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# Anomalous phenomena in DC–ULF geomagnetic daily variation registered three days before the 12 May 2008 Wenchuan $M_s$ 8.0 earthquake

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**Abstract:** The hourly data of the vertical  $Z$  and the horizontal  $H$  components of 37 ground–based DC–ULF geomagnetic stations are examined during 20 April–12 May 2008. On 9 May 2008, three days before the Wenchuan  $M_s$  8.0 shock, anomalies — a double low-point and a decreased amplitude — are registered on the curves of the  $Z$  component at 25 stations in a large-scale area surrounding the Wenchuan epicentral area. The  $H$  component shows none of the double low-point phenomenon but does exhibit a reduced magnitude at the same time. The geomagnetic index  $Kp$  is also examined and indicates that the anomalies appear at a solar quiet period. The appearing time shift ( $T_{zs}$ ) between the first low-point on May 9 and the minimum point occurring time of May 1–5, 2008 is also checked. The results show that  $T_{zs}$  is on the order of 1–2 hours earlier or later than usual and there is a 2–6 hours' gap between these two low-points. However, there is still a transition area which includes the epicenter where  $T_{zs} = 0$ . Variation amplitude examined on vertical  $Z$  increases as the distance from the epicenter decreases. An Earth–air–ionosphere model has been employed to investigate a possible mechanism of this phenomenon and positive results have been unexpectedly attained. All these above-related results tend to prove that the variations of the  $Z$  and  $H$  on May 9, 2008 during the solar quiet period are probably associated with the forthcoming Wenchuan  $M_s$  8.0 earthquake.

**Keywords:** Wenchuan  $M_s$  8.0 earthquake; geomagnetic abnormality; spatial variations; Earth–air–ionosphere model

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## 1. Introduction

At present, short-term earthquake (EQ) prediction is still one of the most challenging targets worldwide. Identifying and investigating possible EQ precursors, especially short-term ones associated with seismic activities, are the most promising approach to short-term EQ prediction.

Electromagnetic observation, as one way of pursuing EQ precursors, has already attracted more and more public attention because electromagnetic anomalies before large EQs have been investigated and confirmed during the last few decades (e.g., [Pulinet and Boyarchuk, 2004](#); [Molchanov and Hayakawa, 2008](#); [Hayakawa, 2015](#)). Seismic electromagnetic variations can be divided into two general categories: direct and indirect effects. Direct effects are electromagnetic signals in a wide frequency range

that originate in the Earth's crust at epicenter depths greater than 10 km (even several hundreds of kilometers) and can be recorded on the Earth's surface. The first example is DC SES (seismic electric signal) ([Varotsos, 2005](#)). Another example is ULF (ultra low frequency) electromagnetic emissions during the Loma Prieta  $M_s$  7.1 EQ on 17 October 1989 ([Fraser-Smith et al., 1990](#); [Bernardi et al., 1991](#)), and the Spitak  $M_s$  6.9 EQ on 7 December 1988 ([Molchanov et al., 1992](#); [Kopytenko et al., 1993](#)). Anomalous ULF emissions were also observed before the 8 August 1993  $M_s$  8.0 Guam EQ ([Hayakawa et al., 1996](#); [Kawate et al., 1998](#)) and the L'Aquila  $M_s$  6.3 EQ on 6 April 2009 ([Prattes et al., 2011](#)). Indirect effects are electromagnetic perturbations in layers of the atmosphere and ionosphere, which have been observed by study of subionospheric VLF (very low frequency) signals before EQs with magnitudes greater than 6.0 and depths less than 40 km over a period of seven years in Japan ([Hayakawa et al., 2010](#)), study of ULF magnetic field depression before the March 11 2011 Tohoku  $M_9$  EQ ([Schekotov et al., 2013, 2016](#)), and study of upper ionosphere signatures before a number of obvious events ([Li M and Parrot, 2012, 2013](#); [Parrot, 2013](#); [Liu J et al., 2014](#)).

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A large EQ with a magnitude  $M_S = 8.0$  hit the Wenchuan area, Sichuan province, at 14:28:01 CST (China Standard Time) on May 12, 2008; its epicenter was located at 103.4°E and 31.0°N at a depth of 19 km. This event caused extensive major damage; 69,000 people lost their lives. This led to a large number of studies that appeared to identify convincing evidence of seismic-related precursors in ground-based ULF/ELF electromagnetic observations (e.g., Gao SD et al., 2010; Li M et al., 2013) and in spatial ionospheric observations (e.g., Yu T et al., 2009; Liu JY et al., 2009; Xu T et al., 2010a, b; Akhoondzadeh et al., 2010; Zhang XM et al., 2009a; Zhang XM et al., 2009b; Zhang XM et al., 2010). Indeed, some anomalous ground-based geomagnetic observations prior to this event have already been reported. Using a rescaled range analysis (R/S) method, Li M et al. (2009) have processed January 1 2006–June 16 2008 geomagnetic vertical  $Z$  data at Tianshui station (TS station in this paper) and found that the Hurst exponent value decreased and fractal dimension value increased 2–3 months before the Wenchuan  $M_S$  8.0 earthquake. Wang WX et al. (2009) were first to report a ‘double low-point’ phenomenon in vertical  $Z$  measurements recorded on May 9 at three ground-based ULF geomagnetic observing stations near the epicenter of the Wenchuan EQ. Then Hu JC et al. (2009) reported further that this kind of variations was observed on the same day at 13 stations in China. In this paper, we now examine data from all geomagnetic observing stations installed during the 10th Five-Year Plan in China. The aim is to characterize comprehensively the spatial variations of the ‘double low-point’ phenomenon mainly on the vertical  $Z$  parameter and to infer, tentatively, a plausible causative mechanism for this phenomenon. A physical model is presented to stimulate further discussion of the proposed mechanism. Geomagnetic observation and its corresponding equipment in China are introduced in Section 2. In Section 3, geomagnetic parameter fluctuations during the Wenchuan EQ, especially on May 9, 2008, are illustrated. Discussion including an analog model and conclusions are presented in Sections 4 and 5, respectively.

## 2. Geomagnetic Observation Networks in China

In the 1980s a network of geomagnetic analog observation stations was constructed in China after the occurrence of the 28 July 1976 Tangshan  $M_S$  7.8 EQ. As one of the scientific achievements during the 10th Five-Year Plan, a geomagnetic digital observation network was gradually set up. It was put into service in 2007. This network includes about 45 independent stations and two geomagnetic seismic-arrays, one involving 7 stations in northwest China and the other with 6 stations in southwest. The experimental fluxgate magnetometer known as GM4 is employed for those magnetic field measurements; this equipment is dedicated to record relative variations of three magnetic components of magnetic oscillations, horizontal  $H$ , vertical  $Z$ , and declination  $D$ . The GM4 magnetometer works in the DC–ULF frequency band of 0–0.3 Hz; the magnetic noise level in this frequency band is less than 0.1 nT. The data from each sensor are digitized at a sampling frequency of 1 Hz and stored in a 1 GB CF memory card. More details on the observing mechanism and data output of this equipment can be found in Wang XM et al. (2008).

