Int. J. Plasma Environ. Sci. Technol. 19(1) e01012 (7pp) 2025

International Journal of Plasma Environmental Science and Technology

Short Communication

DOI: 10.34343/ijpest.2025.19.e01012

On temperature condition and mechanism of voltage generation for a capacitive coupling model between the ionosphere and a fault layer in the crust with supercritical water

Akira Mizuno, Minghui Kao, Ken Umeno*

Department of Applied Mathematics and Physics, Graduate School of Informatics,
Kyoto University, Kyoto, Japan

* Corresponding author: umeno.ken.8z@kyoto-u.ac.jp (Ken Umeno)

Received: 14 April 2025
Accepted: 25 April 2025
Published online: 14 May 2025

Abstract
The study IJPEST-2024-e1003 proposes a capacitive coupling model between the ionosphere and a fault zone containing supercritical water to explain ionospheric anomalies observed before major earthquakes. It suggests that charge accumulation in a fault layer, acting as a capacitor, can generate an electric field to influence the ionosphere. This mechanism is supported by estimates showing comparable magnitudes of stored electrostatic energy and observed ionospheric changes. The paper also points to the role of charged ultrafine particles, formed through abrupt ion product changes, in generating this charge. In response to criticisms that supercritical conditions are unlikely and that high crustal conductivity would prevent significant charge storage, the authors argue that geothermal conditions at earthquake-prone depths make supercritical water plausible, and that long discharge paths and continuous particle generation near rupture may allow for prolonged charge retention sufficient to affect the ionosphere.

Keywords: Earthquake, supercritical water, electrical charge, lithosphere-atmosphere-ionosphere coupling, ionospheric disturbance.

1. Introduction

Recent advancements in satellite telecommunications have enabled precise measurement of the total electron content (TEC) of the ionosphere, as well as accurate monitoring of Earth's surface movements. Notably, several days or hours prior to large earthquakes, numerous reports have documented ionospheric disturbances, such as changes in TEC, the slowdown of medium-scale traveling ionospheric disturbances (MSTIDs), and a lowering of the ionospheric height.

However, the mechanism underlying the coupling between the lithosphere and the ionosphere remains unclear. We have proposed a model in which supercritical water plays a key role: it infiltrates a fractured layer in the Earth's crust, forming a capacitor-like structure. Nanoparticles generated from ions in the supercritical water are thought to charge this "capacitor" within the fractured zone. This mechanism, along with preliminary experimental results, was presented in [1], which is referred to as [MKU24].

A short communication by Yamazaki [2], referred to as [YK25], offered a critical response, raising objections to the proposed supercritical water mechanism. The key points of [YK25] are as follows:

- Incorrect estimation of the temperature rise inside a fracture layer. T_{correct} rarely reaches 1000 K, and the parameters assumed by MKU24 do not give rise to supercritical water as a result of pre-slip.
- Implausible mechanism for generating a voltage across a fracture layer.

A charge inside a fracture layer cannot cause a voltage across that layer (Fig. 1 (a)). Likewise, a positive charge inside a fracture layer and negative charge outside the layer do not cause a potential difference across the layer (Fig. 1 (b)), only between the inside and outside of the layer. A voltage across the layer is only generated by a separation of charges on either side of the layer, i.e., a positive charge on one side and a negative charge on the other (Fig. 1 (c)).

Before addressing these comments, we acknowledge the interest shown by the author of [YK25] in in our paper [MKU24]. Below is our rebuttal, along with explanations regarding our considerations on the mechanism of charge generation described in [1].

