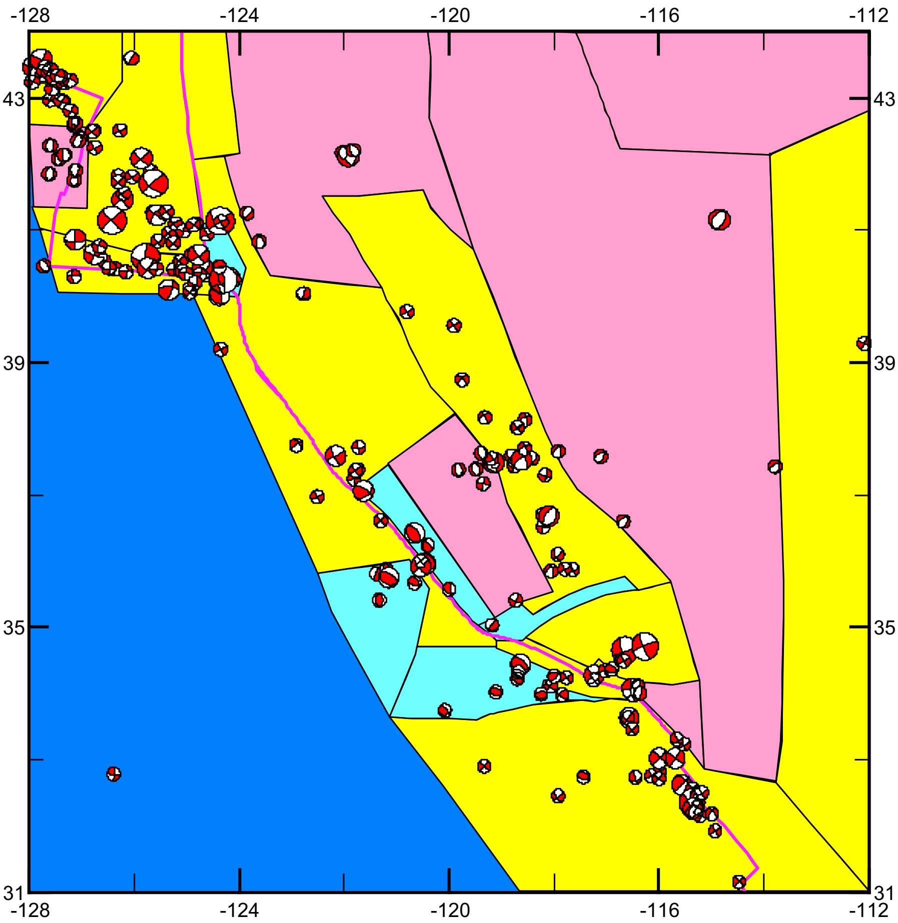

Figure 2
Twenty divisions of the study region with focal mechanism information from Harvard (*X* west longitude, *Y* north latitude, units in degree, *colors* have the same meaning as in Fig. 1)

2.2. *Determination of Loading and Unloading*

LURR theory employs the Coulomb failure hypothesis (JAEGER and COOK 1976) to judge the loading or unloading state according to the sign (+ or −) of the Coulomb failure stress induced by the Earth's tides (YIN 1987; YIN *et al.* 1995). In studying the seismic hazard by earthquake stress triggers, Coulomb failure stress increments are denoted as ΔCFS (e.g., HARRIS 1998, 2000; RESERNBERG and SIMPSON 1992).

$$\Delta CFS = \Delta(\tau_n + f\sigma_n) \tag{4}$$

where σ_n stands for normal stress, τ_n denotes shear stress, f represents the coefficient of internal friction, and n is the normal direction of the fault plane on which CFS reaches its maximum. When 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 10^6–10^8Pa) far exceeds the level of σ_{ij}^t (on the order of 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 tidal stress is much larger than that of tectonic stress (VIDALI *et al.* 1998), thus ΔCFS is mainly due to tidally induced stress that can be calculated precisely in terms of the Runge–Kutta numerical method (MELCHIOR 1978; YIN and YIN 1991).