The vertical component  $Z$  is usually used to detect information thought to be related to lithosphere dynamics, although it cannot be free of influence from other electromagnetic disturbances. In Northern hemisphere low–mid latitude areas, the daily fluctuation of this parameter is characterized by its solar periodic component  $S_q$ , which presents a minimum point approximately at noon local time (LT); at this same time, the horizontal component  $H$  presents a maximum. Both of these parameters  $Z$  and  $H$  are considered in this paper. The distribution area of the magnetometers in China covers four time-zones from the east to the west and so in UT (universal time) there is a transition for the minimum point time from about 3:00 AM in the east to 7:00 AM in the west.

## 3. Double Low-Point Anomalous Phenomenon and Characteristics of Its Evolution

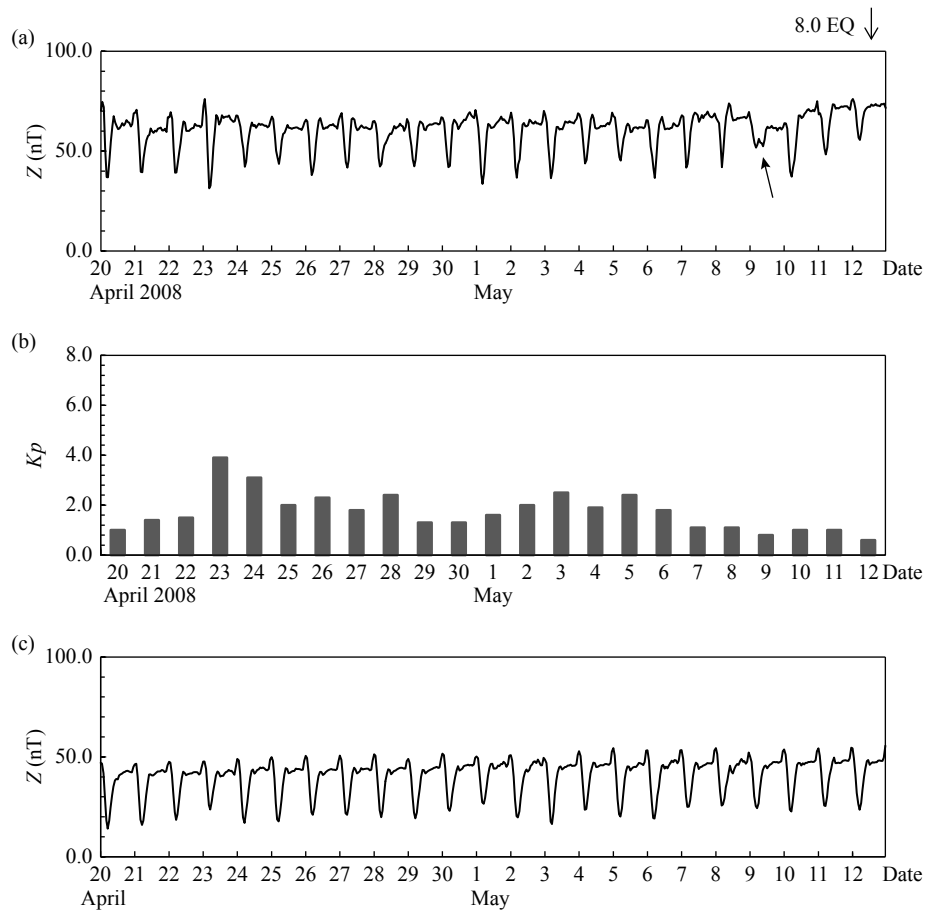
### 3.1 Distinguishing the Double Low-Point Phenomenon Visually

All data utilized in this work are from <http://10.5.109.26>. First we identify 37 DC–ULF geomagnetic observing stations in China with continuous and high quality data recordings (from April 20 to May 12 2008), starting about 20 days before the Wenchuan main shock. Next we choose CD station — the nearest one, only ~30 km away from the epicenter of the Wenchuan EQ, as an example. Using data from station CD, we show how to distinguish anomalous recordings. Finally, we apply the demonstrated process to data from all 37 of the selected geomagnetic observing stations.

CD station lies in the middle of the geographic longitude range in China. Figure 1a shows daily curves for hourly readings of vertical  $Z$  at this station during 20 April–12 May 2008 (the top panel), as well as the variations of geomagnetic index  $K_p$  during this period (Figure 1b). It can be seen from Figure 1a that for CD station the curve fluctuates normally with various daily amplitudes, which mainly reflect outer ionospheric dynamics; the daily minimum point of this parameter usually appears at 4:00 AM or at 5:00 AM UT when we check daily hour variations. However, the daily curve on May 9, 2008, behaves in a different way and displays two typical signatures labeled by a black arrow in the top panel of Figure 1: one is that two low-points (double low-points) are registered and the other is that the amplitude changes are smaller than those observed on other days during the same period. The  $K_p$  (<http://isgi.unistra.fr/>) daily average values shown in Figure 1b are less than 3 (except for 3.9 and 3.1 on 23 and 24 April, respectively), which means there is no obvious solar activity in this time period.

As a comparison, we present in Figure 1c hourly data of the  $Z$  component at the CD station during the same period (20 April–12 May) of the eight years (2009–2016), following the Wenchuan event. One can see from Figure 1c that the curve exhibits regular fluctuations but with only a single daily minimum point, the time of which varies, day-to-day, according to variability in the positions of the foci of the ionospheric current systems (Hasegawa, 1960).

So the double low-point recording of May 9, 2008, with its decreased magnitude on the geomagnetic vertical  $Z$ , presents an anomaly both with respect to variations observed from April 20–May



**Figure 1.** Daily variations of the geomagnetic vertical  $Z$  at the CD station and  $K_p$  index. (a) Daily vertical  $Z$  fluctuations from 20 April to 12 May 2008. The unusual fluctuation on May 9 is labeled by a black arrow and the Wenchuan 8.0 EQ is also labeled. (b) Daily average  $K_p$  index fluctuations from 20 April to 12 May 2008. (c) Average daily vertical  $Z$  fluctuations during 2009–2016 from 20 April to 12 May.

12 2008 during a solar quiet period and with respect to average daily variations during 2009–2016 at the same annual period.

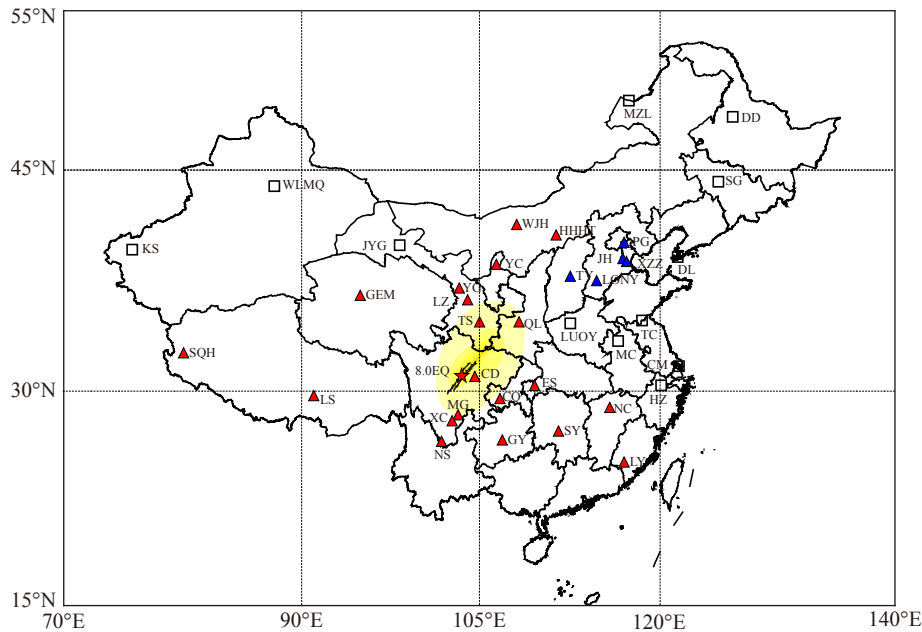
Having verified the abnormality of data recorded at CD station on 9 May 2008 by comparing data recorded at that station over different time scales, we applied the same technique to data from the other 36 stations considered in this investigation to search for further evidence of this kind of anomalous phenomenon.

