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Review of unprecedented ULF electromagnetic anomalous emissions possibly related to the Wenchuan $M_S = 8.0$ earthquake, on 12 May 2008

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Abstract. This work presents ground based ultra low frequency (ULF) electromagnetic field measurements in the frequency range 0.1–10 Hz from January 2007 to December 2008. In this time period a strong earthquake series hits the Wenchuan region with a main shock of magnitude $M_S = 8.0$ on 12 May 2008. The Hebei ULF electromagnetic observation network includes eight observation stations in north China and the observation system named E-EM is employed to record the electric potential difference between two electrodes with an analog automatic real-time continuous pen recorder. First, weak electric signals appeared on 11 October 2007 at Ningjin station, most of which are with relative long periods ∼0.4–3 s and unequal amplitudes ∼0.5–20 mm. Then, similar signals appeared at Gaobeidian station at the end of October. Abnormal behavior with various time intervals appeared randomly and not every day. At the beginning of April 2008, one and a half months before the Wenchuan $M_S = 8.0$ earthquake, the anomalies were gradually subject to an intensive increase mainly in Gaobeidian SN direction and Ningjin EW direction. The abnormal behavior appeared almost every day and the amplitudes of electric signals, with short periods of ∼0.1–0.3 s, enhanced to ∼3–30 mm. Qingxian station started to record marginally high frequency signals in SN and EW components in the middle of April. On 9 May, 3 days before the main shock, the amplitude of high frequency information increased sharply at the same time in two components at Gaobeidian station and the maximum amplitude was up to 70 mm, i.e. 1.3 mV m^{-1} for the electric field. This situation did not stop until 17 May, 5 days after the main event. However, this kind of climax phenomena did not happen at Ningjin station and Qingxian station. Then weak anomalous information lasted about four months again, and strong signals appeared again for a short time before several powerful aftershocks. It is the first time that an abnormity with so large an amplitude and so long a duration time in the observation history of this network though several strong earthquakes were recorded. Furthermore, no obvious interferences have been found during this period. So this event is possibly related to this shock although all these three stations are more than 1300 km away from the Wenchuan earthquake epicenter.

1 Introduction

Electromagnetic emission (EM) phenomena associated with earthquakes (EQs) prior to or during seismic activities have been studied during several decades and they play an important role in the seismic precursory investigation.

An important characteristic of probable electromagnetic precursors is their appearance in a wide frequency band, covering from DC-ULF, VLF and LF to VHF ranges.

Moore (1964) presented the occurrence of strong ULF magnetic field disturbances at Kodiak 1–2 h before the Great Alaska EQ ($M = 9.2$) of 27 March 1964, which is the largest one occurring in the United States during modern times. Especially, since the recording of unusual ULF magnetic signals prior to the Loma Prieta $M_S = 7.1$ EQ, on 17 October 1989 ($f = 0.01$–10 Hz, $d = 7$ km, $A = 1.5$ nT) (Fraser-Smith et al., 1990; Bernardi et al., 1991), more attention has been paid to the ULF band. The ULF band is of particular interest because only EM signals in the ULF range and at lower frequencies can be easily recorded at the Earth's surface without significant attenuation compared with "high" frequency bands because most of the epicenter depths are at more than 10 km, even several hundreds of kilometers, beneath the Earth's surface. Anomalous electromagnetic emissions were also observed before the great crustal $M_S = 6.9$ EQ at Spitak, Armenia, on 7 December 1988 ($f = 0.005$–1 Hz, $d = 120$–200 km, $A = 0.03$–0.2 nT) (Molchanov et al., 1992; Kopytenko et al., 1993), about one month and a few days before the 8 August 1993 $M_S = 8.0$ Guam EQ ($f = 0.02$–0.05 Hz, $d = 65$ km) (Hayakawa et al., 1996; Kawate et al., 1998) and before the great $M_W = 8.2$ Biak EQ in Indonesia, on 17 February 1996 ($f = 0.005$–0.03 Hz, $d = 80$ km, $A = 0.2$–0.3 nT) (Hayakawa et al., 2000). Possible seismic related ULF ($f = 0.01$–0.015 Hz) anomalies occurred 2 weeks before L'Aquila $M = 6.3$ EQ with the distance up to 630 km (Prattes et al., 2011). Short-term geo-electric field signals of particular form and character precede EQs with magnitudes greater than 5 at distances up to several hundreds of kilometers (Varotsos and Alexopoulos 1984a, b; Varotsos and Lazaridou, 1991; Varotsos et al., 1993a, b; Nagao et al., 1996). The geo-electric potential enhancement appeared 1–19 days before five of all six EQs with magnitude >5 that occurred within 75 km in Japan and its duration and intensity were several minutes to 1 h with an amplitude of 0.01–0.02 mV m^{-1} (Uyeda et al., 2000). All these seismic related ULF effects appeared from several hours to several weeks prior to the main events with a distance up to several kilometers.

