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# An Estimation of “Energy” Magnitude Associated with a Possible Lithosphere-Atmosphere-Ionosphere Electromagnetic Coupling Before the Wenchuan $M_s8.0$ Earthquake

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Additional information is available at the end of the chapter

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## Abstract

A large scale of abnormalities from ground-based electromagnetic parameters to ionospheric parameters has been recorded during the Wenchuan  $M_s8.0$  earthquake. All these results present different anomalous periods, but there seems one common climax leading to a lithosphere-atmosphere-ionosphere electromagnetic coupling (LAIEC) right on May 9, 3 days prior to the Wenchuan main shock. Based on the electron-hole theory, this chapter attempts to estimate the “energy source” magnitude driving this obvious coupling with the Wenchuan focus zone parameters considered. The simulation results show that the total surface charges fall in  $\sim 10^7$ – $10^8$  C, and the related upward electric field is  $\sim 10^8$ – $10^9$  V/m. These corresponding parameters are up to  $10^9$  C and  $10^{10}$  V/m when the main rupture happens, and the order of the output current is up to  $10^7$  A. The electric field increasing in the interface between the Earth’s surface and the atmosphere, on one hand, can cause electromagnetic parameter abnormalities of ground-based observation, with the range beyond 1000 km. On the other hand, it can accumulate air ionization above pre-earthquake zone and lead to ionospheric anomaly recorded by some spatial seismic monitoring satellites.

**Keywords:** Wenchuan earthquake, electromagnetic abnormality, lithosphere-atmosphere-ionosphere electromagnetic coupling, electron-hole theory, “energy” magnitude

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## 1. Introduction

A substantial number of effects in the Earth's lithosphere possibly associated with earthquakes (EQs) have been revealed in the past several decades. Electromagnetic observation is one of the geophysical methods which are applied in seismic investigation most early. A large number of electromagnetic emissions related to strong EQs have been reported worldwide.

One considers that direct electromagnetic signals in a wide frequency range originate in the Earth's crust at epicenter depth being more than 10 km (even several hundreds of kilometers) and can be recorded on the Earth's surface. The first example is DC seismic electric signal (SES) [1]. Another example is ultra low frequency (ULF) electromagnetic emissions during the Loma Prieta  $M_s$ 7.1 EQ on 17 October 1989 [2, 3] and the Spitak  $M_s$ 6.9 EQ on 7 December 1988 [4]. Anomalous ULF emissions were also observed before 8 August 1993  $M_s$ 8.0 Guam EQ [5, 6] and the L'Aquila  $M_s$ 6.3 EQ on 6 April 2009 [7].

At the same time, a large number of effects in the Earth's atmosphere and the ionosphere possibly associated with earthquakes have also been reported in the past 20 years. The ionosphere and the upper atmosphere phenomena correlated with seismic events have been examined in numerous experimental and theoretical studies. As a result of these researches, it has been shown that there are obvious ionospheric perturbations associated with strong seismic activities especially after the launch of the DEMETER satellite in 2004 [8]. The total electron content (TEC) abnormalities with an increase of about 67% have been recorded 4–6 days prior to the L'Aquila 6.2 earthquake [9–11]. Using GPS and CHAMP data, Hasbi et al. [12] investigated the ionospheric variations before some large earthquakes occurring during 2004–2007 in Sumatra, and the result shows positive and negative anomalies in TEC and electron density within a few hours to several days before the events. The results attained by Hayakawa et al. [13] have presented subionospheric very low frequency (VLF) perturbations before the 2007 Niigata Chuetsu-oki 6.8 earthquake and the 2010 Haiti 7.0 earthquake with an abnormal radius up to several kilometers.

Furthermore, in very recent years, more and more evidences have been shown that at the last stage of the long-term preparation of an earthquake, there could be a transfer and interchange of energy among the involved layers of lithosphere, atmosphere, and ionosphere, so as to introduce the concept of a lithosphere-atmosphere-ionosphere coupling (LAIC) of the Earth system (e.g., [8, 14–20]).

However, there is still a primary stage for study on the generation and propagation mechanisms of electromagnetic signals related to seismic activities. Many rock-pressure experiments have been performed in order to understand the mechanism of earthquake-related electromagnetic variations and pre-earthquake abnormal phenomena, for example, "selectivity" of the information, and one commonsense is that electromagnetic signals, as well as strong electrical current, are produced during a rock pressure [21–29].

A strong electrical current is produced when rocks are stressed during laboratory rock experiments, especially at the stage of the main rupture, although no clear explanation has been given to interpret the generation of EM emissions and electrical currents observed either during

seismic activity or in the laboratory experiments up to now. So at the present, the study based on a physical model [30–32] and mathematical model [33, 34] is an effective way to investigate electromagnetic generation and propagation mechanism and interpret electromagnetic phenomena recorded before some seismic events.

A seismic activity is a dynamic evolution process, and electromagnetic anomaly emissions are accompanying at every stages of its preparation, development, and occurrence. It is a reasonable explanation that using dynamic-electromagnetic coupling mechanism to explain piezoelectric effect related to seismic electric signals, although Tuck et al. [35] have proposed that the piezoelectric effect of natural rocks is too weak to generate an observable electromagnetic signal for completely random orientation of piezoelectric grains. Not to mention that Sasaoka et al. [36] attained that the percentage of the effective electrokinetic effect during a natural rock experiment is only about 0.1–1%. However, using a model considering the compensation of piezoelectric effect and the dislocation theory of fault, Huang [37] attempted to investigate theoretically the generation of coseismic electric signals. He attained that the induced electric signals would be negligible in the case of the completely random orientation of quartz crystals. While if there are some preferred orientations or piezoelectric fabrics of quartz-bearing rocks in a fault area, it would form transient piezoelectric anomalous fields, which could be large enough to be detected as some seismic EM anomalies. Using a relatively simple model of an underground current source colocated with the earthquake hypocenter, Bortnik et al. [38] proposed that the expected seismotelluric current magnitudes fall in the range ~10–100 kA for an observed 30 nT magnetic pulse at 1 Hz before the Alum Rock  $M_w$ 5.6 earthquake.

The work of Freund [21–25, 29] has gained a new insight into the production of current and electromagnetic signals in stressed rocks, and the electron-hole theory has been created subsequently. Based on this electron-hole theory, Kuo et al. [39, 40] constructed a theoretical coupling model for the stressed rock-Earth surface charges—atmosphere-ionosphere system—and the stressed rock acts as the dynamo to provide the currents for the coupling system. Their simulation results show that the total surface charges of stressed rock are  $1.3 \times 10^6$  C when an earthquake fault surface area being  $200 \times 30$  km and the surface current density  $0.5 \mu\text{A}/\text{m}^2$  are taken into account.

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  $103.4^\circ\text{N}$  and  $31.0^\circ\text{E}$  and a depth of 19 km. This event caused major extensive damage, and 69,000 people lost their lives. At the same time, there are an increasing number of studies to investigate the possible existence of seismic-related electromagnetic precursors. One of the most important phenomena is that the climax of electromagnetic abnormalities from ground-based observation to ionospheric observation happened right on 2008 May 9, 3 days before the Wenchuan event, which indicates a lithosphere-atmosphere-ionosphere electromagnetic coupling (LAIEC). One question is that what and how big is the "energy" source which drives this kind of coupling. So in this paper, a probable LAIEC process associated with the Wenchuan  $M_s$ 8.0 earthquake is given in Section 2 firstly. Then Electron-hole theory is introduced in Section 3. For specified parameters on the Wenchuan earthquake, an "energy" magnitude driving this LAIEC is estimated using electron-hole theoretical model in Section 4. Discussion and conclusions are given in Section 5 and Section 6, respectively.

## 2. LAIEC before the Wenchuan $M_s$ 8.0 EQ

### 2.1. Possible mechanism of “energy” source driving a LAIEC

#### 2.1.1. Different time-scale variations prior to the Wenchuan EQ

An EQ is a dynamic phenomenon of a long-term slow-strain accumulation and culminating with a sudden rupture and displacement of blocks of rock in the rigid lithosphere [41]. The evolutionary process of EQs is characterized by some complex features from stochastic to chaotic or pseudo-periodic dynamics. These events are so sophisticated that they are full of variations for different parameters at their different development stages from a long term to a short term, even several hours. Scientists acknowledge that any 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 (De Santis [42]).