Statistically, all 37 geomagnetic observing stations are divided into three groups: five recorded the double low-point phenomenon on May 8 and May 9 respectively, and they are displayed in Figure 2 with blue triangles; 20 registered this phenomenon only on May 9, shown in Figure 2 with red triangles. So in total, 25 out of 37 stations recorded the same double low-point phenomenon as was seen at the CD station on May 9, 2008; these 25 stations are all located in an area relatively close to the epicenter of the Wenchuan EQ — from ~30 km (CD station) up to ~2200 km (SQH station). Furthermore, 14 of these 25 stations lie 1000 km or less from the Wenchuan epicenter. The remaining 12 stations recorded no obvious abnormalities on the same day and are labeled by black empty squares in Figure 2; all of them are peripheral (see Table 1, below), relatively distant from the epicenter of the Wenchuan event — ~930 km (LUOY station) to ~2730 km (DD station).

For the three groups of stations displayed in Figure 2, Figures 3a–3c

show the typical hourly fluctuations during 7–10 May 2008 of vertical  $Z$  component data recorded at several specified stations for each group. It can be seen from Figure 3a that the curves from five stations located in a small area in north China (with blue triangles in Figure 2) display two instances of double low-points, on 8 and 9 May. It is notable that the double low-point on May 8 seems more obvious than that on the next day. Figure 3b presents fluctuations recorded at six stations (of the 20 labeled by red triangles in Figure 2); it is obvious that the typical fluctuation of the daily curve on May 9 is characterized by two low-points instead of the single minimum recorded on the other days during the 7–10 May 2008 time interval. Meanwhile, the curve on the same day also runs with reduced relative amplitude. Figure 3c, however, presents the corresponding curves recorded at 6 representative stations of the 12 stations at greater distance from the EQ, indicated by empty squares in Figure 2; recordings at these stations exhibit neither the double low-point phenomenon nor obviously smaller magnitudes.

Similarly to the smaller daily variation magnitude recorded by the vertical  $Z$  component at the CD station on May 9 (Figure 1a), we have found that it was almost a common feature for most of the stations. From Figure 3b, it is clear that the amplitude of the  $Z$  component hourly data is noticeably smaller on May 9 than on the other days. This feature is also obvious in Figure 3a but is dif-



**Figure 2.** Location of the geomagnetic observing stations in China during the Wenchuan  $M_5$  8.0 EQ. Red triangles stand for geomagnetic stations registering the ‘double low-point’ anomalous phenomenon in the vertical  $Z$  on 9 May, 2008; blue triangles indicate stations recording this phenomenon on 8 and 9 May, 2008 (see text for explanation). Black empty squares are stations that do not record this kind of anomaly during 20 April–12 May 2008. The location of the Wenchuan  $M_5$  8.0 EQ is indicated by a red star.

ferent: the reduced amplitudes appear on May 8 instead of on May 9. The most important result of this analysis is that this kind of anomaly also occurred for the horizontal  $H$ , as shown in Figure 3d which represents the hourly variations of the horizontal component  $H$  at six stations during 7–10 May 2008; they are characterized by a reduced-amplitude maximum point on May 9.

### 3.2 Evolution Characters of Geomagnetic Abnormal Variations

In order to further illustrate the variation characteristics of the so-called “double low-point” phenomenon observed in  $Z$  component data on May 9, three stations (JH, CD and MG) have been used, together with — for comparison purposes — hourly data of three other stations (SG, CM and WLMQ) whose data lack this feature (see Figure 4). In this figure one can see that there are two low-points, labeled by ‘A’ and ‘B’ in the left panels, for the JH, CD, and MG stations. In the right panels, for the SG, CM, and WLMQ stations, only one minimum point, labeled by ‘A’, can be observed. A noticeable fact from the left panels is that the fluctuations at these three stations exhibit different time gaps between ‘A’ and ‘B’; that is to say, the time difference between the two low-points at each station seems to increase from the top to the bottom in the left panels in Figure 4.

As regards the smaller daily variation magnitude observed in the vertical  $Z$  and the horizontal  $H$  components recorded at all 37 observing stations at this time, the method employed here is to determine the amplitude of variation by subtracting, from hourly readings on May 9, the average value of corresponding hourly readings taken on 1–5 May. Figure 5 shows results of this process for JH, CD and MG stations; the left panels present the  $Z$  component magnitude variations; the right panels, those for the  $H$  com-

ponent. From the left panels in Figure 5, one can see that the fluctuations of all these three curves are extraordinarily similar and regular, which probably indicates that a signal like a sinusoidal wave is added into the original magnetic field  $Z$  component. However, the variation on  $H$  is characterized in a different way with dissimilarity and irregularity for each station listed in the right panel in Figure 5. These indicate that the variation of  $H$  component is more complex. Therefore, the variation amplitude on May 9 is mainly taken into account only for the  $Z$  rather than the  $H$  in the following investigations.

A further statistical analysis by checking hourly data is conducted and the results are shown in Table 1 in order to investigate effectively the complex anomalous variations that appeared in the  $Z$  component measured at these 37 stations during the Wenchuan EQ. The name of each observing station, its location (longitude and latitude), and its distance from the epicenter of the Wenchuan main shock are listed in Columns 1–4 of Table 1, respectively.

In Table 1, for all 37 stations considered, the average time of occurrence, between May 1 and May 5, 2008, of the minimum point of the vertical  $Z$  component (named  $T_{zn}$  and shown in Column 5) is presumed to be the normal occurring time; the parameter  $T_{z\_9a}$  (Column 6) stands for the time of appearance, in UT, of the first low-point ‘A’ on May 9 (see Figure 4);  $\Delta T_{zs}$  (Column 7) denotes the time shift between  $T_{z\_9a}$  and the normal time of appearance,  $T_{zn}$  (i.e.,  $\Delta T_{zs} = T_{z\_9a} - T_{zn}$ ).  $\Delta T_{zs} > 0$  means that the time of the first low-point on May 9 is delayed compared to the normal situation;  $\Delta T_{zs} = 0$  means that the first low point occurred at the usual time;  $\Delta T_{zs} < 0$  means that the first low-point appeared earlier than the usual normal time (average of times on May 1–5) of the normal (single) low point.