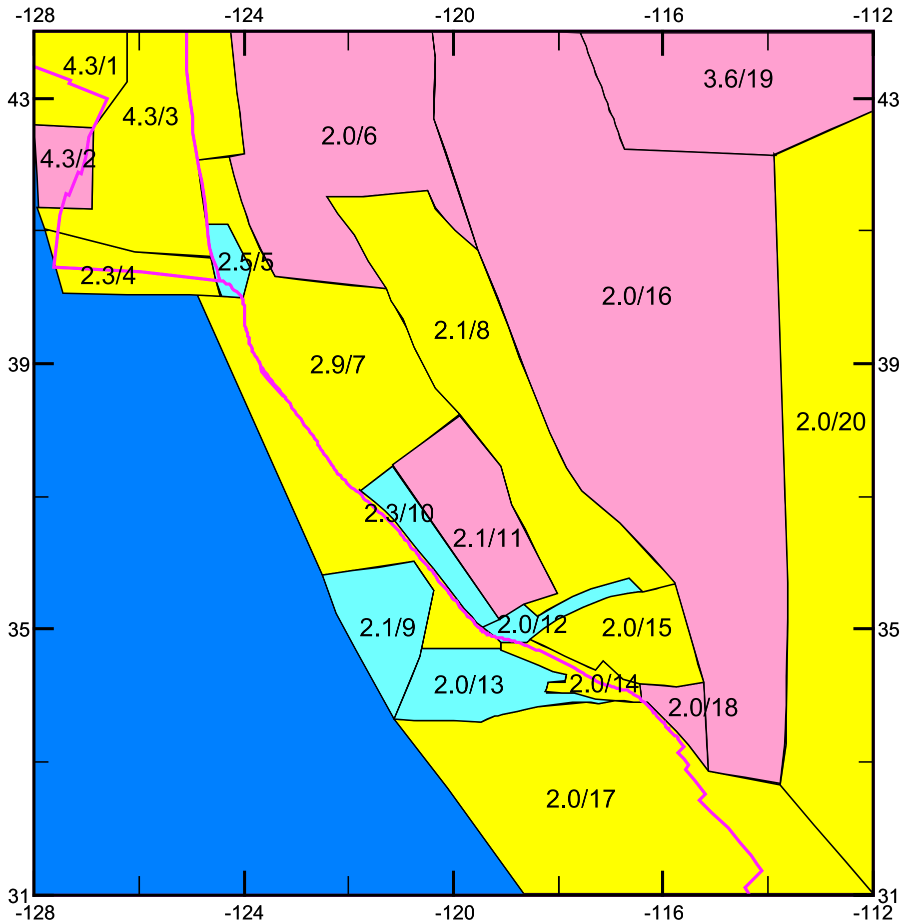

Figure 3
Earthquake completeness cutoff in each division (obtained with catalogue from ANSS by a G-R relation, colors have the same meaning as in Fig. 1)

2.3. *Zoning Map of the Study Region for Determination of Loading or Unloading State*

Based on the assumption that the tectonic shear stress acting on the focal plane is parallel to the slip direction of the pre-existed fault plane or the future plane, we need to project the increment of effective shear stress induced by tidal stress along the slip direction of the plane (Yin 1987; Yin *et al.* 1995). The slip direction of the focal plane can be determined by fault geometry and its focal mechanism, so we gathered the focal mechanisms (from Harvard University, http://www.globalcmt.org/CMTsearch.html) and fault properties (from USGS, http://earthquake.usgs.gov/hazards/qfaults/) in our study region (western United States and its adjacent region: 31°–44°N, −128° to −112°E).

Then we zoned the study region into 20 sub-regions according to the fault geometry and focal mechanisms. In each sub-region, the fault geometry and the focal mechanisms are almost in accordance with each other, indicating that the stress field is almost uniform in each part. Figure 1 shows the distribution of the faults and the 20 divisions in the study region, and Fig. 2 shows the distribution the focal mechanisms of M5.0 and above and the 20 divisions in the study region.

