

Article

Impact of Post-Earthquake Seismic Waves on the Terrestrial Environment

Xiangzhi Zeng ^{1,2} and Wencai Yang ^{2,3,*}

¹ Institute of Geophysics & Geomatics, China University of Geosciences (Wuhan), Wuhan 430074, China; zeng.xz.rc@gmail.com

² Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China

³ Institute of Geophysics, School of Earth Sciences, Zhejiang University, Hangzhou 310027, China

* Correspondence: yangwencai@cashq.ac.cn

Abstract: When an earthquake occurs, it is not only the crustal material in the seismic zone that moves violently; the seismic waves of the earthquake with certain level of energy can act on the crust over large areas, producing remote effects that affect the living environment. According to the records of the long-term observation station of Chinese Continental Scientific Drilling, the effects of near-surface crust caused by the post-earthquake seismic waves include the following four aspects: (1) the pore fissure loosening; (2) the pore pressure rising and groundwater upwelling; (3) gas releasing; and (4) exothermic reaction. The effects of groundwater upwelling, gas releasing and exothermic reaction may be superimposed on the process of global warming, which has a certain impact on the terrestrial environment and requires further studies.

Keywords: crustal movement; long-term observation; seismic waves; remote effects; terrestrial environment



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1. Introduction

It has long been known that when an earthquake occurs, some crustal material in the seismic zones moves, and gas gushes out from the active faults [1–4]. However, at the same time, if large- and medium-sized earthquakes produce a certain amount of energy of seismic waves spreading widely in the land, will it affect the human living environment? If so, to what extent? Based on the analysis of long-term underground observation records, we briefly analyze the recorded data of the crustal movement observation station of Chinese Continental Scientific Drilling (CCSD), in order to understand the remote effects caused by vibration energy of the seismic waves.

2. CCSD Long-Term Crustal Movement Observations

The CCSD project was completed in 2005 by a borehole of 5158 m and achieved fruitful results [3–12]. In February 2007, the Institute of Geology of the Chinese Academy of Geological Sciences (CAGS) began to use this borehole to establish a long-term crustal movement observation station (referred to “CCSD-LOS” below). The CCSD-LOS is located in the eastern part of the Dabie-Sulu ultra-high metamorphic belt and is the first long-term observation experimental base with an observation depth of more than 4000 m in China. The corresponding author of this paper is the scientific consultant and planning master of the CCSD-LOS. Senior engineer Pi Jinyun is responsible for the installation of the instruments and equipment, and Zeng Xiangzhi, the first author of this paper, is responsible for data processing and management [11–15].

The CCSD-LOS is located at Donghai County in Jiangsu Province, with latitude of 34.4° N and longitude of 118.5° E (Figure 1a). In 2010, the CCSD-LOS installs two sets of high-precision digital seismographs in the borehole at four depths (544 m, 1559 m, 2545 m, and 4190 m) and on the ground as well. Compared with the single ground

observation, deep-well seismic observations provide much better signals. A new 452 m hole was drilled at the CCSD-LOS in 2015. More than a dozen observational instruments, including high-precision measurements of stress–strain components, tilt, pore pressure, displacement, radon concentration, geomagnetic, temperature and others [14]. The station aims to achieve the long-term monitoring of crustal movement in eastern China. Because it is only 24 km apart from the Tanlu fault zone, its observation of overtime records may show the mechanical behavior of the active faults, and the changes of regional human living environment as well. The observation borehole of the CCSD-LOS is shown in Figure 1b, some underground probes are shown Figure 1c, and its supervisory control room is shown in Figure 1d.