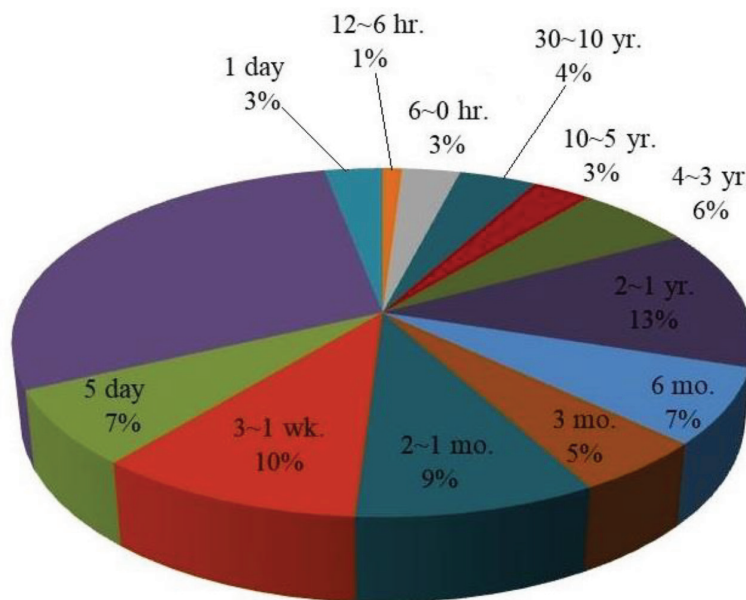
The intensive compressive movement between the Qinghai-Tibet Plateau and the Sichuan basin has generated many strong EQs. On 12 May 2008, the Wenchuan  $M_s$ 8.0 EQ ruptured the middle part of the Longmenshan (LMS) thrust belt [43], with a total length of about 400 km along the west edge of the Sichuan basin and the eastern margin of the Tibetan plateau in China. An increasing large number of preseismic phenomena have been reported after the occurrence of the Wenchuan EQ. Long-term variations basically include seismicity anomalies, deformation measurement anomalies, and strain/stress measurement anomalies. Jiang and Wu [44] have shown decade-scale quiescence along the Longmenshan fault zone. Yu et al. [45] also demonstrated a “load-unload response ratio (LURR)” variation of the seismicity along the Longmenshan fault zone up to 3 years before the Wenchuan EQ. Fang et al. [46] presented the “oscillation anomalies” since 2007 by analyzing GPS horizontal time series, and Zhang and Liu [47] also found a month-to-year-scale disturbance in the borehole strain measurement by analyzing four-component borehole strain observations. Fan and Jiao [48] analyzed fault activity characteristics in Sichuan-Yunnan area and found a two-year-scale increase of regional stress. These regional strain/stress changes and redistributions subsequently lead to a gradual variation of the electrical properties in the lithosphere beneath the Earth, conductivity/resistivity, for example. Lu et al. [49] analyzed shallow apparent resistivity data at Pixian, Jiangyou, and Wudu stations on the Longmenshan tectonic zone in western China and found that, at Pixian station 35 km away from the Wenchuan epicenter, a gradual decrease of apparent resistivity of up to 6.7% had been recorded clearly about 2 years prior to the  $M$ 8.0 Wenchuan event, and a small coseismic change of  $-0.61\%$  occurred during the earthquake.

However, one must keep in mind that electromagnetic emissions should be a candidate mentioned almost in all big events during the climax stage and plays an important role not to be ignored during pursuing the precursors prior to EQs. Ma and Wu [50] performed a work by collecting more than 200 papers published since the Wenchuan EQ, including seismic deformation, strain/stress, structure variations, gravity and broadband seismic recordings, and geomagnetic, geothermal, atmospheric, and ionospheric abnormalities. **Figure 1** shows their statistical result according to the time scale of different anomalies collected this time. One must notice that the percentage of the anomalies appearing 2–3 days prior to the Wenchuan

EQ is 29%, the biggest one among 12 kinds of abnormalities with different time scales from 30 to 10 years to 6–0 hours (see **Figure 1**). The most important is these anomalies are almost electromagnetic fields recorded by ground-based observation and ionospheric parameters recorded by GPS and DEMETER satellite and the rest are geothermal and thermosphere parameters if we check the context of the paper.

### 2.1.2. Possible "energy" source driving a LAIEC

The concept of lithosphere-atmosphere-ionosphere (LAI) coupling among the three involved layers of the Earth system has been proposed due to the transfer of energy among these three layers during some last stages of the long-term process of preparation [8, 15–17, 19, 20, 51, 52]. A few hypotheses for this LAI coupling have been proposed [53]: (1) chemical channel based on radon emanation [19], (2) atmospheric oscillation channel [51, 54], and (3) electrostatic channel due to positive hole carriers [55]. The main player of the first channel is the emanation of radon, which induces changes in the atmospheric conductivity and then atmospheric electric field and finally leads to the ionospheric plasma change. The third channel based on the generation of positive holes during the stressed rocks is likely to generate the electrostatic electric field, influencing the ionosphere. The second channel seems to be different from those mechanisms, in which some kinds of changes on the ground (or emanation of charged aerosols) are the possible excitors of atmospheric oscillations (either acoustic or internal gravity waves). Though a lot of evidences in support to this mechanism have been obtained, internal gravity waves tend to propagate obliquely so that it might be difficult to explain the most intense perturbation above the EQ epicenter. As the conclusion, this mechanism is most plausible but is poorly understood at the moment because of the lack in observational facts [52]. So Pulinets and Davidenko [56] have thought it is the smooth transition from acoustic-driven mechanisms to the electromagnetic coupling. The reason of this is very simple: acoustic coupling



**Figure 1.** Temporal distribution of the appearance of all the reported anomalies (adapted from [50]).

mechanism has shown recently its very low effectiveness that it is difficult to produce an order of the ionospheric variations which are really observed before EQs.

Except for the electron-hole theory proposed by Freund [24], the results of rock-pressure experiments conducted by Qian et al. [28] indicate that they are rich in self-potential and magnetic signals with obviously different shapes during the early, mid, and late terms of the experiments. However, the large shorter-period magnetic pulses appearing at the last stage of the experiment may be induced by instantaneous electric current of the accumulated charges during the main cracking acceleration. These experiment results would effectively support a large number of electromagnetic observations during strong EQs.

## 2.2. Electromagnetic variations in the atmosphere

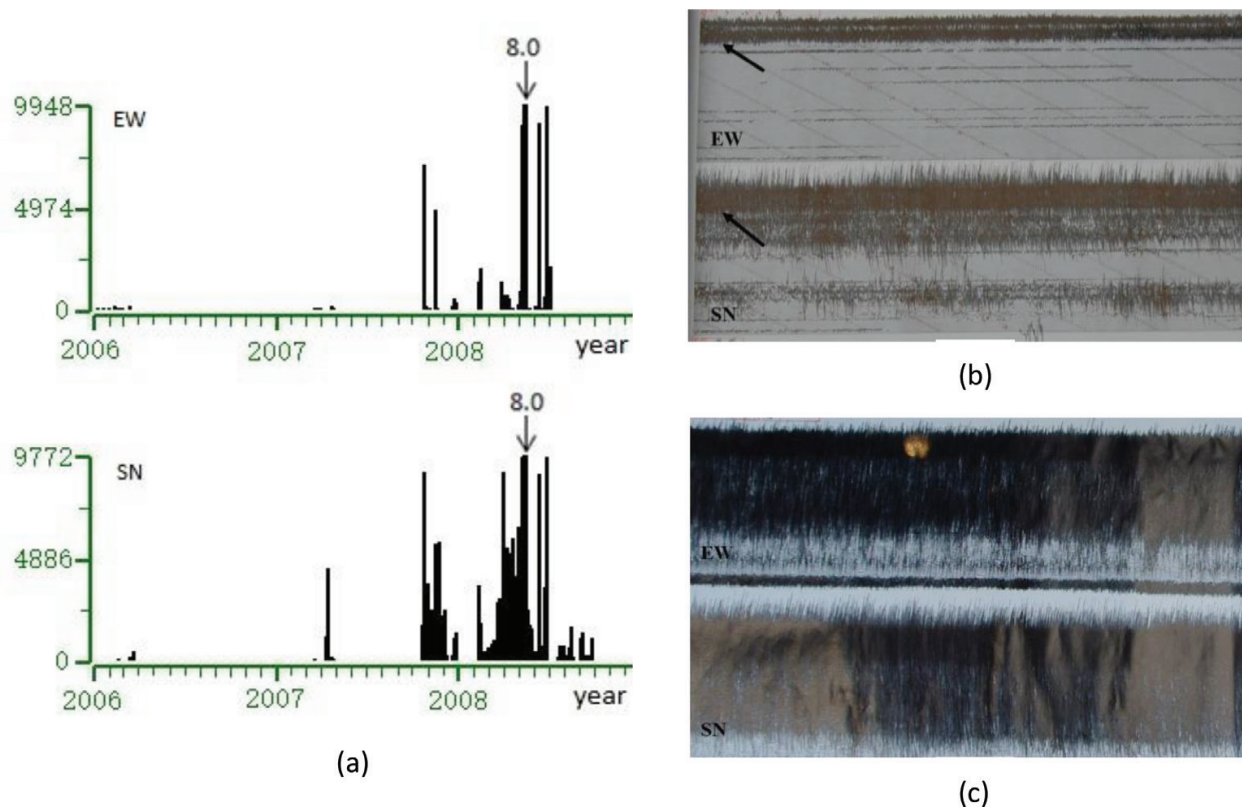
It is inferred that a northward pushing of the India plate and an intensive southeast movement of Qinghai-Tibet Plateau are strongly resisted by the Sichuan basin, from which the dynamic resources of the Wenchuan EQ probably originate. There is a long-time elastic strain accumulation and strengthening in Longmenshan nappe structural belt, and eventually this strain is beyond a threshold of friction strength of the faults, which leads to the Wenchuan  $M_s$ 8.0 EQ on 12 May 2008 [57].

