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Comparison Between LURR and State Vector Analysis Before Strong Earthquakes in Southern California Since 1980

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Abstract—There are seven strong earthquakes with M $\geq$ 6.5 that occurred in southern California during the period from 1980 to 2005. In this paper, these earthquakes were studied by the LURR (Load/Unload Response Ratio) method and the State Vector method to detect if there are anomalies before them. The results show that LURR anomalies appeared before 6 earthquakes out of 7 and State Vector anomalies appeared before all 7 earthquakes. For the LURR method, the interval between maximum LURR value and the forthcoming earthquake is 1 to 19 months, and the dominant mean interval is about 10.7 months. For the State Vector method, the interval between the maximum modulus of increment State Vector and the forthcoming earthquake is from 3 to 27 months, but the dominant mean interval between the occurrence time of the maximum State Vector anomaly and the forthcoming earthquake is about 4.7 months. The results also show that the minimum valid space window scale for the LURR and the State Vector is a circle with a radius of 100 km and a square of 3°×3°, respectively. These results imply that the State Vector method is more effective for short-term earthquake prediction than the LURR method, however the LURR method is more effective for location prediction than the State Vector method.

Key words: LURR, state vector, characteristics of anomaly, earthquake prediction, Southern California.

1. Introduction

LURR (Load/Unload Response Ratio) is an earthquake prediction method put forward by Yin (1987). LURR (Load/Unload Response Ratio) is defined as (YIN, 1987)

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

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where X^+ and X^- are the response rates during loading and unloading measured by some method. The intention of this concept is that when a seismogenic system is in a stable state, its response to loading is nearly the same as its response to unloading, whereas when the system is in an unstable state, the response to loading is stronger than that to unloading.

Based on the theory of LURR and its recent development (YIN, 1987; YIN and YIN, 1991; YIN *et al.*, 1995, 2000; WANG *et al.*, 1999; MORA *et al.*, 2000a,b, 2002), spatial and temporal variation of Y/Y_c in Southern California and its adjacent area (32°N to 40°N, 114°W to 125°W) during the period from 1980 through March, 2002 has been studied (Zhang *et al.*, 2004). Here Y_c is the critical value of LURR that depends on the number of earthquakes under different specified confidence levels (ZHUANG and YIN, 1999). 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). Here we chose the confidence level as 99%. The scanning results show that obvious Y/Y_c anomalies occurred before 5 of the total 6 earthquakes with M $\geq$ 6.5, the area with Y/Y_c anomalies is near the epicenters of the strong earthquakes, and the Y/Y_c anomalies occur months to years prior to the earthquakes. After March, 2002, another earthquake with M $\geq$ 6.5 occurred in Southern California; that is the San Simeon M 6.5 (35.7°N, 121.1°W) earthquake on Dec. 22, 2003. In order to obtain the evolutionary process of LURR before this quake, ZHANG *et al.* (2004, 2006) calculated Y/Y_c in Southern California with earthquake catalogue of ANSS from April 2002 to June 2004 under the same calculation parameters. The results show that the characteristic of LURR before the San Simeon earthquake is similar to the former ones.

In recent years, a new earthquake prediction method named State Vector was put forward by YIN *et al.* (2004a,b). Their results show that significant anomalies occurred several months prior to the Tangshan M 7.8 and Haicheng M 7.3 earthquakes. YU *et al.* (2004) confirmed the phenomena of State Vector anomaly before rock failure by a rock mechanical test. WU *et al.* (2006) applied this method to study 25 strong earthquakes with $M \geq 6.8$ in the China mainland and obtained the results that there are obvious State Vector anomalies three years prior to 19 out of 25 strong earthquakes and among these 19 strong earthquakes there are obvious state vector anomalies 60 days before 10 of them. These results show considerable promise for short-term earthquake prediction.

Is the State Vector effective in other tectonic regions? What is the difference between the characteristics of the LURR and the State Vector? In order to obtain the answers, we apply the State Vector method to the Southern California region to see if there are obvious anomalies before strong earthquakes in this region, and compare the characteristics of State Vector anomalies to those of LURR.

The earthquake catalogue we used in this paper is downloaded from the web site http://www.ncedc.org/anss/catalog-search.html, which is the *ANSS* (*A*dvance *N*ational *S*eismic *S*ystem) composite earthquake catalogue.