**Table 1.** List of geomagnetic observing stations recording the ‘double low-point’ phenomenon on May 9, with information on various parameters

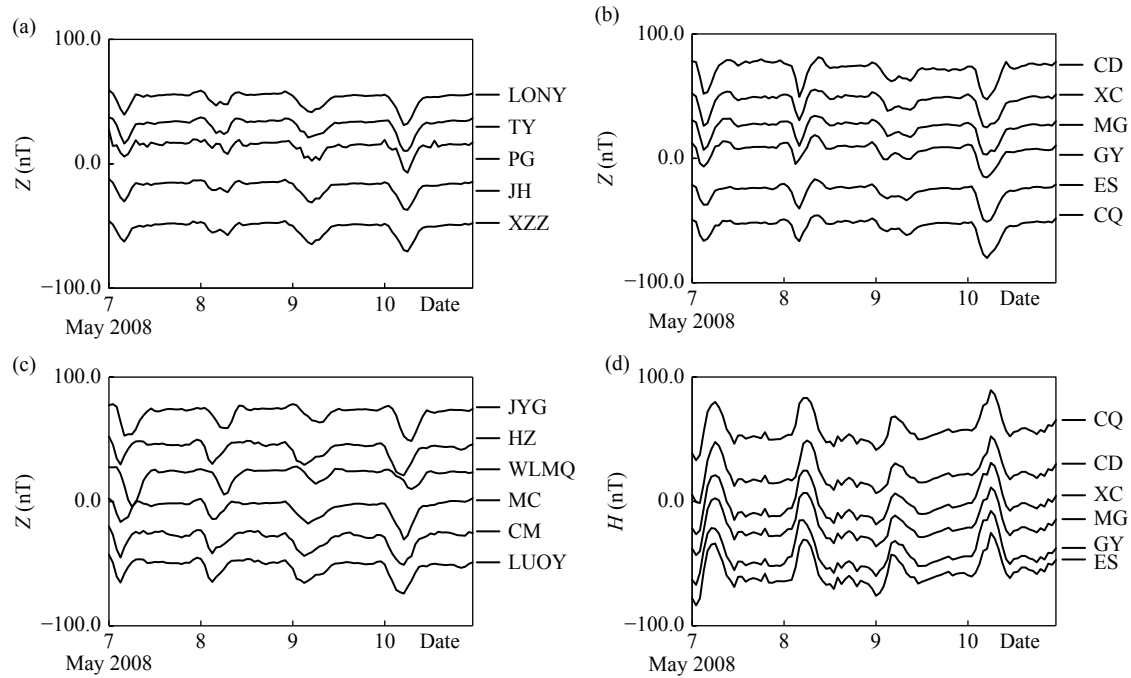
Station	Lon (°E)	Lat (°N)	$D$ (km)	$T_{zn}$ (UT)	$T_{z\_9a}$ (UT)	$\Delta T_{zs}$ (h)	$T_{z\_9b}$ (UT)	$\Delta T_z$ (h)	$\Delta V_z$ (nT)
PG	117.0	40.0	1580	3:00	5:00	2	7:00	2 00	18.7
JH	116.9	38.9	1500	3:00	5:00	2	7:00	2:00	18.5
YG	103.2	36.9	650	4:00	6:00	2	8:00	2:0	24.4
WJH	108.0	41.2	1200	4:00 or 5:00	6:00	1	8:00	2:00	18.0
XZZ	117.2	38.7	1520	3:00 or 4:00	5:00	1	7:00	2:00	17.5
YC	106.3	38.5	870	4:00	5:00	1	8:00	3:00	20.1
LONY	114.7	37.4	1260	3:00 or 4:00	5:00	1	7:00	2:00	17.8
LZ	103.9	36.1	570	4:00 or 5:00	6:00	1	8:00	2:00	25.6
HHHT	111.3	40.5	1270	4:00	4:00	0	8:00	4:00	16.2
TY	112.5	37.7	1120	3:00 or 4:00	4:00	0	8:00	4:00	18.9
GRM	94.9	36.4	990	5:00	5:00	0	8:00	3:00	20.4
TS	104.9	34.6	420	4:00	4:00	0	8:00	4:00	23.8
QL	108.2	34.6	600	4:00 or 5:00	4:00	0	8:00	4:00	20.1
SQH	80.1	32.5	2200	5:00 or 6:00	6:00	0	9:00	3:00	13.3
CD	103.7	30.9	30	3:00 or 4:00	4:00	0	9:00	5:00	26.7
LS	91.0	29.6	1200	5:00	5:00	0	8:00	3:00	23.1
NC	115.8	28.8	1220	3:00 or 4:00	4:00	0	8:00	4:00	17.5
GY	106.8	26.6	590	3:00 or 4:00	3:00	0	9:00	6:00	24.2
ES	109.5	30.3	590	4:00 or 5:00	3:00	−1	8:00	5:00	21.8
CQ	106.6	29.4	350	4:00 or 5:00	3:00	−1	8:00	5:00	24.6
MG	103.1	28.3	300	4:00 or 5:00	3:00	−1	9:00	6:00	22.4
XC	102.6	27.9	350	4:00 or 5:00	3:00	−1	9:00	6:00	22.1
SY	111.5	27.2	890	3:00	2:00	−1	8:00	6:00	20.2
NS	101.7	26.5	530	4:00 or 5:00	3:00	−1	9:00	6:00	23.0
LY	117.0	25.1	1480	3:00 or 4:00	2:00	−1	8:00	6:00	17.5
MZL	117.4	49.6	2370	3:00 or 4:00	6:00	2	–	–	13.0
DL	121.5	39.0	1870	3:00	5:00	2	–	–	17.0
CM	121.6	31.6	1730	2:00 or 3:00	3:00	0	–	–	18.2
HZ	120.1	30.6	1600	2:00 or 3:00	3:00	0	–	–	16.4
MC	116.5	33.4	1260	3:00 or 4:00	4:00	0	–	–	18.6
TC	118.5	34.7	1460	3:00 or 4:00	4:00	0	–	–	17.5
LUOY	112.5	34.6	930	3:00 or 4:00	5:00	1	–	–	19.3
JYG	98.2	39.8	1080	4:00 or 5:00	7:00	2	–	–	19.2
WLMQ	87.7	43.8	1980	5:00 or 6:00	6:00	0	–	–	11.0
SG	124.9	44.1	2370	3:00	6:00	3	–	–	15.0
DD	126.1	48.5	2730	3:00 or 4:00	6:00	2	–	–	12.5
KS	75.8	39.5	2660	6:00 or 7:00	5:00	1	–	–	9.1

On the left panels in [Figure 5](#), the maximum and the minimum amplitudes are labeled by MaxA and MinA, respectively, for each curve from the top to the bottom; the variation amplitude  $\Delta V_z$  for the Z at each station on May 9 is equal to the difference between these two value extremes, i.e.,  $\Delta V_z = \text{MaxA} - \text{MinA}$ . Data from all