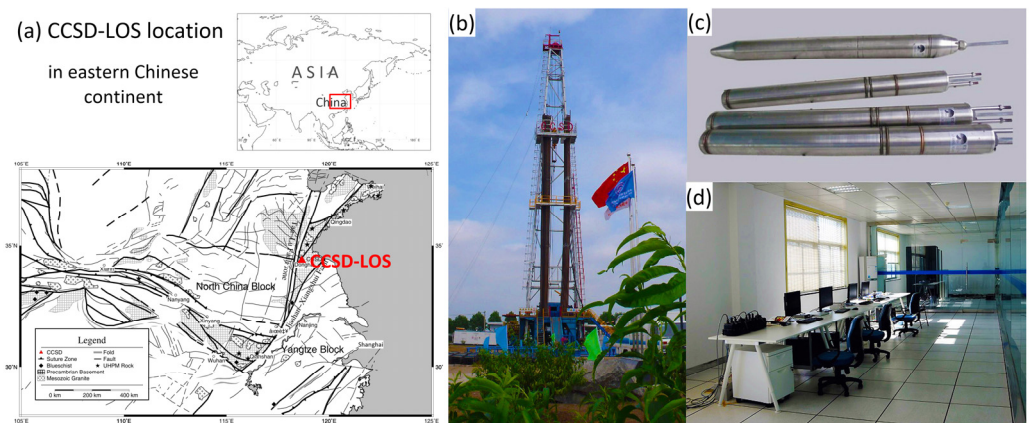


Figure 1. The CCSD long-term crustal movement observation station (CCSD-LOS). (a) The location of the station in China; (b) the observation borehole of the CCSD-LOS. The picture shows the derrick and drill pipes for the installation of instruments, with a 5158 m-deep hole below; (c) some underground probes installed in the boreholes. They have now been installed in 4 layers underground; and (d) the supervisory control room.

3. Gas Anomalies in the CCSD-LOS during the Magnitude-9 Earthquake in Sumatra

In situ fluid analysis was carried out during the CCSD drilling in 2002–2005. The drilling mud was degassed by using the freeze-drying method to remove steam from the gas, then it was extracted from vacuum pump to the OmniStar spectrometer for on-line analysis of gas components, in order to measure real-time concentration data of He, CH₄, CO₂, H₂, Ar, He, N₂ and other components [16,17]. Figure 2 shows the variations of methane, carbon dioxide and hydrogen with depths observed in the main borehole during the scientific drilling [11]. It can be seen from the records that a high concentration of methane gas rose abnormally in the underground fracture rocks from 2400 m to 3700 m. High concentrations of carbon dioxide and hydrogen are abnormal in a deeper formation below 4900 m. Since these high concentration anomalies of gases are located far from the surface, they seem not coming from the atmosphere. The observation records (Figure 2) prove that certain amount of some gases, such as methane, carbon dioxide and hydrogen, may originate from the deep Earth as their contents usually increases with the depth. The questions are, do they come to the near-surface strata and, if so, how?