2. Method to Calculate LURR and State Vector

2.1. LURR

LURR (Load/Unload Response Ratio) is an approach to testing for crustal criticality put forward by YIN (1987). Its hypothesis is that an earthquake is the failure or instability of the focal media or seismogenic system. When the system is in a stable state, its response to loading is nearly the same as its response to unloading, whereas when the system is in an unstable state, the response to loading is more sensitive than that to unloading (YIN, 1987; YIN and YIN, 1991; YIN *et al.*, 1995, 2000). YIN (1987) defined LURR in formula (1).

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

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

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 and 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, and Y_c is chosen as Y value under the confidence level of 99%.

Earthquake energy E_i in formula (2) is related to magnitude by the following formula (GUTENBERG and RICHTER, 1956)

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

where M_i is the magnitude of i-th earthquake, and the unit of energy E_i is erg ($\times 10^{-5}$ J).

The periods of loading and unloading are determined by calculating perturbations in the Coulomb Failure Stress ΔCFS induced by earth tides (YIN *et al.*, 1995; ZHANG *et al.*, 2006). We divided the Southern California region into 11 units (ZHANG *et al.*, 2004, 2006), and in each of them the stress distribution (ZOBACK, 1992) and fault parameters SCECDC (Southern California Data Center) are generally uniform.

In order to speed up the calculations and avoid the perturbation caused by outstanding earthquakes, we chose magnitude thresholds according to the linear part of the Gutenberg–Richter relation in each unit area.

According to the relationships between the spatial window, time window and the magnitude obtained in the earthquake case studies conducted by YIN *et al.* (2002a,b) and ZHANG *et al.* (2005), when the spatial window is chosen as a circular region with the radius of about 100 km, and the time window is one year, the magnitude of the forthcoming earthquake could be predicted as larger than M 6. In this region a value of

Y/Y_c (LURR/critical LURR) was calculated for a specific time window (1 year), and the time step is 1 month. The circle center was moved step by step in both latitude and longitude by increments of 0.25 degrees so the contour of Y/Y_c in each month could be obtained.

2.2. *State Vector*

The State Vector is an idea from statistical physics (REICHL, 1980). YIN *et al.* (2004b) extended this idea to describe the evolution of the damage of rock specimens. The whole specimen is divided into n regions. The AE (Acoustic Emission) energy or AE event rate at time t_k in region i denotes the i-th component e_i, and the whole n components construct a state vector $\vec{V}_t$ of n dimensions (YIN *et al.*, 2004b).

$$\vec{V}_t = (e_1(t), e_2(t), \ldots, e_n(t)). \tag{4}$$

In earthquake prediction practice, e_i in formula (4) is defined as the sum of the logarithms of each earthquake energy E_j in the i-th subsquare during the period from $t-T$ to t, as the following

$$e_i(t) = \sum_{j=1}^{k} \lg E_j\Big|_{t-T}^{t}. \tag{5}$$

Here T refers to the time window for calculation, and the earthquake energy E_j is calculated by formula (3).

Figure 1 illustrates the schematic diagram of time window T and time step Δt in the calculation.

In our study, the time widow is chosen as $T = 1$ year and the time step is $\Delta t = 30$ days.

The following parameters associated with State Vector could be obtained:

a. Modulus of the State Vector at time t

$$M_t = \left|\vec{V}_t\right|. \tag{6}$$

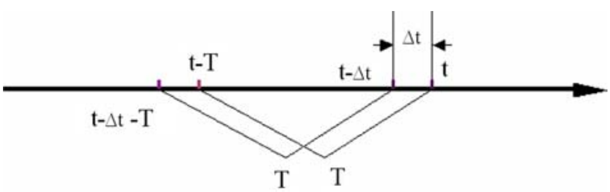

Figure 1
Schematic diagram of time window T and time step Δt.

b. Modulus of the increment of the State Vector during time t-Δt to t

$$\Delta M_{t-\Delta t,t} = \left|\Delta \vec{V}_{t-\Delta t,t}\right|. \tag{7}$$

c. Angle between State Vectors from time t-Δt to t

$$\varphi_{t-\Delta t,t} = \arccos\left(\frac{\vec{V}_{t-\Delta t} \cdot \vec{V}_t}{V_{t-\Delta t} V_t}\right). \tag{8}$$

When n = 3, the State Vector could be illustrated by 3D phase shown in Figure 2. $\vec{V}_1$ stands for the State Vector at time t_1, $\vec{V}_2$ is the State Vector at time t_2, and $\vec{V}_3$ is the State Vector at time t_3. $\Delta\vec{V}_{12}$ is the increment of the State Vector from t_1 to t_2, and $\Delta\vec{V}_{23}$ is the increment of the State Vector from t_2 to t_3. φ_{12} is the angle between $\vec{V}_1$ and $\vec{V}_2$.