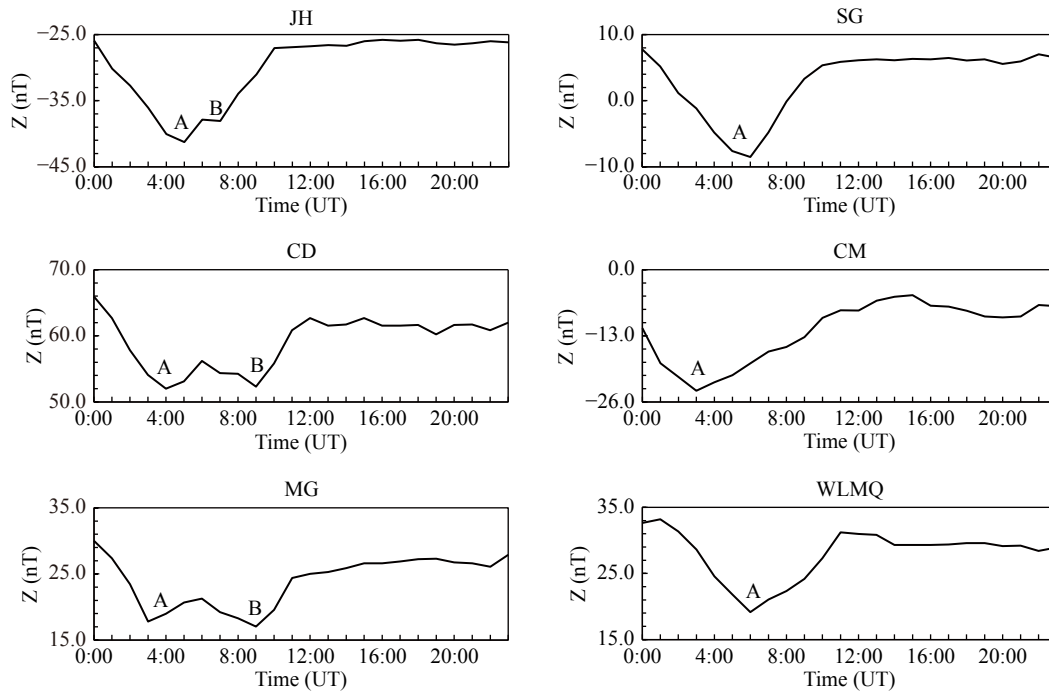
the stations here are handled in the same way; their corresponding variation values are listed in Column 10 of [Table 1](#).

In addition, for all 25 stations recording double low-points,  $T_{z\_9b}$  (Column 8 of [Table 1](#)) corresponds to the time of the second low-point ‘B’ on May 9, as shown on the left panels of [Figure 4](#).  $\Delta T_z$





**Figure 3.** Daily variations of geomagnetic component  $Z$  for each group of stations (a) recording double low-point phenomenon on 8 and 9 May respectively, (b) recording this phenomenon only on 9 May, and (c) not recording the double low-point on either day. The panel (d) displays the  $H$  component when smaller magnitudes are observed on May 9 at representative stations.

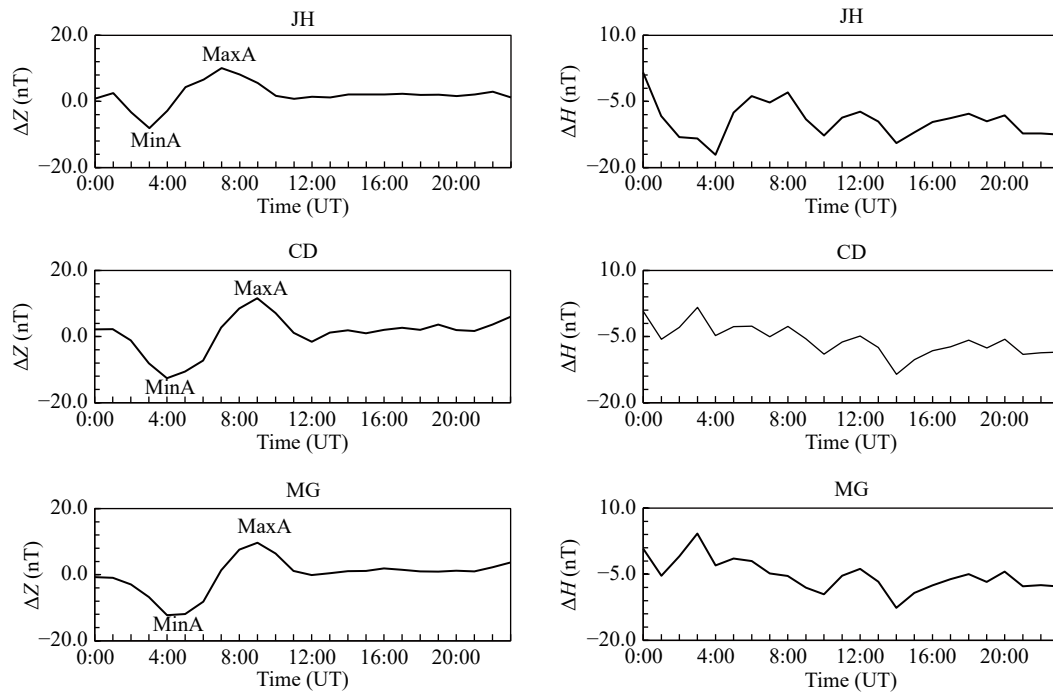


**Figure 4.** Daily variations of the geomagnetic vertical  $Z$  at three stations (JH, CD and MG) that recorded the double low-point phenomenon on May 9, 2008, as well as at three other stations (SG, CM and WLMQ) that recorded no such phenomenon at the same period.

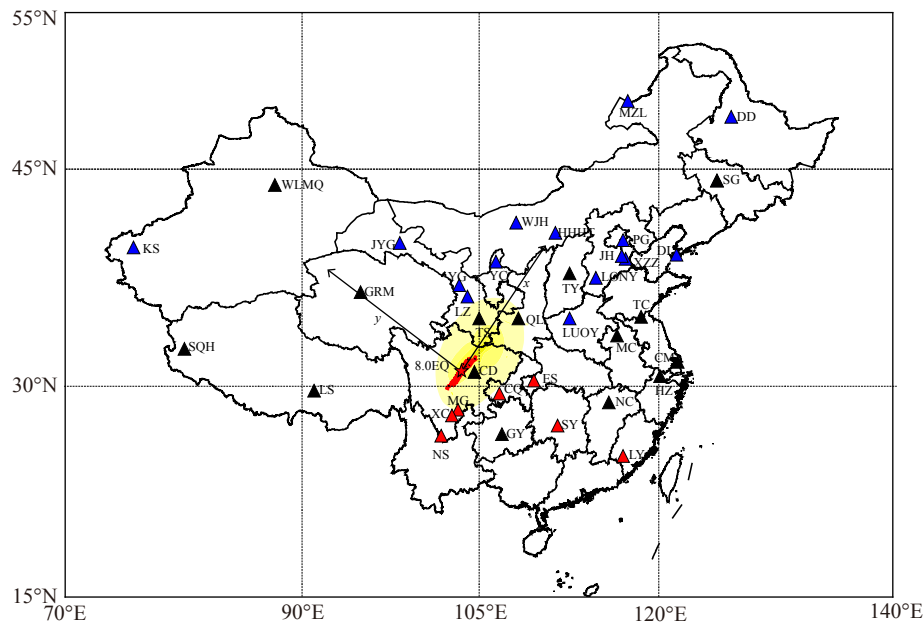
(Column 9) presents the time gap between  $T_{z\_9b}$  and  $T_{z\_9a}$  (Column 6), i.e.,  $\Delta T_z = T_{z\_9b} - T_{z\_9a}$ . It is readily observable that, among the 25 stations,  $\Delta T_z$  ranges from 2 to 6 hours and tends to become smaller with an increase in the latitude of the station.