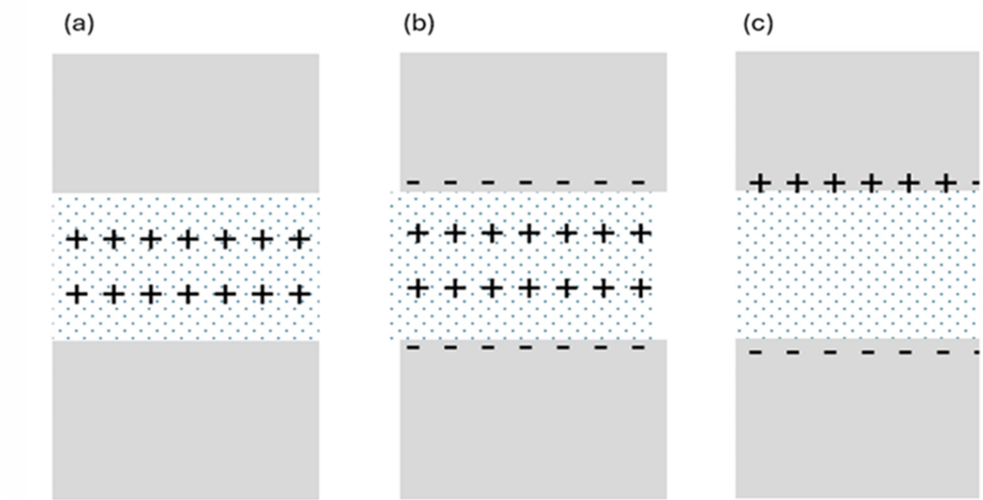

Fig. 1. Three possible distributions of electrical charge. The "+" and "–" symbols represent positive and negative charges, respectively, and the dotted area represents the fracture layer around a fault. (a) Positive charges inside the fracture layer. (b) Positive and negative charges inside and outside the fracture layer, respectively. (c) Positive and negative charges on the upper and lower sides of the fracture layer, respectively. (Reproduced with the permission from IJPEST)

2. Temperature considerations

2.1 Temporal change of the temperature by the friction

If Eq. (2) in [YK25] is correct, then the temperature is given as follows:
(Equation and parameters from [2] are referenced here.)

$$T_{correct} \cong \frac{Q}{\sqrt{kC\rho t_0 \pi}} \tag{1}$$

The parameters are also given in [2] as follows:

$$Q = 4 \times 10^5 \text{ J m}^{-2}, \quad k = 0.6, \; C = 4 \times 10^3 \quad \text{J kg}^{-1}\text{K}^{-1}, \quad \rho = 1 \times 10^3 \text{ kg m}^{-3}, \tag{2}$$

Then,

$$T_{correct} \cong \frac{Q}{\sqrt{kC\rho t_0 \pi}} = 1.45673 \times 10^2 \times \frac{1}{\sqrt{t_0}} \tag{3}$$

As shown in the following graph, the supercritical condition can be achieved during $t_0 < 0.15\ sec.$ In this process. This calculation assumes that the initial temperature is 0 ℃, indicating the possibility of generating a supercritical condition. It should be noted that the actual temperature in deep parts of the crust is much higher than 0 ℃, and the surrounding temperature is a crucial factor in generating a supercritical condition, as discussed in the following Section1.3. Yamazaki [2] neglects the effect of surrounding temperature, which is a significant misunderstanding.

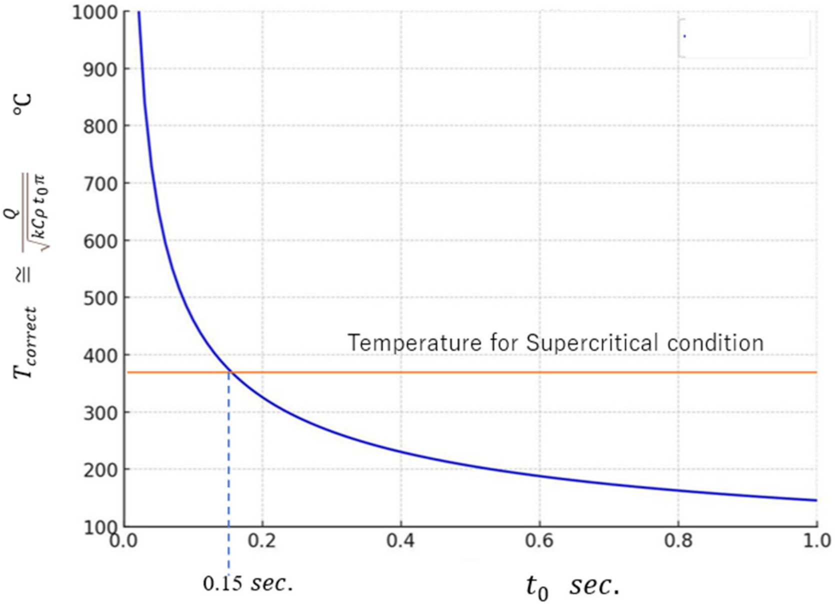

Fig. 2. Calculated time course of the temperature due to friction using the equation provided by [2].