However, Fraser-Smith et al. (1994) have not recorded any ULF emissions associated with either the 1992, $M = 7.4$ Landers earthquake or the same Northridge earthquake. EM is of the character of selectivity or directivity and it is only recorded before part of strong EQs or at some stations in the observation networks. Selectivity is one of the most important properties of SES (seismic electric signals) which are related to EQs (Varotsos and Lazaridou, 1991). Analytical solutions of Maxwell equations, as well as numerical ones, convince that selectivity results from the fact that EQs occur by slip on faults, which are appreciably more conductive than the surrounding medium (Varotsos et al., 2006; Uyeda et al., 2000; Sarlis et al., 1999). Based on the ULF/ELF observations in Nakatsugawa in Japan, Ohta et al. (2001) found abnormal enhancement in ULF/ELF noise intensity one day before and after the famous Chi-Chi EQ in Taiwan (21 September 1999, $M = 7.6$) and their goniometric direction finding suggested that those noise are coming from the direction of the EQ epicenter. Furthermore, using a simple physical model, Bortnik et al. (2010) estimated that for an observed 30 nT pulse at 1 Hz ($d = 2$ km), the expected seismotelluric current magnitudes fall in the range ∼10–100 kA, and the simulation results show that deep nulls in the signal power develop in the non-cardinal directions relative to the orientation of the source current, indicating that a magnetometer station located in those regions may not observe a signal even though it is well within the detectable range.

The results of rock pressure experiments indicate that at the initial stage with slow changes in strain, self-potential and magnetic field suddenly appeared firstly near the source of initial cracking, and then extended as the crack developed on. There were more electromagnetic signals in the direction with developed micro-cracks than in other directions of the sample, and they were first recorded by the sensor near the original crack. The shape of the ULF electric and magnetic anomaly varied obviously in early-, mid- and late-term of the experiments. However, the large magnetic pulses of shorter-periods which appeared at the last stage of the experiment may be induced by instantaneous electric current of the accumulated charges during the main cracking acceleration (Qian et al., 2001, 2003; Hao et al., 2003).

A large EQ of magnitude $M_S = 8.0$ hit Wenchuan, Sichuan province at 14:28:01 CST (China Standard Time) on 12 May 2008 with an epicenter located at 103.4° N and 31.0° E and a depth of 19 km. This event caused major extensive damage and 69 000 people lost their lives. At the same time, it triggered a number of studies to investigate the possible existence of seismic-related electromagnetic precursors. One of the most important phenomena is that, in Hebei electromagnetic observation network, obvious ULF electromagnetic anomalies during the Wenchuan EQ were recorded by three observation stations. Part of anomalous information of Gaobeidian station and Ningjin station has been simply depicted before by Li and Lu (2009). As more details about this ULF electromagnetic observation have been collected it is necessary for us to show more details and to discuss again this event.

2 Observation network

The Hebei electromagnetic observation network was constructed at the beginning of 1980s after the occurrence of the 28 July 1976, Tangshan $M_S = 7.8$ EQ with the aim of monitoring fluctuations in the electromagnetic radiations in the 0.1–10 Hz (ULF) frequency band before seismic activities occurred. In the ensuing decade eight observation stations were gradually established and started to operate using the same equipment and observation system named E-EM. They are distributed in a relative broad area around Beijing, and are named Langfang, Sanhe, Qingxian, Huailai, Changli,

