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Electric Displacement by Earthquakes

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1. Introduction

Electromagnetic emission in the atmosphere usually occurs in relation with charge acceleration between clouds and the Earth's surface. Lightning is the best known electromagnetic emission in nature and takes place in thunderstorms. We can also ask the question, if it is possible to have electromagnetic emission -for example, a flash of light- in the atmosphere originating in the Earth´s interior. The answer is affirmative and in this chapter we will try to describe some theories about it.

2. Electromagnetic observations

Electromagnetic emission is a secondary effect which can take place in the atmosphere caused by earthquakes (Richter 1958). Among the secondary effects of earthquakes electromagnetic emission is the brightest area of seismology. In the report on the great Chilean earthquake of 1960, Warwick associated 18 MHz radio emission (Fig. 1.) with rock fracture (Warwick et al. 1982). The first evidence with hard data of co-seismic electromagnetic radiation was found during the Matsushiro earthquake swarm between 1965 and 1967 in Japan. Color and black and white photographs were taken by many observers and reproduced by Derr (Derr 1973). One of these photographs is shown here (Fig. 2.). An excellent film of earthquake lights was made during the Peruvian earthquake of 15 August 2007 (Fig. 3.) by a television cameraman, http://www.youtube.com/watch?v=SHmHsP1gd8I. We found a time difference correlation between seismic waves and light flashes in Lima, 150 km from the epicenter (Lira 2008; Heraud and Lira 2011).

3. Theories of earthquakes lights

One of the older theories to explain the relation between earthquakes and light emissions is the piezoelectric theory, due to Finkelstein (Finkelstein et al. 1973). This theory involves the idea that earthquake lightning could be caused by piezoelectric fields produced in rocks by seismic waves. This piezoelectric theory has several disadvantages: first, the electrical resistivity of the rock would need to be of the order of 10^9 Ωm. Second, high-frequency pressure waves would be necessary. Third, as an alternative it would be necessary to have localized high-conductivity channels in high-resistivity surroundings from rock layers at depths of the order of 10 km to Earth's surface.

Mitzutani proposed an electrokinetic theory to provide a possible means of earthquake prediction (Mitzutani et al. 1976). Diffusion of fluid through rocks into a dilatant focal
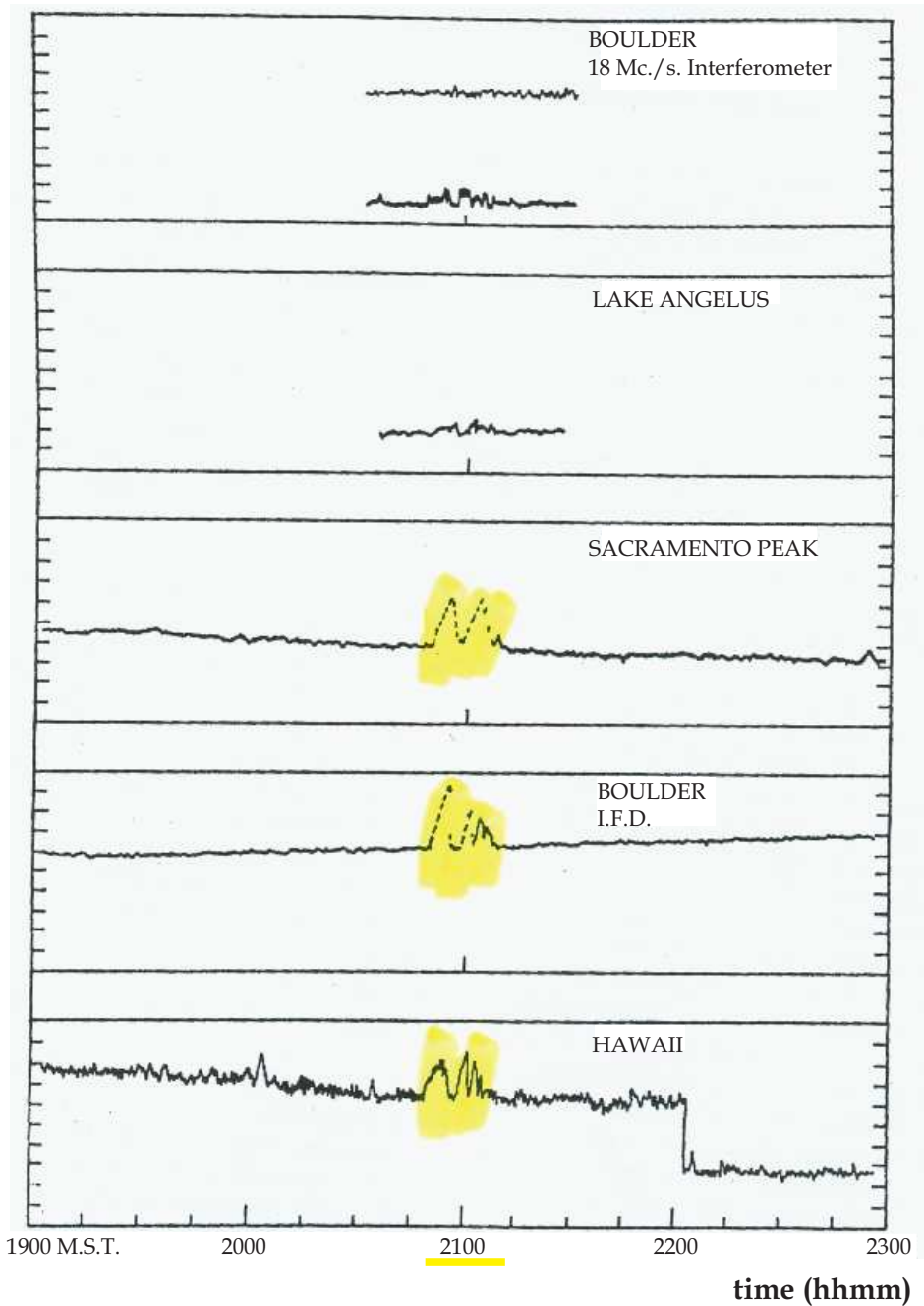
Fig. 1. Radio emission seen 6 days prior to the great Chilean earthquake of 1960 (Warwick et al. 1982)