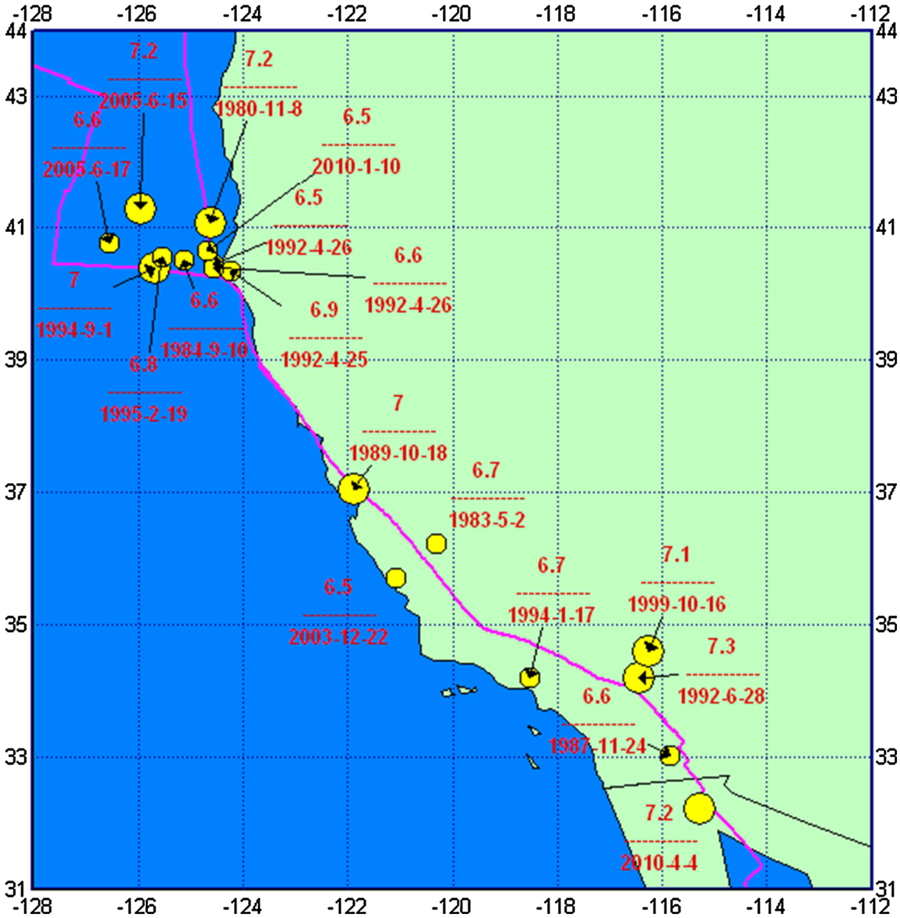

Figure 4
Distribution of big earthquakes larger than M6.5 in the study region from 1980 to 2011

2.4. *Data and Scanning Parameters*

The earthquake catalogue we used in this paper is from the Advanced National Seismic System (ANSS; http://earthquake.usgs.gov/monitoring/anss/). In order to speed up the calculations and avoid disturbance from outstanding earthquakes, we chose magnitude thresholds according to the Gutenberg-Richter (G-R) relation. The completeness cutoff of earthquakes in each sub-region is shown in Fig. 3. From this figure we can see that seismic monitoring in the northwest corner is very low, such that we do not have enough earthquakes for a LURR calculation.

The scanning parameters are as follows:

Time window: 1 year

Time moving step: 1 month

Space window: $R = 100$ km

Space moving step: 0.5° latitudinally and longitudinally

Earthquake catalogue thresholds: 2.9–4.5 (excluding regions 1, 2, 3 and 19)

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 latitudinally and longitudinally by increments of 0.5°.

