Short-term and imminent geomagnetic anomalies of the Wenchuan $M_S8.0$ earthquake and exploration on earthquake forecast*

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Abstract The diurnal variation of the geomagnetic vertical component is exhibited mainly by changes of phase and amplitude before strong earthquakes. Based on data recorded by the network of geomagnetic observatories in China for many years, the anomalous features of the appearance time of the minima of diurnal variations (i.e., low-point time) of the geomagnetic vertical components and the variation of their spatial distribution (i.e., phenomena of low-point displacement) have been studied before the Wenchuan $M_S8.0$ earthquake. The strong aftershocks after two months' quiescence of $M6$ aftershocks of the $M_S8.0$ event were forecasted based on these studies. There are good correlativities between these geomagnetic anomalies and occurrences of earthquakes. It has been found that most earthquakes occur near the boundary line of sudden changes of the low-point time and generally within four days before or after the 27th or 41st day counting from the day of the appearance of the anomaly. In addition, the imminent anomalies in diurnal-variation amplitudes near the epicentral areas have also been studied before the Wenchuan earthquake.

Key words: geomagnetic low-point displacement; diurnal-variation amplitude; Wenchuan earthquake; short-term and imminent geomagnetic anomaly; forecast of strong earthquakes

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1 Introduction

Occurrences of earthquakes are related not only to seismogenic processes in focal areas, but also to regional stress fields in the focal areas and the inner (inside the earth) and outer (earth-sun space) environments. The changing geomagnetic field is the natural medium that connects all these environmental factors (Ding et al, 1989). The relationship between diurnal-variation anomalies of geomagnetism and earthquakes have been studied (Ding et al, 1994, 2008; Duma and Ruzhin, 2003). Existence of reliable short-term and imminent geomagnetic precursors has been proved in practice since the Xingtai $M_S7.2$ earthquake in China in 1966. Application of the diurnal-variation anomalies of the

vertical component (Z) in geomagnetic field to earthquake prediction has become one of the most effective ways for routine earthquake monitoring and prediction, especially for the short-term and imminent prediction (Ding et al, 2006).

The diurnal-variation anomalies of the geomagnetic vertical component before strong earthquakes are mainly exhibited by changes of phase and amplitude and their deviations from normal background, and the anomalies of their spatial distribution are called diurnal-variation anomaly of geomagnetic field. These anomalous phenomena show good correlativities with occurrences of strong earthquakes. The diurnal-variation anomalies of geomagnetic field such as low-point displacement (LPD) have been used for earthquake prediction.

The present paper studies the anomalous features of appearance time of the minima of diurnal variations (i.e., low-point time) of the geomagnetic vertical components (Z) and the variation of their spatial distribution (i.e.,

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phenomena of LPD) before 112 earthquakes with $M_s \geq 6.0$, including 23 earthquakes with $M_s \geq 7.0$, especially the Wenchuan earthquake on May 12, 2008. In addition, the anomalies of diurnal-variation amplitude near the epicentral area have also been studied before the Wenchuan earthquake.

2 Relationship between phenomena of geomagnetic low-point displacement and strong earthquake

The low-point time (Beijing time) at each station satisfies normal distribution. It is necessary to use the data of many stations in a large area to determine geomagnetic anomalies of low-point time. There are good correlations between these phenomena of geomagnetic anomalies and occurrences of earthquakes. It has been found that most earthquakes occurred near the boundary line of sudden changes of the low-point time with an error of the distance between the stations in the vicinity of the boundary line and 80% of them occurred within

four days before or after the 27th or 41st day from the day of appearance of the anomaly, that is

$$T_t(\text{the date of LPD}) + 27 (\text{or } 41) \text{ days} \\ = T_e(\text{occurrence date}),$$

where LPD is low-point displacement. The low-point time at stations in one large region is obviously different from those in another large region, and the low-point time at stations in each large region is relatively consistent. The low-point time difference of stations in the vicinity of the boundary line of sudden changes is above two hours. If the usual distribution of low-point is broken on one day or a few days, two large regions for the low-point times at geomagnetic stations in China can be identified. There is an obvious boundary line (or a close curve) of sudden changes between these two large regions. And the difference of low-point time in the two regions is more than two hours but less than two hours in each region. Then the anomaly on this day (or a few days) is considered as anomaly for strong earthquakes with $M_s \geq 6.5$. If two regions for the low-point time are

Table 1 Anomalies of LPDs and the occurrences of strong earthquakes ($M_s \geq 7.0$)