Li et al. [58] have reported an unprecedented ULF (0.1–10 Hz) electromagnetic emission anomaly appeared at Gaobeidian observing station lying in north China and 1440 km away from the epicenter. **Figure 2a** shows the daily total cumulative amplitude  $A$  (black bar) of electromagnetic information recorded at Gaobeidian station from January 2007 to December 2008. This emission is characterized by a 6-month-scale term by appearing weak information at the end of October 2007, on one hand, and, on the other hand, an abrupt increase of total information by appearing larger magnitude and higher frequency signals for both south-north (SN) and east-west (EW) directions at the same time on 9 May 2008, and this climax does not stop until May 17, 5 days after the main event on 12 May 2008 (see **Figure 2a** and **b**).

A “double low-point” phenomenon of vertical  $Z$  recorded on 9 May 2008 at most ground-based DC-ULF (0–0.3 Hz) geomagnetic observing stations around the epicenter of the Wenchuan EQ in China has been presented, and the amplitude variation of the  $Z$  component in most of the middle and western stations is up to 10–20 nT [59, 60].

## 2.3. Electromagnetic variations in the ionosphere

The pre-earthquake dynamo releases large number of charges and induces a strong electrical field over the epicenter areas. This field may provide air ionizations, leading to the presence of both positive and negative ions in the air, and enhance the air conductivity. The enhancement of the air conductivity advantageously contributes to a transmission of the electromagnetic fields from near ground surface to the atmosphere. The fields reach the bottom of the ionosphere and cause broadly ionospheric changes. The work of Hayakawa et al. [61] and Li et al. [32] shows lower ionospheric perturbations, as well as weak lithospheric radiation in ULF frequency by analyzing the vertical  $Z$  and horizontal  $H$  based on ground-based geomagnetic observation.

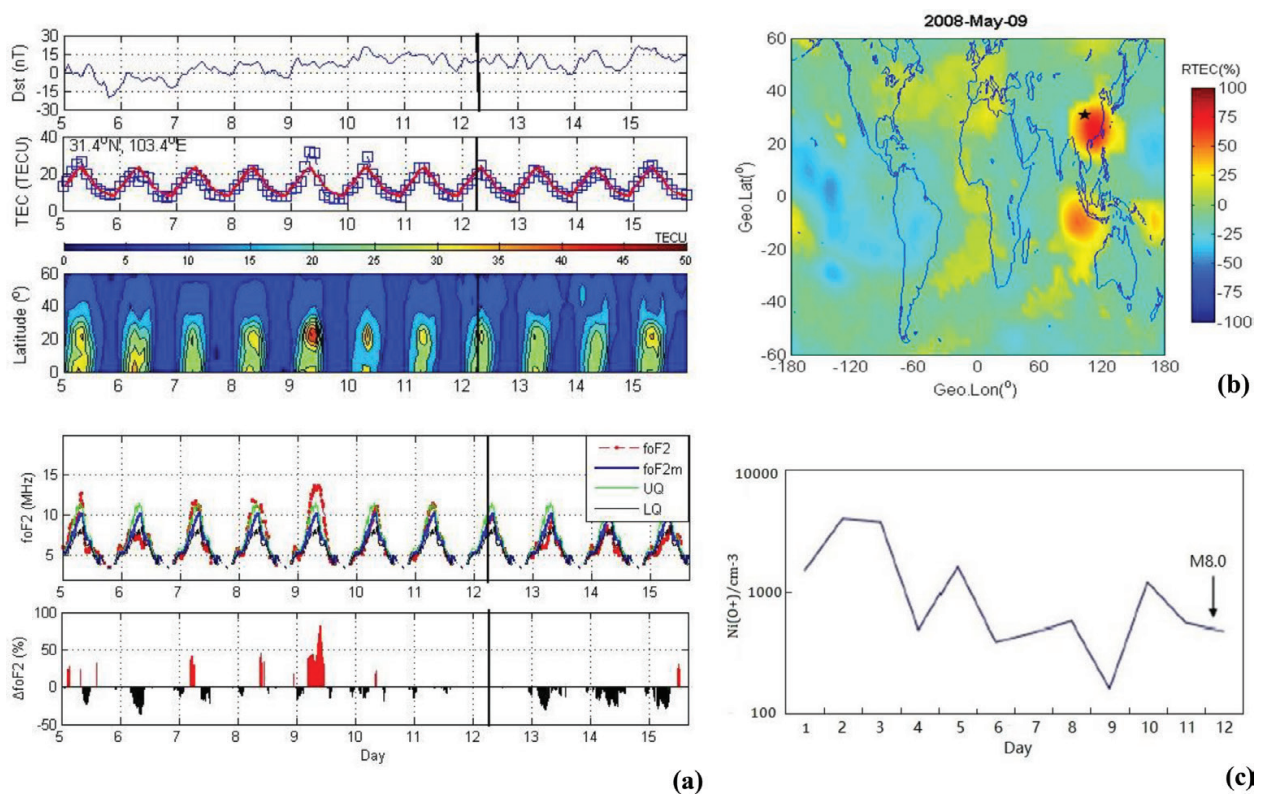


**Figure 2.** ULF electromagnetic variations during the Wenchuan  $M_s 8.0$  EQ (modified from [58]). (a) Timeline of daily total cumulative amplitude A (black bar) of electromagnetic information recorded at Gaobeidian station from January 2007 to December 2008. The Wenchuan EQ is indicated by an arrow. Copy of a part of an original record (b) from 9:00 AM, 9 May 2008, to 9:00 AM, 9 May 2008, and (c) from 9:00 AM, 9 May 2008, to 9:00 AM, 10 May 2008, at Gaobeidian station. Two observation components are shown with EW and SN, respectively. The abrupt increasing time on 9 May 2008 of emissions is denoted by black arrows for these two components in the right top panel.

The ionospheric variations, occurred right on the same day, i.e., 9 May 2008, partly are the followings. An obvious strength of 10–15 TECU for TEC happened at 16–18 LT in the range of  $\sim 20^\circ$  in the southeast of the Wenchuan epicenter, as well as an obvious increase in its magnetically conjugated point area (see **Figure 3a**), and 40–80% increase for  $f_0F_2$  from noon to sunset on May 9 (see **Figure 3b**). The ionospheric F2 peak electron density,  $N_mF_2$ , and height,  $h_mF_2$ , significantly decrease approximately 40% and descend about 50–80 km, respectively, when the GPS TEC anomalously reduces (e.g. [9, 62–70]).

The observed effects were strongest on May 9 for ionospheric ELF electromagnetic field [71]. By analyzing the data of DEMETER ion density  $O^+$ , Zhang et al. [64] found that the value reaches to its minimum of  $10,000/\text{cm}^3$  on May 9, 3 days before the event (see **Figure 3c**). The minimum percent of  $-2.40\%$  on May 9 on  $O^+$  is also found by Akhoondzadeh et al. [9]. There is an abrupt change for electron density  $N_e$  on May 9, and the value reaches its minimum with a 3% decrease during 1 second recorded by DEMETER [72]. All these parameters from ground-based electromagnetic observation to spatial ionospheric observation recorded a climax on 9 May 2008, 3 days before the Wenchuan  $M_s 8.0$  EQ, which seems to indicate a clear lithosphere-atmosphere-ionosphere electromagnetic coupling.





**Figure 3.** Variations of ionospheric parameters during the Wenchuan  $M_s8.0$  EQ. (a) Variations of Dst, TEC, and foF2 during 5–15 May 2008 (modified from [62]). (b) Distribution of TEC variation on 9 May 2008 (from [63]). (c) Daily averaged Ni (O+) on local nighttime during 1 to 12 May 2008 (from [64]).

In summary, all these results present different anomalous periods, but there seems one common climax leading to a lithosphere-atmosphere-ionosphere coupling (LAIC) just right on May 9, 3 days prior to the Wenchuan main shock. In this sense, LAIC is induced by a sudden change in ground and underground electrical properties, which is high probably originated from a fast development of the main rupture. At the same time, this evolutionary process is highly coincident with the LAI electromagnetic coupling model established by Kuo et al. [39, 40] that a current originated from 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 conjugated point, causing electromagnetic disturbances, respectively, on the Earth's surface, in the atmosphere and the ionosphere and its conjugate point. Some magnetically conjugated ionospheric abnormalities have also been reported (e.g., [62, 67, 68]; see also **Figure 3b**).

