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A capacitive coupling model between the ionosphere and a fault layer in the crust with supercritical water

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Abstract

Changes in the total electron content, TEC, lowering of ionosphere, and the velocity and direction of TID (Traveling Ionospheric Disturbance) have been reported as potential precursors of major earthquakes. There is a growing interest in the mechanism of the crust-ionosphere coupling. As stratified fractures begin to occur within the crust, rocks can be expected to undergo friction under high pressures, resulting in extremely high temperatures. Recently smectite-rich gouges have been found by boring surveys. Smectite contains water, and with the fracture, the water is squeezed out. In high pressure and temperature, water becomes supercritical state, and the electrical resistivity increases. When the fracture begins and the layer starts to move, fine particles will be generated and charged within the fractured layer. Tribo-charging could also possibly take place. Then the voltage across the fractured layer increases, and at a certain voltage, electrical breakdowns take place inside the layer, generating electromagnetic wave. This electrical breakdown limits the maximum voltage generated across the fractured layer to be about 300 V as estimated. Because thickness of the fractured layer is small, the capacitance is large compared to that between the surface of the earth and the ionosphere. The voltage generated in the fractured layer inside the crust, or the electric field to cause perturbation, is then transferred to the ionosphere by the capacitance coupling. A crude model of the capacitance coupling between the crust and ionosphere is proposed. The order estimation of the amount of charge and energy per unit area of the fractured layer inside the crust matches those necessary for the downward drift of electrons in the ionosphere for approximately 20 km. In addition, the 300 V increase of the surface potential could cause approximately 1 mV m^{-1} electric field in the ionosphere. This value can change the velocity of middle scale TID. To see a possibility of this capacitance coupling, we made a preliminary charging test of clay/water mixture at high temperature and high pressure. Although the experimental results require further verification, the observation suggests that the electrification in supercritical conditions should be considered as one of the possible causes of voltage generation for the perturbation associated with intense earthquakes.

Keywords: Supercritical water, earthquake, pre-earthquake phenomena, lithosphere-atmosphere-ionosphere coupling, ionospheric disturbance.

1. Introduction

It has been reported that the ionosphere exhibits anomalies before an earthquake of magnitude 6 or higher, which may be useful for earthquake prediction [1−7]. If this anomaly is caused by the fracture of the earth's crust before the earthquake, the electromagnetic field generated by the crustal fracture should have an effect on the ionosphere.

To date, the generation of electromagnetic waves has been observed as a precursor to earthquakes [2]. This indicates that an electric current is flowing due to the destruction of the earth's crust, and there is no doubt that electric charges are generated when the crust breaks. Possible mechanism of the charge generation has been proposed [2, 8] that includes (1) the generation and diffusion of hole charge carriers in which holes in rocks move to the surface due to high pressure inside the earth's crust, (2) piezoelectric effect, (3) thermoelectric effect, and (4) fluid charging caused by movement of water in the crust.

Recent geological surveys by boring near the epicenters of large earthquakes have revealed that gouges of fault crust contain slippery smectite that may contain absorbed water [9−11]. It has been pointed out that slow slip occurs at weak parts of the interface, leaving behind strain in the strongly fixed parts, which may then suddenly rupture and cause earthquakes.

Concerning the anomality prior to intense earthquakes, there have been many reports on abnormal propagation of VLF-LF electromagnetic wave [1, 3, 12]. The downward drift of lower part of ionosphere as well as upper F2 layer perturbation were reported from the analysis of the abnormal propagation [12]. At the Tohoku-oki earthquake in 2011, an increase in the total number of electrons, TEC, in the ionosphere was observed [7, 13]. About an hour prior to the main shock, the TEC started to increase. The downward drift of the ionosphere for about 20 km was also reported. Furthermore, during the Kumamoto Earthquake in 2016, velocity of Middle Scale Traveling Ionospheric Disturbance, MSTID, was found to slowdown just before the main shock [5].

These phenomena indicate that voltage may be generated when smectite-rich crust is fractured. The fracture takes place within thin layers, and at first the sliding distance of the fractured layer is small. Due to high pressure, the sliding movement could increase the temperature of the layer instantly, and water could become supercritical state. Specific dielectric constant of supercritical water is 2, and electrical conductivity becomes small [14, 15], therefore, the fractured layer with supercritical water can become a capacitor. Positive charge may appear due to positive holes [16, 17], or even tribo-charging may charge the capacitor, and a voltage could appear across the fractured layer. The capacitance of the fractured layer inside the Earth's crust is extremely large compared to that between the surface of the earth and the lower part of the ionosphere. Therefore, this capacitance coupling could transfer the voltage to the ionosphere to cause the reported anomaly. We propose the capacitance coupling model with the insulating supercritical water. A preliminary experimental study was carried out to see a possibility of charging of water-cray mixture at elevated temperature and pressure.