3. *Characteristics of Y/Y_c Anomalies Before Big Earthquakes Larger Than M6.5*

384 Images of Y/Y_c contours during the period from 1980 to 2011 were obtained based on the

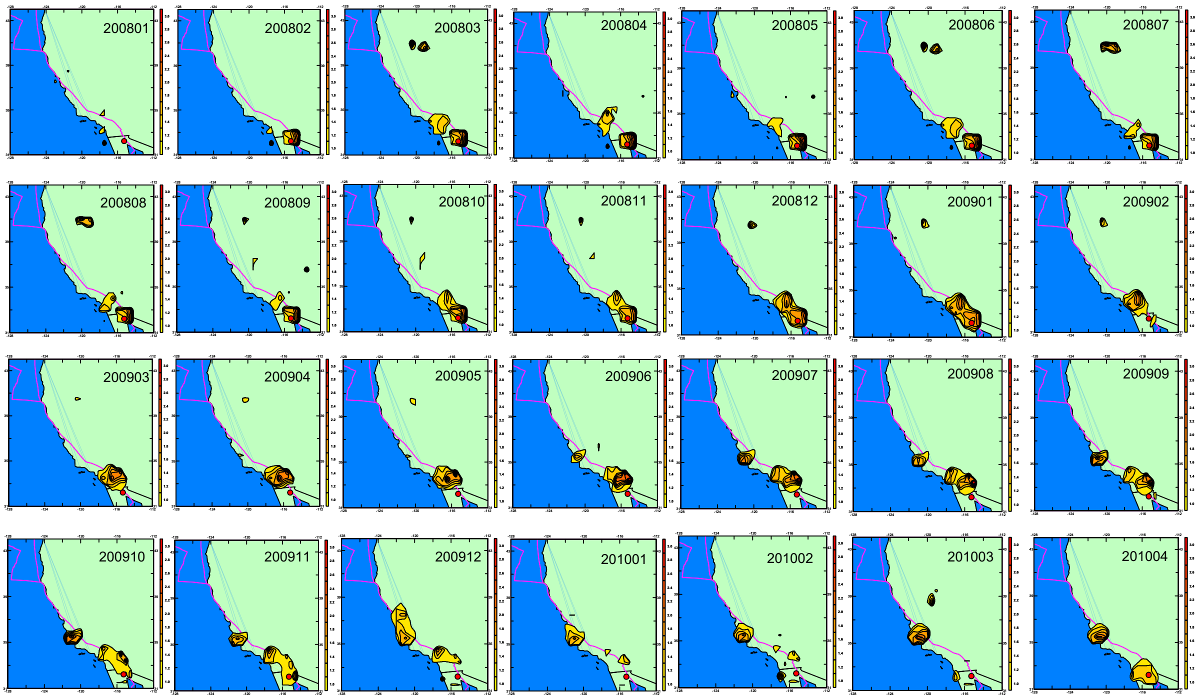

Figure 5
Monthly snapshots of Y/Y_c evolution before Mexico M7.2 earthquake on April 4, 2010 (*red dot* denotes the epicenter of the quake)

scanning parameters listed above. During this period, 18 earthquakes larger than M6.5 occurred in this region, as shown in Fig. 4.

Figure 4 shows that, among the eighteen big earthquakes, ten occurred in the northwest corner without enough earthquakes of M2.9 to 4.5 for calculation (the cutoff magnitude in regions 1, 2 and 3 is M4.3, as shown in Fig. 3). As such, we could not obtain credible Y/Y_c values in these areas, and, hence, no expected Y/Y_c anomalies prior to these earthquakes near their epicenters.

Now we focus on the remaining eight big earthquakes in Fig. 4: (1) Coalinga (36.23°N, 120.31°W) M6.7 on May 2, 1983; (2) Superstition Hills (33.02°N, 115.85°W) M6.6 on Nov. 24, 1987; (3) Loma Prieta (37.04°N, 121.88°W) M7.0 on Oct. 18, 1989; (4) Landers (34.20°N, 116.44°W) M7.3 on Jun. 28, 1992; (5) Northridge (34.21°N, 118.54°W) M6.6 on Jan. 17, 1994; (6) Hector Mine (34.59°N, 116.27°W) 7.1 on Oct. 16, 1999; (7) San Simeon (35.7°N, 121.1°W) M6.5 on Dec. 22, 2003; (8) Mexico (32.22°N, 115.3°W) M7.2 on April 4, 2010.

With the evolution of Y/Y_c contours and relations with the big earthquakes, we can summarize the characteristics of Y/Y_c before the big earthquakes. For example, Fig. 5 shows the Y/Y_c evolution during the period from Jan. 2008 to April, 2010. From this figure, we can see what happened before the Mexico M7.2 earthquake in April 2010.

Figure 5 shows that Y/Y_c anomalies appeared successively from Feb. 2008 till Nov. 2009 near the epicenter of the Mexico M7.2 earthquake. The Y/Y_c anomaly increased from Feb. 2008, reached the maximum in June, 2009, then disappeared in Dec. 2009. Five months after the Y/Y_c anomaly near the epicenter disappeared, the Mexico M7.2 earthquake occurred.

Figure 6 shows the plot of the time series of Y/Y_c at the epicentral region before and after the Mexico M7.2 earthquake during the period from 2005 to 2010. It shows that Y/Y_c values of each month before Feb. 2008 were always less than 1.1, indicating no obvious LURR anomaly occurred during this period. But from Feb. 2008 to Nov. 2009, the values of Y/Y_c successively increased to more than 1.1, illustrating an obvious LURR anomaly occurred during this period. The peak value of Y/Y_c is 2.2, appearing in June, 2009 (Fig. 6).