### 3. The “energy” source magnitude associated with the Wenchuan $M_s8.0$ earthquake

#### 3.1. Electron-hole theory model

The concept of defect electrons or positive holes had been proposed firstly by Freund and Wengeler [22]. They first identified that peroxy defects consist of pairs of covalently bonded

oxygen anions in the valence state  $1^-$  instead of the usual  $2^-$  in MgO single crystals. Then the electron-hole theory has been of a development and an improvement gradually during laboratory experiments [21, 23–25]. It demonstrates that, as rocks come under stress, stresses give rise to slight displacements of mineral grains in the rocks, which then activates peroxy defects that preferentially sit on or across grain boundaries. The peroxy breakup causes positive holes ( $h^*$ ), and the positive holes  $h^*$  are able to flow from stressed to unstressed rock, traveling fast and far by way of a phonon-assisted electron hopping mechanism using energy levels at the upper edge of the valence band [29]. At the rock-air interface, they cause (i) positive surface potential, (ii) field ionization of air molecules, and (iii) corona discharges. Positive surface charges are produced at the surface as an accumulation of positive hole charge carriers  $h^*$  as shown in **Figure 4**. The electric field at the edge of rock surface may cause air molecules to be ionized, that is,  $O_2 \rightarrow O_2^+ + e^-$ , producing  $O_2^+$  ions and electrons. There is more  $h^*$  influx in the bulk rock as electrons escape out to the rock surface. The effect of the field ionization of air molecules can be seen as to move some of the positive surface charges to the air with  $O_2^+$  ions across the air-rock interface [25]. Electric currents along the stress-gradient direction with current density  $J_{rock}$  is generated during these processes, as illustrated in **Figure 4**.

### 3.2. Electron: hole theoretical formulas

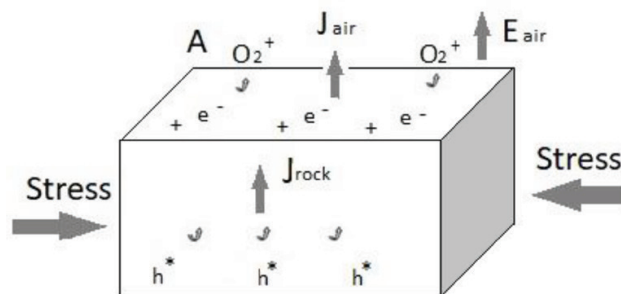
We still use some theoretical formulas of the electron-hole theory described by Kuo et al. [39], and only a simple description is given here. For the Earth-air interface, the electric field  $E_{air}$  and the current density  $J_{air}$  near the air are the following:

$$E_{air} = q_s / \epsilon_0 \quad (1)$$

$$J_{air} = \sigma_{air} E_{air} \quad (2)$$

Let  $q_s$  be the surface charge density.  $\epsilon_0$  is the electric permittivity of free space (i.e.,  $8.854 \times 10^{-12}$  Farad/m), and  $\sigma_{air}$  is the air conductivity. The electric field will drive an upward current density  $J_{air}$  for the finite air conductivity.

Let  $A$  be the surface area of the stressed rock, and  $Q = A q_s$  will be the total surface charges above the rock. From Eqs. (1) and (2), the total surface charges of stressed rock can be expressed as



**Figure 4.** Sketch of electronic charge carriers and electric currents produced as rocks are subjected to a stress.

$$Q = A q_s = A J_{\text{air}}(\epsilon_0/\sigma_{\text{air}}) \tag{3}$$

The time variation of Q can be written as

$$dQ/dt = A J_{\text{rock}} - A J_{\text{air}} = A J_{\text{rock}} - \sigma_{\text{air}} Q/\epsilon_0 \tag{4}$$

If we ignore the conductivity caused by the stress-induced surface positive charge carriers, the analytic solution for the total surface charges Q in Eq. (4) can be obtained from

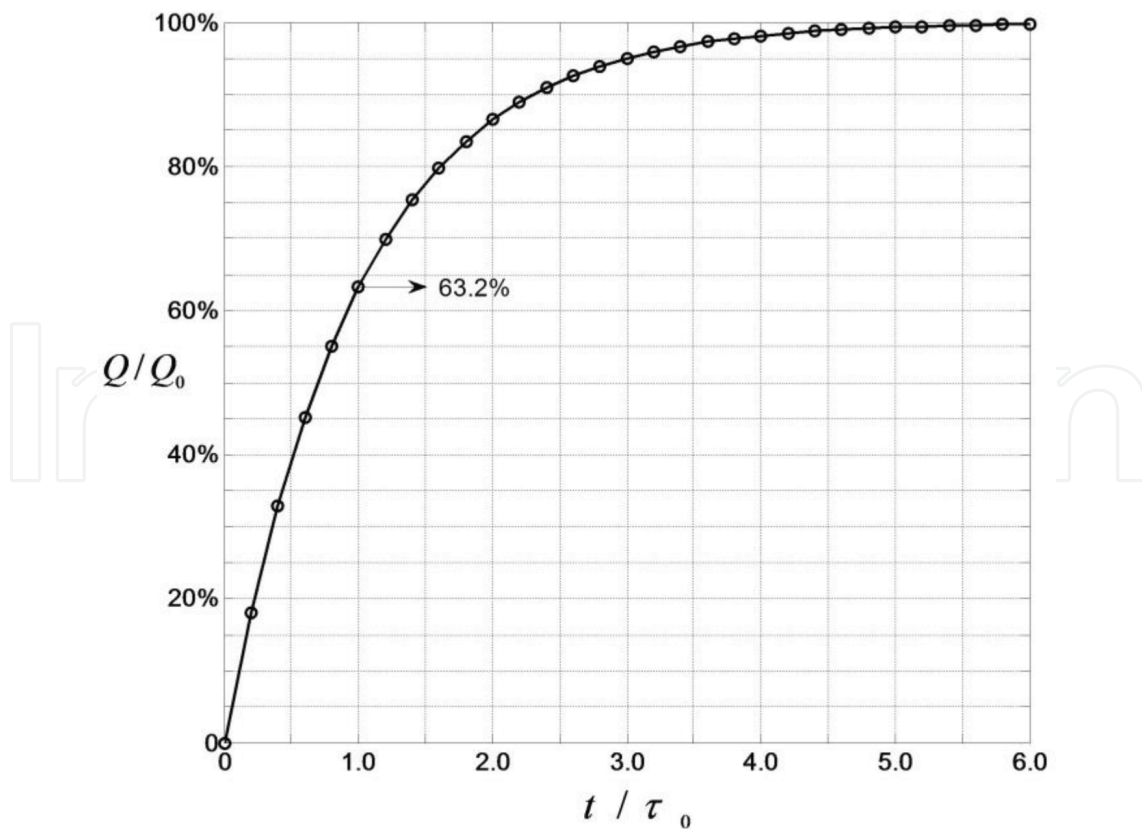
$$Q(t) = Q_0(1 - e^{-t/\tau_0}) \tag{5}$$

where  $\tau_0 = \epsilon_0/\sigma_{\text{air}}$ ,

$$Q_0 = A J_{\text{rock}} \tau_0 = A J_{\text{rock}}(\epsilon_0/\sigma_0) \tag{6}$$

where  $Q_0$  is the asymptotic value of Q as  $t \rightarrow \infty$  and  $\tau_0 = \epsilon_0/\sigma_0$  (~440 s) near ground. More details can be referred to Kuo et al. [39].

**Figure 5** shows Q as a function of time. The total surface charge Q as a function of charging time t,  $Q(t) = Q_0(1 - e^{-t/\tau_0})$ , where  $Q_0 = A J_{\text{rock}} \tau_0$  is the asymptotic value of Q when  $t \rightarrow \infty$  and  $\tau_0 = \epsilon_0/\sigma_0$



**Figure 5.** The total surface charge Q as a function of charging time t.

(~440 s) near ground. From **Figure 5**, one can see that  $Q(t)$  is quickly close to its asymptotic  $Q_0$  as the charging time  $t$  increases. In Eq. (5) and **Figure 5**,  $\tau_0$  is the characteristic time for the buildup of surface charges to reach 63.2% of  $Q_0$ . When  $Q$  reaches its asymptotic value  $Q_\infty = Q_0$ , the output total current  $AJ_{\text{air}}$  into atmosphere equals input total current  $I_{\text{rock}} = AJ_{\text{rock}}$  from rock, since  $dQ/dt = 0$ .

## 4. The "energy source" magnitude associated with the Wenchuan LAIEC

In order to attain the "energy" magnitude related to the Wenchuan event, two principal parameters should be confirmed according to input total current  $I_{\text{rock}} = AJ_{\text{rock}}$  from rock into atmosphere based on the electron-hole theory illustrated above. One is the effective stressed area  $A$ , and another is the surface current density  $J_{\text{rock}}$  output into the air associated with the Wenchuan  $M_s 8.0$  earthquake.

