Systematic examination of ‘precursor waves’ of strong earthquakes by using the wavelet method*

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Abstract Based on the borehole strainmeter recordings immediately before the strong earthquakes ($M_S \geq 7.5$) during the period from 2001 to 2005 observed at the Taian observation station, Shandong Province, the authors make a systematic and objective examination of the precursor waves of the quakes. The effects of Earth tides with periods larger than 128 min are eliminated through high-pass filtering; and atmospheric-pressure inferences are removed by linear regression. The 2–128 min signals are then separated into six frequency bands by employing the wavelet method. Results indicate that the wavelet method is capable of picking out information of weak variations in the signals. According to the characteristics of the ‘precursor waves’ obtained from wavelet transformation, the method of overrun ratio analysis is put forward for examination. All the detailed components of the wavelets have been analyzed. For the time series of the overrun rate in all these components, statistical calculation has been made for the slopes of fit curves, and mean values and standard deviations were obtained and positive-negative slope ratios were analyzed. The three statistical data show that ‘precursor waves’ are not widely recorded by borehole strainmeter within 15 days before remote strong earthquakes.

Key words: borehole strainmeter; precursor waves; wavelet method; overrun rate analysis

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1 Introduction

Today earthquake prediction, in particular prediction of short-term and impending earthquakes is still a problem worldwide. The key to this problem is to find out universal signals of foreshock anomalies with definite physical meaning. So “precursor waves” seem to possess such property. Study of “precursor waves” has aroused interest among scientists engaged in earthquake prediction.

The term ‘precursor wave’ was first put forward by Kanamori and Cipar (1974). In 1974, from the long-period seismograph records at the Pasadena earthquake observatory station in California, USA located nearly 10 000 km away from the epicenter, they found that 15 min before the May 22, 1960 great Chilean earthquake ($M_S 8.3$), a long-period wave was recorded with an oscillation period between 300 s and 600 s, and named it ‘precursory long-period wave’. Later, Cifuentes

and Silver (1989) used the data of the Earth’s free oscillation excited by this earthquake to research the low-frequency characteristics. Feng et al (1984) had been engaged in a study of long-period deformational waves before earthquakes by using the theories of fracture mechanics and wave propagation in rheologic medium. He suggested with his results that long-period deformational waves could be some kinds of precursors. Yang et al (2003) reported that a slow earthquake was observed by the seismic network stations of Xinjiang, China, 3.5 days before the Great $M_S 8.1$ Kunlun mountain, China, earthquake on November 14, 2001 and a long-period precursory waves lasted 47 hours. Some events collected since 1960 (Zhao et al, 2001; Chen, 2006) show several properties of “precursor waves”: they generally appeared during 7 days before earthquakes; records before great earthquakes were evident; the higher earthquake magnitude was, the longer observational distance would be; a majority of strain changes range between 10^{-8} – 10^{-7} , some were to the order of 10^{-9} .

There is not yet strict definition about precursor long-period waves up to date. Generally, they are surficial undulation of periods between several minutes and

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several hours. Their typical period is longer than that of normal earthquakes, but relatively short compared with tidal deformation scale (Wu, 2001).

In spite of the many descriptions of precursory phenomena hours to days before earthquakes (Zhang et al, 2005; Xu et al, 2003; Gao et al, 2005; Che et al, 2002; Wang et al, 2007; Wang et al, 2005; Wang et al, 2002), the information did not constitute compelling evidence for existence of precursor waves. The assertions are of a qualitative nature since the records are mostly for a single station or earthquake. In order to investigate whether precursory waves exist or not, we study all of a certain class of earthquakes, namely, $M_S \geq 7.5$ events.

Precursor waves are reportedly recorded by many instruments in some literatures, such as long-period seismometers, strainmeters, tiltmeters, gravimeter etc. High resolution borehole strainmeter provides an ideal type of instrument for observing modern tectonic deformation in the Earth's crust. A large number of such instruments have been used in the Plate Boundary Observation (PBO) project, USA (Qiu and Shi, 2004, see also Qiu, 2007). There are more than 30 stations for borehole strain precursor surveillance in China. Taian (TA) station's instrumental operation has been assessed the best among all the instruments from 2001 to 2005. The dilatometers of TA began to work on September 1998. The sensor was installed in granite borehole at the depth of 70 m. The strain resolution of the transducer reaches the order of 10^{-9} . Its continuous recording is sampled minutely and shows obvious Earth tide (Wang et al, 2004).