No.	Anomaly date a-mo-d	K index	Earthquakes occurred			Interval days between anomaly date and date of earthquake occurrence
			Date a-mo-d	M_s	Epicenter	
1	1966-02-21	1122 1101	1966-03-22	7.2	Xingtai	29
2	1969-06-20	3343 2111	1969-07-18	7.4	Bohai	28
3	1969-11-24	1112 2222	1970-01-05	7.7	Tonghai	42
4	1972-12-23	5543 1111	1973-02-06	7.6	Luhuo	45
5	1973-06-19	3453 4333	1973-07-14	7.5	Bakehalu	25
6	1974-03-30	4433 3433	1974-05-11	7.1	Zhaotong	42
7	1974-12-19	2222 2133	1975-02-04	7.3	Haicheng	47
8	1976-05-02	5545 6455	1976-05-29	7.3, 7.4	Longling	27
9	1976-07-04	3443 3222	1976-07-28	7.8	Tangshan	24
10	1976-07-04	3443 3222	1976-08-16	7.2	Songpan	43
	1976-07-19	2232 2221				28
	1976-07-21	2223 2211				26
11	1976-07-13	1121 1111	1976-08-23	7.2	Songpan	41
12	1985-07-16	2321 1123	1985-08-23	7.1	Wuqia	38
	1985-07-25	4333 1332				29
13	1988-09-20	3422 1232	1988-11-06	7.4	Lancang	47
	1988-10-23	3242 2222		7.2	Gengma	14
14	1990-03-14	4334 4332	1990-04-26	7.0	Gonghe	43
	1990-03-24	3211 3232				33
15	1994-08-05	3323 1112	1994-09-16	7.3	Taiwan Strait	42
	1994-08-07	1111 1212				40
	1994-08-13	3563 4424				34
16	1995-06-14	1211 1232	1995-07-12	7.3	Menglian	28
17	1996-01-05	1222 3221	1996-02-03	7.0	Lijiang	29
18	1996-10-23	5534 2432	1996-11-19	7.1	Kalakunlunshan	27
	1996-09-29	2232 3220				51
19	1997-10-11	5532 2112	1997-11-08	7.5	Mani	28
20	2001-10-08	3235 4434	2001-11-14	8.1	Kunlunshan	37
21	2002-05-27	3365 3320	2002-06-29	7.2	Wangqing	33
	2002-06-05	2320 1112			(540 km)	24
22	2008-02-16	2130 2310	2008-03-21	7.3	Yutian	34
23	2008-04-24	3334 3222	2008-05-12	8.0	Wenchuan	18
	2008-05-09	3433 3320				3

identified in an area with the size about half Chinese territory, it can be considered as the anomaly for earthquakes about $M_S 6.0$.

The effectiveness of the prediction method is better for earthquakes with $M_S \geq 6.0$ (especially $M_S \geq 6.5$). As listed in Table 1, for earthquakes with $M_S \geq 7.0$, the predicted occurrence time is relatively accuracy and a few false predictions and failed predictions were made, but the predicted areas are large (Ding et al, 2004).

For example, geomagnetic LPD appeared on October 8, 2001 before the great Kunlun Mountain $M_S 8.1$ earthquake on November 14, 2001. The low-point time of geomagnetic vertical component on Chinese mainland is divided into two large regions with the boundary line of sudden change located at longitudes of 90°E – 100°E and in the north-south direction. The low-point time in the eastern region was about 13 o'clock and 15–16 o'clock in the western region. There was an obvious boundary line of sudden change with time difference more than two hours. The Yongsheng earthquake of $M_S 6.0$ occurred on the boundary line on October 27, the 19th day after the anomaly. Subsequently, there was the great Kunlun Mountain $M_S 8.1$ earthquake on the boundary line on November 14, the 37th day after the anomaly. The occurrence date is within four days before or after the 41st day counting from the day of appearance of the anomalies (Ding et al, 2004).

2.1 The geomagnetic LPD anomaly before the 2008 Wenchuan $M_S 8.0$ earthquake

There was a LPD anomaly in geomagnetic field on Chinese mainland on April 24, 2008. The boundary line of sudden change was in general along the North-South seismic belt with longitude of 103°E to 110°E . Two large regions of the low-point time appeared with time difference of more than two hours, and the low-point time of the eastern part at about 11–12 o'clock while that of the western part at about 14 o'clock. The Wenchuan earthquake occurred near the boundary line of sudden change of the low-point time on the 18th day after the anomaly (Figure 1).