region preceding or following an earthquake would cause significant variation of electric field near the focal region and may be related to earthquake lightning. Mitzutani obtained

$$\text{grad } V \,/\, \text{grad } P = 10^2 \text{ - } 10^3 \text{ volt/kbar,} \tag{1}$$

where V is the streaming potential and P the pressure of the fluid (Fig. 4.). For a M6.4 earthquake he estimated

$$\text{grad } P = 1 \text{ - } 10^2 \text{ bar/km} \tag{2}$$

So we have an electric potential gradient of 1 - 1000 volts for 10 km, the linear dimension characteristic to the earthquake. This voltage is not big enough for earthquake lightning.

Fig. 2. Photograph of a light in the sky during the Matsushiro earthquake swarm between 1965 and 1967 (Derr 1973)
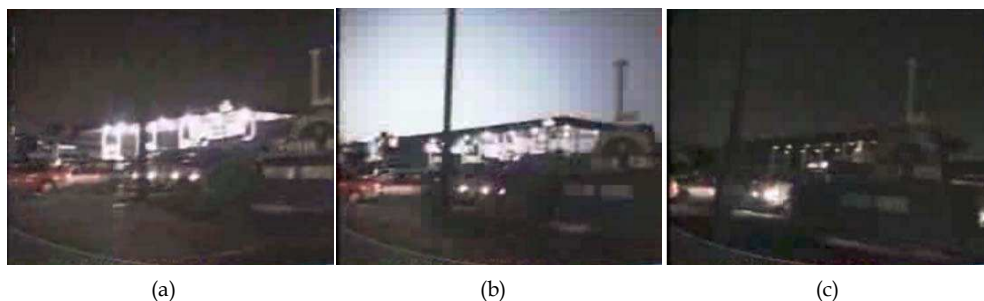

| (a) | (b) | (c) |

Fig. 3. Lights in the sky of Lima filmed during the Peruvian earthquake of 2007. (a) Before a light. (b) During a light. (c) After a light. (Lira 2008)

Lockner proposed a friction-vaporization theory to explain the generation of earthquake lights (Lockner et al. 1983). In this theory a central conductor, a few centimeters wide on the fault axis surrounded by a low conductivity sheath of rock containing vaporized pore water arises through the earthquake. This central conductor would collect charge in the shear