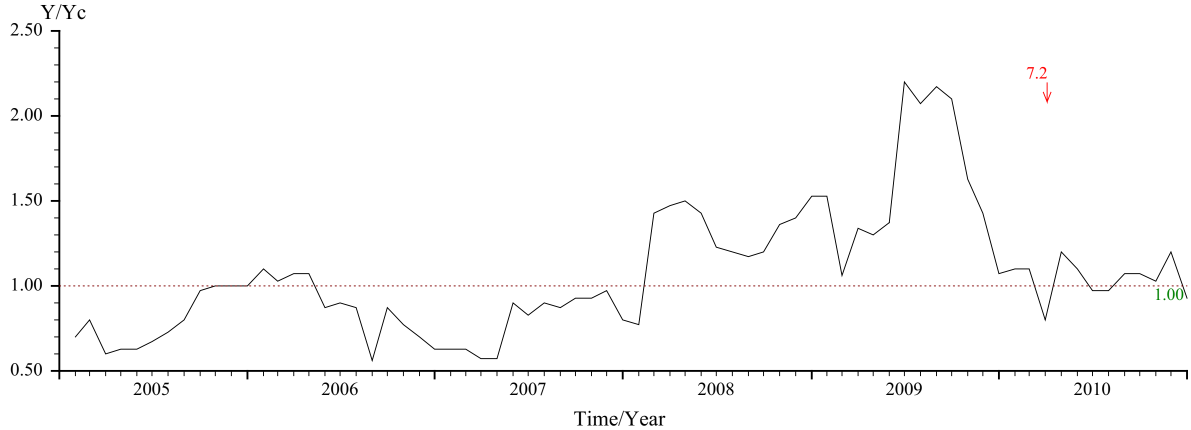

Figure 6
Time series of Y/Y_c at the epicentral region before and after the Mexico M7.2 earthquake (Fig. 1)

Table 1

Characteristics of Y/Y_c anomalies before eight big earthquakes larger than M6.5 in the study region during the period from 1980 to 2011

No.	Date (UT)	Location	Magnitude	Beginning time-ending time of Y/Y_c anomaly	Peak point time of Y/Y_c anomaly (/m)	Characteristic time durations $T/T_1/T_2$ (/m)
1	1983-05-02	Coalinga	6.7	1980-09–1981-08	1981-04	31/6/25
2	1987-11-24	Superstition Hills	6.6	1982-04–1985-06	1983-11	67/19/48
3	1989-10-18	Loma Prieta	7.0	1984-09–1985-10 1989-04–1989-09	1989-06	60/57/34
4	1992-06-28	Landers	7.3	1989-08–1992-03	1991-08	34/12/22
5	1994-01-17	Northridge	6.6	1992-07–1993-07	1992-12	17/5/12
6	1999-10-16	Hector Mine	7.1	1995-09–1997-02 1997-10–1999-02	1998-03	49/30/19
7	2003-12-22	San Simeon	6.5	1996-11–1998-03 2001-07 2002-08–2002-09	1999-07	85/32/53
8	2010-04-04	Mexico	7.2	2008-02–2009-11	2009-06	26/16/10

Yin *et al.* (2010) defined the duration T from the beginning of the LURR anomaly ($Y/Y_c > 1$) to the occurrence of a strong earthquake as the seismogenic duration, and the peak point of the LURR anomaly indicates the nucleation of the earthquake. The peak point divides T into two parts, T_1 is duration from the beginning of LURR anomaly to the peak point, and T_2 is the period from the peak point of LURR to the occurrence time. So T_2 is the nucleation period of a strong earthquake.

Table 1 lists some characteristics of the eight big earthquakes, such as the beginning time and ending times of the LURR anomaly, the peak point time of the LURR anomaly, time durations of T, T_1 and T_2, etc. Fig. 7 shows the characteristics of time durations of T, T_1 and T_2 of the eight big earthquakes.

Table 1 characteristics of Y/Y_c anomalies before eight big earthquakes larger than M6.5 in the study region during the period from 1980 to 2011

From Table 1 and Fig. 7, we can summarize that obvious Y/Y_c anomalies occurred 17–85 months (T) before the eight big earthquakes ($M \geq 6.5$), and the nucleation time period (T_2) is in the range of 4–53 months. Due to the limited number of earthquakes, the relationships between characteristic durations (T, T_1 and T_2) with magnitudes could not be obtained.