### 4.1. Estimation of surface current density $J_{\text{rock}}$

A gabbro sample with a porosity of ~0.3 and <1% total water and with a size of  $30 \times 15 \times 10$  cm from Shanxi, China, was used in a test performed by Freund [24]. Before loading, the background ion current was in the low pA range. It remained low at low loads. A positive ion current of 10–25 nA is presented over an area of collector plate  $200 \text{ cm}^2$  when the load is between 10,000 and 25,000 lbs. However, a 55 nA current has recorded about 2 s before failure, with the load being at about 30,000 lbs. (~13,600 kg), and the maximum spike reaches 450 nA when the main failure took place. According to this experiment, the surface current density out of stressed rock  $J_{\text{rock}}$  is of ~0.5–2.75  $\mu\text{A}/\text{m}^2$  before the failure, and it reached up to 22.5  $\mu\text{A}/\text{m}^2$  when the main failure happened.

The intensive compressive movement between the Qinghai-Tibet Plateau and the Sichuan basin results in the Wenchuan  $M_s 8.0$  EQ on 12 May 2008, with a total length of 240–350 km and width of 30 km surface rupture belt 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 [57, 73, 74]. The micro-epicenter of this event lies in the middle fault of the Longmenshan rupture belt, and there are full of granitic layers with different thickness surrounding its hypocenter [75].

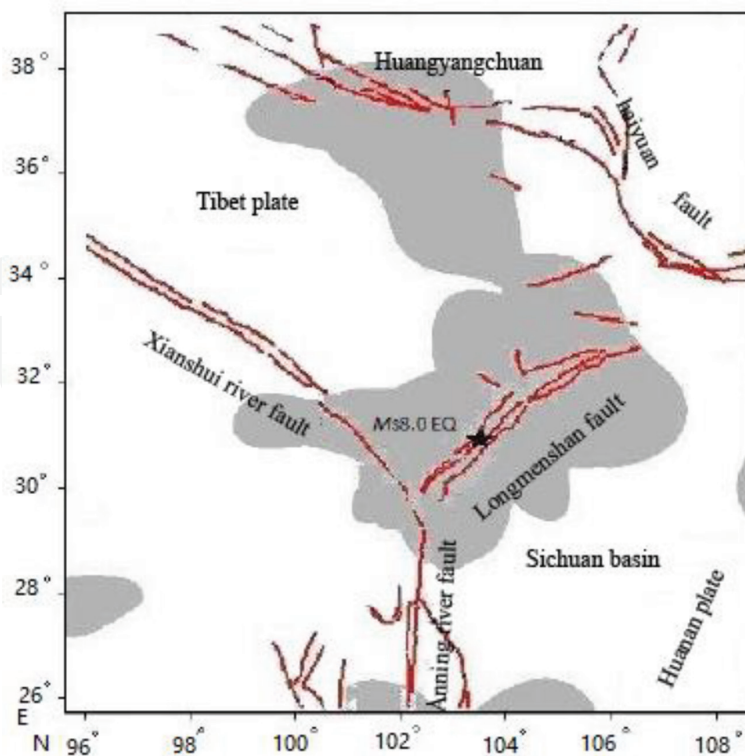
An et al. [76] conducted the ground stress measurement with hydraulic fracturing in nine boreholes along both sides of the LMS fault zone. The results show the measured maximum major horizontal principal stress is 14 MPa (about two times of the stress used by Freund [24]) for the Wenchuan borehole, 400 m away from the Wenchuan epicenter, and the horizontal principal stress increases as the depth. Hao et al. [27] found in their experiment that the self-potential  $\Delta V$  is proportional to the stress rate  $\Delta \gamma$  when the rock sample is under a biaxial compression. Therefore, with the depth effect on the horizontal principal stress ignored, the surface charge density  $J_{\text{rock}}$  would be less than ~5.5  $\mu\text{A}/\text{m}^2$  ( $2.75 \times 2 = 5.5 \mu\text{A}/\text{m}^2$ ) in the Wenchuan epicentral areas if its minimum value of the charge density is presumed to be the tested value ~0.5  $\mu\text{A}/\text{m}^2$  above attained by Freund [24]. While the charge density in the

Wenchuan preparation zone will be up to  $J_{\text{rock}} \sim 45.0 \mu\text{A}/\text{m}^2$  ( $22.5 \times 2 = 45.0 \mu\text{A}/\text{m}^2$ ) during micro-cracks, developing quickly leads to the main failure.

#### 4.2. Estimation of effective stressed plate A

The radius of seismic area where changes can be expected can be estimated using the Dobrovolsky formula  $R = 10^{0.43M}$ , where  $R$  is the radius of the EQ preparation zone and  $M$  is the EQ magnitude [77]. It gives that the radius of this Wenchuan  $M_s 8.0$  case preparation zone is more than 2,700 km although this event only ruptured a  $300 \times 30$  km ground surface rupture belt. At the same time, Liu et al. [66] have found that GPS TEC extremely enhances in the afternoon of day 3 before the Wenchuan earthquake. The spatial distributions of the anomalous indicate that the earthquake preparation area is about 1650 and 2850 km from the epicenter in the latitudinal and longitudinal directions, respectively.

The investigation results of Li et al. [78] have presented that the 7 day's synthetic surface latent heat flux (SLHF) abnormality area during 6–12 May 2008 covers around Longmenshan Faults and the epicenter of the main shock locates in the center of the abnormality area (see **Figure 6**). From **Figure 6**, one can see that the SLHF basically forms a  $6 \times 6$  degree square anomalous area. The Longmenshan faults are consisted of three fault belts, named Shanqian fault, Middle fault, and Houshan fault. These three faults are paralleled to each other and extend about 500 km from southwest to northeast direction. From the data listed above, we select the effective area bearing the principal stress of the Wenchuan earthquake to be  $500 \times 500$  km, which will be used to calculate in the following section.



**Figure 6.** Synthetic surface latent heat flux abnormality during 6–12 May 2008 [78].

### 4.3. Calculation of "energy source" magnitude

Considering the Wenchuan earthquake plate area of  $A = 500 \times 500 \text{ km}^2$ , output surface current density  $J_{\text{rock}} = 0.5\text{--}5.5 \mu\text{A/m}^2$ , the air conductivity  $\sigma_0 = 2.0 \times 10^{-14} \text{ S/m}$ , and the electric permittivity of free space  $\epsilon_0 = 8.854 \times 10^{-12} \text{ Farad/m}$ , we get the total surface charges of the  $Q_0 = (5.6\text{--}61) \times 10^7 \text{ C}$  and the upward electrical field  $E_{\text{air}} = (6.9\text{--}75) \times 10^8 \text{ V/m}$  based on the Eqs. (1) and (6).  $Q_0 = 5.0 \times 10^9 \text{ C}$  and  $E_{\text{air}} = 6.1 \times 10^{10} \text{ V/m}$ , respectively, for  $J_{\text{rock}} \sim 45.0 \mu\text{A/m}^2$  when the main rupture occurred.

Presuming the asymptotic value of the total surface charges  $Q$  being  $Q_\infty$ , when the total charges  $Q$  reaches its asymptotic  $Q_\infty$ , then  $Q_\infty = Q_0$ . At this time,  $dQ/dt = 0$  and the total current input air  $I_{\text{air}} = AJ_{\text{air}}$  should be equal to output current from the stress fault  $I_{\text{rock}} = AJ_{\text{rock}}$ . The corresponding calculated output current is  $I_{\text{rock}} = (1.3\text{--}14) \times 10^5 \text{ A}$ . The corresponding value is  $I_{\text{rock}} = 1.1 \times 10^7 \text{ A}$  as the main rupture took place. This is greater than the threshold of required  $E$  field for air ionization ( $\sim 3 \times 10^6 \text{ V/m}$  near ground). The presence of these charges and electric field will modify the air conductivity and further cause the air ionizations at the ground-to-air interface.

## 5. Discussion

All rock-pressure experiments reach one common result that a strong current and geomagnetic climax occurred as the load increases, especially at the main rupture stage, although these experiments present different anomalous periods. Stressed rocks are like a dynamo (battery) to drive currents along the earthquake faults and propagating in the surrounding areas. This process gives rise to obvious variations from near-ground electromagnetic parameters like electrical field, geomagnetic field, and others to ionospheric parameters and leads to an ultima LAIE coupling prior to the Wenchuan event.