2. Theory

2.1 Temperature rise inside the fractured layer and transition to supercritical state

When the Earth's crust fractures due to lateral forces, the fractured area becomes a thin layer. The fractured layer is under a pressure of several hundred atmospheres, and as it slides, it becomes hot due to frictional heat [18]. A boring investigation of the fracture surface indicates that the temperature may have exceeded 200 ℃ [9]. Since kinetic energy is converted to heat, the temperature rise can be estimated as follows: For example, suppose an area of 1 m × 1 m breaks and moves 10^{-2} m in the horizontal direction. It is assumed that the thickness of the rupture layer is 10^{-5} m, and the pressure is 1000 atm.

Vertical force; 10^{7} kg m^{-2}

If the friction coefficient is 0.4, the force required for the lateral movement is 4×10^{6} kg m^{-2}. Suppose the distance of lateral movement is10^{-2} m, the energy required is “$4 \times 10^{6} \times 9.8 \times 10^{-2}$ = approx. 4×10^{5} J m^{-2}”. This energy is converted into heat; 4×10^{5} J m^{-2} is injected into a volume of 10^{-5} m^{3}. Under the above assumptions, the temperature can exceed 1000 °C. Clay materials such as smectite contain water, and as the temperature rises, the water expands, increasing the pressure and becoming supercritical. At this time, the pre3ssure increase should reach several hundred atmospheres, and the fractured layer will expand and the gaps between the fractured layers will become larger, making it more slippery.

2.2 Consideration of possible effect of the temperature rise inside the fracture layer

When the crust breaks down due to lateral forces, the fractured area is supposed to be a thin layer. Temperature of this thin layer shall increase to become very high because the strong sheer stress destroys and moves the layer under very high pressure.

Smectite is known to easily incorporate water molecules and positive ions between its constituent silicate layers, and these water molecules and positive ions are easily released at high temperature and pressure. If water exists in the fractured layer, it becomes supercritical state. The ion product of water, 10^{-14} mol^{2} kg^{-2} under low temperature, becomes its peak of about $10^{-10.5}$ mol^{2} kg^{-2} at around 250 ℃. Therefore, during the increase of the temperature of water, Al and Si contained in smectite in the fractured layer are easily dissolved [14].

In supercritical condition, the specific dielectric constant of water decreases greatly from 80 to 2. Dissolved ions could then precipitate sharply, and fine particles are formed [19]. Those fine particles are densely present in a narrow fractured layer, triboelectric charging may contribute to the charging of fine particles because the conductivity of water becomes small in supercritical state. The high temperature due to the friction at high pressure may produce positive holes from SiO_2 [17]. Thermal ionization could also possibly take place. Then, positively charged Si ions could be formed. At the meantime, negatively charged oxygen ions and hydroxide ions are formed, and those ions are highly reactive. They could react with the surface of the fractured layer and lose their charge. This process could generate positive ionic space charge of Si and other metal ions derived from smectite and other rocks in the fractured layer.

Existence of charged particles inside the fractured layer causes a voltage across the layer. If the separation of the layer increases, the voltage increases because of the reduction of capacitance across the layer. When the voltage across the layer exceeds the threshold, electrical discharges take place [20]. Paschen's law is likely to hold, but the threshold value is unknown because the ionization coefficient and attachment coefficient in the supercritical water are unknown, and it will need to be clarified experimentally in the future. According to Paschen's law, below minimum breakdown voltage, the breakdown is triggered by field emission of electrons [21]. However, there is no measured data, therefore, here the breakdown voltage is assumed to be 300 V, that is the same level of the minimum breakdown voltage due to field emission, instead of electron avalanche mechanism [21]. If this value applies, a potential difference of up to 300 V occurs in each layer, so the generated voltage increases with the number of fractured layers. As mentioned above, various possibilities can be considered for the charging, but further study is necessary to investigate the mechanism of charge generation in supercritical water.