According to Column 7 of Table 1, 7 of the 37 stations recorded

the first low-point 1 hour ahead of the normal time while 15 other stations registered a 1–2 hour delay. The remaining 15 stations recorded the first low-point as usual, but with a reduced magnitude, compared to normal recordings. The geographical distribution of the stations is shown in Figure 6 on a map, sorted according to  $T_{zs} > 0$ ,  $T_{zs} = 0$  and  $T_{zs} < 0$ .



**Figure 5.** Variation amplitude obtained by using hourly readings on May 9, subtracting the corresponding average values of hourly readings from 1–5 May for three stations (JH, CD and MG) in the vertical  $Z$  on the left panels and in the horizontal  $H$  on the right panels.



**Figure 6.** Distribution of geomagnetic observing stations in China with different time shift between the first low-points and the normal minimum points during the Wenchuan  $M_5$  8.0 EQ. Red triangles stand for stations with  $T_{zs} < 0$ , black triangles for stations with  $T_{zs} = 0$ , and blue triangles for stations with  $T_{zs} > 0$ , respectively. The Wenchuan  $M_5$  8.0 EQ is indicated by a red star. The surface coordinate system used in the three-layer model presented in the discussion section is also added.

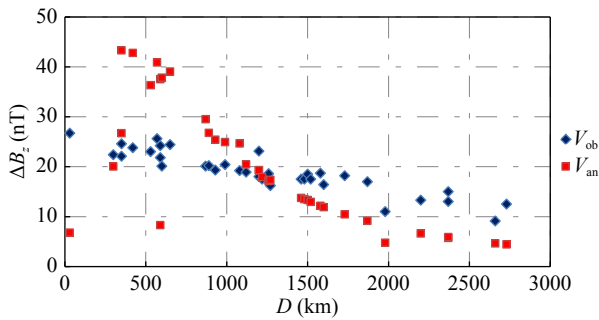
Figure 6 suggests that there is an obvious spatial evolution characteristic. Stations recording the first low-point on May 9 1–2 hours later than usual lie in the north of the Wenchuan epicenter; stations in the south tend to record the first low-point 1 hour earlier than usual. However, an obvious belt of stations from the northwest to the southeast of the epicenter recorded the first low-

point at the usual time: no time shift (i.e.,  $T_{zs} = 0$ ); moreover, this belt includes the CD station nearest to the epicenter. An interesting feature is that these three belts tend to meet in the epicentral area.

To check whether the observed amplitude variation is related to the stations' distances from the Wenchuan epicenter, the para-



meter  $\Delta V_z$  ( $V_{ob}$ ) has been plotted as a function of this distance; the result is shown in Figure 7 for the 37 stations taken into account here. It can be seen that in fact the parameter tends to increase as



**Figure 7.** Amplitude difference  $\Delta V_z$  ( $V_{ob}$  blue diamonds) between the minimum vertical  $Z$  component recorded on May 9, compared with the average of the minima recorded on 1–5 May; red squares ( $V_{an}$ ) show analog values using a long dipole current source as a function of the distance from the Wenchuan epicenter.

the distance from the epicenter decreases (also see Table 1).

#### 4. Discussion

The “double low-point anomalous phenomenon” observed in this analysis is the term we apply to the appearance within a 2–6 hour interval (Column 9 of Table 1) on May 9, 2008, of two low-points in hourly data on the vertical  $S_q$  ( $Z$ ), instead of the usual single low point. This anomalous double low-point was recorded at most geomagnetic stations surrounding the epicenter of the Wenchuan  $M_s$  8.0 EQ in China. We apply the term also to double low-points recorded the previous day, May 8, in a small area in the north of China.

The other parameter  $S_q$  ( $H$ ) examined in this study did not exhibit this kind of phenomenon and ran as usual during the same period, but did exhibit a relative reduction in magnitude.

We examined the geomagnetic  $Kp$  index (Figure 1b) at the times in question in order to control for the possible influence of geomagnetic disturbances, which can affect both of these parameters; the relevant data rule out that possibility. We can thus conclude that the appearance of this anomalous phenomenon is most likely due to local irregularities in the  $S_q$  current system rather than to a geomagnetic storm. The same cause may explain a low-point displacement on April 24, 2008, depicted by Zhang XM et al. (2009b), who proposed that the  $Z$  component data at stations near the epicentral area showed apparent aberrations of daily variation comparable to those at stations in eastern China on May 9, 2008 (Zhang XM et al., 2010).

Daily variations of the geomagnetic field on the Earth’s surface are dominated by the solar quiet daily variation  $S_q$ . The total  $S_q$  field on the Earth’s surface is comprised of the surface magnetic potential of the external electric current system originating from the ionosphere, and the surface magnetic potential of the induced currents in the Earth. Each part will have maximum and minimum points and these points may be called the  $S_q$  potential foci (Hasegawa, 1950).

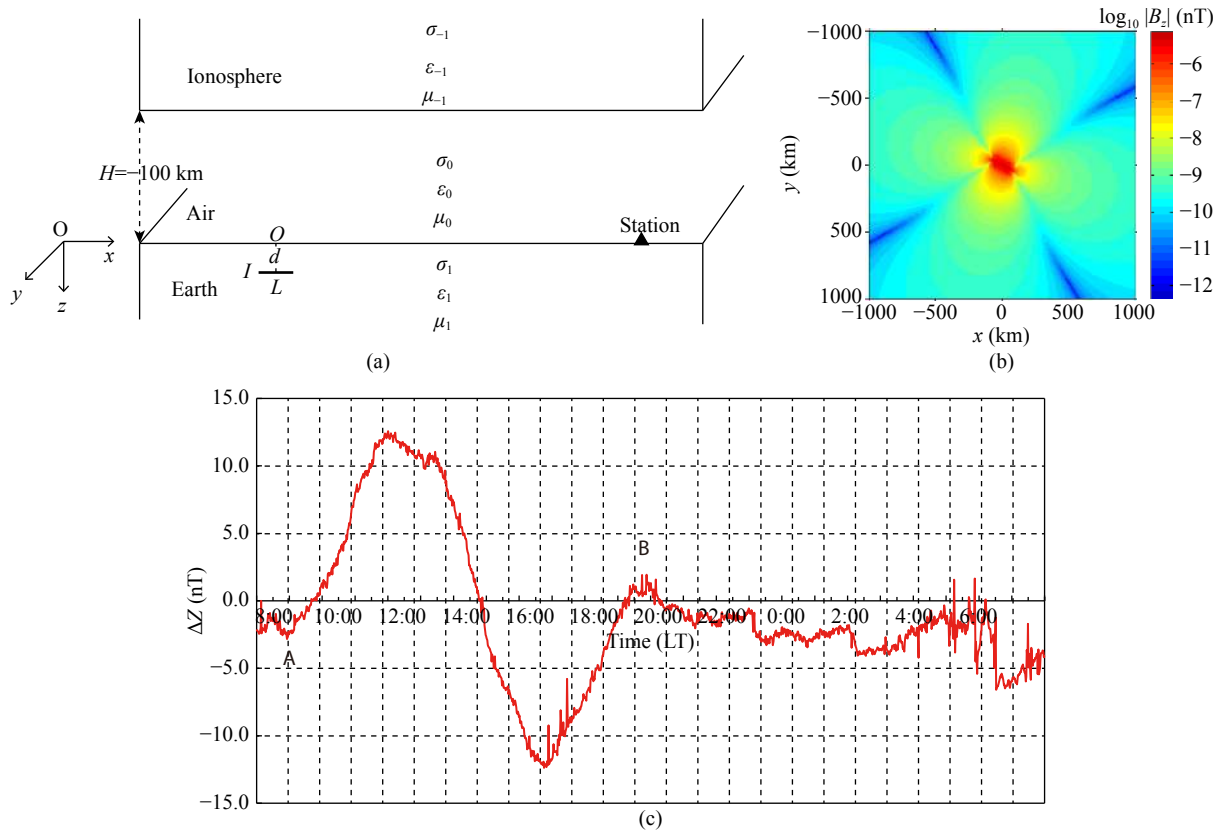
There are different viewpoints on the issue of day-to-day variability in the solar quiet daily variation ( $S_q$ ). Obiekezie and Okeke (2010) proposed that this day-to-day variability can be attributed to variabilities of the ionospheric process and physical structures, such as conductivity and wind structures. However, Hasegawa (1950) suggested that the day-to-day variability in  $S_q$  is due to variability in the positions of the foci of the ionospheric current systems rather than changes in the distribution of ionization and conductivity. The  $S_q$  has also a relationship with crustal and upper mantle electromagnetic properties, and the underground conductivity and (or) permeability can change its shape and magnitude. Obviously, the formation of a local current system depends primarily on any regional conductivity anomaly, and the greater part of the current induced by this anomaly will be distributed in the deep mantle, with a small part in the ocean (Rikitake, 1966, 1973; Obiekezie et al., 2013).