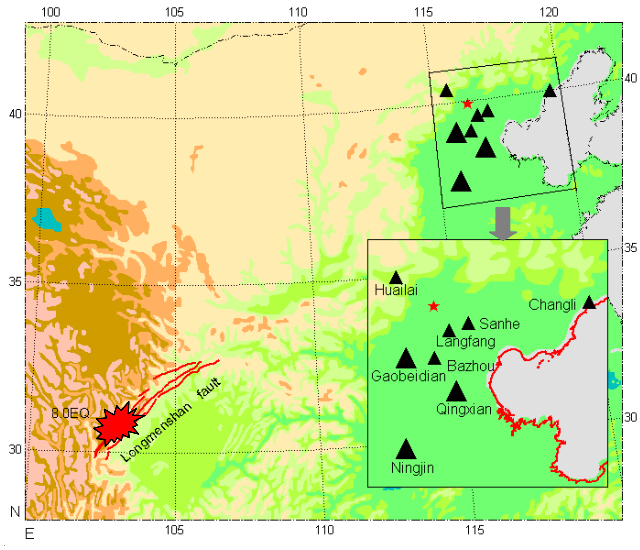

Fig. 1. Distribution of the Wenchuan EQ epicenter and observation stations. Black solid triangles show the related locations of observation stations in Hebei electromagnetic observation network and bigger ones indicate the stations where abnormal information was recorded. The red star denotes Beijing.

Bazhou, Gaobeidian and Ningjin. Langfang is the central station 50–260 km far from the others and all observation data are collected here (see Fig. 1). At each station, two pairs of electrodes are installed along perpendicular axes and they form two observation directions SN (South–North) and EW (East–West). The electrodes are buried from 6 m to 12 m deep, and 40 m apart. All wires used for signal transmission are screened by high quality metal nets, covered by waterproof pipes, and buried 0.6–0.8 m below the surface. More details of the observation system can be found in Zhuang et al. (2005).

The system measures electrical signals and a DJ-1 recorder is employed to record the potential difference between two electrodes. The recording method uses an analog automatic real-time continuous pen record with a speed of 1 mm s^{-1}. In general, only parallel lines with perpendicular automatic clock marked signals on the record paper around a drum and six lines are left per hour. A blank record paper replaces the recorded one at 09:00 LT everyday. A cumulative amplitude A is used to roughly estimate the daily anomalous amount of information. This parameter A takes into account the amplitude of the signal and its duration (Zhuang et al., 2005). In general, the equipment is calibrated every year and runs stably without background noise. It is free of annual variation, season variation, rain, temperature and magnetic storm. However interference pulses due to low-sky or sky-to-ground lighting are sometimes recorded. They are easy to identify and even the equipment is usually turned off when thunderstorms are coming (Guan et al., 2003).

After the construction of this network, a group of electromagnetic signals was first recorded about two months before five EQs with magnitudes $M_L = 4.2$–5.0 which took place around Tanshan area from 23 July to 3 August 1988. The abnormality information covered five observation stations among eight within a distance of 160–260 km and with A up to 720 s mV m^{-1} (Chen and Du, 1989). After, this network also recorded obvious electric information variations before eight strong EQs with magnitudes equal to or larger than 5.0, and some middle-small ones, happening around the northern China. Among these, the biggest one is the Zhangbei $M_S = 6.2$ EQ (41.1° N, 114.5° E) on 10 January 1998. At Sanhe station, the first weak emission appeared at the beginning of August 1997, about five months before the main shock, and then, signals were observed gradually at Langfang, Huailai, Qinxian and Ningjin. These signals increased mainly in the middle of December and A was up to 6657.4 s mV m^{-1} at a distance of 100–400 km (Guan et al., 1999).

In summary, this electromagnetic network performs well before some seismic activities mainly in the north of China (Fig. 1) and plays a key role to understand the seismic electromagnetic influence. Although the recorded electromagnetic information is very different from one event to another and also for each station, the common characteristics are

- Abnormal information variations comply with the law of weak-strong-weak and most events take place after a peak.
- In general, the larger the EQ magnitude is, the longer the duration of the abnormity is (from several days to several months).
- For each obvious EQ recorded, emissions usually appear at more than one station.
- Some stations are more sensitive to events occurring in a similar direction.
- Lower frequency electric signals appear earlier than higher ones which always increase several days before the main event.

In recent years, as the equipment becomes more and more old and no new one was available as an alternative, three of the stations gradually stopped running; in addition, Langfang station experienced serious civil interferences from 2004. Then, only four stations, Gaobeidian, Ningjin, Sanhe and Qingxian, were active before the Wenchuan $M_S = 8.0$ EQ, and three among them recorded obvious electromagnetic emissions.