zone, and because it is hundreds of meters deep and only some centimeters wide, it will concentrate the charge along its edges, where the curvature is at its highest. If the conductor is shallow enough, the charge concentrated along its top edge would produce an intense electric field at the Earth's surface, and would induce coronal discharge. This theory has a problem: if the high heated vaporized water reaches the Earth's surface it will come out like a steam jet, even though no reported observation has ever confirmed this. However, water vapour expelled at Enceladus, a satellite of Saturn, was photographed 2009 by the Cassini spacecraft, as shown in Fig. 5. and reported from Hartogh (Hartogh et al. 2011).
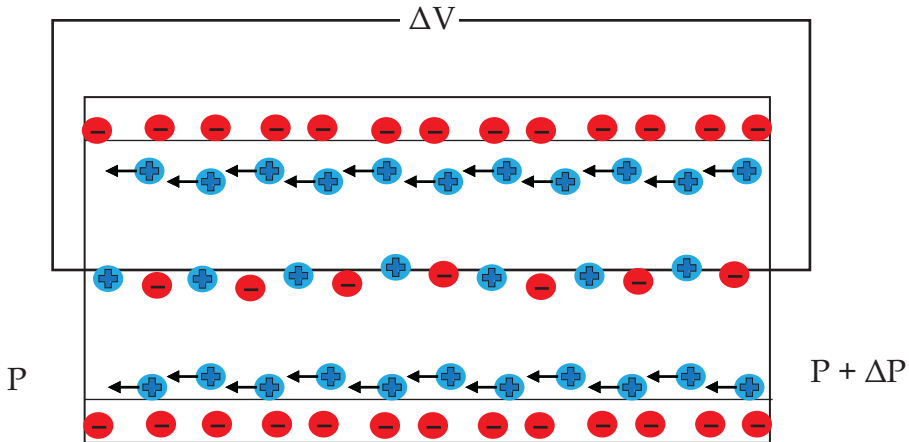

Fig. 4. Potential difference ΔV and pressure difference ΔP in a capillary
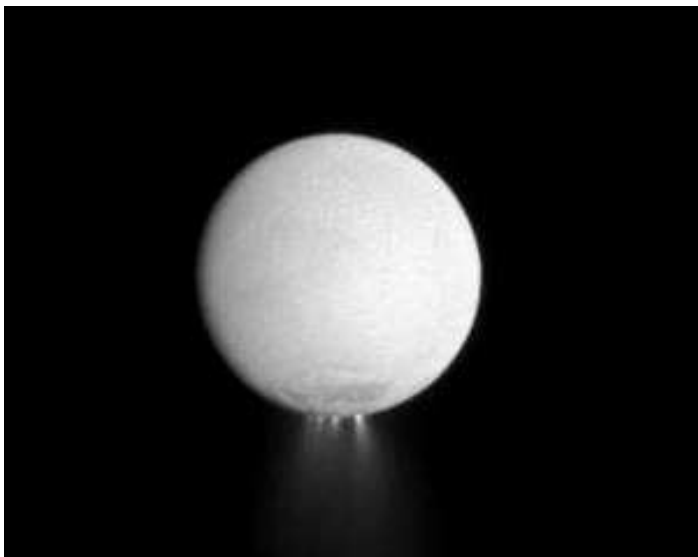

Fig. 5. Photograph of vapour water jets at Saturn's satellite Enceladus, taken by the Cassini spacecraft (Photo: NASA/JPL/Space Science Institute)

One of the more sophisticated theories to account for the electrification of the Earth's surface by earthquakes, is that of F. T. Freund (Freund 2007). In this theory the Earth's crust works like a semiconductor diode and the physical "battery" is driven by pressure. Positive holes and electrons are the charge carriers, and they are activated when rocks are subjected to stress, as shown in Fig. 6. The interesting part is that the flow of positive holes, thus generated, occurs also through the uncompressed rock beyond the stressed volume and flow by diffusion even through gravel and sand. According to Freund, his model still does not address the case of faults filled with water.
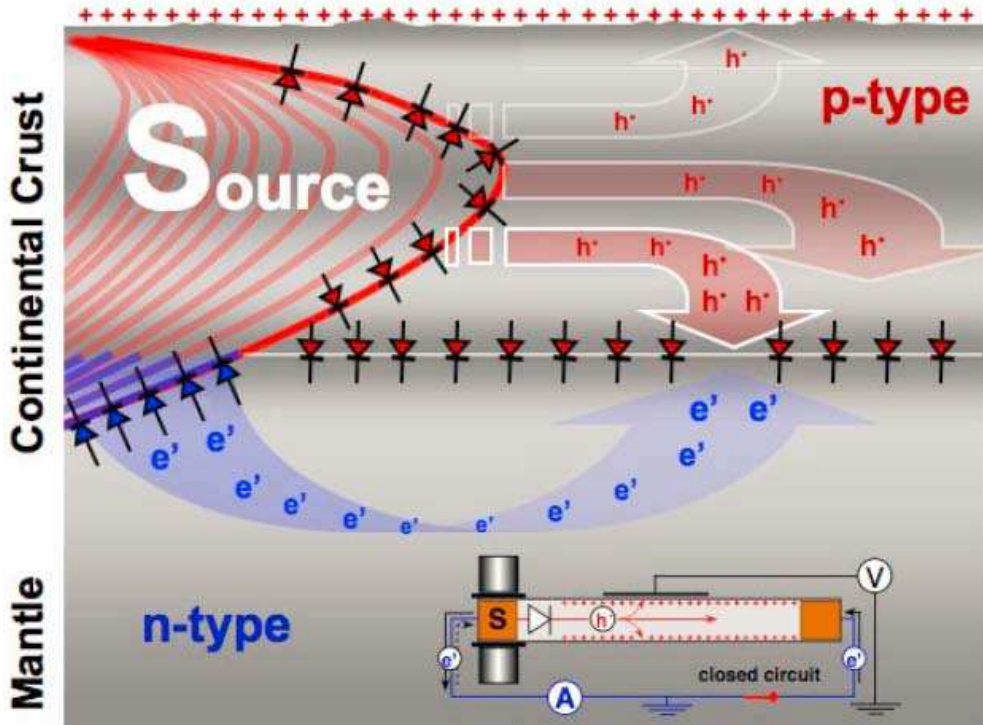