2.3. Generation of voltage within the fracture layer

When charged particles exist inside the fractured layer, a voltage V_l is generated between the layer with the thickness of d. Let Q_0 be the amount of electric charge in unit area of the fractured layer, the capacitance Co per unit area of the fractured layer is

$$C_0 = Q_0/V_l = \varepsilon_0 \varepsilon_s \frac{1}{d} \qquad \mathrm{F\,m^{-2}} \tag{1}$$

Assuming that;

$$\varepsilon_0 = 10^{-11} \quad \mathrm{F\,m^{-1}} \tag{2}$$

where ε_0 dielectric constant of vacuum, ε_s specific dielectric constant
Then,

$$C_0 = 2 \times \frac{10^{-11}}{d} \qquad \mathrm{F\,m^{-2}} \qquad V_l = 5 \times 10^{10}\, Q_0\, d \qquad \mathrm{V} \tag{3}$$

In this way, when the amount of charge within a layer is constant, the interlayer voltage increases as the layer thickness increases. When the charge density between the fracture layers becomes high enough and the interlayer voltage exceeds a threshold, dielectric breakdown occurs.

The breakdown of insulating gas layer follows Paschen’s law [21], that breakdown is caused by electron multiplication due to impact ionization, and that the breakdown voltage, V_s, depends on the product of pressure, p, and the interlayer distance, d, and Vs shows minimum value at a certain pd value. However, it is known that when d becomes smaller than the value indicating the minimum V_s, the breakdown depends not on electron multiplication but on electron emission due to a high electric field. When the interlayer distance is 10 μm, V_s is about 300 V (electric field strength is about 3×10^7 V m^{-1}).

Ionization, adhesion, and electron emission coefficients of supercritical water are unknown, several assumptions need to be applied for the breakdown condition of the fractured layer, that are; Electrical breakdown takes place at V_s = 300 V, and with the thickness of the layer, d = 10 μm.

If there are multiple fractured layers, total voltage will become $V_s \times$ number of the layer. Assuming that the maximum interlayer voltage, V_{lmax} = 300 V, and the layer thickness is 10^{-5} m, the capacitance and maximum charge per unit area of the fractured layer are;

$$C_0 = 2 \times 10^{-6} \quad \mathrm{F\,m^{-2}} \qquad Q_0 = 6 \times 10^{-4} \quad \mathrm{C\,m^{-2}} \tag{4}$$

The generated charge is discharged directly within the fractured layer and through the surrounding quasi-conductive crust. If electrical breakdown takes place in the fractured layer, electromagnetic waves are generated. The observed electromagnetic waves could be generated due to these discharge phenomena. In addition, the voltage measurement inside the crust would provide information of the pre-fracture of crust before a major breakdown.

2.4 Equivalent circuit of capacitive coupling between the earth's crust and the ionosphere

Since the thickness of the fractured layer is small, the capacitance is extremely large and the stored electrical energy could be large even the voltage across the capacitance is rather small value of 300 V, and this electrical charge could affect the ionosphere by a capacitance coupling as depicted in figure 1.

We assume that

(1) the distance between the earth surface and the ionosphere, $D = 3 \times 10^5$ m,
(2) the specific dielectric constant, ε_s, inside the layer, $\varepsilon_s = 2$,
(3) the thickness of the fractured layer, d = 10^{-5} m, or 10 μm,
(4) the maximum voltage of the fractured layer, V_{lmax} = 300 V.

Using these assumptions, the order of the charge and energy stored in the capacitance of the fractured layer were estimated to discuss if those values are enough to make a downward drift of the ionosphere as reported. As shown in the schematic diagram in Fig. 1, the potential of the lower side of the fractured layer is 0, then the voltage of the upper part of the fractured layer 300 V. The surface potential is also 300 V if no current flows. However, the stored charge in the fractured layer will disperse through the side of the crust above the fractured layer, and also through electrical discharge inside the fractured layer.