3 Analysis of the electromagnetic emissions recorded

Figure 2 shows a timeline of daily total cumulative amplitude data recorded at (a) Gaobeidian station and (b) Ningjin

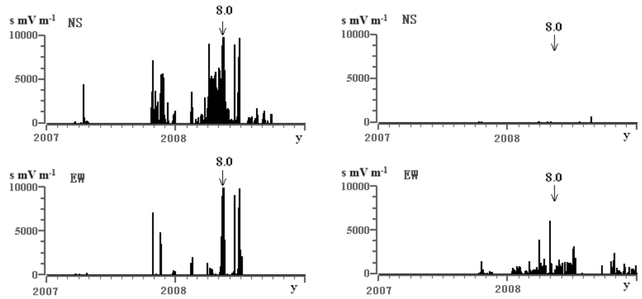

Fig. 2. Timeline of daily total cumulative amplitude A (black bar) of electromagnetic information recorded at **(a)** Gaobeidian station and **(b)** Ningjin station from January 2007 to December 2008. Wenchuan EQ is indicated by an arrow.

station covering the period from January 2007 to December 2008. Gaobedian station lies in the intersections of the Taihang Mountain and the Hebei plain where the east Taihang fault meets with the Jizhong fault in tectonic structures. It is shown in Fig. 2a from March to May 2007 that a weak perturbation was recorded for several days both in NS component and EW component. This is not taken into consideration because this kind of abnormality is usually attributed to local small seismic activities. So there are three basic periods for signal fluctuations recorded at this station covering all Wenchuan EQ series. For the first one, some electromagnetic emissions with A equal to 1728.2 s mV m^{-1} primarily appeared in the SN component on 23 October 2007. They increased suddenly on 28 October, and obvious electric signals appeared in the EW component with A being 8000 s mV m^{-1} (at the same time in the SN component A was now equal to 7073.3 s mV m^{-1}). But these high values only lasted one day and then it declined fast. At this stage, abnormal information did not appeared every day and the daily total cumulative amplitude shows several clusters with durations from several days to more than one month. For instance, there is no abnormality appearance from January to the middle of February 2008, whether in the SN direction or in the EW direction. The electric anomalies appeared randomly without fixed time. Most of real-time records are like Fig. 3a, which indicates a part of the real-time record from 09:00 LT, 22 to 09:00 LT, 23 January 2008. From Fig. 3a, we can see that most of the signals, with relative long period ∼0.4–3 s (Guan et al., 2003) and small amplitudes ∼0.5–3 mm, are mixed with some short-period ∼0.1–0.3 s (Guan et al., 2003) and big amplitude ones, which did not appear continuously. The two components have the same signal appearance time. Compared with the EW orientation, the electromagnetic signal is more obvious in the SN orientation, with a single signal amplitude from several mm to 20 mm.

This kind of situation lasted till the beginning of April 2008, from when high frequency ∼0.1–0.3 s and large amplitude ∼3–30 mm signals were recorded almost every day with a persistent time. This led to the daily total cumulative amplitude increasing gradually in the SN orientation. While it is not the same as the EW orientation, where the signals appeared occasionally and the amplitude became far lower than during the last period, see Fig. 2a. The daily total amplitude is of 1010.9 s mV m^{-1} in SN and none in EW on 8 May. On 9 May, 3 days before the Wenchuan $M_S = 8.0$ EQ, the amplitudes of signals with short period ∼0.1–0.3 s were suddenly subjected to an abrupt enhancement at the same time, between 05:00 LT and 07:00 LT, both in the SN and EW directions. Intensive high frequency and larger amplitude ∼30 mm signals replaced the previous low frequency swarm ones, especially in the EW component (Fig. 3b). From then on, the amplitude of the recorded signals becomes more and more large and the last time also extends. The corresponding daily total cumulative amplitudes increased dramatically up to 9832.2 s mV m^{-1} and 9001.4 s mV m^{-1} on 10 May. On 12 May, when the Wenchuan EQ took place 1440 km away from the station, the total amplitude remained equal to 9677.9 s mV m^{-1} and 9692.9 s mV m^{-1}, respectively. With a maximum amplitude of 70 mm, the record paper is covered alternatively with abundant high frequency and large amplitude signals which are so mixed together that we cannot distinguish one from others. We also have difficulties knowing whether abnormal signals appeared at the moment the main shock took place, see Fig. 3c. This kind of signals does not stop until 17 May, 5 days after the main shock.

