Excitation Mechanism and Behaviors of Co-seismic Electromagnetic Waves

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Abstract

For clarifying the excitation mechanism of co-seismic electromagnetic (EM) waves, I have been observing earthquake-related EM waves in the deep earth and above the ground together with measurements of seismic waves, and also conducted a laboratory experiment. As the result, I have found that EM waves were easily excited by seismic P-wave oscillations in the earth's crust due to piezo-electric effect. The amplitude of the EM wave was enlarged at arrival of seismic S-wave which largely deformed the P-wave amplitude. It has been confirmed, from observed waveforms, that a large amplitude of co-seismic EM wave always appears in the wave-front of the seismic S-wave. Since the EM wave was radiated but rapidly decayed due to a large electrical conductivity of the earth's crust, we could imagine a composite wave system, in which a rapidly decaying co-seismic EM wave is antecedent to the seismic S-wave, and the system is moving with the velocity of the seismic S-wave.

It has been also confirmed that a co-seismic EM wave detected above the ground showed ellipsoidal polarization although another EM wave simultaneously detected in the earth showed a linear polarization, which is a result of phase shifts of the EM wave in its penetration through a boundary of two media (from the earth medium to the air).

1. Introduction

So far, EM signals in ELF (extreme-low frequency: 0.3-3kHz) and VLF (very-low frequency: 3-30 kHz) have been studied as precursors of earthquakes [1-5]. On the other hand, co-seismic EM signals detected by magnetotelluric (MT) methods [6-8] have been studied. However, the physics of the relationship between these EM waves and earthquakes has remained unclear. Since the clarification of causality between earthquakes and excitations of co-seismic EM waves is important to decide the potentiality of earthquake precursors, I have been conducting simultaneous observations of seismic waves and co-seismic EM waves in boreholes of 100 m in depth and above the ground, and a laboratory experiment.

2. Observation System

Observations were conducted in the campus of Kyoto Sangyo University, Kyoto, Japan. The EM sensor system is composed of tri-axial magnetic induction (search) coils which were wound by a wire of 26000 turns around a perm-alloy core of 8 cm in length and 1.2 cm in diameter. One sensor system was inserted into an electrically non-conducting borehole of 10 cm in diameter and 100 m in depth, and another was installed above the ground. Signals detected by each search coil and seismic accelerators were led to 16-bit analog-to-digital (AD) converters installed in personal computers with a clock synchronized with the GPS time. These signals were acquired with a sampling frequency of 512 Hz.

3. Results of Observation and Experiment

3.1 Basic Waveforms of Co-seismic EM Wave detected in the Earth and Seismic Wave

Fig. 1 shows waveforms of co-seismic EM wave detected in the earth and of seismic wave when an earthquake (M2.2) occurred at 16 km west of the EM observation site at 03:19:5.6 JST on March 26, 2013. (a) shows captured waveforms of the east-west component of magnetic flux density B_{ew} detected at 80 m depth in the borehole, and of the north-south component S_{ns} of seismic wave detected on the ground surface. (b) shows their time-expanded waveforms in three time domains, from which relations of fluctuation period between B_{ew} and S_{ns} were examined.

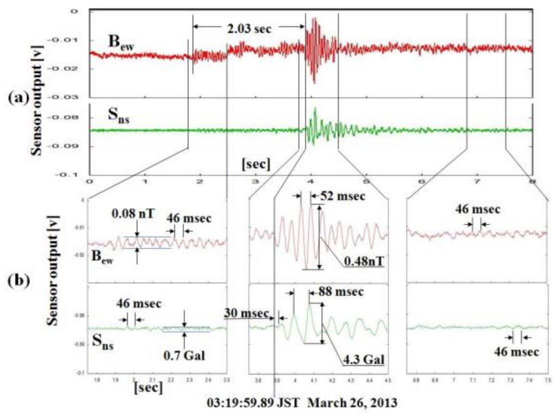

Figure 1 (a) Waveforms of east-west component of magnetic flux density B_{ew} of EM wave detected in the borehole and of north-south component S_{ns} of seismic wave detected on the ground surface. (b) Their time-expanded waveforms. In the time domains before arrival of seismic S-wave, and after its passage, the fluctuation periods of 46 millisecond in B_{ew} are the same as that in S_{ns}. The periods of B_{ew} and S_{ns} in the time domain of the S-wave arrival were different with each other [10].

At 03:19:59.89 JST when the seismic S-wave S_{ns} arrived at the EM observation site, the amplitude of B_{ew} became large. However, the period of B_{ew} signal is different from that of S_{ns}. Therefore, it was confirmed that B_{ew} signal was not induced by the earthquake dynamo mechanism which is insisted in papers [6-8]. It is regarded that a large amplitude of co-seismic EM wave was formed at arrival of seismic S-wave, because the P-wave amplitude was largely deformed by S-wave. The fact that fluctuations of a dominant period of 46 millisecond are seen in both B_{ew} and S_{ns} before and after the passage of the seismic S-wave is regarded that P-wave was pervading for a long time in the earth's crust long after the earthquake, and that the EM wave was sensitively excited as a co-seismic wave.