The capacitance C_0 and the amount of charge Q_0 per unit area of the fractured layer are calculated by the eq. (4). The capacitance between the surface and the ionosphere per unit area, Ca, with $D = 3 \times 10^5$ m, and S = 1 m^2, is

$$Ca = \varepsilon_0 \frac{S}{D} = 3.3 \times 10^{-17} \quad \mathrm{F\,m^{-2}} \tag{5}$$

Hayakawa *et al.* have reported that the abnormal radio wave propagation [1] is a precursor of large earthquake, and this is due to the downward drift of the ionosphere. Heki *et al.* have reported that the ionosphere drifted downward by $\Delta h = 20$ km before the earthquake [7]. In addition, Umeno *et al.* have reported that the propagation velocity of a middle scale travelling ionosphere disturbance, MSTID has decreased prior to intense earthquakes, and that this abnormal change of the velocity can be caused by an electric field of 0.58 mV m^{-1} [5]

Assume that the electron density in the ionosphere is $n_e = 10^{11}$ m^{-3} [22]. To trigger the downward drift of the ionosphere, the external electric field should drive the electrons of the ionosphere. Possible increase in the earth's surface potential above the fractured layer is 300 V. The electric field strength between the surface and the ionosphere is

$$E_i = \frac{300}{D} = 1.0 \times 10^{-3} \quad \mathrm{V\,m^{-1}} \tag{6}$$

The electric field, E_i, will superimpose to the original electric field to cause the perturbation of the ionosphere. 1.0×10^{-3} V m^{-1} is sufficient to trigger the decrease in the propagation velocity of MSTID [5].

When the distance of the downward drift of the ionosphere is $\Delta h = 2 \times 10^4$ m, the amount of transferred charge, Q_{ie}, is

$$Q_{ie} = n_e \cdot e \cdot \Delta h = 3.2 \times 10^{-4}\ \mathrm{C\,m^{-2}}, \tag{7}$$

Where, e is the electronic charge, 1.6×10^{-19} C.

The amount of energy per unit area, $W_{(\Delta h=2\times10^4\,m)}$ necessary to move the electrons for $\Delta h = 2 \times 10^4$ m by the electric field, E_i, is

$$W_{(\Delta h=2\times10^4\,m)} = Q_{ie} \cdot E_i \cdot \Delta h = 6.4 \times 10^{-3}\ \mathrm{J\,m^{-2}} \tag{8}$$

The electrical energy, W_0, stored in the fractured layer in unit area is

$$W_0 = \frac{1}{2} C_0 \cdot {V_{lmax}}^2 = 9 \times 10^{-2}\ \mathrm{J\,m^{-2}} \quad \text{where} \quad V_{lmax} = 300\ \mathrm{V} \tag{9}$$

Amount of the stored charge in the layer capacitance is $6 \times 10^{-4}\ \mathrm{C\,m^{-2}}$ as shown in Eq.4. The stored electrical energy and the charge in the fractured layer is large enough to disturb the ionosphere to cause the 20 km downward drift.

The effect of lightning near the surface of earth to the ionosphere can be estimated as follows; The potential difference between the bottom and top of a thundercloud is 10^8 V. Hight of the thundercloud is assumed to be D/10, or 33,000 m. Then the capacitance per unit area of the thundercloud is $3.3 \times 10^{-16}\ \mathrm{F\,m^{-2}}$. The amount of charge stored in this capacitance is $3.3 \times 10^{-8}\ \mathrm{C\,m^{-2}}$. This amount of stored charge in the capacitance of the thundercloud can drive the electrons in the ionosphere for 2 m, as indicated by Eq.7. This simple estimation suggests that a lightning may not affect significantly to the position of ionosphere.