After 18 May, the total signal amount decreases sharply and the last stage began. In this stage, the character of the signals is more like that of the first one. There is only relative obvious information preceding several powerful aftershocks. No anomalous emission is recorded in the EW component and in the SN component from 10 July till the end of September 2008, as it is shown in Fig. 2a. Then the total period covers more than 11 months.

Ningjin station lies in the most south part of the electromagnetic network and with a distance of 1350 km from the epicenter. The timeline of daily total cumulative amplitude A (black bar) from January 2007 to December 2008 is shown in Fig. 2b. Weak signals were recorded as early on as 11 October 2007, the same day in the SN component and in the EW component with A of 45.5 s mV m^{-1} and 64.9 s mV m^{-1}, respectively. From Fig. 2b, low abnormality only appeared for several days in the SN direction, while it is not the same in the EW direction where groups of perturbation information are recorded with different time intervals. The total fluctuation is more like that of Gaobeidian, but the total amplitude A is smaller in the Ningjin station. Most of original records are like Fig. 3d, which shows a part of the real-time record from 09:00 LT, 19 to 09:00 LT, 20 January 2008. From Fig. 3d, we can see for the EW component that most of the creep signals have a relative long period ∼0.4–3 s and low amplitudes ∼0.5–2 mm. A few of them are with large amplitudes of about 30 mm and high frequency occasionally appeared.