In order to study the evolution of the State Vector before strong earthquakes in Southern California, we chose a square region of $m°\times m°$ subsquares with the epicenter of the target strong earthquake at the center, where m is varied from 3 to 11 to obtain the result with the best goodness of fit. To determine the best goodness of fit, we calculate the parameters of State Vector in different space scales. If obvious variation occurs before the quake and there are no other major changes in other periods (say, the change of the parameter is larger than two times the standard deviation), we take the space scale as the critical scale for the seismogenic region (Wu *et al.*, 2006).

Considering the completeness of the earthquake catalogue and avoiding the turbulence of the result affected by major earthquakes, we chose the cutoff of the magnitude as $2.0 \leq m_j \leq m_0 - 0.5$, where m_0 is the magnitude of the target earthquake.

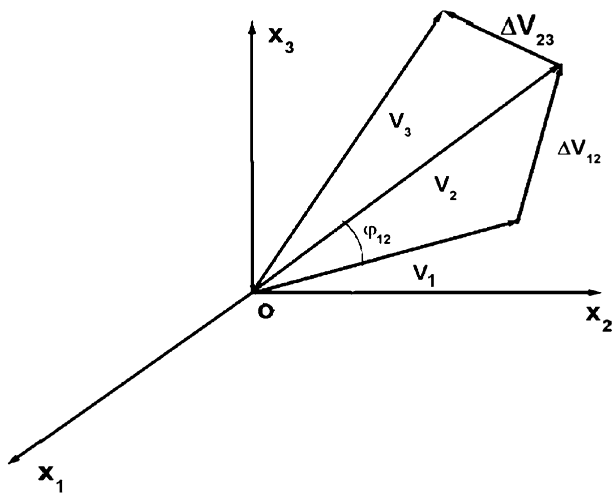

Figure 2
State Vector in 3D phase.

3. Characteristics of the LURR Anomaly before Strong Earthquakes in Southern California

According to Zhang *et al.* (2004, 2006), among the seven strong earthquakes with $M \geq 6.5$ in Southern California since 1980, obvious LURR anomalies occurred prior to six of them. The characteristics of the LURR anomalies are listed in Table 1.

We can see from Table 1 that except for the Coalinga earthquake in 1983, Y/Y_c anomalies occurred before the other six earthquakes in Southern California. The forthcoming strong earthquake occurred 1 to 19 months after the time when Y/Y_c reached its peak value. According to the common conception of long-term (several years to ten years), medium-term (one year to several years), short-term (several months) and imminent (several days to ten days) earthquake prediction in China (Mei *et al.*, 1993), Table 1 implies that LURR is valid for medium-term to short-term prediction. The dominant Δt is from 8 to 13 months, and the mean value is about 10.7 months. This might be applied to earthquake forecasting in this region.

Table 1 also shows that the distance between the epicenter of the forthcoming earthquake and the maximum Y/Y_c point is from 0 to 200 km, and the dominant Δ (km) is about 100 km. This implies that if the location of the maximum Y/Y_c point is detected, we might forecast that there probably will be a strong earthquake with $M \geq 6.5$ occurring within 200 km from the maximum Y/Y_c point.

4. Characteristics of the State Vector Anomaly before Strong Earthquakes in Southern California

For the seven strong earthquakes in Southern California in Table 1, we calculated the time series of the modulus of the State Vector, the modulus of the increment of

Table 1

Characteristics of Y/Y_c before strong earthquakes in Southern California since 1980.

Date	Epicenter and location	Magnitude /Δ (km)	Max Y/Y_c	Lasting time of anomalous Y/Y_c (month)	$\Delta\tau$ (month)
1983.5.2	(36.23°N, 120.32°W) Coalinga	6.7/None	None	None	None
1987.11.24	(33.01°N, 115.85°W) Superstition Hills	6.6/0	1.4	21	11
1989.10.18	(37.04°N, 121.88°W) Loma Prieta	7.0/100	1.2	24	10
1992.6.28	(34.20°N, 116.44°W) Landers	7.3/100	1.0	18	8
1994.1.17	(34.21°N, 118.54°W) Northridge	6.6/200*	1.2	25	13
1999.10.16	(34.59°N, 116.27°W) Hector Mine	7.1/100	1.4	15	1
2003.12.22	(35.7°N, 121.1°W) San Simeon	6.5/50	1.4	15	19

Notes: Δ (km) is the distance between the forthcoming earthquake and the maximum Y/Y_c point.
$\Delta\tau$ is the interval between the occurrence time of the maximum Y/Y_c anomaly and the occurrence time of the forthcoming earthquake.
* The distance between the maximum point of ΔM and the forthcoming 1994 earthquake is 200 km, not 80 km as mentioned in the early paper (Zhang *et al.*, 2004). We corrected it in the later paper (Zhang *et al.*, 2006), but did not give the annotation.

the State Vector, and the angle between the State Vectors according to formula (4) to (6).