The intensive compressive movement between the Qinghai-Tibet Plateau and the Sichuan basin is a long-time elastic strain accumulation and strengthens the Longmenshan nappe structural belt. The strain accumulation can activate hole carriers. The carriers form current and produce additional electrical fields. A large number of holes are produced mainly along the main fault and spread around surrounding areas gradually arousing geomagnetic parameters' changes in near surface of the Earth, and the anomalous area can be beyond 1000 km. A notable example is that ULF electromagnetic information becomes strong at the beginning of April 2008 at Gaobeidian station in north China, 1440 km away from the Wenchuan EQ. On May 9, 3 days before the main shock, the seismic fault comes into its main culture, and strong current induces electrical field propagating in different directions. This process gives rise to higher frequency and big amplitude signals for both SN and EW directions at the same time, and electromagnetic climax occurred subsequently. The corresponding electrical field is up to 1.3 mV/m. In addition, a "double low-point" phenomenon on vertical  $Z$  has been recorded on May 9, 2008 at most ground-based DC-ULF (0–0.3 Hz) geomagnetic observing stations around the epicenter of the Wenchuan EQ.

Based on the electron-hole theoretical formulas established, the outflow current and the corresponding field are  $I_{\text{rock}} = 1.1 \times 10^7 \text{ A}$  and  $E_{\text{air}} = 6.1 \times 10^{10} \text{ V/m}$  if the Wenchuan effective area

$A = 500 \times 500 \text{ km}^2$  and surface current density  $J_{\text{rock}} \sim 45.0 \text{ } \mu\text{A}/\text{m}^2$  being considered during micro-cracks developing quickly lead to the main failure. This current result is near to what have been gained by Li et al. [30]. Using a finite length dipole current source colocated at the Wenchuan hypocenter in a three-layer (Earth-air-ionosphere) physical model and a two-layer (Earth-air) model, they have gotten that the seismotelluric currents with and without ionospheric effect are about  $5.0 \times 10^7$  and  $3.7 \times 10^8 \text{ A}$ , respectively, for an observable ULF signal  $\sim 1.3 \text{ mV}/\text{m}$  recorded at 1440 km Gaobeidian station. While using an infinitesimally short horizontal dipole colocated with the earthquake hypocenter, Bortnik et al. [38] have attained the expected seismotelluric current is of  $\sim 10\text{--}100 \text{ kA}$  for the "Alum Rock"  $M_w = 5.6$  earthquake for an observed  $30 \text{ nT}$  pulse at  $1 \text{ Hz}$  and  $D = 2 \text{ km}$ . These results are probably in a reasonable range.

An abrupt strengthening of local electrical field accelerates ionization of surrounding air molecules, leading to a charge accumulation near the ground in the preparation zone of the forthcoming Wenchuan EQ. This makes air molecule to ionize further. Air ionization could strengthen the conductivity of the air. It is advantageous for charges spreading to the height of the ionosphere, leading to a large-scale ionospheric abnormalities of ionospheric parameters, such as TEC, foF2, Ni, Ne, and so on, and the magnitude is up to 60% on May 9, 3 days before the Wenchuan shock.

However, in this study, there are still two uncertainty parameters, i.e., the effective area of stressed plate A and outflow surface current density  $J_{\text{rock}}$  during the Wenchuan calculations. The result of the ground stress measurement with hydraulic fracturing shows that the measured maximum major horizontal principal stress increases as the depth. The hypocenter depth of the Wenchuan EQ is 19 km. So the major horizontal principal stress should be larger than the number of 14 MPa used during our calculations, and the probable electrical results would be also larger than what we get now. Thus, the larger charges can lead to a larger ionospheric disturbance. However, whether these charges can give rise to a recorded ground-ionospheric electromagnetic variation or not needs a further test.

## 6. Conclusions

In this paper, a double pressing effect of the Wenchuan fault between the Qinghai-Tibet Plateau and Huanan plate is equivalent to a rock-pressure mode in order to simulate and interpret the reason that there are large-scale accompanying electromagnetic abnormalities 3 days before the Wenchuan  $M_s 8.0$  earthquake.

According to the electron-hole theory, strong stress activates hole carriers, and the carriers accumulate rapidly in the surface of the stressed Longmenshan belt. Then a current pulse and an additional electrical field are generated and flow mainly along the main faults, especially at the stage of the main rupture. With the Wenchuan earthquake plate area of  $A = 500 \times 500 \text{ km}^2$  and output surface current density  $J_{\text{rock}} = 0.5\text{--}5.5 \text{ } \mu\text{A}/\text{m}^2$  considered, we get the total surface charges of the  $Q_0 = (5.6\text{--}61) \times 10^7 \text{ C}$  and the upward electrical field  $E_{\text{air}} = (6.9\text{--}75) \times 10^8 \text{ V}/\text{m}$ . We also attain that the output current is  $I_{\text{rock}} = 1.1 \times 10^7 \text{ A}$  and the corresponding upward electrical field  $E_{\text{air}} = 6.1 \times 10^{10} \text{ V}/\text{m}$  for  $J_{\text{rock}} \sim 45.0 \text{ } \mu\text{A}/\text{m}^2$  when the main rupture took place.

Therefore, substantial charge carriers are produced along the main fault when the Wenchuan fault is under the bilateral effect. Stressed rocks are like a dynamo (battery) that drive currents along the earthquake faults and propagate in the surrounding areas. This process gives rise to, on one hand, obvious variations of near ground electromagnetic parameters like electrical field, geomagnetic field, and others. On the other hand, an abrupt strengthening of local electrical field accelerates ionization of surrounding air molecules. Air ionization could strengthen the conductivity of the air. It is advantageous for charges spreading to the height of the ionosphere, leading to a large-scale ionospheric abnormalities of ionospheric parameters recorded by satellites. These processes could contribute to a LAIE coupling on 9 May 2008, 3 days before the Wenchuan  $M_s$ 8.0 earthquake.

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## References

- [1] Varotsos PA, Sarlis NV, Tanaka HK, Skordas ES. Similarity of fluctuations in correlated systems: The case of seismicity. *Physical Review E*. 2005;**72**(4):041103
- [2] Bernardi A, Fraser-Smith AC, McGill PR, Villard Jr OG. Magnetic field measurements near the epicenter of the  $M_s$ 7.1 Loma Prieta earthquake. *Physics of the Earth and Planetary Interiors*. 1991;**68**:45-63
- [3] Fraser-Smith AC, Bernardi AE, McGill PR, Ladd ME, Helliwell RA, Villard OG Jr. Low-frequency magnetic measurements near the epicenter of the  $M_s$ 7.1 Loma Prieta earthquake. *Geophysical Research Letters*. 1990;**17**:1465-1468. DOI: 10.1029/GL017i009p01465
- [4] Kopytenko YA, Matiashvili TG, Voronov PM, Kopytenko EA, Molchanov OA. Detection of ultra-low frequency emissions connected with the Spitak earthquake and its aftershock activity, based on geomagnetic pulsations data at Dusheti and Vardzia observatories. *Physics of the Earth and Planetary Interiors*. 1993;**77**:85-95. DOI: 10.1016/0031-9201(93)90035-8



- [5] Hayakawa M, Kawate R, Molchanov OA, Yumoto K. Results of ultra-low-frequency magnetic field measurements during the Guam earthquake of 8 august 1993. *Geophysical Research Letters*. 1996;**23**:241-244. DOI: 10.1029/95GL02863
- [6] Kawate R, Molchanov OA, Hayakawa M. Ultra-low frequency magnetic fields during the Guam earthquake of 8 august 1993 and their interpretation. *Physics of the Earth and Planetary Interiors*. 1998;**105**:229-238. DOI: 10.1016/S0031-9201(97)00094-0
- [7] Prattes G, Schwingenschuh K, Eichelberger HU, Magnes W, Boudjada M, Stachel M, Vellante M, Villante U, Wesztergom V, Nenovski P. Ultra low frequency (ULF) European multi station magnetic field analysis before and during the 2009 earthquake at L'Aquila regarding regional geotechnical information. *Natural Hazards and Earth System Sciences*. 2011;**11**:1959-1968. DOI: 10.5194/nhess-11-1959-2011
- [8] Hayakawa M, Molchanov OA, editors. *Seismo-Electromagnetics: Lithosphere-Atmosphere-Ionosphere Coupling*. Tokyo: TERRAPUB; 2002
- [9] Akhoondzadeh M, Parrot M, Saradjian MR. Electron and ion density variations before strong earthquakes ( $M > 6.0$ ) using DEMETER and GPS data. *Natural Hazards and Earth System Sciences*. 2010;**10**:7-18
- [10] Dabas RS, Das RM, Sharma K, Pilai KGM. Ionospheric precursors observed over low latitudes during some of the recent major earthquakes. *Journal of Atmospheric and Solar: Terrestrial Physics*. 2007;**69**:1813-1824
- [11] Stangl G, Boudjada MY. Investigation of TEC and VLF space measurements associated to L'Aquila (Italy) earthquakes. *Natural Hazards and Earth System Sciences*. 2011;**11**:1019-1024
- [12] Hasbi AM, Mohd Ali MA, Misran N. Ionospheric variations before some large earthquakes over Sumatra. *Natural Hazards and Earth System Sciences*. 2011;**11**:597-611. DOI: 10.5194/nhess-11-597-2011
- [13] Hayakawa M, Horie T, Yoshida M, Kasahara Y, Muto F, Ohta K, Nakamura T. On the ionospheric perturbation associated with the 2007 Niigata Chuetsu-oki earthquake, as seen from subionospheric VLF/LF network observations. *Natural Hazards and Earth System Sciences*. 2008;**8**:573-576
- [14] Kamogawa M. Pre-seismic lithosphere-atmosphere-ionosphere coupling. *Eos, Transactions American Geophysical Union*. 2006;**87**(40)
- [15] Molchanov OA, Fedorov E, Schekotov A, Gordeev E, Chebrov V, Surkov V, Rozhnoi A, Andreevsky S, Iudin D, Yunga S, Lutikov A, Hayakawa M, Biagi PF. Lithosphere-atmosphere-ionosphere coupling as governing mechanism for preseismic short-term events in atmosphere and ionosphere. *Natural Hazards and Earth System Sciences*. 2004;**4**(5/6):757-767
- [16] Pulinets SA, Legen'ka AD, Alekseev VA. Pre-earthquakes effects and their possible mechanisms. In: *Dusty and Dirty Plasmas, Noise and Chaos in Space and in the Laboratory*. New York: Plenum Publishing; 1994. pp. 545-557