3.2 Laboratory Experiment for Confirming Excitation Mechanism of Co-seismic EM waves [9, 10]

For clarifying excitation mechanism of the co-seismic EM waves detected in the earth, we carried out a laboratory experiment. The experimental setup is shown in Fig. 2. In the central part of the granite pillar (10 cm x 10 cm x 50 cm), four sets of EM sensor system which is composed of an electric cross-dipole antenna of 5 cm tip-to-tip and a magnetic search coils of the same size with those in the field observation were arrayed along the side of the granite pillar at every 7 cm spacing without contacting to the granite surface.

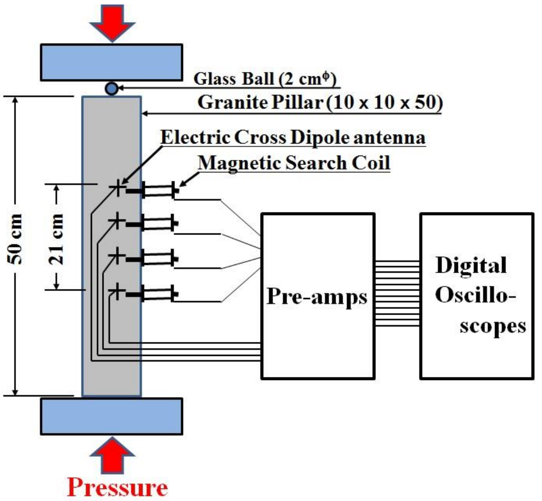

Figure 2 Experimental setup for confirming EM pulse excitations in a granite pillar. EM fields radiated from the granite pillar (10 cm x 10 cm x 50 cm) were detected by four sets of the sensor system arrayed every 7-cm spacing along the granite pillar without contacting to the granite surface. Waveforms of the detected signal were captured by digital oscilloscopes [10].

When a glass ball of 2 cm in diameter set on the top of the granite pillar was fractured, a negative stress impact was given to the granite top, then a shock wave would propagate from the top to bottom of the granite pillar. Waveforms of 12 channel EM signals detected by the EM sensors were captured by digital oscilloscopes as shown in Fig. 3. Delays of stating times of signal detections were recognized in the waveforms detected by sensors at the lower positions. The delay time, for 21 cm distance of the maximum sensor separation, was 40 micro-second, which resulted the velocity of 5.25 km/s. This is the same velocity as that of seismic P-wave in the granite.

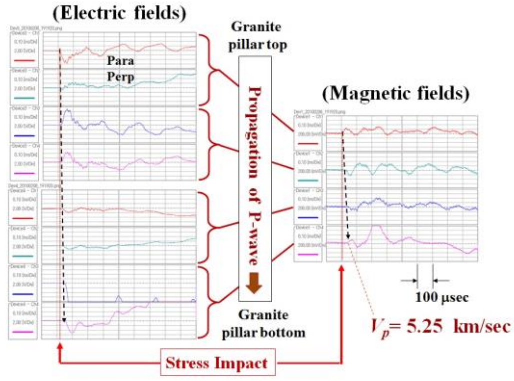

Figure 3 Waveforms of EM fields detected at each sensor position. The starting time of EM field detections in each waveform shows larger delays in accordance with sensor positions from top to bottom. The delay time of 40 microsecond for 21 cm distance resulted the velocity of 5.25 km/sec, which is the same velocity of the seismic P-wave propagation in the granite.

From these two facts that the fluctuation period of 46 millisecond of the co-seismic EM waves in the earth was the same as that of the seismic P-wave as shown in Fig. 1(b) and that the velocity derived from the EM signal detection times coincided with the velocity of the P-wave in a granite in Fig. 3, I am confident that co-seismic EM waves in the earth were surely excited by seismic P-waves.

3.3 Polarizations of Seismic S-waves and Co-seismic EM Waves in the Earth.

Figure 4 shows polarization loci, projected on tri-axial planes, of a seismic S-wave and a co-seismic EM wave simultaneously detected 4 sec after earthquake (M3.0) occurred at 10 km depth and at 5.5 km north-east of the EM observation site at 03:57:56 JST, Dec. 25, 2013. The EM wave shows a linear polarization which is oscillating in the direction from ENE to WSW with the deviation angle of 25° from the east-west direction on the horizontal plane, despite that those of seismic S-wave were very complicated. I checked polarizations of other co-seismic EM waves for different earthquakes. However, their polarization forms showed the same linear one as shown