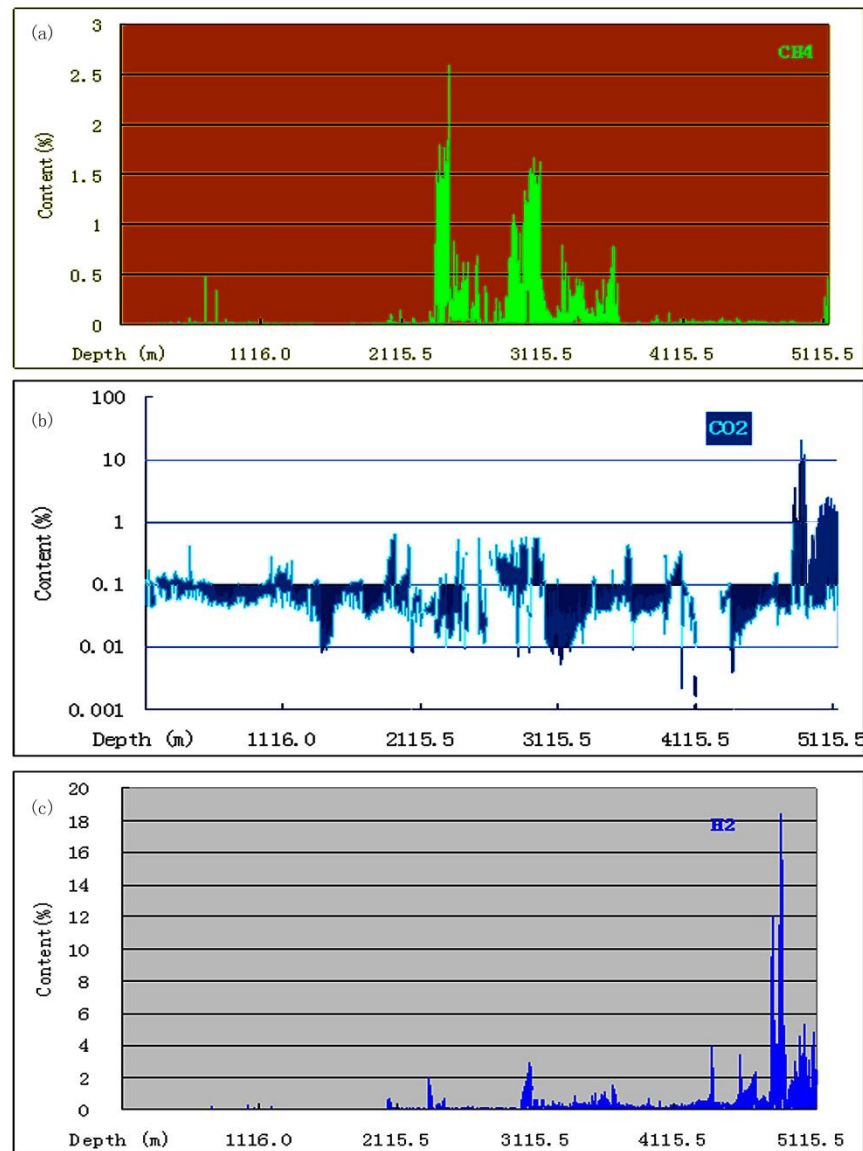


Figure 2. The gas anomaly records observed during the CCSD drilling: (a) methane, (b) carbon dioxide, and (c) hydrogen.

During the CCSD project performance, it is found that the gas contents in the borehole were changed significantly after big earthquakes. Records of gas contents during main earthquakes of magnitude 8 or larger occurred in Asia were obtained by the CCSD project; among them, the magnitude 8.7–9 Sumatra earthquake, occurring on December 26th of 2004, is outstanding. The earthquake occurred near the northern part of Sumatra, the focal coordinates are 2.30° N and 93.10° E with the epicenter depth of 20.0 km. Figure 3a shows a three-component record of the Sumatra earthquake observed on the CCSD-LOS during scientific drilling, the depth of the seismograph detector is at 1559 m. The strong underground vibrations caused by the seismic waves were clear at the drilling site, and the surface wave caused by the earthquake lasted for 4–5 days after the earthquake, then slow down.

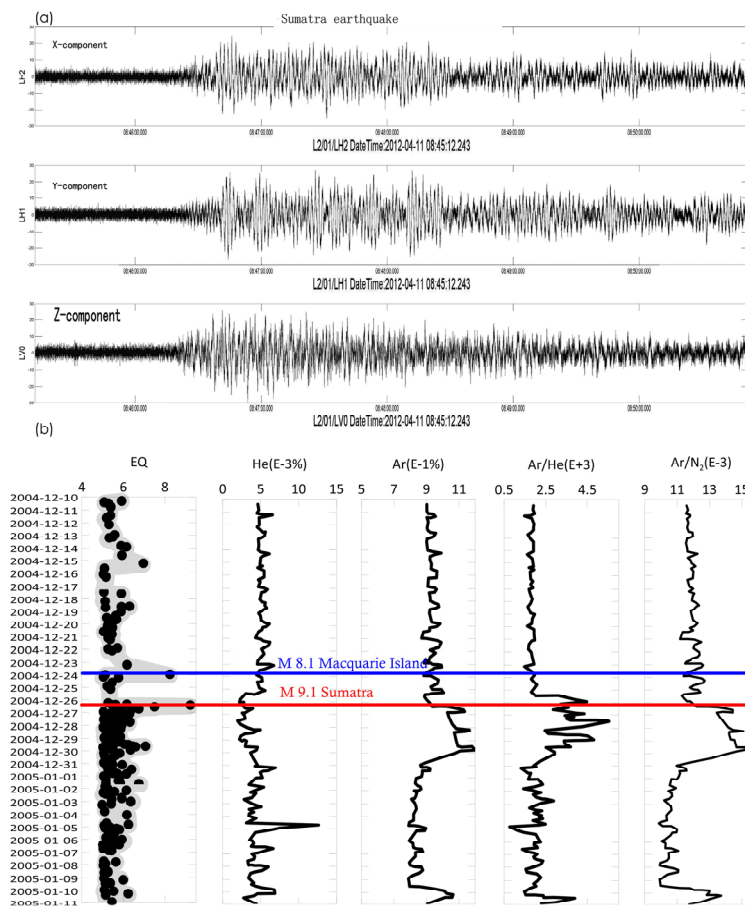


Figure 3. (a) A 3-component record of Sumatra earthquake observed. (b) Real-time gas anomalies observed during the CCSD drilling; the vertical ordinate is the date of observation; columns from the left to right are the seismic magnitude, records of helium, argon, argon/helium, and argon/nitrogen, respectively.