By using the borehole strain observations of TA, we systematically study strain variations before great earthquakes ($M_S \geq 7.5$) during the period from 2001 to 2005. It is quantitatively investigated whether precursor waves exist with wavelet method and overrun ratio analysis (ORA) that we first put forward.

2 Data used in the study

To sum up, long-period precursor waves should generally appear within 7 days before great earthquakes. In order to cover the time in which precursory waves might occur, we actually use data of 30 days (43200 minute-values) before great earthquakes since January 1, 2001.

According to China Seismological Network Catalog (CSNC), parameters of all the great earthquakes ($M_S \geq 7.5$) during the period from 2001 to 2005 are listed

in Table 1. Following are some comments about the earthquakes. No.1 and No.2 earthquakes are not analyzed because the data before these two events cover only 10–13 days. It is impossible to distinguish anomalous waveforms from normal strain variations in such short time. There are data of only 26 days before No.3 earthquake. No.5 and No.8 earthquakes are also not analyzed because of data shortage. There are usually many aftershocks after great earthquakes. We can not distinguish precursor waves from aftershock records, thus those earthquakes taking place within three days should be analyzed as one event.

Figure 1 shows the locations of TA station and the epicenters of $M_S \geq 7.5$ earthquakes during the period from 2001 to 2005. No.5 event took place west to TA station with an epicentral distance of 17 748.4 km, which is the longest for the events in Table 1. No.17 event took place east to TA with an epicentral distance of 2 336.96 km, the shortest for the events in Table 1. The chosen great earthquakes happened nearly in all directions around TA.

3 Pretreatment of strain data

It is obvious that borehole strainmeter responds to Earth tides and atmospheric pressures. In order to obtain tectonic signals, changes caused by Earth tides and atmospheric pressures must be eliminated. Firstly, missing data are processed using spline interpolation; then, strain changes caused by earth tides whose periods are over 128 minutes are filtered by a zero phases 8-order Butterworth high-pass filter, whose normalized stop-frequency is 0.015 6, thus dominant periods of the high-pass data are the same with that of typical precursor waves; afterwards strain changes produced by atmospheric-pressure are removed with linear regress method.

We apply the above steps to process the data of 30 days before 18 earthquakes in Table 1. An example is shown in Figure 2. Figure 2a clearly shows the volumetric strain changes dominated by Earth tides. This phenomenon indicates that the data are high-quality. It also shows strain changes caused by Earth tides might merge precursor waves existing in volumetric signals. There is not obvious correlation between the atmospheric-pressure change curve (Figure 2b) and the volumetric strain curve (Figure 2a). The correlation of the signals after high-pass filtering (Figures 2c and 2d) is very clear. Figure 2e shows the volumetric strain curve after high-pass filtering, from which strain changes produced by atmospheric-pressure are removed.

Table 1 Parameters of $M_S \geq 7.5$ great earthquakes during the period from 2001 to 2005