Since the parameter of the angle between State Vectors does not show a regular feature before these earthquakes, we only discuss the characteristics of the modulus of the State Vector and the modulus of the increment of the State Vector in this paper.

Here we give examples of the evolution of the modulus of the State Vector and the modulus of the increment of the State Vector before the Coalinga earthquake.

Figure 3 shows the curve of ΔM with time before the Coalinga M 6.7 earthquake. For this earthquake we chose square regions with scales ranging from $3° \times 3°$ to $11° \times 11°$ with the epicenter of the Coalinga earthquake at the center. The curve with the scale of $3° \times 3°$ shows the obvious anomaly of the State Vector before the quake, so we take the region of $3° \times 3°$ ($m = 3$) as the critical scale for the seismogenic region.

From this figure we can see that the maximum ΔM value occurred on Jan. 1, 1983, and the Coalinga earthquake occurred 4 months later on May 2, 1983. Two smaller peaks of ΔM appeared on May 1, 1980 and May 1, 1981 without earthquakes larger than M 6.5 occurring after them. However, what interests us is that, during the period from 1970 to May 2, 1983, two earthquakes of M 6.2 (37.50°N, 118.81°W) and M 5.9 (37.50°N, 118.81°W) occurred on May 27, 1980 and Sept. 30, 1981, respectively. In fact, there were only these three earthquakes with M $\geq$ 5.9 in this selected region since 1970. What is the relationship between the two peak values and the M 6.2 and M 5.9 earthquakes? Are there any ΔM anomalies before smaller earthquakes like the two earthquakes of M 6.2 and M 5.9? We will study this phenomenon in the future.

For the modulus of the State Vector M, the result also shows positive prospect. Figure 4 shows the curve of M with time before the Coalinga earthquake. From this figure, we can see that the maximum M value occurred on April 1, 1983, and the Coalinga

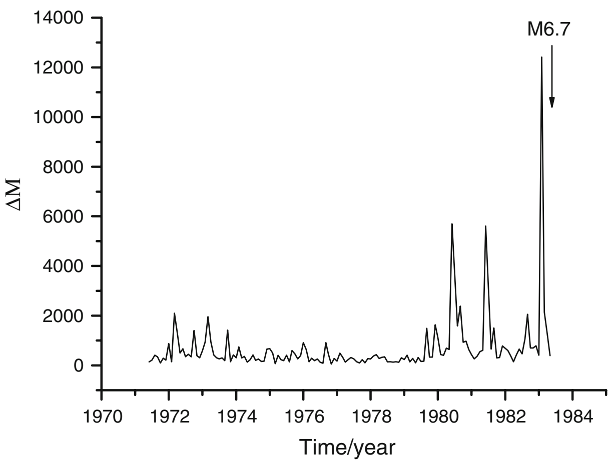

Figure 3
Evolution of the modulus of state vector increment before the Coalinga earthquake.

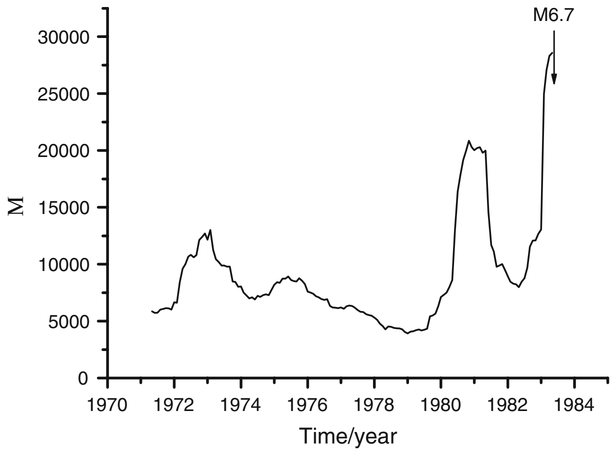

Figure 4
Evolution of the modulus of State Vector before the Coalinga Earthquake.

earthquake occurred 1 month later on May 2, 1983. For the second peak of M, which appeared on Oct. 1, 1980, there is a M 6.2 earthquake (37.50°N, 118.81°W) that occurred on May 27, 1980, that did not occur after the peak. However, M rises from the base value of about 13052 (on Jan.1, 1983) to 28591 (on April 1, 1983) before the M 6.2 earthquake. In other words, M rises rapidly before strong earthquakes, however some earthquakes might occur after M reaches the peak value, and others might occur before M reaches the peak value.