2.2 Temperature in the crust

At depths greater than approximately 15 km, the temperature is expected to be quite high due to geothermal heat, as suggested by the measured geothermal temperature gradient [3−5]. If moisture is present in the crustal fracture zone, it is highly likely to be in a supercritical state. Additionally, when the Earth's crust fractures and shifts, frictional heat is generated. Even if the temperature rise due to frictional heating is small, as pointed out in [YK25], the actual temperature is influenced by the surrounding area. Based on underground temperature gradients, a high-temperature, high-pressure state for supercritical conditions is already present before friction occurs. This contradicts the assertion in [YK25] that a supercritical state is not established. Furthermore, borehole surveys have reported the presence of illite on fractured surfaces, suggesting that smectite may have undergone thermal alteration [6, 7] at high temperatures.

3 Mechanism of voltage generation

3.1 Voltage generation across the fractured layer

Yamazaki [2] claims that voltage across the fractured layer can be generated only in case (c) of Fig. 1. We assume that the primary source of charge is nano-particles generated by a sudden pressure change due to development of a fracture, causing sudden reduction of ion product of supercritical water [8, 9]. At high temperatures, thermal electron emission could occur from nano-particles, leading to diffusive electrons dissipating into the crust while positively charged nano-particles remain in the supercritical water. Additionally, tribo-charging may further increase the charge on the particles. Therefore, we believe that these charged nano-particles could generate voltage across the fractured layer.

In order to consider the charge distribution and the voltage generation, here, consider a simple case that one positive charge Q is existing against an infinite conductive plate, as shown in Figure 3. This figure is often used to explain the image method to calculate the electric field and potential. Potential of the surface of the infinite plane is $V = 0$. For the calculation, an image charge of $-Q$ is placed at the symmetrical position. The voltage at any point P(x, y) is expressed as follows:

$$V(x,y) = \frac{Q}{4\pi\varepsilon_0}\left(\frac{1}{\sqrt{(a-x)^2+y^2}} - \frac{1}{\sqrt{(a+x)^2+y^2}}\right) \quad (1)$$

The equipotential lines are indicated in Fig. 3 [10]. In this configuration, with a ground plate and a point charge, the equipotential lines surround the point charge, meaning a charge near a ground surface will produce a voltage around the charge.

If another electrically insulated plate is introduced near the charge Q, voltage will appear on this floating plate as the equipotential line of the charge reaches it. This simple consideration shows that voltage is induced in a floating plate by a single charge. When multiple point charges exist near an insulating plate, the voltage and electric field result from the superposition of those generated by each individual charge, allowing for induced voltage.

However, the charge distributions in Fig. 1 in Ref. [2] are not properly illustrated. The charge distribution in Fig. 1 (a) is not possible, as induced charge should appear on the surfaces of both the upper and lower electrodes. The charge distribution in Fig. 1 (b) is possible when both the upper and lower electrodes are grounded, in which case a negatively induced charge appears on the surfaces of both electrodes. However, no voltage could appear between the electrodes, as pointed out. It should also be noted that the charge distribution in Fig. 1 (c) is not a possible configuration for a fractured layer to behave as a capacitor, as electrical charge carriers are required to establish a voltage.