Figure 3b shows the gas content curves of the borehole fluids underground observed during the CCSD drilling from 7 December 2004 to 11 January 2005. The vertical ordinate is the date of observation; columns from the left to right are the seismic magnitude, records of helium, argon, argon/helium, argon/nitrogen, respectively. It shows that, from December 10 to 26, some earthquakes of magnitude 6 occurred in Sumatra. They caused fluctuations in the concentration of helium and argon slightly. After the magnitude 8.7–9 earthquake in Sumatra on December 26th, helium concentration slightly decreased, and the argon concentration sharply increased. The high argon anomaly lasted for about five days, as well as the ratio of Ar/He or Ar/N₂.

Positive anomalies of argon, argon/helium and argon/nitrogen ratios after the strong earthquakes indicate that there is a certain proportion of high Ar and low He fluid upwelling into the rocks below the CCSD-LOS after the earthquake. The distance between the CCSD-LOS and the epicenter of Sumatra earthquake is about 4000 km. This fluid upwelling at the CCSD-LOS after the earthquake could not come directly from the Sumatra seismic zone. However, seismic waves of the earthquake came about 17 min after the earthquake, consistent with the CCSD high Ar concentration anomalies. The fact indicates that these gas anomalies were triggered by the seismic waves triggered by this earthquake. Based on a theory we know, a sudden drop of the stress field in the seismic zones stimulates the crustal fluid upwelling and causes geoelectric, geomagnetic and other anomalies [18–20]. However, there have been no detailed studies on the long-distance effects of a strong earthquake, which cover thousands of kilometers from the epicenter. The surface waves from a big earthquake are relatively strong and slow to decay, and can spread in the global

crust for several days. The energy of the seismic surface waves loosens the pore fissures exist in underground strata and promotes pore fracture connectivity, causing fluid release from the deep crust. The records of Figure 3 prove that there was a crustal gas-releasing effect after the strong earthquake occurred. If the post-earthquake seismic waves cause the corresponding degassing effect and fluid upwelling, it may have an impact on the terrestrial environment. However, the occurrence of earthquakes as strong as Sumatra is unusual; on average, this occurs once every a few years. Moderate earthquakes have much higher frequency of occurrence. If the post-earthquake seismic waves of a moderate earthquake also produce large-scale crustal effects and fluid movement, its impact on the living environment cannot be ignored. The question is, does a moderate earthquake also produce the large-scale crustal effects of fluid motion? Let us see once more a set of records of a typical moderate-intensity earthquake observed at the CCSD-LOS.

4. Multi-Parameter Anomalies during the Magnitude-5 Earthquake in Philippine

The most typical of moderate earthquakes was the magnitude-5 earthquake in the Philippines, which occurred on 17 June 2018. The coordinates of the quake epicenter are 20° N and 119.82° E. The distance between the CCSD-LOS and the epicenter is about 2000 km. As the installation of various geophysical monitoring instruments in 2015, we have rich comprehensive observation data about the Philippine earthquake, including the stress, magnetic field, pore pressure, temperature, water level, and gas radon.