At the same time, the low-mid latitude area to the south of the Wenchuan epicenter is usually controlled by the northern EIA (equatorial ionization anomaly) and the Wenchuan epicenter locates to the north of the northern crest of the EIA. Zhao et al. (2008) have proposed that the most possible cause for pre-earthquake anomalies at low latitudes could be the strong vertical electric field bear in the earthquake preparation area, which modifies the whole structure of the EIA and the most often observed effect is the equatorward shift of both crests of the EIA up to their complete disappearance (Pulinets and Boyarchuk, 2004; Liu et al., 2001). What they have proposed seems to partly explain the zonal evolution of distributions of the time shifts for the first low-point recorded at various stations on May 9 2008 (Figure 6).

Lu J et al. (2016) have reported that there are a 6.7% negative apparent resistivity anomaly at Pixian station (CD station here in Figure 2) before the Wenchuan EQ and coseismic changes of  $-0.61\%$  at this station. Li M et al. (2013) suggested that the main rupture developed rapidly over the three days before the main shock, producing a strong seismo-telluric current that propagated mainly along the Longmenshan fault; Li M et al. (2016) have similarly interpreted the observable  $1.3 \text{ mV}\cdot\text{m}^{-1}$  electrical field at  $f = 1 \text{ Hz}$  at Gaobeidian station, 1440 km away from the Wenchuan epicenter, using an ionospheric influence physical model. The three-layer model employed here, in our analysis, has also been proposed as a partial explanation of the geomagnetic daily variation observed.

An  $x$ -directed dipole of a length  $L$  and a current  $I$  is placed in the bottom medium (Earth:  $z > 0$ ) in a three-layer (Earth–air–ionosphere) model (Figure 8a), which is homogeneous and has the electrical properties: magnetic permeability  $\mu_1$ , permittivity  $\epsilon_1$ , and conductivity  $\sigma_1$ . The middle medium (air:  $-100 \text{ km} < z < 0$ ) is described by its electrical properties  $\mu_0$ ,  $\epsilon_0$  ( $8.854 \times 10^{-12} \text{ Farad}\cdot\text{m}^{-1}$ ) and  $\sigma_0$  ( $10^{-14} \text{ S}\cdot\text{m}^{-1}$ ). The top medium (ionosphere:  $z < -100 \text{ km}$ ) is characterized by electrical properties  $\mu_{-1}$ ,  $\epsilon_{-1}$  and  $\sigma_{-1}$  ( $10^{-5} \text{ S}\cdot\text{m}^{-1}$ ). More details can be found in Li M et al (2016).

According to the actual observations, we set the  $x$ -direction to be along the Longmenshan fault of north  $30^\circ$  east (Xu, 2009); the surface coordinate system can be seen in Figure 6. We also use parameters utilized by Li M et al. (2016), the dipole length  $L = 150 \text{ km}$ , the Earth conductivity  $\sigma_1 = 10^{-3} \text{ S}\cdot\text{m}^{-1}$ , depth  $d = 19 \text{ km}$  of the Wen-



**Figure 8.** (a) An  $x$ -directed dipole current source, with its central coordinate  $(0, 0, d)$ , is placed in the bottom medium (Earth) of a three layer model (Earth–air–ionosphere model), where  $z$  is defined positive in the downward direction. (b) 2-D distributions of vertical magnetic field power  $|B_z|$  after a logarithm calculation for the Wenchuan source using the Earth–air–ionosphere model. (c) Variation amplitude obtained by using minute readings on May 9 subtracting the corresponding average value of minute readings from 1–5 May for CD station.

chuan hypocenter, and  $I = 5.0 \times 10^7$  A. At the same time, taking the observed geomagnetic frequency 0–0.3 Hz into account, the frequency of the electrical current source is set to be  $f = 0.3$  Hz.

We present electromagnetic wave fields for the Wenchuan source and this is done in the ground plane region  $-1,000 \text{ km} < x < 1,000 \text{ km}$  and  $-1,000 \text{ km} < y < 1,000 \text{ km}$  in order to visualize the 2-D distribution of the wave power surrounding the electrical source. Figure 8b displays the 2-D power distributions of the vertical magnetic field components  $|B_z|$  after making a logarithmic calculation on the Earth's surface. It can be seen first from Figure 8b that the emission power propagates mainly in the  $x$ -direction, which is exactly the direction of the Wenchuan main fault. This indicates that variations in the vertical magnetic component along the propagating direction of the current are greater than variations along its vertical direction, along which the flow of power is relatively weak. It seems that this pattern of power flow can partly explain the near regional evolution of distributions of the double low-point phenomenon as recorded at various stations on May 9 2008. And this pattern also can partly explain a sensitive variation at such stations as PG, JH, XZZ, LONY, and TY in north China. But it does not help explain the fact that no double low-point anomaly was recorded at some stations, even some near to the EQ, such as LUOY and TC. The dynamic source of the Wenchuan event originates from the intensive compressive movement between the Qinghai–Tibet Plateau and the Sichuan basin; and the shock rup-

tured the middle segment of the Longmenshan (LMS) thrust belt. So it is possible that the geological structure of the south China block is different from that of the Qinghai–Tibet Plateau. In any case, our analysis supports the conclusion that the anomaly phenomenon is of a regional nature and caused by tectonic activities beneath the Earth rather than disturbances outside.

However, there is not a good fit between analog values of  $|B_z|$  and observed variations on the vertical  $Z$  component for all stations considered (Column 10 of Table 1) because of a fast attenuation of analog ones.