No.	Date a-mo-d	Origin time h:min:s	Long /°	Lat /°	Depth /km	M_S	Epicentral distance to TA station/km	Reference site	Remark
1	2001-01-10	16:02:40	-153.80	56.94	22	7.5	6 675.12	Kodiak Island region	Shorter data, no being analyzed
2	2001-01-13	17:33:34	-88.70	13.00	60	8.2	13 930.96	Off coast of Central America	Shorter data, no being analyzed
3	2001-01-26	03:16:40	70.45	23.48	10	8.1	4 676.02	India	Use the data of 26 days
4	2001-06-23	20:33:14	-73.60	-16.30	33	8.4	17 564.29	Near coast of Peru	
5	2001-07-07	09:38:43	-72.10	-17.50	33	7.7	17 748.40	Off coast of Northern Chile	Data shortage, no being analyzed
6	2001-11-14	09:26:10	90.53	35.92	11	8.2	2 387.75	Qinghai Province	
7	2001-12-18	04:02:58	122.95	23.92	27	7.5	1 476.63	Taiwan region	
8	2002-01-02	17:22:48	168.34	-17.54	27	7.5	8 021.59	Vanuatu (New Hebrides)	Data shortage, no being analyzed
9	2002-10-10	10:50:19	134.60	-1.92	22	7.5	4 595.04	West Irian region	
10	2002-11-02	01:26:10	96.04	3.14	14	7.8	4 254.89	Off west coast of Northern Summerdale	
11	2002-11-03	22:12:41	-147.40	63.50	4	8.1	6 733.80	Central Alaska	Analyzed together with No. 10
12	2003-01-20	08:43:06	161.08	-9.96	21	7.6	6875.55	Solomon Islands	
13	2003-01-22	02:06:35	-104.10	18.80	24	7.9	12 541.92	Near coast of Jellico, Mexico	Analyzed together with No. 12
14	2003-07-15	20:27:47	68.00	-2.99	10	7.9	6 687.72	Carlsberg Ridge	
15	2003-08-04	04:37:20	-43.40	-60.50	10	7.8	16 981.05	Scotia Sea	
16	2003-08-21	12:12:50	166.68	-45.33	18	7.5	10 309.81	Off west coast of South Island, N.Z.	
17	2003-09-25	21:07:59	143.29	41.65	16	7.5	2 336.96	Hokkaido region	
18	2003-09-25	19:50:05	143.71	41.79	16	8.2	2 373.42	Hokkaido region	Analyzed together with No. 17
19	2003-09-27	11:33:25	87.87	50.02	16	7.7	2 802.48	Kazakhstan-Xinjiang border region	Analyzed together with No. 17
20	2003-11-17	06:43:06	178.57	51.23	30	7.6	5 061.25	Rat Islands	
21	2004-02-07	02:42:33	135.31	-3.88	11	7.5	4 825.35	West Irian region	
22	2004-12-14	23:20:13	-81.40	19.00	10	7.5	13 601.79	Caribbean Sea	
23	2004-12-23	14:59:04	161.30	-49.30	10	8.0	10 425.63	North of Macquarie Island	
24	2004-12-26	04:21:28	92.80	6.94	40	7.7	4 079.09	Nicobar Islands region	Analyzed together with No. 23
25	2004-12-26	00:58:51	95.79	3.15	40	8.9	4 266.99	Off west coast of Northern Summerdale	Analyzed together with No. 23
26	2005-03-28	16:09:35	97.05	2.03	34	8.6	4 312.81	Off west coast of Northern Summerdale	
27	2005-07-24	15:42:04	92.19	7.83	19	7.6	4 036.16	Nicobar Islands region	
28	2005-10-08	03:50:39	73.66	34.42	26	7.9	3 923.39	Pakistan

Figure 1 Distribution of TA station and the epicenters of $M_S \geq 7.5$ earthquakes during the period from 2001 to 2005.

Figure 2 The pretreatment result of data of 30 days before No.23 earthquake. (a) is the volumetric strain observation; (b) is the atmospheric pressure change observation; (c) is the atmospheric pressure change after high-pass filtering; (d) is the volumetric strain after high-pass filtering; (e) is the high-pass volumetric strain after removing the atmospheric pressures influence.

4 Wavelet transform

Wavelet transform method was first put forth by Grossmann (1984) and Morlet (1982). Grossmann and Morlet constructed the theory system with scaling and translating function. Meyer (1985) created smooth wavelet which had certain attenuation. Daubechies (1988) demonstrated that it is possible for orthonormal wavelet basis to have compact support and proposed discrete wavelet transform method. In 1989, Mallat (1989) proposed a fast algorithm for multi-resolution analysis of a signal and made wavelet transform be used abroad. Yang et al (2005) studied discrimination between earthquakes and nuclear explosions with wavelet analysis. Li et al (2006) revealed the geomagnetic precursors of the Zhangbei earthquake using wavelet method. We first investigate whether great earthquakes' precursor waves exist or not using this method.