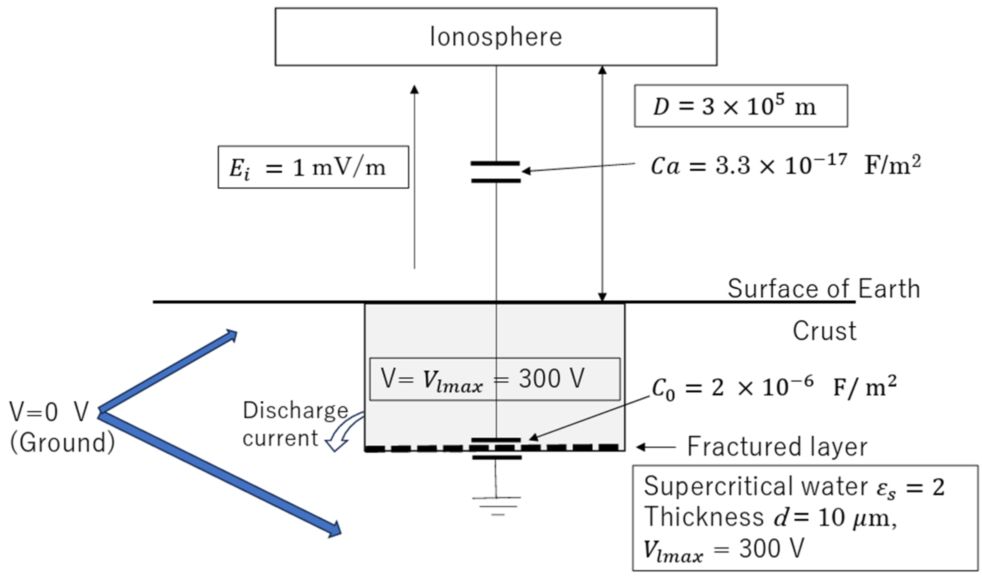

Fig. 1. The perturbation of the electric field E_i between the ionosphere and the fractured layer with supercritical water. E_i would superimpose to the original electric field for the global circuit. Numbers in the square are the assumed values for this capacitance coupling model.

3. Results and Discussion

3.1. Preliminary experiment on charging of clay/water mixture in near supercritical condition

We made a preliminary measurement of charging of clay/water mixture at high temperature and pressure. As shown in Fig. 2, the experiment was made using a stainless steel tube with the outer diameter of 3.2 mm (1/8 inch), inner diameter of 2.7 mm and length of 100mm. One end of the tube is plugged firmly. The other end is attached with thin aluminum foil to seal the end by modifying a Swagelok. Number of aluminum foil is adjusted so that the aluminum foil is broken at a certain pressure and temperature. A mixture of clay/water is loaded in the tube.

Inside the tube, 200 μL of water and 50 mg of clay were mixed and enclosed. As a preliminary test, common clay for ceramics, consisting of SiO_2 70 %, Al_2O_3 20 %, Fe_2O_3 and others 10 %, was used. The internal volume of the stainless steel tube is 600 mm^3, and with the inclusion of 200 μL of water, the specific gravity at the time of evaporation is 0.3 (not including the weight of clay).

The temperature is increased up to 400 °C, and the pressure increased accordingly with the temperature. At a certain temperature, the aluminum foil seal was broken by the pressure, and the clay and water are ejected explosively. Polarity and quantity of the charge of the ejected clay and water was measured using a Faraday cage with a capacitance of 10^{-8} F.

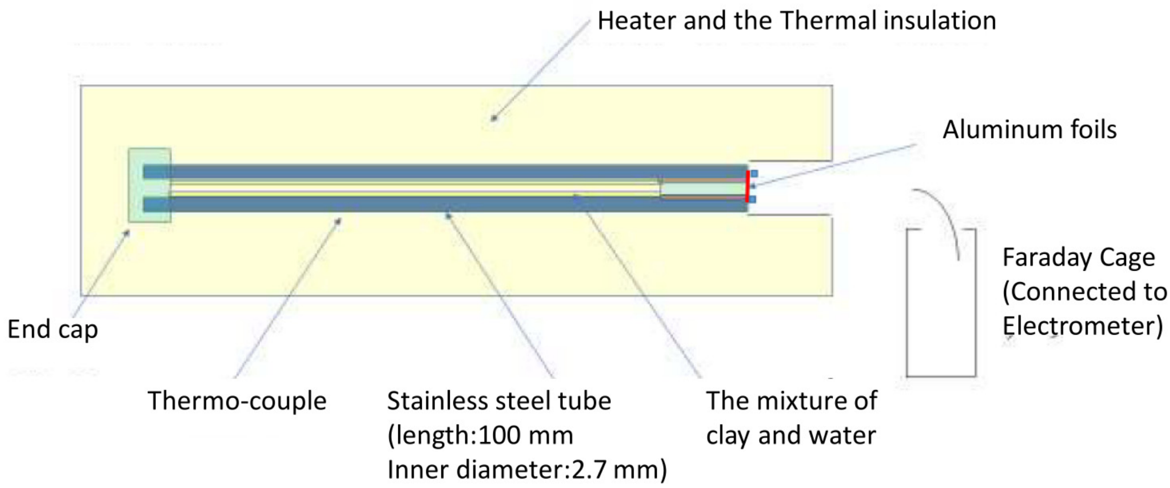

Fig. 2. Schematic diagram of experimental equipment to verify whether the mixture of clay and water is charged at high temperature and pressurized.