- [17] Pulinets SA, Alekseev VA, Legen'ka AD, Khegai VV. Radon and metallic aerosols emanation before strong earthquakes and their role in atmosphere and ionosphere modification. *Advances in Space Research*. 1997;**20**:2173-2176
- [18] Pulinets SA, Khegai VV, Boyarchuk KA, Lomonosov AM. Atmospheric electric field as a source of ionospheric variability. *Physics-Uspekhi*. 1998;**41**:515-522
- [19] Pulinets SA, Boyarchuk KA, Hegai VV, Kim VP, Lomonosov AM. Quasielectrostatic model of atmosphere-thermosphere-ionosphere coupling. *Advances in Space Research*. 2000;**26**:1209-1218
- [20] Pulinets SA, Ouzounov D. Lithosphere-atmosphere-ionosphere coupling (LAIC) model, an unified concept for earthquake precursors validation. *Journal of Asian Earth Sciences*. 2011;**41**:371-382
- [21] Freund F, Sornette D. Electro-magnetic earthquake bursts and critical rupture of peroxy bond networks in rocks. *Tectonophysics*. 2007;**431**:33-47
- [22] Freund F, Wengeler H. The infrared spectrum of OH<sup>-</sup>compensated defect sites in C-doped MgO and CaO single crystals. *Journal of Physics and Chemistry of Solids*. 1982;**43**:129-145
- [23] Freund F. Charge generation and propagation in igneous rocks. *Journal of Geodynamics*. 2002;**33**:543-570
- [24] Freund F. Stress-activated positive hole charge carriers in rocks and the generation of pre-earthquake signals. In: Hayakawa M, editor. *Electromagnetic Phenomena Associated with Earthquakes*. Trivandrum, India: Transworld research network, Chapter 3; 2009. pp. 41-96
- [25] Freund F. Toward a unified solid state theory for pre-earthquake signals. *Acta Geophysica*. 2010;**58**(5):719-766
- [26] Hao JQ, Qian SQ, Gao JT, Zhou JG, Zhu T. ULF electric and magnetic anomalies accompanying the cracking of rock sample. *Acta Seismologica Sinica*. 2003;**25**(1):102-111 (in Chinese with English abstract)
- [27] Hao JQ, Liu LQ, Long HL, Ma SL, Guo ZQ, Qian SQ, Zhou JG. New result of the experiment on self-potential change of rocks under biaxial compression. *Chinese Journal of Geophysics*. 2004;**47**(3):475-482 (in Chinese with English abstract)
- [28] Qian SQ, Ren KX, Lv Z. Experimental study on VLF, MF, HF and VHF electromagnetic radiation characteristics with the rock breaking. *Acta Seismologica Sinica*. 1996;**18**(3):346-351 (in Chinese with English abstract)
- [29] Scoville J, Sornette J, Freund F. Paradox of peroxy defects and positive holes in rocks part II: Outflow of electric currents from stressed rocks. *Journal of Asian Earth Sciences*. 2015;**114**:338-351
- [30] Li M, Tan H, Cao M. Ionospheric influence on the seismo-telluric current related to electromagnetic signals observed before the Wenchuan  $M_s$  8.0 earthquake. *Solid Earth*. 2016;**7**:1405-1415. DOI: 10.5194/se-7-1405-2016

- [31] Li M, Tan H, Wang Z, Zhang X, Cao M. Using the electron-hole theory to estimate the “energy” magnitude related with the electromagnetic abnormalities before the Wenchuan  $M_s$  8.0 earthquake. *Acta Seismologica Sinica*. 2015a;**37**(5):842-852 (in Chinese with English abstract)
- [32] Li Q, Schekotov A, Asano T, Hayakawa M. On the anomalies in ULF magnetic field variations prior to the 2008 Sichuan earthquake. *Open Journal of Earthquake Research*. 2015b;**4**:55-64. DOI: 10.4236/ojer.2015.42005
- [33] Huang QH, Lin YF. Selectivity of seismic electric signal (SES) of the 2000 Izu earthquake swarm: A 3D FEM numerical simulation model. *Proceedings of the Japan Academy, Ser. B*. 2010;**86**(3):257-264
- [34] Ren HX, Chen XF, Huang QH. Numerical simulation of coseismic electromagnetic fields associated with seismic waves due to finite faulting in porous media. *Geophysical Journal International*; **188**(3):925-944 2012
- [35] Tuck GJ, Stacy FD, Starkey J. A search for the piezoelectric effect in quartz-bearing rocks. *Tectonophysics*. 1977;**39**(4):T7-T11
- [36] Sasaoka H, Yamanaka C, Ikeya M. Measurements of electric potential variation by piezoelectricity of granite. *Geophysical Research Letters*. 1998;**25**(12):2225-2228
- [37] Huang QH. One possible generation mechanism of co-seismic electric signals. *Proceedings of the Japan Academy*. 2002;**78**(7):173-178
- [38] Bortnik J, Bleier TE, Dunson C, Freund F. Estimating the seismotelluric current required for observable electromagnetic ground signals. *Annales de Geophysique*. 2010;**28**(8): 1615-1624
- [39] Kuo CL, Huba JD, Joyce G, Lee LC. Ionosphere plasma bubbles and density variations induced by pre-earthquake rock currents and associated surface charges. *Journal of Geophysical Research*. 2011;**116**(A10):A10317. DOI: 10.1029/2011JA016628
- [40] Kuo CL, Lee LC, Huba JD. An improved coupling model for the lithosphere-atmosphere-ionosphere system. *Journal of Geophysical Research: Space Physics*. 2014;**119**(4): 3189-3205
- [41] McCaffrey R. Earthquakes and crustal deformation. In: Harsh KG, editor. *Encyclopedia of Solid Earth Geophysics*. 218-226, 2011, doi: 10.1007/978-90-481-8702-7
- [42] De Santis A, Franceschi GD, Spogli L, Perrone L, Alfonsi L, Qamili E, Cianchini G, Giovambattista RD, Salvi S, Filippi E, Pavon-Carrasco FJ, Monna S, Piscini A, Battiston R, Vitale V, Picozza PG, Conti L, Parrot M, Pincon JL, Balasis G, Tavani M, Argan A, Piano G, Rainone ML, Liu W, Tao D. Geospace perturbations induced by the earth: The state of the art and future trends. *Physics and Chemistry of the Earth*. 2015;**85-86**:17-33
- [43] Burchfiel BC, Royden LH, Van der Hilst RD, Hager BH, Chen Z, King RW, Li C, Lu J, Yao H, Kirby E. A geological and geophysical context for the Wenchuan earthquake of 12 May 2008. Sichuan, People’s Republic of China, *GSA Today*. 2008;**18**(7):4-11. DOI: 10.1130/GSATG18A.1