In our study, discrete wavelet transform (DWT) method is used to distinguish different frequency signals. A digital signal $f(x)$ can be expressed as follows

$$\text{DWT}_{a,b} = \int_R f(x) \Psi_{m,n}(x) dx, \quad (1)$$

where 'a' is scaling factor and 'b' is translating factor ($a, b \in R$). In the calculation, 'a' equals to 2^k . The larger the 'k' is, the lower the signal frequency is. When $k=0$, sig-

nal frequency is Nyquist frequency. When $k=1$, signal frequency is split into two equal sub-band.

$f(x)$ can be approximately expressed as

$$f(x) \cong A_j f(x) = a_k^j f(x) + d_k^j f(x), \quad (2)$$

where $a_k^j f(x)$ and $d_k^j f(x)$ are respectively approximation part and detail part of signal in different frequency sub-bands at resolution 'j'.

Given frequency band of signal $\{f_i\} (i=0, 1, \dots, N-1)$ after sampling to be $[0, \Omega]$, thus frequency band of a_k^0 is $[0, \Omega]$. Frequency band of a_k^1 is $[0, \Omega/2]$ and that of d_k^1 is $[\Omega/2, \Omega]$. Frequency bands of a_k^j are $[0, \Omega/2^j]$ and that of d_k^j are $[\Omega/2^j, \Omega/2^{j-1}]$ (Figure 3).

Figure 3 The approximation parts and detail parts of wavelet decomposition.

Figure 4 shows the analysis result. Anomalous waveforms like typical precursor waves is unobvious in the high-pass curves (remarked ‘removepa’), but the wavelet decomposition detail parts (d1, d2, d3 and d4) show signals resembling to ‘precursory long-period waves’ (remarked ‘?’). Their amplitudes range within $\pm 0.5 \times 10^{-9}$, with main periods within 2–4 min and dura-

tive time about 1 day. The signals gradually attenuate from d2 to d4, and vanish in d5. From Figure 4 we see that waveforms like precursor waves exist in volumetric strain observations. This information can be efficiently extracted with wavelet method and wavelet analysis results can show frequency distribution characteristics of such anomalous waveforms.

Figure 4 The wavelet analysis result of No.23 great earthquake. ‘removepa’ represents the signal after pretreatment, d1–d6 are detail parts, ‘a6’ is the 6th approximation part.

5 Overrun rate analysis

The so-called “precursor waves” given by literatures are different from earthquake signals. They are long-period deformation waves whose amplitude variation obviously exceeds background noises and durative time is longer than earthquake waves. The signals remarked ‘?’ in Figure 4 seem like them. We put forward overrun ratio analysis (ORA) for quantitatively investigating whether this waveform exists or not in volumetric strain observations.

After filtration and removing strain changes caused by atmospheric pressures, observation curve looks like quite smooth except some earthquake signals. Therefore, we can express average of the curve with its arithmetic mean and describe strain change ranges with its standard deviation. Points exceeding standard deviation during certain time are defined as overrun rate (OR). When

anomalous waveform appears, according to the waveform characteristics, OR should be much higher than usual time. Although some earthquake signal points also were higher than standard deviation, durative time of earthquake signals is far shorter than that of anomalous waveform, thus OR of earthquake signals will be lower than that of anomalous waveform.

Though ‘precursor waves’ are usually supposed to occur during seven days before earthquakes, we adopt data of 30 days before earthquakes for not losing these signals. A time series of OR is obtained by computing overrun rate over 30 days before earthquakes. As an approximation curve, straight line is used to fit ORA time series. If only precursory waves appeared anytime during 15 days before earthquakes, OR will ascend during corresponding time. Fitting straight line slopes will also be greater than zero because of higher OR during 15 days before earthquakes. Statistic analysis of all

slopes can describe whether precursor waves generally exist or not.

According to the above idea, we do data processing as follows:

1) Calculate arithmetic mean values and standard deviations of data, which have been decomposed into 6 scales with wavelet transform. It needs be emphasized that ‘bad points’ exceeding standard deviation must be eliminated. Otherwise, arithmetic mean values and standard deviations would be as large as background noise values and precursor waves thus can not be distinguished. Those data that are larger than three times standard deviation are ruled out in present paper.

2) Generate overrun rate time series with the above arithmetic mean values and standard deviations. The unit time is 1 day (1 440 min), that is, overrun points of one day are computed for an OR value.