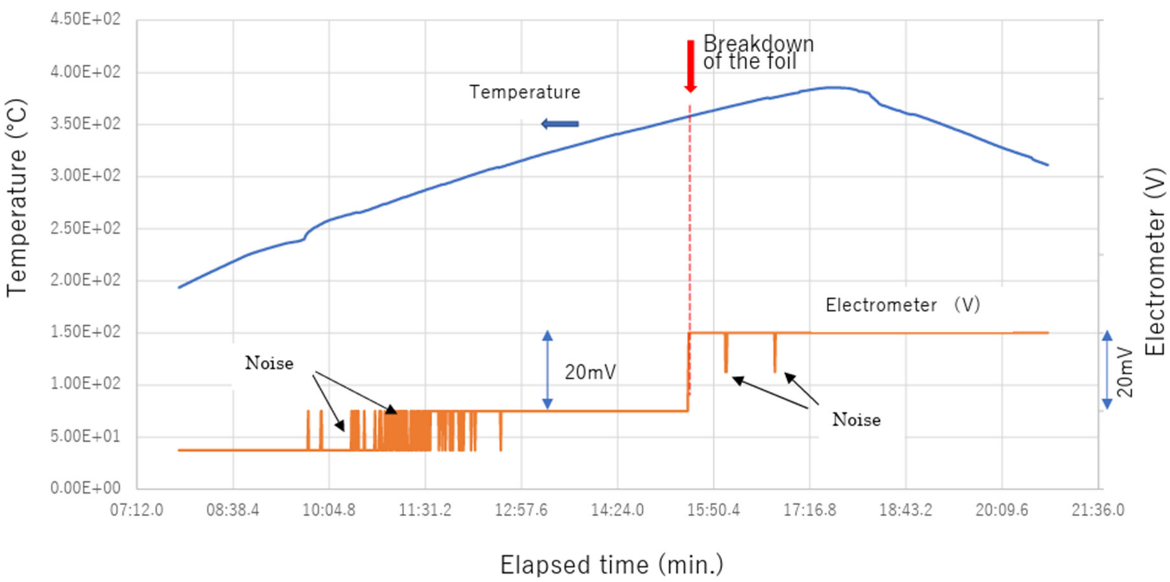

Fig. 3. Time-lapse change of the temperature and the Faraday cage (Electrometer) signal.

Fig. 3 shows the time-lapse change of the temperature and Faraday cage voltage measured by an Electrometer. A slight disturbance in the temperature was observed at around 240°C, and the voltage of the Faraday cage increased by about 10 mV. This could be due to electrical noise to the electrometer. Thereafter, the voltage of the Faraday cage rose by 20 mV stepwise at a temperature at around 350 °C when the aluminum foils broke, and some of the water-clay mixture was ejected and deposited in the Faraday cage as fine particles. The stepwise increase in the voltage indicated 200×10^{-12} C positive charge. The weight of clay particles deposit in the Faraday cage was 9 mg. The charge/unit weight of the clay was 22×10^{-9} C g^{-1}. The measurement was repeated 3 times, and the identical results were obtained. Quantity of the charge obtained in this condition was too small to simulate the charge in the fractured layer to be charged to 300 V. We need to improve the experimental apparatus and the procedure to simulate better for the charging in high temperature and pressure and to conduct the experiment safely.

At least the preliminary experimental results indicated that the clay-water mixture can be positively charged in near supercritical condition.

4. Conclusion

As a potential precursor of intense earthquakes, we consider the charge generated inside a fractured layer that constitute a capacitor will affect the ionosphere. In the fractured layer, water often exists, contained in smectite. Friction in high pressure in the fracture will increase the temperature, and water becomes supercritical state, decreasing the electrical conductivity. The thin fractured layer will become a capacitor with a large capacitance compare with that of the capacitance between the earth surface and the ionosphere. Therefore, the ionosphere will be affected by the voltage of the fractured layer due to the capacitance coupling.

Fine particles are generated in the fractured layer, and the friction in high pressure and high temperature would generate electrical charge, and supercritical condition would hold the charge for a certain period to affect the ionosphere. Using several assumptions, we have estimated the charge and energy stored in the fractured layer are sufficient to cause the downward drift of the ionosphere for 20 km and deceleration of MSTID which are reported as potential precursors.

In order to study the possibility of charging of clay/water mixture in supercritical state, a preliminary experiment was made. The result indicated that the clay acquired positive charge, indicating a possibility of electrification at high temperature and pressure. Further precise experimental verifications are necessary to investigate the level of electrification to support the proposed model of the capacitance coupling of the crust and ionosphere.

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