In order to make the analog values fit the observed ones more closely, we change the range of other selected parameters and find that the correlation coefficient increases as  $L$  and  $d$  increase, and as  $f$  decreases. As we have mentioned, the left panels in Figure 5 indicate that the difference between the hourly readings on May 9 and average hourly readings during 1–5 May 2008 possibly indicates that a sinusoidal wave-like signal is added to the original magnetic field  $Z$  readings. In order to specify the period of this signal, the difference between the minute readings on May 9 and average readings at the same minutes during 1–5 May 2008 has been calculated and the result is shown in Figure 8c. It is obvious that the anomalous signal starts at about 9:00 LT and ends at 20:00 LT and its period is about 11 hours. So the possible main frequency of this signal is  $\sim 3 \times 10^{-5}$  Hz. The correlation coefficient is up to 0.8 between the analog  $|B_z|$  and observed variations when  $L$

= 2000 km,  $d = 400$  km and  $f = 3 \times 10^{-5}$  Hz. The key point is that, at this time, this correlation coefficient value is kept the same as what has been given by the two-layer model (Earth–air model) because the electromagnetic fields are free from ionospheric influence for this  $f = 3 \times 10^{-5}$  Hz. The related values are shown, respectively, in Figure 7 with red squares for the analog values and blue diamonds for the observed values. Unexpectedly, these results match closely the values reported by Zhang XM et al. (2008), who have shown that spectral values at periods of 8.5 and 13.7 hours increase when the time shift of the minimum point on geomagnetic vertical  $Z$  is more than 2 hours relative to the normal minimum point time. The detection depth of these two frequencies is  $\sim 400$  km, which indicates that the electromagnetic effect during this time shift originated in the mantle, in the lithosphere beneath the Earth, just as Rikitake (1966, 1973) had suggested: that the greatest part of the current induced by local resistivity anomalies is distributed in the deep mantle.

As illustrated above, we tend to infer that the electrical environment in a broad area around the focus zone of the approaching Wenchuan EQ apparently changed because of the main rupture occurring on May 9, which led directly to irregular change in the inner current system; or a new current system was formed near the Wenchuan epicentral area. The foci of the new internal current system and that of the external current system were delayed with respect to each other during different time periods on May 9 at most geomagnetic observing stations surrounding the epicenter of the Wenchuan EQ. This conclusion is confirmed by Pan H et al. (2014), who conducted an inversion analysis for hourly readings of geomagnetic elements  $X$ ,  $Y$ , and  $Z$  of 37 stations during the ‘lowest-point shift’ phenomenon before the 10 January 1998 Zhangbei  $M_5$  6.2 EQ. Their results show that the interior equivalent current system produces an upward magnetic field, which is opposite to the external one, and the combined influence of these two magnetic fields leads to a reduction of the magnitude of the vertical  $Z$  component. Furthermore, the authors also suggested that the focus of the interior equivalent current system is characterized by a latitudinal displacement.

The irregular change in the inner current system ultimately leads to obvious variations of ground-based observing signals, ionospheric electrical parameters, and even of the external electric current system. The external current system also has a converse influence on the inner current system and geomagnetic parameters, the magnitude reductions in  $Z$  and  $H$  are probably the case. It seems that the pre-EQ criticality has taken place in a wide area of the lithosphere, and the criticality is also recognized in the lower ionosphere with a small time difference of one day or so (Hayakawa et al., 2015a). The work of Hayakawa et al. (2015b) and Li Q et al. (2015) shows lower ionospheric perturbations, as well as weak lithospheric radiation in the ULF frequency, by analyzing the vertical  $Z$  and horizontal  $H$  based on ground-based geomagnetic observation. There are also an increasing number of reports corresponding to these ionospheric variations, GPS TEC and  $f_0F_2$ , and DEMETER parameters in both the Wenchuan epicentral area and its magnetically conjugate point area (Liu JY et al. 2009, 2014; Xu T et al. 2010a, 2010b; Akhoondzadeh et al. 2010; Zhu FY et al. 2009; Zeng ZC et al. 2009; Yu T et al., 2009; Zhang XM et al. 2009a;

Zhang Y et al. 2009; etc). All ionospheric results present different anomalous periods but there seems one common climax leading to the LAI coupling on May 9, three days prior to the Wenchuan main shock. In this sense, LAI coupling appears to be induced by a sudden change in ground and underground electrical properties, which most likely originated in a fast development of the main rupture. At the same time, this evolutionary process is highly coincident with the LAI coupling model proposed by Kuo CL et al. (2011, 2014): that a current originating in the stressed-rock in the focal zone propagates along the magnetic lines from the epicenter area of an earthquake, via the ionosphere, and to its magnetically conjugate point, causing electromagnetic disturbances on the Earth’s surface, in the atmosphere, and in the ionosphere and its conjugate point, in that order.

## 5. Conclusions

On May 9, 2008, three days before the Wenchuan  $M_5$  8.0 shock, two low-points in hourly data of the vertical  $Z$  component were registered at 25 among 37 ground-based ULF geomagnetic observing stations in a large-scale area surrounding the Wenchuan epicenter in China, while the horizontal  $H$  recordings during the same period included no sign of this phenomenon and ran as usual, but with a smaller magnitude than usual. In the Northern hemisphere low-mid latitude area, the predominant factor in daily variations of the geomagnetic components on the Earth’s surface is the solar quiet daily variation  $S_q$ ; these variations typically exhibit one minimum for the vertical  $Z$  component and one maximum for the horizontal  $H$  component, at around noon LT. Examination of the geomagnetic index  $K_p$  verifies that this abnormality, occurred during 20 April–12 May 2008, was at a time of solar quiet.

Relative to the Wenchuan epicenter, on May 9, 2008, three days prior to the main shock, the first low-point of the vertical  $Z$  appeared 1 hour earlier than usual to the south and 1–2 hours later to the north; also on May 9, at a large number of recording stations an anomalous second low-point appeared 2–6 hours after the first. We infer that during the preparation process of the Wenchuan earthquake, adjustment of stress led to variations in electrical properties (such as conductivity) in a focal area, which in turn caused an irregular change in the inner Earth current system, or a new current system formed. The new (or altered) current system had different foci, leading to a time shift in geomagnetic components, especially for  $Z$ , or led to a combined influence with the  $S_q$  current systems during this period.

However, in one transition area, along the NW orientation from the northwest to the southeast of the epicenter and including the epicenter itself, the first low-point appeared as usual and had no time shift, e.g.  $T_{zs} = 0$  (indicated by black triangles in Figure 6), suggesting that the focus of the newly formed current (induced by rapid variations of regional conductivity because of the main rupture occurrence) inhabited the hypercentral area. This inference seems to be supported by the variation amplitudes of the parameter  $Z$  for all observing stations considered here, which show that the variation amplitude has an obvious relationship to distance from the epicenter: the amplitude reduction increases as the observing station’s distance from the epicenter decreases. The positive results attained from an Earth–air–ionosphere model can

provide a partial explanation of the variations discussed here, although some difficulties need further investigation. What has been established, however, is that distinct anomalies in geomagnetic parameters recorded at multiple ground-based stations appeared on May 9, three days prior to the Wenchuan  $M_s$  8.0 earthquake, and in GPS and DEMETER satellite ionospheric observations; these observations strongly suggest that a lithosphere–atmosphere–ionosphere coupling occurred three days before the EQ.

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