The critical scale of 3°×3° shows the obvious ΔM_{max} and M_{max} anomalies preceding the Coalinga earthquake. The ΔM_{max} anomaly occurred on Jan. 1, 1983, about 4 months before the earthquake, and M_{max} occurred on April 1, 1983, about 1 month before the earthquake.

In the same way, we obtained the characteristics of ΔM_{max} and M_{max} before the seven strong earthquakes in Southern California since 1980, as shown in Table 2.

From Table 2, we can summarize that for strong earthquakes with M $\geq$ 6.5 in Southern California, the interval between ΔM_{max} and the forthcoming strong earthquake is from 3 to 27 months, and the average of $\Delta\tau_1$ is about 9 months. The interval between M_{max} and the forthcoming strong earthquakes is from 1 to 71 months, and the average of $\Delta\tau_2$ is 22.4 months.

Table 2 also shows that the critical scale for different strong earthquakes is different. The largest scale is 8°× 8° for the Loma Prieta M 7.0 earthquake, while for the Hector Mine M 7.1 earthquake, the critical scale is only 3° × 3°. Why the critical scales for different earthquakes with similar magnitude differ so much is reserved as a question.

Table 2

Characteristics of ΔM_{max} and M_{max} before strong earthquakes in Southern California since 1980.

Date	Epicenter and location	Magnitude	Date 'of ΔM_{max} / $\Delta\tau_1$ (month)	Date of M_{max} / $\Delta\tau_2$ (month)	m
1983.5.2	(36.23°N, 120.32°W) Coalinga	6.7	1983.1.1/4	1983.4.1/1	3
1987.11.24	(33.01°N, 115.85°W) Superstition Hills	6.6	1987.6.24/5	1987.5.24/6	4
1989.10.18	(37.04°N, 121.88°W) Loma Prieta	7.0	1987.7.18/27	1987.05.18/29	8
1992.6.28	(34.20°N, 116.44°W) Landers	7.3	1992.03.28/3	1992.05.28/1	4
1994.1.17	(34.21°N, 118.54°W) Northridge	6.6	1993.06.17/7	1993.03.17/10	5
1999.10.16	(34.59°N, 116.27°W) Hector Mine	7.1	1999.02.6/8	1996.07.16/39	3
2003.12.22	(35.7°N, 121.1°W) San Simeon	6.5	2003.01.22/11	1998.01.22/71	5

Note: ΔM_{max} is the maximum value of the modulus of increment of state vector.
M_{max} is the maximum value of the modulus of the State Vector.
$\Delta\tau_1$ is the interval between time of the modulus of the maximum increment State Vector and the occurrence time of the forthcoming earthquake.
$\Delta\tau_2$ is the interval between time of the modulus of the maximum State Vector and the occurrence time of the forthcoming earthquake.
m is the number of grids along latitude or longitude direction of the square region.

5. *Comparison of the Characteristics of the LURR and the State Vector*

Table 1 and Table 2 list the characteristics of LURR and State Vector anomalies before 7 strong earthquakes with $M \geq 6.5$ in Southern California since 1980. Here we compare three kinds of intervals, $\Delta\tau$, $\Delta\tau_1$ and $\Delta\tau_2$, before each strong earthquake. $\Delta\tau$ denotes the interval between the time of the peak LURR and the occurrence time of the forthcoming earthquake, $\Delta\tau_1$ is the interval between the time of the modulus of the maximum increment State Vector and the occurrence time of the forthcoming earthquake, and $\Delta\tau_2$ is the interval between the time of the modulus of the maximum State Vector and the occurrence time of the forthcoming earthquake.

Figure 5 shows that the maximum LURR values appear within 12 months before the Superstition Hills, Loma Prieta, Landers and Hector Mine earthquakes. The maximum *M* values appear within 12 months before the Coalinga, Superstition Hills, Landers and Northridge earthquakes, while the maximum ΔM values appear within 12 months before Coalinga, Superstition Hills, Landers, Northridge, Hector Mine and San Simeon earthquakes. The above results suggest that the ΔM parameter is more valid for earthquake prediction within 12 months, than the *M* parameter, and for almost half of the earthquakes (e.g., Superstition Hills, Landers, Northridge), the LURR and State Vector methods both work well.