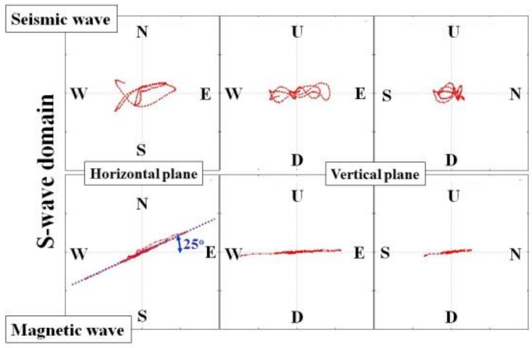

Figure 4 Polarization loci projected on tri-axial planes of seismic S-wave and magnetic waves obtained 4 sec after an earthquake (M3.0) occurred at 5.5 km north-east of the EM observation site. Polarization loci of the co-seismic EM wave show a linear form on the horizontal plane although that of the seismic S-wave was very complicated.

in Fig. 4 although their amplitudes were different.
This means that co-seismic EM waves had not been propagating from earthquake hypocenters, but were locally excited in the earth's crust very close to the EM sensors. Thus a behavior of co-seismic EM wave can be imagined as described in the next section.

3.4 Radiation and Decay of Co-seismic EM waves in the Earth

The fact that co-seismic EM waves were excited everywhere in the earth's crust has been confirmed from the analysis of waveforms of a seismic wave and its related co-seismic EM wave shown in Fig. 5. These waveforms were the same data used in **3.3**. In Fig. 5(a), the amplitude of the seismic S-wave shows a sharp increase. However, in (b), the amplitude of the magnetic component B_{ew} of the co-seismic EM wave increases exponentially until the arrival of the S-wave. This result can be explained by the following behaviors.

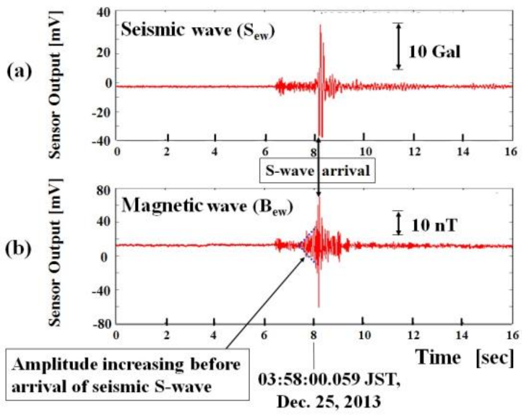

Figure 5 Simultaneously detected waveforms of (a) east-west component S_{ew} of seismic wave and (b) magnetic east-west component B_{ew} of co-seismic EM wave which were same data used in **3.3** 4 sec after the occurrence of the earthquake (M3.0). The amplitude of B_{ew} increases exponentially until the arrival of seismic S-wave [11].

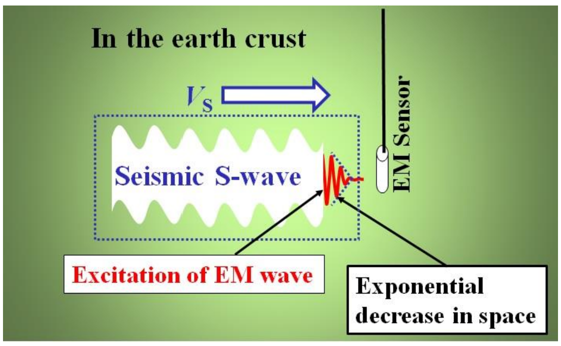

Figure 6. Schematic illustration of a composite wave system enclosed by the dotted line, in which an EM wave with a large amplitude was always radiated and rapidly decayed exponentially in the wave-front of the seismic S-wave. The composite wave system was reaching the EM sensor with the velocity V_s in the earth's crust.

As described in **3.1** and **3.3**, co-seismic EM waves were always excited everywhere in the earth's crust and were enlarged at positions of S-wave arrival, and the enlarged co-seismic EM wave was radiated in the earth's crust. However the radiated EM wave was rapidly decayed during its propagation due to the large electrical conductivity of the crust. From these behaviors, we can imagine a composite wave system enclosed by dotted line in Fig.6, in which a spatially decaying EM wave always appears in the wave-front of the seismic S-wave. The composite wave system was moving with the velocity V_s of the seismic S-wave in the earth's crust. When the composite wave system was reaching the EM sensor, an exponentially increasing waveform was detected until the arrival of the seismic S-wave as shown in Fig. 5(b) [11].

3.5 Polarization Change of Co-seismic EM waves Radiated out of the Ground Surface.

An earthquake (M2.7) occurred at 15 km depth and at 10.4 km south-west of the EM observation site at 05:23:19 JST, Sep. 25, 2014. Two co-seismic EM waves simultaneously detected both in the earth and above the ground are shown in Fig. 7(a) and (c), respectively, and the seismic wave is shown in Fig. 7(b).