We can also realize from Fig. 7 that the seismogenic process of each big earthquake varies. For

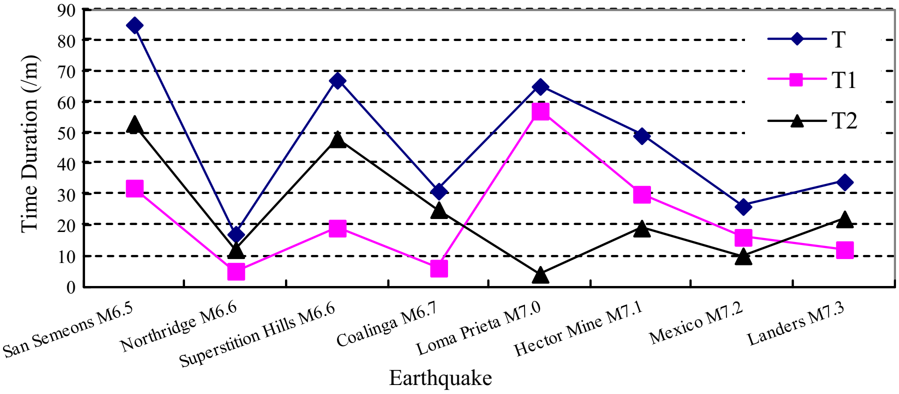

Figure 7
Characteristics of Y/Y_c anomalies in terms of time duration of T, T_1 and T_2

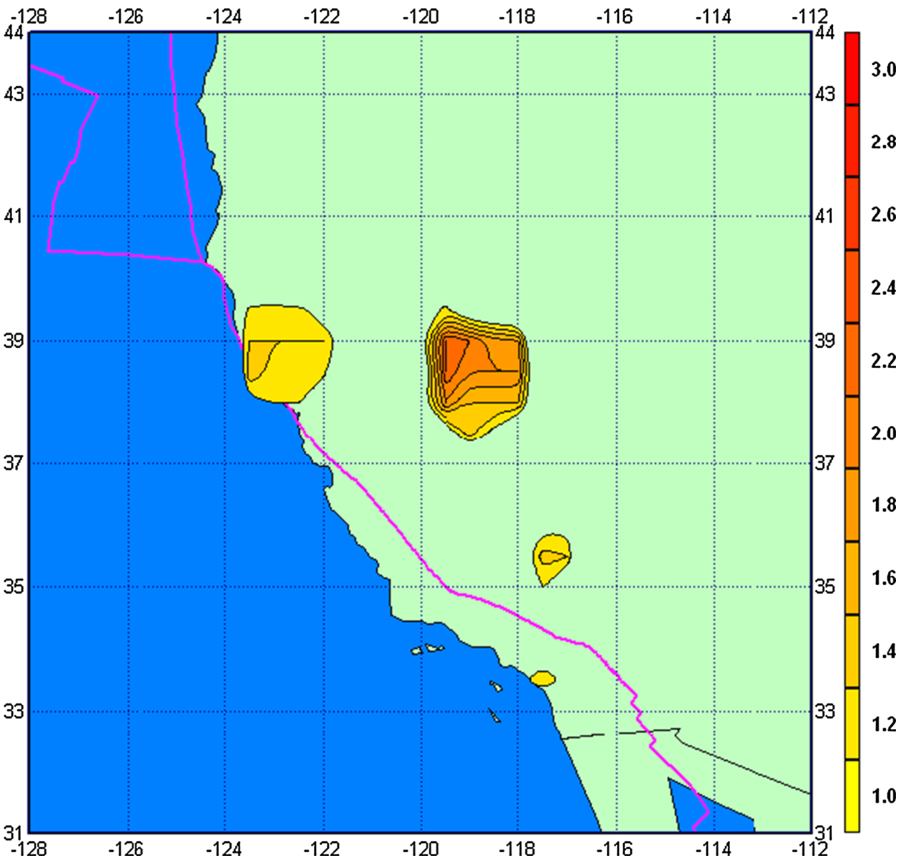

Figure 8
Potential earthquake risk regions illustrated by the contour of the Y/Y_c anomaly in Mar. 2012

example, the seismogenic duration of the San Simeon M6.5 earthquake is the longest even though its magnitude is the smallest among the eight big earthquakes. For the Superstition Hills and Northridge earthquakes with the same magnitude (M6.6), the seismogenic durations are very different from each other. However, for the Landers and Hector Mine earthquakes with almost the same magnitude and location (see in Fig. 4), the characteristics of their seismogenic durations are similar, which implies that the seismogenic process is associated with tectonic settings and the environment.