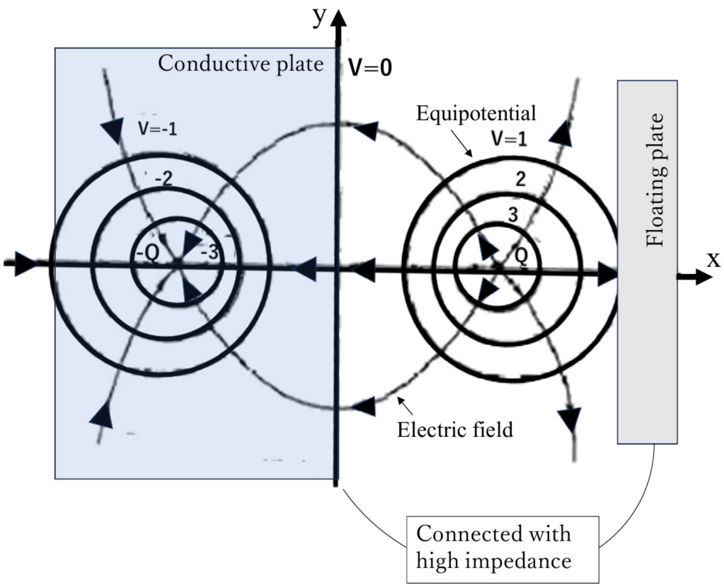

Fig. 3. Equipotential lines and electric field around a charge in front of a conductive plate at $Q/4\pi\varepsilon_0 = 1$ (The original figure is in p.13, Fundamentals of Electromagnetism, University text series, Institute of Electrical Engineer, Japan, Ohm Publishing Co., 1988, in Japanese. The original figure is redrawn and modified by adding the conductive plate and the floating plate.)

3.2 Generation of charged particles during expansion of supercritical water

The ion product of water reaches a maximum at around 250–300°C [8]. If ion-containing supercritical water is present in a crustal fracture, a strong possibility exists that, upon crack formation, this high-temperature, high-pressure ion-containing water rapidly enters the gap, reducing ion products, and forming ultrafine particles [9]. Given that the electrical conductivity of supercritical water is low, the entry of supercritical water into cracks and subsequent formation of ultrafine particles are expected to cause fluid electrification [11] and tribo-charging [12]. When ions in supercritical water precipitate as ultrafine particles, electron emission is likely to occur under high-temperature conditions, leading to predominantly positively charged particles.

3.3 Charge distribution inside a fractured layer

When a fluid containing positively charged particles flows through a thin gap, a negative charge will be induced on the surface of the lower crust, which is connected to the Earth and has a potential of zero because this surface is electrically grounded. Meanwhile, the upper layer is electrically separated from the ground (connected to the ground through the boundary of the fracture, meaning the impedance to the ground is high). Therefore, the upper layer is electrically in a floating condition. Consequently, the positive charge in the flow will charge the upper layer, giving it a positive polarity. The voltage of the upper layer is determined by the integral of the electric field, expressed as div$D = \rho$ (D: electric flux density, ρ: charge density of the space). The charge distribution in this case is illustrated in Fig. 4. A negative charge appears on the surface of the lower crust with $V = 0$. The Earth is regarded as the electrical ground, and the lower crust is connected to this ground. Positive space charge from nano-particles flows in the middle of the fractured layer, and the upper floating layer is charged by the positive charge, resulting in a positive voltage. This charge distribution causes the fractured layer to behave like a capacitor with a voltage across it.

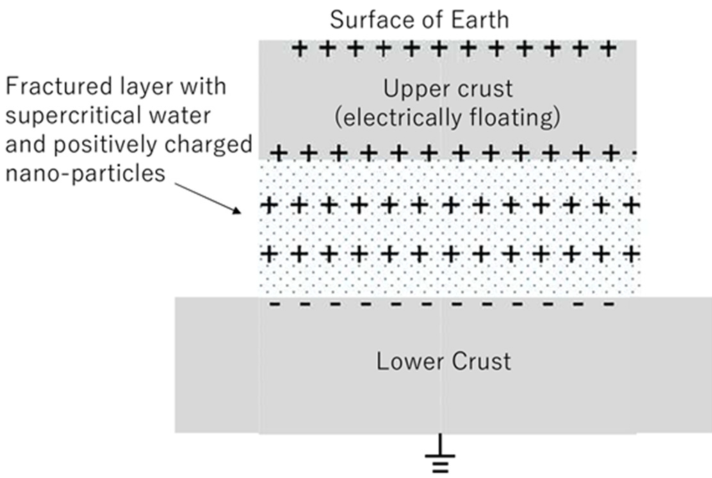

Fig. 4. Schematic charge distribution in the fractured crust.