Figure 4 shows the variation of some underground monitoring parameters before and after the earthquake in the Philippines, including the in situ stress components of multiple directions, the geomagnetic field components of six directions, the in situ tilt components of two directions, the groundwater level, the gas radon content, the underground temperature, pressure, and the pore pressure at depth of 500 m. One can see that, after the earthquake, the crustal stress in the CCSD-LOS had a sharp jump, lasting only a few hours. At the same time, the pore pressure also synchronously had a sudden jump. After the earthquake, the groundwater level, radon content, formation temperature and pressure all changed obviously. The underground water level in the shallow observation hole had been rising continuously for 4 months, and the rising amplitude has reached 0.4 m. Underground formation temperature rose for 2 months; the rise reached 25°C , and then slowly decreased. Radon levels rose more than two days after the earthquake and then returned to a baseline; however, they rose again two months later. The formation pressure fluctuated obviously for 3 months before the earthquake, and then rose suddenly after the quake for another 3 months. The pore pressure of the formation began to rise slowly half a year before the earthquake, with a sudden jump of several hours after the earthquake, and then a slow rise of three months thereafter. The facts show that moderate-intensity earthquakes also produce remote effects, which must be caused by large-scale propagation of the post-earthquake seismic waves. The effects include a stress sharp and pore pressure rise for hours, gas radon content sudden jump for 2–3 days, and continuously delayed rise of groundwater level, as well as a rise in the formation temperature and pore pressure. According to these observation records, we find that the range of remote effects from moderate-intensity earthquakes can be over 2000 km.