LPD in geomagnetic field appeared anomalously on Chinese mainland on May 9, 2008, with the boundary line of sudden change in the north-south direction near the North-South seismic belt. There were two large regions of the low-point time with time difference of more than three hours. The low-point time in the eastern part was about 10–12 o'clock and that in the western part about 15–17 o'clock. The Wenchuan earthquake occurred near the boundary line on the third day after the appearance of the anomaly (Figure 2).

2.2 Forecast of $M 6.0$ aftershocks of the Wenchuan $M_S 8.0$ earthquake

A group of $M 6.0$ aftershocks occurred successively after two months' quiescence of $M 6.0$ aftershocks since the main shock. According to the LPD anomalies ap-

Figure 1 The geomagnetic LPD anomaly on April 24, 2008 before the Wenchuan $M_S 8.0$ earthquake (lack of the data from Taiwan).

Figure 2 The geomagnetic LPD anomaly on May 9, 2008 before the Wenchuan earthquake (lack of the data from Taiwan).

Figure 3 The geomagnetic LPD anomaly on June 13, 2008 (lack of the data from Taiwan).

peared on June 13 and 17, 2008, the following forecast was made, that is, an earthquake with magnitude 6 would occur possibly with epicenter in the northern part of the North-South seismic belt within four days before or after July 14 or 28, 2008.

1) There was a LPD anomaly in Chinese geomagnetic field on June 13, 2008. Two large regions of the low-point time appeared with time difference of more than three hours, and their boundary line of sudden

change ran across Tibet, Sichuan, Gansu and Inner Mongolia. The low-point time of the eastern part was about 11–13 o'clock and that of the western part was about 16 o'clock (Figure 3).

2) LPD in geomagnetic field of Chinese mainland appeared anomalously on June 17, 2008. The boundary line of sudden change struck in NE direction. It ran across south Tibet, Sichuan province and central Inner Mongolia. There were two large regions of the low-point

Figure 4 The geomagnetic LPD anomaly on June 17, 2008 (lack of the data from Taiwan).

time with time difference of more than two hours. The low-point time of the eastern part was about 12–13 o'clock and that of the western part was about 14–15 o'clock (Figure 4).

Two boundary lines of low time displacement intersected at the Wenchuan seismic area in Sichuan province. A group of aftershocks with magnitude 5 occurred on July 15, 2008, and a group of aftershocks with magnitude 6.0 occurred before or after July 28, 2008, including the $M_{6.0}$ earthquake on July 24, the $M_{6.1}$ earthquake on August 1, and the $M_{6.1}$ earthquake on August 5. These were the strongest aftershocks from May 25 to the end of August in 2008. These two groups of aftershocks occurred within four days before or after July 14 or 28, 2008, on the 27th or 41st day after the appearing of LPD in June.

3 The diurnal-variation amplitude anomaly before strong earthquakes

The intensity of geomagnetic field is not only related to the field in outer space, but also to the distribution and strength of electroconductivity of underground materials. The electromagnetism properties of the medium, such as electric conductivity, change with increasing stress in the seismogenic environment before strong earthquakes. Thus the local or regional magnetic anomalies related to earthquakes can be detected. The distribution and variation of geomagnetic normal back-

ground field are correlated in space and extendible in time. The anomaly of the diurnal-variation amplitude belongs to anomaly of short periods from a few minutes to a few hours and with anomalous amplitudes over 10 nT or even 20 nT. That at a single station is quite complicated even if the large change cannot be considered as an anomaly before an earthquake. It is necessary to eliminate the variation of normal background of geomagnetic field. The most direct and simple method to distinguish anomaly from normal changes is to compare data at all geomagnetic stations of the same latitude or longitude in China. If there is a local or regional change, it can be considered as the anomalous phenomenon related to an earthquake.

For example, prominent anomalies of diurnal-variation amplitude in the area west to the North-South seismic belt in China appeared imminently before the great Kunlun Mountain $M_{8.1}$ earthquake on November 14, 2001. There were not only large changes in diurnal-variation amplitude and phase but also obvious anomalies in form of diurnal-variation distortion on November 6. Although an active magnetic storm appeared on November 6, its effect was not large for the distortion of the diurnal variation in the area west to the North-South seismic belt. The distortion of diurnal variations were quite rare in recent years at the station Golmud (the nearest one to the epicenter) and geomagnetic stations at Jiayuguan, Kashi, Lhasa, etc around the earthquake epicenter. Moreover, the diurnal-variation

amplitude at stations at Golmud and Lhasa were over 20 nT (Ding et al, 2004).