3.4 Discharge time constant

The electrical conductivity of supercritical water within the fractured layer is low, implying that the charge decay time due to the internal passage of the discharging electric current is long.

Charge dissipation likely occurs through the fringe of the fractured layer, where the capacitance is connected via the conductive crust. Although this peripheral current path in the surrounding crust may cause faster charge dissipation, it does not provide a direct pathway for the charge in the inner part of the capacitor. This is because the length of the electric field increases, as expected from the typical pattern of the electric field at the fringe of a capacitor, as indicated in Fig. 5, showing that the length of the electric field lines connecting the parallel electrodes increases with distance from the edge. A longer path along an electric field line for discharge significantly increases electrical resistance, resulting in a long time constant for charge dissipation.

In addition, the electrical conductivity around the fractured crust remains unknown. The electrical conductivity is sensitive to the water content in the crust, and at this stage, it is difficult to estimate an accurate value for the electrical conductivity [14−16]. Therefore, the discharge time constant is still not well predicted. Further investigations are necessary to determine the electrical properties of the underground crust.

3.5 Possibility of continuous charging

Fractures expand before the major rupture of the crust. During this period, the fractured zone is expanding, and supercritical water containing ions may generate charged nano-particles. If continuous electrification occurs during the propagation of the fractured zone, a longer charge decay time could be expected. To clarify the mechanism of charge generation, further experimental verification is needed. It should also be noted that excess charge will dissipate via electrical breakdown within the layer. This electrical breakdown can generate electromagnetic waves, which have been reported as precursors to large earthquakes.

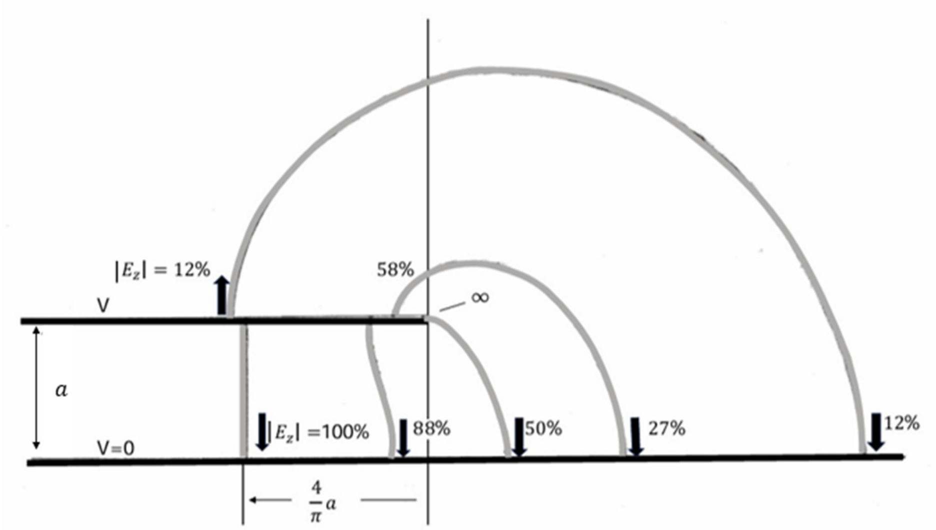

Fig. 5. Example of electric field lines of a fringe of a plate electrode with potential of V, placed in parallel to the ground electrode with distance a. Ez is the electric field strength, and is expressed as a relative value (%) when V/a = 100%.
(This figure is the modification of the figure 66 of Ref.[13].

4. Conclusion

The assertion in [2] does not consider geothermal heating in the crust. Even without this consideration, a supercritical condition is possible according to the equations provided in [2]. Accounting for geothermal heating, the supercritical condition is established with high probability.

Charged particles carry positive charge, which can establish voltage across the fractured layer. The plausible charge distribution is depicted in Figure 4.