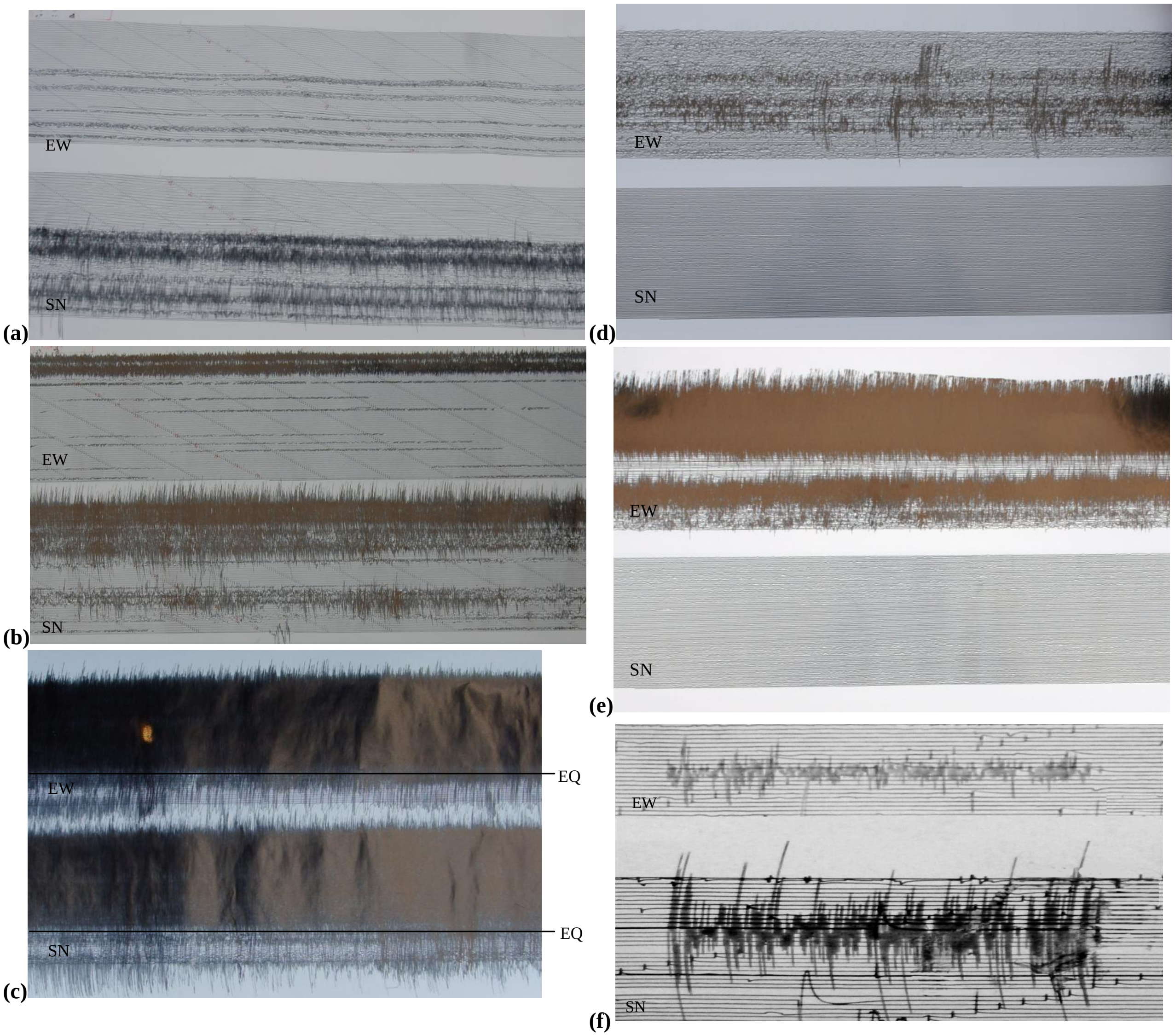

Fig. 3. **(a)** Copy of a part of an original record from 09:00 LT, 22 to 09:00 LT, 23 January 2008 at Gaobeidian station. Two observation components are shown with EW and SN respectively, the same for **(b)–(f)**. **(b)** Copy of a part of an original record from 09:00 LT, 8 to 09:00 LT, 9 May 2008 at Gaobeidian station. **(c)** Copy of a part of an original record from 09:00 LT, 12:00 to 09:00 LT, 13 May 2008 at Gaobeidian station. Estimated positions of the occurring time of the Wenchuan $M_S = 8.0$ EQ are indicated by black lines. **(d)** Copy of a part of an original record from 09:00 LT, 19 to 09:00 LT, 20 January 2008 at Ningjin station. **(e)** Copy of a part of an original record from 09:00 LT, 29 to 09:00 LT, 30 April 2008 at Ningjin station. **(f)** Copy of a part of an original record from 09:00 LT, 15 to 09:00 LT, 16 April 2008 at Qingxian station.

Compared with the EW orientation, the record paper stays nearly normal except for several weak signals in the SN orientation. On 30 April, short periods ∼0.1–0.3 s and about 60 mm amplitude signals almost covered the record paper in the EW component, and the total cumulative amplitude A is up to 6063.4 s mV m^{-1} (Fig. 3e). But no abnormality information can be seen in the SN component. Unlike Gaobeidian station, there is no abnormity climax during 9–17 May, just before the main shock in the Ningjin station and also in the Qingxian station, where weak signals appeared in the SN and EW components from the middle of April to June 2008. The shape of the signals is like Fig. 3f. The abnormal information only appeared for a short time and almost all the signals were with short periods ∼0.1–0.3 s, which indicates that the shock is coming soon, and at the same time with a maximum amplitude of about 20 mm. None of the total cumulative amplitude is available because only sporadic abnormality information was recorded.

Three among four stations in the Hebei ULF network, located at more than 1300 km from the epicenter of the Wenchuan $M_S = 8.0$ EQ, recorded remarkable electric field abnormality during 11 months, mainly from October 2007 to September 2008. A significant signal enhancement began 3 days before the main shock with an amplitude up to 70 mm. The scaling factor for the Gaobeidian station is $0.73\,\mathrm{mV\,mm^{-1}}$ and the distance between two electrodes is 40 m. So the electric field can be calculated to be $1.3\,\mathrm{mV\,m^{-1}}$. It is the first time that the abnormality is with such a large amplitude and such a long duration in the observation history of this network although several strong EQs were recorded before.

4 Discussion and conclusion

It was found that, the Loma Prieta EQ and the Spitak EQ have very similar characteristics (Molchanov et al., 1992). The intensity of the signals began to increase 3–5 days before the EQ at Spitak and 12 days before that at Loma Prieta, and it exhibited a maximum 3 h before the Spitak event and 4 h before the Loma Prieta event. The electromagnetic abnormal signals recorded this time in Hebei network, especially with the Gaobeidian station, show similar features but on a larger scale. Intensity information appeared on the beginning of April 2008, about one and a half month before the event. A maximum emerged on 9 May, 3 days before the EQ, and it remains 5 days after the main shock. Then, anomalous electric-field variations lasted about 4 months again, among which obvious abnormities were found before only several of the main aftershocks. As it was during the Spitak event (Kopytenko et al., 1993), the emission appears several hours before some of the powerful aftershocks. No obvious interferences can be attributed to this remarkable abnormality during this stage. It may be due to the existence of a critical magnitude and a relationship with the focal mechanism of the events. Of particular relevance here are observations of anomalous magnetic-field variations not only before but for several months after the Loma Prieta main shock. Multiple, but not mutually exclusive, physical explanations have been proposed to explain these observations (Draganov et al., 1991; Fenoglio et al., 1995; Merzer and Klemperer, 1997). Compared with the abovementioned events where $d =\sim 7$–630 km, the distance from the epicenter of the Wenchuan EQ to all three stations is more than 1300 km, which has not been reported before. The radius of seismic area where changes can be expected can be estimated using the Dobrovolsky formula $R = 10^{0.43\,M}$, where R is the radius of the EQ preparation zone, and M is the EQ magnitude (Dobrovolsky et al., 1979). It gives that the radius of this event preparation zone is more than 2700 km. Thus all the observation stations are well within this range.