Fig. 6. Freund's theory for the generation of positive holes (Freund 2007)

4. Laboratory investigation of electromagnetic emission by earthquakes

Laboratory experiments show that pressure on rocks produces an electrical potential (Freund 2003) and electromagnetic radiation (Brady and Rowell 1986), as shown in Fig. 7.

As seen in the last section, different theories have been proposed to explain the electrification of the Earth's surface by earthquakes, but the actual process in the crust of the Earth remained unknown until Akihiro Takeuchi, at an underground mine in Japan, observed electrification on the floor of a gallery at the arrival of seismic waves (Takeuchi et al. 2010), as schematically shown in Fig. 8. He discovered, that the arrival of S waves is synchronized with an electric pulse, that flows across the internal resistance of a voltmeter, as shown in Fig. 9.
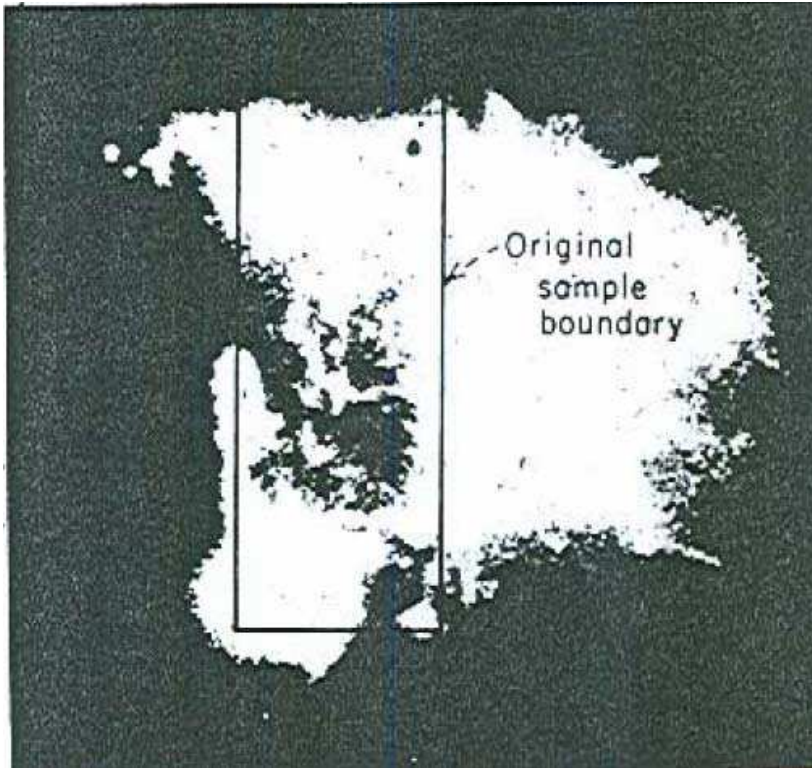
Fig. 7. Light emission from rock fracture (Brady and Rowell 1986)
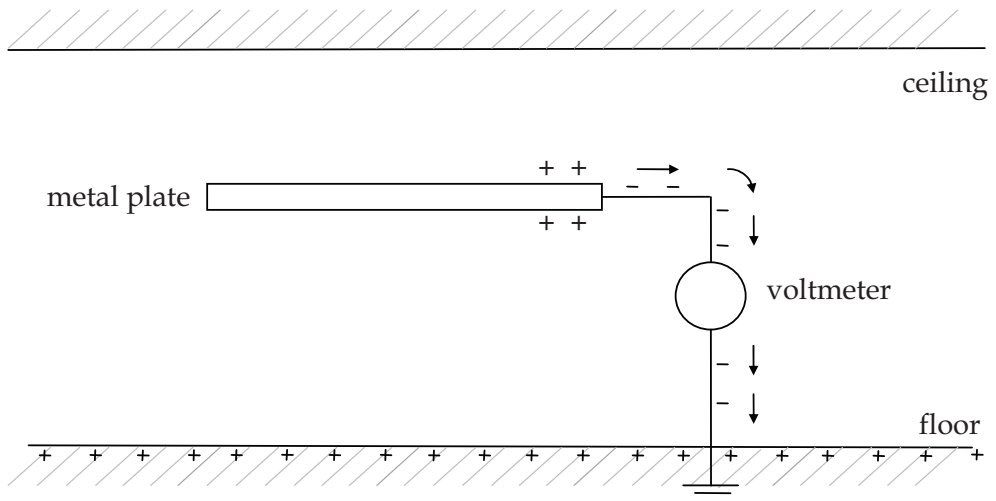