4. Estimation of Potential Earthquake Risk in the Western United States

From the evolution of Y/Y_c contours after the Mexico M7.2 earthquake, two regions with LURR anomalies were detected, one is between the northern region of the Bay Area and the Mendocino triple junction (38°–40°N, −124° to −122°E) and the other is between Lake Tahoe and Mono Lake (37.5°–39.5°N, −120° to −118°E) along the border of California and Nevada (Fig. 8).

The LURR anomaly in the first region began Jan. 2011 and reached its maximum in April 2011. For the second region, the LURR anomaly began April 2011 and reached its maximum in Mar. 2012. According to the characteristics of seismogenic duration in Table 1, the potential risk of an earthquake larger than M6.5 exists in these two regions in the not-too-distant future (1–7 years).

5. Conclusions and Discussion

In this paper, the variation of Y/Y_c in the western United States and its adjacent area during the period from 1980 to 2011 was studied by using a spatial and temporal scanning method based on the seismic catalogue, fault geometry and focal mechanisms. Calculations covered a span of 32 years, within which 8 big earthquakes larger than M6.5 occurred in regions with high quality seismic data. This volume of data provided for credible LURR calculation. According to the results above, the following conclusions can be drawn:

1. Y/Y_c (value of LURR/critical value of LURR) anomalies are obvious near the epicenters of each of the 8 big earthquakes (>M6.5) that occurred between 1980 and 2011 in the western United States and its adjacent area.
2. Y/Y_c anomalies are first evident about 17–85 months prior to the big earthquakes; they initially grow, then subsequently weaken. The peak LURR point appeared 4–53 months before the big earthquakes. In other words, the seismogenic duration is between 17 and 85 months, and the time scale of the nucleation process (T_2) is between 4 and 53 months for the eight big earthquakes larger than M6.5 in the western United States.
3. Two regions with LURR anomalies were detected with high seismic risk, with a time scale of 1–7 years. One region is between the North Bay Area and the Mendocino triple junction (38°–40°N, −124° to −122°E), and the other is between Lake Tahoe and Mono Lake (37.5°–39.5°N, −120° to −118°E) along the border of California and Nevada.

Zhang *et al.* (2005b) obtained a statistical relation between T_2 and the magnitude M of a subsequent earthquake for most of the earthquakes on the Chinese mainland, and Yin *et al.* (2013) applied dimensional analysis to reveal the relation between M, T_2 and other parameters for more reliable earthquake prediction, as shown in formula (5), (6) and Table 2.

$$T = 80\,(1 - 2.5 \times 10^{-0.09M}) \tag{5}$$

$$T_2 = 60\,(1 - 2.3 \times 10^{-0.08M}) \tag{6}$$

In their studies, for an earthquake with magnitude about M7.0, the seismogenic duration T is about 33 months, and the nucleation duration is about 22 months. Compared with the statistical results, our mean seismogenic duration T for the eight big earthquakes with magnitude about M7 is about 47 months, and the nucleation duration T_2 is about 24 months. Obviously, there are some differences between them. The differences might be caused by the tectonic background, the calculating parameters

Table 2

T, T_1 and T_2 of different magnitudes of earthquakes

Magnitude	T (/m)	T_1 (/m)	T_2 (/m)
5	9	4	5 ± 2
6	22	8	14 ± 4
7	33	11	22 ± 6
8	42	14	28 ± 8
9	49	15	34 ± 10

such as slip direction of the fault plane, time and space windows, earthquake catalogue cutoffs, etc. Futhermore, seismogenic processes are very complicated; there are some extreme cases not following the statistical relation.

Although the evolution of Y/Y_c contours were obtained during 1980–2011, we only discussed the relationship between the LURR anomalies with big earthquakes larger than M6.5 in this paper. There are some other issues left to be discussed, such as the relationship between the spatial scale of the LURR anomaly and the magnitude of the subsequent earthquake, the quantitative evaluation of LURR forecast efficiency under a prediction regulation, etc. We'll discuss these issues in forthcoming papers.

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