3) Calculate 30 OR values with data of 30 days before earthquake. We fit these OR values with straight line and thus obtain the slopes.

4) Statistically analyze the fitting straight line slopes of 18 earthquakes listed in Table 1.

We process the wavelet-decomposition detail parts

of 18 earthquakes in Table 1 following the above steps. Figure 5 is the ORA result of No.23 great earthquake. It shows that the OR values marked ‘11’ are 500, 672, 624 and 624 respectively. There are also 464, 532, 728 and 688 OR values respectively marked ‘12’. The ORA values marked ‘11’, ‘12’ are larger than others in the same scales. This indicates that the OR values marked ‘?’ in Figure 4 occurred on the 11th and the 12th days. It is coincident with our qualitative estimation for this anomalous waveform. In Figure 5, the OR value marked ‘3’ in ‘fitd1’ is 586. It is the maximum of the OR values in this scale. Since these large values appear beyond 15 days before No.23 earthquake, fitting straight line slopes from d1 to d4 are -1.63 , -3.77 , -1.84 and -5.41 respectively. Slopes in fitd5 and fitd6 are -3.39 , -4.40 because these larger OR values are beyond 15 days before the earthquake.

There are also some other large OR points in Figure 5. Since our major interest is in the statistical results of fitting straight line slopes of OR time series, individual large values that might be caused by accidental causes are not analyzed in particular.

Figure 5 The ORA result before No.23 earthquake. fitd1–fitd6 are ORA time series (*) and their fitting straight lines.

Statistical results of ORA study are listed in Table 2. It shows that fitting straight line slopes in all wavelet-decomposition detail parts are significantly less than their standard deviations. Most of arithmetic mean-values are less than zero. It also shows that the slopes do not tend to be positive because total of posi-

tive slopes is less than that of negative slopes. The arithmetic mean-values, standard deviations and positive-negative ratios show that precursor waves are not generally recorded by the borehole strainmeter during 15 days before these strong earthquakes.

In Table 2, $k(d1) - k(d6)$ of No.4, No.15 and No.26

earthquakes are all greater than zero; five slopes of No.21, No.22 earthquakes are greater than zero; four slopes of No.10, No.14, No.20 earthquakes are greater

than zero. The slopes of these eight earthquakes are basically coincided with our criteria that precursor waves exist. The eight earthquakes deserve further study.

Table 2 Statistic results of the ORA study

Earthquakes No. in Table 1	Date a-mo-d	Origin time (GWT) h:min	M_S	$k(d1)$	$k(d2)$	$k(d3)$	$k(d4)$	$k(d5)$	$k(d6)$
3	2001-01-26	03:16	8.1	-2.03	0.89	-1.55	-1.61	1.30	-2.06
4	2001-06-23	20:33	8.4	0.11	2.03	0.65	1.84	3.07	5.05
6	2001-11-14	09:26	8.2	-0.33	-1.52	-3.09	-0.54	-0.37	-1.08
7	2001-12-18	04:02	7.5	9.93	2.66	-1.25	-1.16	-3.62	1.11
9	2002-10-10	10:50	7.5	1.07	0.56	-1.35	-4.03	1.10	-3.15
10	2002-11-02	01:26	7.8	-0.52	0.25	0.27	1.46	4.86	-1.74
12	2003-01-20	08:43	7.6	-3.10	-3.99	-4.57	-4.51	-6.89	-2.93
14	2003-07-15	20:27	7.9	1.01	-0.27	-0.19	3.27	2.53	6.78
15	2003-08-04	04:37	7.9	2.09	2.68	2.34	3.26	3.40	0.14
16	2003-08-21	12:12	7.8	-5.35	-5.33	-4.12	-7.73	-8.79	-8.16
17	2003-09-25	19:50	7.5	-0.67	-1.17	-0.53	-2.99	-3.56	-4.71
20	2003-11-17	06:43	7.6	0.40	-0.23	0.58	1.86	1.92	-5.41
21	2004-02-07	02:42	7.5	0.31	-0.08	1.83	3.03	0.60	1.92
22	2004-12-14	23:20	7.5	0.60	-0.07	0.49	1.00	3.97	2.96
23	2004-12-23	14:59	8.0	-1.63	-3.77	-1.84	-5.41	-3.39	-4.40
26	2005-03-28	16:09	8.6	3.08	4.65	5.19	5.83	7.80	6.28
27	2005-07-24	15:42	7.6	6.80	4.56	1.37	-1.33	-3.32	-7.33
28	2005-10-08	03:50	7.9	-0.08	-2.10	-2.47	-3.46	-3.40	-3.55
Averages				0.65	-0.01	-0.46	-0.62	-0.16	-1.13
Standard deviations				3.43	2.75	2.40	3.60	4.33	4.42
Positive-negative ratios				10/8	8/10	8/10	8/10	10/8	7/11