Similarly there appeared prominent diurnal-variation anomalies of the vertical component (Z) in geomagnetic field in a very large region before the Wenchuan earthquake in Sichuan province on May 12, 2008. The changes in amplitude and phase were large, and the distortions of the vertical component variation were

prominent at stations in or around Sichuan province. For example, the geomagnetic vertical component at the stations at Chengdu, Xichang and Huili showed diurnal distortions with about 10–20 nT, which were rarely seen in recent years, just a few days before the Wenchuan earthquake, especially before and after May 9; while for the station Shanghai at the same latitude the change was normal (Figure 5).

Figure 5 The geomagnetic diurnal-variations during 5–15 May, 2008.

4 Discussion

1) Strict statistical test based on experiences is necessary on the condition that the basic physics of earthquake precursors and prediction methods is not known. In order to assess the present level of earthquake prediction and test the effectiveness of earthquake prediction, R -value grading method is generally used at present (Xu, 1989). The following formula is used by R -value grading,

$$R = \frac{\text{Number of successfully predicted earthquakes}}{\text{Total number of earthquakes}} \cdot \frac{\text{Time used by prediction}}{\text{Total time for study on earthquake prediction}}$$

R -value grading represents the ratio of correct prediction after deducting the ratio of the occupying time of the prediction, i.e., ratio of successful prediction after deducting their random probability. Another problem of the test is to make statistics of confidence level of R -values. If the number of effective predictions is smaller, it is necessary to have a higher R -value to guarantee enough confidence level. The statistical tests

of the predictions based on geomagnetic low-point displacements show $R=0.6$ for strong earthquakes with $M_s \geq 6.5$ in the region with monitoring ability in Chinese mainland. It suggests that the effectiveness of strong earthquake predictions is good.

2) The application of geomagnetic diurnal-variation anomalies to earthquake prediction is still in the phase of exploration. The preliminary results indicate that on the one hand it can be used to detect and explore the short-term underground anomalous changes, including changes in the earthquake sources and earth environment through induced magnetic effects. And on the other hand it could act as a special regional magnetic disturbance and the outside factor of special catastrophe change for modulation and triggering in the source area in the imminent phase (Ding et al, 2003). It could be referred to as the exploring-inducing-triggering mechanism for earthquake forecast.

3) It is necessary to take into account the normal background change of geomagnetic field in order to identify the anomalous phenomena related to earthquakes. Geomagnetic LPDs and diurnal-variation am-

plitude anomalies are all non-random deviation from the normal background field. In addition, the daily change of diurnal-variation is complicated and the effect of the outer space field is large. In order to eliminate the magnetic anomalies unrelated to earthquakes the planet magnetic field should be considered when the relationship between geomagnetic LPDs and earthquakes are studied (Xu, 1985).

4) Precursory anomalies of geomagnetic field are usually divided into anomaly of continuous tendency and sudden anomaly. According to these two kinds of geomagnetic anomalies, prediction methods are divided into progressive and leaping-over ones. For example, the LPD can be used for prediction that can be characterized by leaping-over prediction. An earthquake occurs in the time interval before or after the 27th or 41st day from the day of appearance of the anomalies. They may be closely related to the periodicity of geomagnetic field. 27 days and 13.5 days (or $27+13.5 \approx 41$ days) are most prominent in the periodic components less than six months (Báth, 1974). Combination of progressive and leaping-over methods in the analyses of precursory anomalies of geomagnetic field during the time interval determined by leaping-over prediction method will benefit the impending earthquake prediction. That is to say there is a good correlation between geomagnetic diurnal-variation anomalies and strong earthquakes. LPDs appear one or two months before strong earthquakes and there is diurnal-variation amplitude anomaly in the epicentral areas a few days before the events. For example, there were LPD and diurnal-variation amplitude anomalies in geomagnetic field over China on April 24, 2008, and the former was more obvious. These anomalies also appeared on May 9, 2008, with the latter changing distinctively both in phase and amplitude. Part of earthquake cases shows that there is obvious change before and after earthquakes, but more attention should

be paid to the pre-earthquake anomalous changes which is of benefit to prediction and tracking occurrence time of the earthquake.

The mechanism of the application of the diurnal-variation anomalies in earthquake prediction is a very difficult scientific problem. Long-term exploration and scientific data accumulation is necessary.

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