At this stage, there is uncertainty of the conductivity of the crust, especially that of the peripheral of a fractured layer where discharging current flows, therefore, estimation of the discharge time constant is difficult.

Prior to a major crustal breakdown, fractures expand, and charged particles may continuously be generated. This continuous generation may allow for a longer charge decay time, affecting the electric field in the ionosphere.

The mechanism of charged particle generation in supercritical conditions is not yet fully understood, and further research is required to clarify this phenomenon.

References

[1] Mizuno A., Kao M., and Umeno K., A capacitive coupling model between the ionosphere and a fault layer in the crust with supercritical water, *Int. J. Plasma Environ. Sci. Technol.*, Vol. 18 (1), e01003, 2024.

[2] Yamazaki K., Comment on "A capacitive coupling model between the ionosphere and a fault layer in the crust with supercritical water" by Mizuno *et al.*, *Int. J. Plasma Environ. Sci. Technol.*, Vol. 19 (1), e01012, 2025.

[3] Batir J.F., Blackwell D.D., and Richards M.C., Heat flow and temperature-depth curves throughout Alaska: finding regions for future geothermal exploration, *J. Geophys. Eng.,* Vol. 13, pp. 366−378, 2016.

[4] Kolawole F., and Evenick J.C., Global distribution of geothermal gradients in sedimentary basins, *Geoscience Frontiers,* Vol. 14, 101685, 2023.

[5] Tanaka A., Yamano M., Yano Y., and Sasada M., Geothermal gradient and heat flow data in and around Japan (I) Appraisal of heat flow from geothermal gradient data, *Earth, Planets and Space,* Vol. 56, pp. 1191−1194, 2004.

[6] Kimura G., Hamada Y., Yabe S., Yamaguchi A., Fukuchi R., Kido Y., Maeda L., Toczko S., Okuda H., and Ogawa N., Deformation process and mechanism of the frontal megathrust at the nankai subduction zone, *Geochem. Geophys. Geosystems,* Vol. 23 (4), e2021GC009855, 2022.

[7] Sugiyama Y., Ebishu K., Iizuka A., Kawai K., and Sasaki Y., Modeling of shere failure of the plate boundary decollement zone, *Jpn. J. JSCE A2,* Vol. 71 (2), pp. I_605−612, 2015. (in Japanese)
[8] Ono T., and Inomata H., Supercritical water -properties and applications-, *Jpn. J. Appl. Phys.,* Vol. 80, pp. 875−880, 2011.
[9] Yoko A., Seong G., Tomai T., and Adschiri T., Continuous flow synthesis of nanoparticles using supercritical water: Process design, surface control, and nanohybrid materials, *KONA Powder and Particle Journal,* Vol. 37, pp. 28−41, 2020.
[10] Kouno T., and Katsurai M., *Basics of Electromagnetism*. Tokyo: Insttute of Electrical Engineers Japan, OHM Publishing Co., 1988.
[11] Touchard G., Flow electrification of liquids, *J. Electrostat.,* Vol. 51−52, pp. 440−447, 2001.
[12] Matsuyama T., and Yamamoto H., Maximum electrostatic charge of powder in pipe flow, *J. Soc. Powder Technol,* Vol. 45, pp. 373−379, 2008.
[13] Prinz H., *Hochspannungsfelder*. Wien: R. Oldenbourg Verlag Nunchen, 1969. , (Japanese translation by Masuda S. and Kouno T., Asakura publishing, 1974)
[14] Fujita T., Fujimitu Y., Akibayasi S., Kosukegawa Y., Yamamoto Y., and Mizuta T., Experimental study on temperature dependence of resistivity of dried rocks, *J. Geothermal Res. Soc. Jpn.,* Vol. 17, pp. 111−121, 1995. (in Japanese)
[15] Yoshino T., Research on core and mantle dynamics based on the electrical conductivity of materials of the Earth and planetary interior, *Jpn. Magazine of Mineralogical and Petrological Sci.,* Vol. 53 (1), pp. 1−16, 2024.
[16] Ueshima M., Estimation of water volume fraction in the crust from electrical conductivity structure, *J. Geography,* Vol. 114, pp. 862−870, 2005.