Note: $k(d1)$ — $k(d6)$ are the slopes of the linear fits of ORA time series for $d1$ — $d6$.

We specially explain No.26 earthquake whose all slopes are positive and greater obviously than standard deviations. The anomalous signals appear six days before the earthquake. Figure 6 shows the results of wavelet transform and ORA. There is no $M > 6$ earthquakes in CSNC at the instants remarked ‘?’. They should not be atmospheric-pressure influences as well. Finally they are found to be caused by human activities.

6 Conclusions

We adopt high-quality volumetric strain observations at TA station, China, to systematically study strain changes before great earthquakes ($M_S \geq 7.5$) during the period from 2001 to 2005 and quantitatively investigate whether precursory long-period waves exist or not.

Since there are no precursory anomalous changes in observations of TA station, we thus think, even if such changes existed before great earthquakes, they might be merged by other dominant signals. Earth tide components whose periods are longer than 128 min are ruled out by filtering. Atmospheric-pressure influences are removed using linear regress method.

The high-pass data can be decomposed to detail and approximation parts of different scales with wavelet

transform, therefore signal properties of different frequency bands can be studied. Comparing them with normal strain changes, we can extract weak anomalous strain changes existing in the signals.

We put forth ORA for statistically investigate whether precursor waves exists or not. Data during 30 days before 18 earthquakes in Table 1 are analyzed. If precursor waves existed during 15 days before these earthquakes, overrun rate would be high in corresponding time. Arithmetic mean values of the fitting straight line slopes would be positive and larger than their standard deviations. Statistical results show arithmetic mean values approximate to zero, far less than their standard deviations, and positive-negative slope ratios of fitting straight lines approximate to 1. All data imply a characteristic of stationary random process and indicate that precursor waves are not generally recorded during 15 day before these great earthquakes. Although eight fitting straight line slopes are positive, it still needs be individually analyzed whether they were precursor waves.

We put forward ORA to statistically investigate whether precursor waves exist or not. The results indicate that precursor waves do not generally exist within 15 days before these strong earthquakes. It is not ruled

out that precursor waves might exist before some earthquakes. Our results are constrained by the earthquakes picked out. It is possible that precursor waves attenuate

too rapidly to be recorded by dilatometers far away from epicenter. We would further investigate $M_S < 7.5$ earthquakes whose epicenters are near observation stations.

Figure 6 (a) Wavelet decomposition result of No.26 earthquake; (b) ORA result of No.26 earthquake; tagging is the same as Figures 4 and 5.

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References

- Che Y T, Yu J Z, Zhang S L, Fan X F, Guo J J, Zhang T Y and Yang J L (2002). The records of water level ‘precursors’ and their discussion in well Shuozhou, Shanxi Province. *Acta Seismologica Sinica* **24**(2): 210–216 (in