The intensive compressive movement between the Qinghai-Tibet Plateau and the Sichuan basin has generated many strong EQs. On 12 May 2008, the Wenchuan $M_S = 8.0$ EQ ruptured the middle segment of the Longmenshan (LMS) thrust belt (Burchfiel et al., 2008), with a total length of the fault trace being approximately equal to 400 km along the edge of the Sichuan basin and the eastern margin of the Tibetan plateau, in the middle of the north–south seismic belt of China. This fault shows a strong NW–SE thrust movement with a dextral strike-slip horizontal component and its strike is towards to NE. In addition, it can be inferred that the principal stress is with near EW orientation in the light of the focal mechanism of the Wenchuan EQ (Li and Lu, 2009). Finite source inversion of seismic data indicates that the rupture initiated in the southwest of the LMS fault zone and propagated toward the northeast along a SW–NE striking fault (Ji et al., 2008). The Hebei ULF electromagnetic observation network lies right in the NE direction, the extension direction of the fault (Fig. 1), which is the dominant direction to record electromagnetic abnormalities. So it is easy to infer that, when the main seismogenic fault is subjected to a pressure coming from the Qinghai-Tibet Plateau, it produces micro-cracks, which lead to long period $\sim$0.4–3 s weak electromagnetic emissions first recorded on 11 October 2007 both in the SN and EW components at the Ningjin station, the nearest one among the four stations in the Hebei network. These micro-cracks gradually change the local distribution of the stress, which leads to a stress concentration in other places and the properties of the emissions change subsequently. So this can partly interpret why two directions at the Gaobeidian station recorded the electric signals till on 26 October, two weeks after the Ningjin station, where no information appeared at this time. At the beginning of April 2008, almost one and a half months before the Wenchuan EQ, as the number and the size of the micro-cracks developed, intensive abnormalities correspondingly improved resulting in large amplitude $\sim$30 mm and short period $\sim$0.1–0.3 s signals recorded at three among the four stations. However, the emissions show different properties for all the three stations: the starting and ending time, the fluctuation features, even for different observation components at the same station. The selectivity effect is a complex phenomenon that may be attributed to a superposition of the following three factors: “source characteristics”, “travel path” and “inhomogeneities close to the station” (Varotsos and Lazaridou, 1991; Varotsos et al., 2005).

From 9 May, 3 days before the main shock, the main rupture developed quickly to produce a strong seismo-telluric current. It propagated mainly along the LMS fault and induced the electromagnetic field which suddenly became strong around the focus zone. One of the electromagnetic phenomena induced by this event is that the maximum of the electric signals was clearly shown both in the SN and EW directions at the Gaobeidian station, with a short period $\sim$0.1–0.3 s and a large amplitude $\sim 1.3\,\mathrm{mV\,m^{-1}}$, almost covering all the record paper. This situation did not stop until 17 May, 5 days after the Wenchuan $M_S = 8.0$ earthquake. The whole ULF electromagnetic influence is of much similarity with the results of rock pressure experiments found by Qian et al. (2001, 2003) and Hao et al. (2003). Fortunately, Wang et al. (2009) studied ground based ULF geomagnetic vertical Z component in China and found, on 9 May 2008, that the amplitude variation of the Z component in most of the middle and western stations is up to 10–20 nT. It could not be an absolute coincidence. Scientists acknowledge that a seismic electromagnetic anomaly is a climax of some process which begins a few days before the main event and stays until a few days after it (Akhoondzadeh et al., 2010). No other strong events occurred during this period. So it is possible to consider these unprecedented electric signals as an electromagnetic precursor of the Wenchuan event.

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