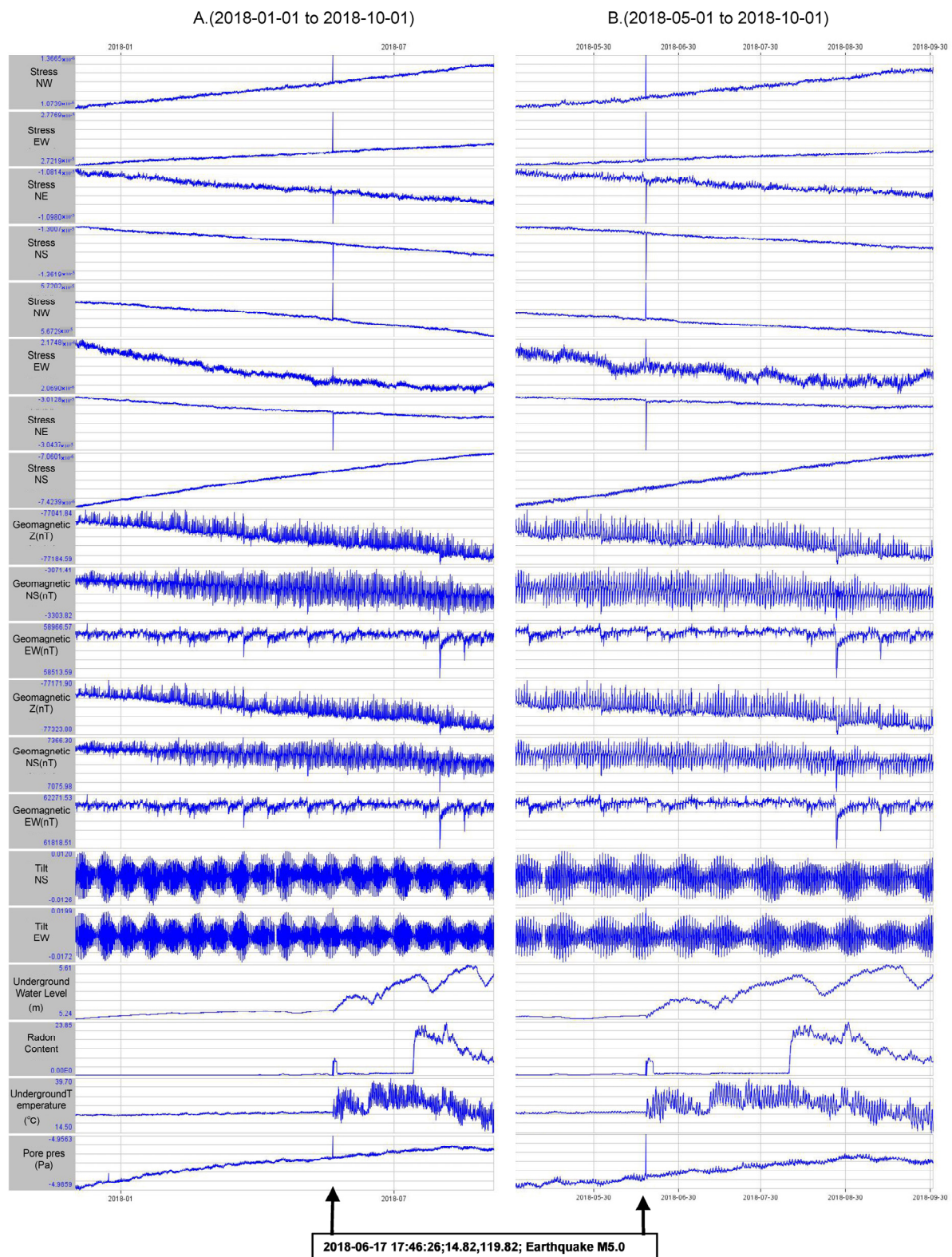


Figure 4. Records of underground monitoring parameters before and after the Philippine magnitude-5 earthquake. The monitoring parameters from the top to the bottom are as follows: the in situ stress components of eight azimuths, geomagnetic field components of six azimuths, the earth tilt components of two azimuths, underground water level, gas radon content, underground formation temperature and pressure, and pore pressure.

The monitoring parameters also include the earth tilt component and the geomagnetic field components in six directions, whose changes are not clear in Figure 4. In fact, they also have minor changes after the Philippines earthquake. Figure 5 shows these magnified parameter records. It shows that the geomagnetic component in the east–west direction increases obviously for 3 days after the earthquake, and then decreases obviously for about 100 days. Both ground tilt components had a small, serrated jump within 3 days after the earthquake. Thus, moderate-intensity earthquakes also have minor remote influences on the geomagnetic fields and ground tilt.

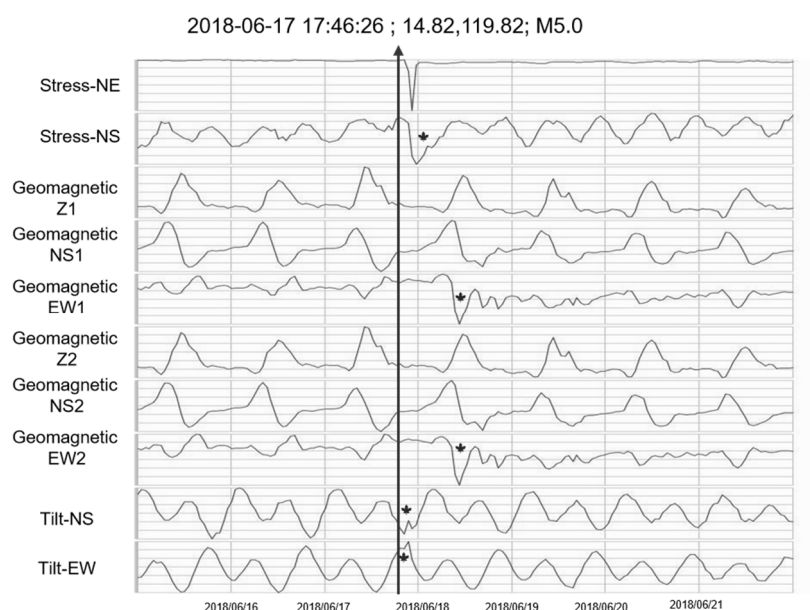


Figure 5. The magnified records of some parameters in Figure 4: the two stress components, six geomagnetic field components, and two earth tilt components.

5. Conclusions

In sum, earthquakes with moderate intensity or larger can generate remote effects on near-surface spaces in a large area of more than 2000 km. The effects are caused by the vibration energy of seismic waves, especially surface waves. The effects cause the following four types of changes in the near surface: (1) pore fissure loosening, i.e., vibration of the post-earthquake waves make pore fissure loosening and connecting; (2) the pore-pressure rising and groundwater upwelling. Because fractures connect, fluid motion makes pore pressure increase and fluid moves, resulting in groundwater upwelling; (3) gas releasing through the connected fractures from the deeper crust. The releasing gas include methane, carbon dioxide, hydrogen, helium, argon, and radon; and (4) exothermic reaction. Mass movement releases heat energy that may cause the exothermic reaction, which has a certain impact on the terrestrial environment. The degree of the effects requires further studies.

Author Contributions: X.Z., the first author, is responsible for data processing, management, as well as discovering and providing the data and figures used in this paper, joined determination of the conclusions. W.Y., finding scientific meanings in the data and writing the draft of this paper, joined determination of the estimation scheme and supplied the constrains. Both authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare that they have no conflict of interests.

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