- [44] Jiang CS, Wu ZL. Seismic moment release before the May 12, 2008, Wenchuan earthquake in Sichuan of Southwest China. *Concurrency Computation Practice and Experience*. 2010;**22**(12):1784-1795
- [45] Yu H, Cheng J, Wan Y. Load/unload response ratio and stress accumulation model before large earthquakes. *Acta Seismologica Sinica*. 2010;**32**(5):517-528. (in Chinese with English abstract)
- [46] Fang Y, Jiang Z, Gu G. Oscillation analysis of GPS horizontal time series before the Wenchuan earthquake. *Journal of Seismological Research*. 2010;**33**(2):125-130 (in Chinese with English abstract)
- [47] Zhang J, Liu Q. Processing and analysis of four component borehole strain observations. *Journal of Geodesy and Geodynamics*. 2010;**30**(6):6-9 (in Chinese with English abstract)
- [48] Fan G, Jiao Q. Analysis of fault activity characteristics in Sichuan-Yunnan area before Wenchuan  $M_s$ 8.0 earthquake. *Journal of Geodesy and Geodynamics*. 2008;**28**(6):27-30 (in Chinese with English abstract)
- [49] Lu J, Xie T, Li M, Wang Y, Ren Y, Gao S, Wang L, Zhao J. Monitoring shallow resistivity changes prior to the 12 May 2008  $M$ 8.0 Wenchuan earthquake on the Longmen Shan tectonic zone, China. *Tectonophysics*. 2016;**675**:244-257. DOI: 10.1016/j.tecto.2016.03.006
- [50] Ma T, Wu Z. Precursor-like anomalies prior to the 2008 Wenchuan earthquake: A critical—but—constructive review. *International Journal of Geophysics*. 2012;**1687-885X**:55-64. DOI: 10.1155/2012/583097
- [51] Molchanov OA, Hayakawa M. *Seismo Electromagnetics and Related Phenomena: History and Latest Results*. Tokyo: TERRAPUB; 2008. p. 189. DOI: 10.1016/j.pce.2006.05.001
- [52] Sorokin V, Chemyrev V, Hayakawa M. *Electrodynamic Coupling of Lithosphere-Atmosphere-Ionosphere of the Earth*. Nova Science Publishers Inc; 2015. 326p
- [53] Hayakawa M, Molchanov OA, NASDA/UEC team. Summary report of NASDA's earthquake remote sensing frontier project. *Physics and Chemistry of the Earth*. 2004;**29**:617-625
- [54] Hayakawa M. Lower ionospheric perturbations associated with earthquakes, as detected by subionospheric VLF/LF radio waves. In: Hayakawa M, editor. *Electromagnetic Phenomena Associated with Earthquakes*. Trivandrum, India: Transworld research network, chapter 6. 2009; pp. 137-185
- [55] Freund F. Earthquake forewarning—a multidisciplinary challenge from the ground up to space. *Acta Geophysica*. 2013;**61**(4):775-807. DOI: 10.2478/s11600-013-0130-4
- [56] Pulnits SA, Davidenko D. Ionospheric precursors of earthquakes and global electric circuit. *Advances in Space Research*. 2014;**53**(5):709-723
- [57] Xu XW. *Album of 5.12 Wenchuan 8.0 Earthquake Surface Ruptures*. Seismological press; 2009 (in Chinese with English abstract)

- [58] Li M, Lu J, Parrot M, Tan H, Chang Y, Zhang X, Wang Y. Review of unprecedented ULF electromagnetic anomalous emissions possibly related to the Wenchuan  $M_s=8.0$  earthquake, on 12 May 2008. *Natural Hazards and Earth System Sciences*. 2013;**13**(2):279-286. DOI: 10.5194/nhess-13-279-2013
- [59] Hu JC, Liu W, Guo MR, Zheng H. The "Double low-points" anomaly of daily vertical component variation of geomagnetic field before the  $M8.0$  Wenchuan earthquake. *Acta Seismologica Sinica*. 2009 (in Chinese with English abstract);**31**(5):589-593. DOI: 10.3321/j.issn:0253-3782.2009.05.012
- [60] Wang W, Ding J, Yu S, Zhang Y. Short-term geomagnetic abnormality before Wenchuan  $M_s8.0$  earthquake and strong earthquake prediction explore. *Earthquake Science*. 2009;**31**(2):172-179 (in Chinese with English abstract)
- [61] Hayakawa M, Schekotov A, Potirakis SM, Eftaxias K, Li Q, Asano T. An integrated study of ULF magnetic field variations in association with the 2008 Sichuan earthquake, on the basis of statistical and critical analyses. *Open Journal of Earthquake Research*. 2015;**4**:85-93. DOI: 10.4236/ojer.2015.43008
- [62] Yu T, Mao T, Wang YG, Wang JS. Study of the ionospheric anomaly before the Wenchuan earthquake. *Chinese Science Bulletin*. 2009;**54**(6):1086-1092 (in Chinese with English abstract)
- [63] Zhao B, Yu T, Wang M, Wan W, Lei J, Liu L, Ning B. Is an unusual large enhancement of ionospheric electron density linked with the 2008 great Wenchuan earthquake? *Journal of Geophysical Research*. 2008;**113**:A11304. DOI: 10.1029/2008JA013613
- [64] Zhang X, Shen X, Liu J, Ouyang X, Qian J, Zhao S. Analysis of ionospheric plasma perturbations before Wenchuan earthquake. *Natural Hazards and Earth System Sciences*. 2009;**9**:1259-1266
- [65] Liu J, Huang J, Zhang X. Ionospheric perturbations in plasma parameters before global strong earthquakes. *Advances in Space Research*. 2014;**53**(5):776-787. DOI: 10.1016/j.asr.2013.12.029
- [66] Liu JY, Chen YI, Chen CH, Liu CY, Chen CY, Nishihashi M, Li JZ, Xia YQ, Oyama KI, Hattori K, Lin CH. Seismoionospheric GPS total electron content anomalies observed before the 12 May 2008  $M_w7.9$  Wenchuan earthquake. *Journal of Geophysical Research*. 2009;**114**:A04320. DOI: 10.1029/2008JA013698
- [67] Xu T, Hu YL, Wu J, Wu ZS, Suo YC, Feng J. Giant disturbance in the ionospheric F2 region prior to the  $M8.0$  Wenchuan earthquake on 12 May 2008. *Annales Geophysicae*. 2010a;**28**:1533-1538. DOI: 10.5194/angeo-28-1533-2010
- [68] Xu T, Hu YL, Wu J, Wu ZS, Suo YC, Feng J, Huang CJ. Abnormal perturbations in the ionospheric F2 region before Wenchuan earthquake on 12 May 2008. *Science in China Series D: Earth Sciences*. 2010b;**53**(11):1671-1674. DOI: 10.1007/s11430-010-4046-4
- [69] Yan XX, Shan XJ, Cao JB, Tang J, Wang FF. Seismoionospheric anomalies observed before Wenchuan earthquake using GPS and DEMETER data. *Seismology and Geology*. 2012;**34**(1):160-171. DOI: 10.3969/J ISSN. 0253-4967. 2012. 01. 015

- [70] Zhu FY, Wu Y, Lin J, Zhou YY, Xiong J, Yang J. Anomalous response of ionospheric VTEC before the Wenchuan earthquake. *Acta Seismologica Sinica*. 2009;**31**(2):180-187 (in Chinese with English abstract)
- [71] Blecki J, Parrot M, Wronowski R. Studies of the electromagnetic field variations in ELF frequency range registered by DEMETER over the Sichuan region prior to the 12 May 2008 earthquake. *International Journal of Remote Sensing*. 2010;**31**:3615-3629. DOI: 10.1080/01431161003727754
- [72] Zeng ZC, Zhang B, Fang GY, Wang DF, Yin HJ. The analysis of ionospheric variations before Wenchuan earthquake with DEMETER data. *Chinese Journal of Geophysics*. 2009;**52**(1):11-19 (in Chinese with English abstract)
- [73] Ding ZF, Wu Y, Wang H, Zhou XF, Li GY. Variations of shear wave splitting in the 2008 Wenchuan earthquake. *China Science Series D: Earth Sciences*. 2008;**51**(12):1712-1716 (in Chinese with English abstract)
- [74] Xie ZD, Zhu YQ, Lei XL, Yu HY, Hu XL. Pattern of stress change and its effect on seismicity rate caused by  $M_s$ 8.0 Wenchuan earthquake. *China Science Series D: Earth Sciences*. 2010;**53**(9):1260-1270 (in Chinese with English abstract)
- [75] Zhu YT, Wang XB, Yu N, Gao SQ, Li K, Shi YJ. Deep structure of magnetotelluric profile on Longmen Mts. and its relation to the  $M_s$ 8.0 Wenchuan earthquake. *Acta Geologica Sinica*. 2008;**82**(12):1769-1777 (in Chinese with English abstract)
- [76] An QM, Ding LF, Wang HZ, Zhao SG. Research of property and activity of Longmen mountain fault zone. *Journal of Geodesy and Geodynamics*. 2004;**24**(2):115-119 (in Chinese with English abstract)
- [77] Dobrovolsky IP, Zubkov SI, Miachkin VI. Estimation of the size of earthquake preparation zones. *Pure and Applied Geophysics*. 1979;**117**:1025-1044. DOI: 10.1007/BF00876083
- [78] Li M, Kang C, Li Z, Jing F, Xue Y, Yan W. Abnormal surface latent heat flux prior to the Wenchuan  $M_s$ 8.0 earthquake. *Earthquake*. 2010;**30**(3):64-71 (in Chinese with English abstract)