- Chinese with English abstract).
- Chen D F (2006). Space-time characteristics of tidal deformation precursor. *Journal of Geodesy and Geodynamics* **26**(2): 24–30 (in Chinese with English abstract).
- Daubechies I (1988). Orthonormal bases of compactly supported wavelets. *Communication on Pure and Applied Math* **41**: 990–996.
- Feng D Y, Pan Q L, Zheng S H, Xue F and Kan X Y (1984). Long-period deformational waves and short impending earthquake precursors. *Acta Seismologica Sinica* **6**(1): 41–56 (in Chinese with English abstract).
- Gao J Z, Lv Z, Zhang H Y and Shao X B (2005). Progress in the observation and research on earthquake precursor wave. *South China Journal of Seismology* **25**(1): 53–58 (in Chinese with English abstract).
- Grossmann A and Morlet J (1984). Decomposition of hardy function into square integrable wavelets of contant shape. *SIAM J Math Anal* **15**: 723–726.
- Cifuentes I L and Silver P G (1989). Low-frequency source characteristics of the great 1960 Chilean earthquake. *J Geophys Res* **94**: 643–663.
- Kanamori H and Cipar J J (1974). Focal process of the great Chilean earthquake on May 22, 1960. *Phys Earth Planet Inter* **9**: 128–136.
- Li J, Liu X Q, Li H, Mao Y H and Zhen S T (2005). Analyses on normal background characteristics about deformation observation data on the basis of wavelet transform method. *Acta Seismologica Sinica* **27**(1): 33–41 (in Chinese with English abstract).
- Li Q, Lin Y F and Zeng X P (2006). Wavelet analysis as a tool for revealing geomagnetic precursors of the Zhangbei earthquake. *Chinese J Geophys* **49**(3): 855–863 (in Chinese with English abstract).
- Mallat S (1989). Multi resolution approximations and wavelet orthogonal bases of $L(R)$. *IEEE Trans AMs* **315**: 68–87.
- Meyer Y (1985). Principle D'incertitude bases Hilbertiennes et Algebra D'Operateur. Bourbaki Seminaire. *Asterisque* (Societe Mathematique de France) **2**: 662–690.
- Morlet J G, Arens G and Fourgcau E (1982). Wave propagation and sampling theory: Complex signal and scattering in multi-layered media. *Geophysics* **47**(1): 203–211.
- Qiu Z H and Shi Y L (2004). Developments of borehole strain observation outside China. *Acta Seismologica Sinica* **17**(Suppl.): 172–178.
- Qiu Z H, Ma J, Chi S L and Liu H M (2007). Earth's free torsional oscillations of the great Sumatra earthquake observed with borehole shear strainmeter. *Chinese J Geophys* **50**(3): 797–805 (in Chinese with English abstract).
- Wang M, Li F, Kong X Y and Liu H M (2004). Identification of disturbance of digital deformation observations. *Journal of Geodesy and Geodynamics* **24**(1): 94–98 (in Chinese with English abstract).
- Wang M, Qu T L and Kong X Y (2002). The analysis of the sudden jump of the data recorded by the digital body-strainmeter. *Earthquake* **22**(1): 111–114 (in Chinese with English abstract).
- Wang Q L, Zhang X D, Cui D X, Wang W P and Hu W X (2005). Understanding the mechanisms of premonitory anomalies and imminent precursor. *Recent Developments in World Seismology* (5): 131–144 (in Chinese).
- Wang W X, Ma L and Huang J P (2007). Analysis of anomaly in gravity observation before and after strong earthquakes. *Earthquake* **27**(2): 53–63 (in Chinese with English abstract).
- Wu Z L (2001). 'Dark matters' in seismology—'Silent earthquakes' and the future of earthquake prediction. *Recent Developments in World Seismology* (9): 1–4 (in Chinese).
- Xu Z Y, Yang R H, Hu Y L, Xu J and Wang B B (2003). A study of mechanism for slow earthquake and precursors. *Earthquakes* **23**(2): 12–20 (in Chinese).
- Yang X H, Shen P, Liu X Q and Zhen Z Z (2005). Application of method of spectral component ratio of wavelet-packets to discrimination between earthquakes and nuclear explosions. *Chinese J Geophys* **48**(1): 148–156 (in Chinese with English abstract).
- Yang Y L, Zhao G M, Gao G Y, Yang G S and Han R Q (2003). The slow earthquake event occurring before west to Kunlun mountain pass earthquake of $M_s 8.1$ of November 14, 2001. *Recent Developments in World Seismology* (9): 1–4 (in Chinese).
- Zhang C J, Shi Y L and Ma L (2005). Some problems in studying slow earthquakes. *Journal of the Graduate School of the Chinese Academy of Sciences* **22** (3): 258–269 (in Chinese with English abstract).
- Zhao G M, Yang G S and Chen H R (2001). Quiescent foreshock and earthquake prediction. *Earthquake* **21**(1): 69–77 (in Chinese with English abstract).