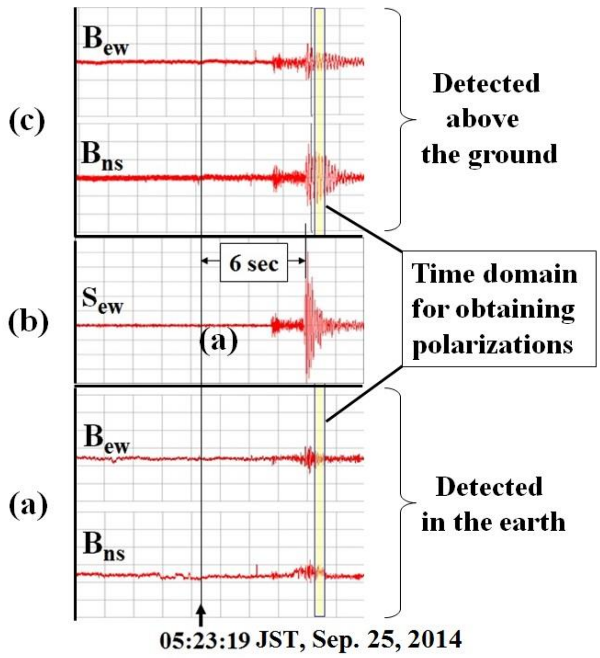

Figure 7. Waveforms of co-seismic EM waves detected (a) in the earth and (c) above the ground and (b) seismic wave. An earthquake (M2.7) occurred at 15 km depth and at 10.4 km south-west of the EM observation site at 05:23:19 JST, Sep. 25, 2014. Waveforms in the rectangles were used for obtaining their polarizations.

Using the waveforms in the time domain indicated by rectangles in Fig. 7, polarizations, projected on the horizontal plane, for EM waves detected in the earth and above the ground were obtained as in Fig. 8. In Fig. 8(a), a linear polarization is seen for the co-seismic EM wave detected in the earth. In (b), on the other hand, an ellipsoidal polarization locus was obtained for another co-seismic EM wave simultaneously detected above the ground. The difference of these polarizations can be explained that when an EM wave with a linear polarization is obliquely incident to a boundary of two media (from the earth to the air) with largely different dielectric constants, two reversely circular-polarized components of the linear polarization wave were affected with different phase shits in their penetrations through the boundary [12], and the resultant polarization locus of the EM wave in the air became an ellipsoid. The similar property was already confirmed by detections of EM pulses of lightning in the earth, which penetrated from the air. Whereas obliquely incident lightning EM pulses detected above the ground showed liner polarizations, the penetrated EM pulses simultaneously detected in the deep earth showed ellipsoidal polarization loci, although their frequency were ~5 kHz [13]. This property is useful to determine EM waves as earth origins in case the EM waves detected above the ground showed ellipsoidal polarizations.

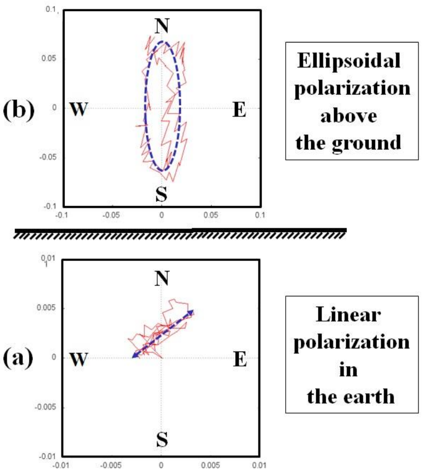

Figure 8. Polarization loci of co-seismic EM waves obtained from the waveforms in the time domain indicated by the rectangles in Fig.7. (a) A linear polarization was obtained from the waveform detected in the earth, and (b) an ellipsoidal polarization was obtained from the waveform detected above the ground.

4. Discussion and Conclusion

I have clarified the excitation mechanism of co-seismic EM waves and their behaviors in the earth and above the ground. Important points obtained in the present study are that the EM waves are easily excited by seismic P-waves in the earth's crust due to piezo-electric effect and were enlarged by S-waves. However the excited EM waves could not propagate for a long distance in the earth's crust because of their rapid decays due to electrically high conductivity of the earth's crust [11]. I have also found a method for determining earth origin EM waves from finding ellipsoidal polarizations above the ground.

Besides the properties described above, I have found that EM waves excited at hypocenters could not be detected at far EM observation sites, because, in addition to rapid decay of EM waves in the earth, their radiations from the earth were almost vertically upward because of extremely small critical angle (~9.1°) due to large dielectric constant (ε'~44) of the sedimentary layer. Therefore, it is necessary to investigate other electromagnetic phenomena than EM waves if you want to search precursors of earthquakes.

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