In order to provide a simple and easy understanding of the effects of LURR and State Vector in time forecasting, we draw the spectrum of $\Delta\tau$, $\Delta\tau_1$ and $\Delta\tau_2$ in Figure 6. We can see from this figure that 4/7 of $\Delta\tau$ distribute from 9 to 13 months, and the mean value of the dominant $\Delta\tau$ is 10.7 months; 4/7 of $\Delta\tau_1$ distribute mainly from 3 to 11 months, and the mean value of $\Delta\tau_1$ is 4.7 months; 4/7 of $\Delta\tau_2$ distribute from 1 to 10 months, and the mean value of $\Delta\tau_2$ is 4.5 months. The results imply that the State Vector is a valid

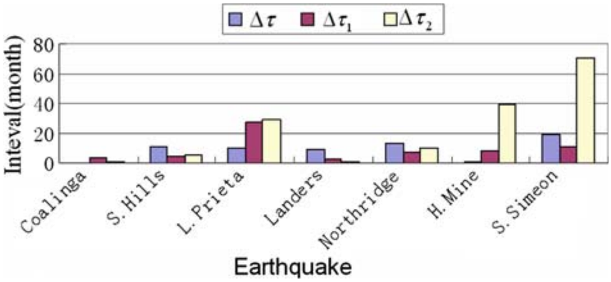

Figure 5
$\Delta\tau$, $\Delta\tau_1$ and $\Delta\tau_2$ for the strong earthquakes in Southern California since 1980.

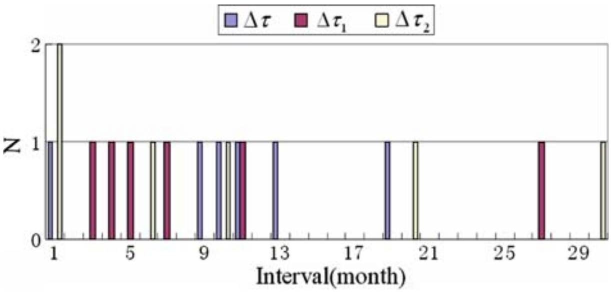

Figure 6
Spectrum of $\Delta\tau$, $\Delta\tau_1$ and $\Delta\tau_2$.

method for short-term earthquake forecasting, and the LURR is a valid method for medium-term earthquake forecast in Southern California since 1980. The ΔM parameter seems to be more stable than the M parameter.

6. Conclusions and Discussion

There are only seven strong earthquakes with M $\geq$ 6.5 in Southern California since 1980. From the above results, we can draw the following conclusions:

(1) LURR anomalies occurred before 6 earthquakes out of 7 and State Vector anomalies occurred before all of these 7 earthquakes.
(2) For LURR, the interval between the maximum Y/Y_c value and the forthcoming earthquake ranges from 1 to 19 months, and the dominant mean interval is about 10.7 months. For the State Vector method, the interval between the maximum modulus of the increment State Vector and the forthcoming earthquake ranges from 3 to 27 months, but the dominant mean interval between the occurrence time of the maximum State Vector anomaly and the forthcoming earthquake is about 4.7 months.

(3) The minimum valid space window scale for the LURR and State Vector is a circle with a radius of 100 km and a square of $3° \times 3°$, respectively.

From the above results, the State Vector method seems to be more effective for short-term earthquake prediction than the LURR method, however the LURR method is more effective for location prediction than the State Vector method.

The above conclusions are based on limited earthquake cases in Southern California. Are they tenable for other strong earthquakes in other regions? YIN *et al.* (2004a,b) and WU *et al.* (2006) studied the earthquake cases in China, and their results show that several months before many strong earthquakes, significant State Vector anomalies did occur. YU *et al.* (2004) also confirmed the phenomena of the State Vector anomaly before rock failure by rock mechanical testing, which proved the solid mechanical base for the State Vector method. However, more earthquake cases should be studied before drawing the confirmed conclusions.

Some questions are left behind in this study, such as why the critical scales for different earthquakes with similar magnitude differ so much. Is the square region the best to calculate parameters related to the State Vector? How should the threshold for the State Vector calculation be chosen? Is the subdivision of Southern California into 11 areas reasonable? There are many details to be concerned with and statistical checks to be done before the LURR and the State Vector could be used as earthquake predictors.

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