Fig. 8. Measuring the electrification on the floor of an underground mine gallery through a voltmeter at the arrival of seismic waves
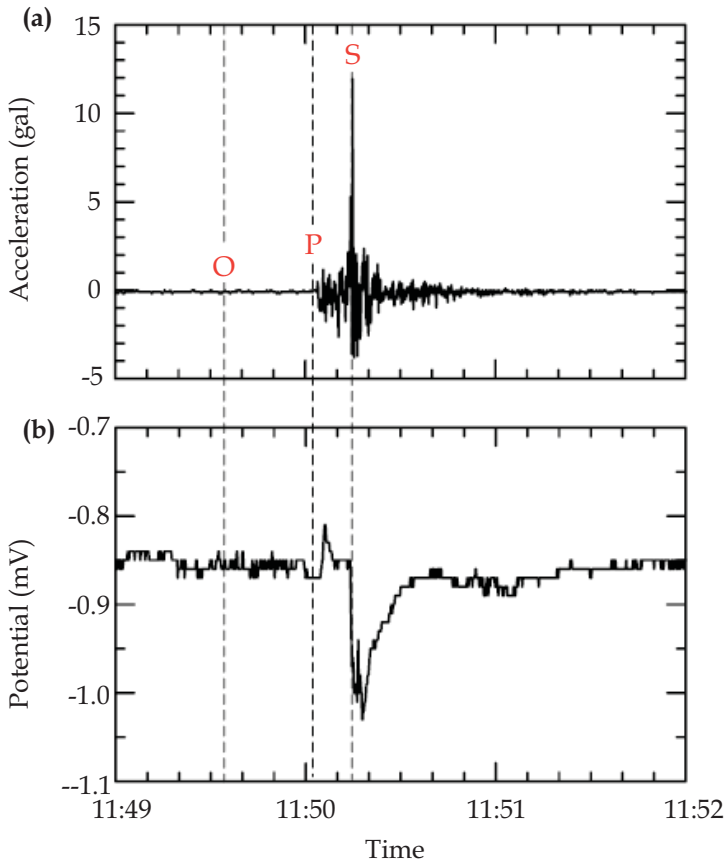
(a)

(b)

Fig. 9. Electric pulse (b) detected at the arrival of a S wave (a) (Takeuchi et al. 2010)

5. Electric currents in the crust of the Earth

The crust of the Earth is composed of a great variety of igneous, metamorphic and sedimentary rocks. The electrical resistivity of crustal rocks may vary over several orders of magnitude ($10^{-1} – 10^5$ Ωm), as shown in Fig. 10., depending on a wide range of petrological and physical parameters.

From an electrical point of view we will suppose that the Earth´s crust consists of a number of plane strata of different materials. In this case, insulators and imperfect conductors form a series electrical circuit, and the total electric resistance becomes

$$R_T = \sum R(\text{insulators}) + \sum R(\text{imperfect conductors}) \qquad (3)$$

Under the action of external electric forces no conduction current is produced, except when disruptive discharge occurs. We shall now suppose, for the sake of simplicity, that the Earth's crust consists of an isotropic homogeneous insulator with permittivity ε, and that in the interior of the Earth, at a distance d away from the Earth's surface, an electric charge q is

generated due to an earthquake, which we would consider as a point charge, as shown in Fig. 11.
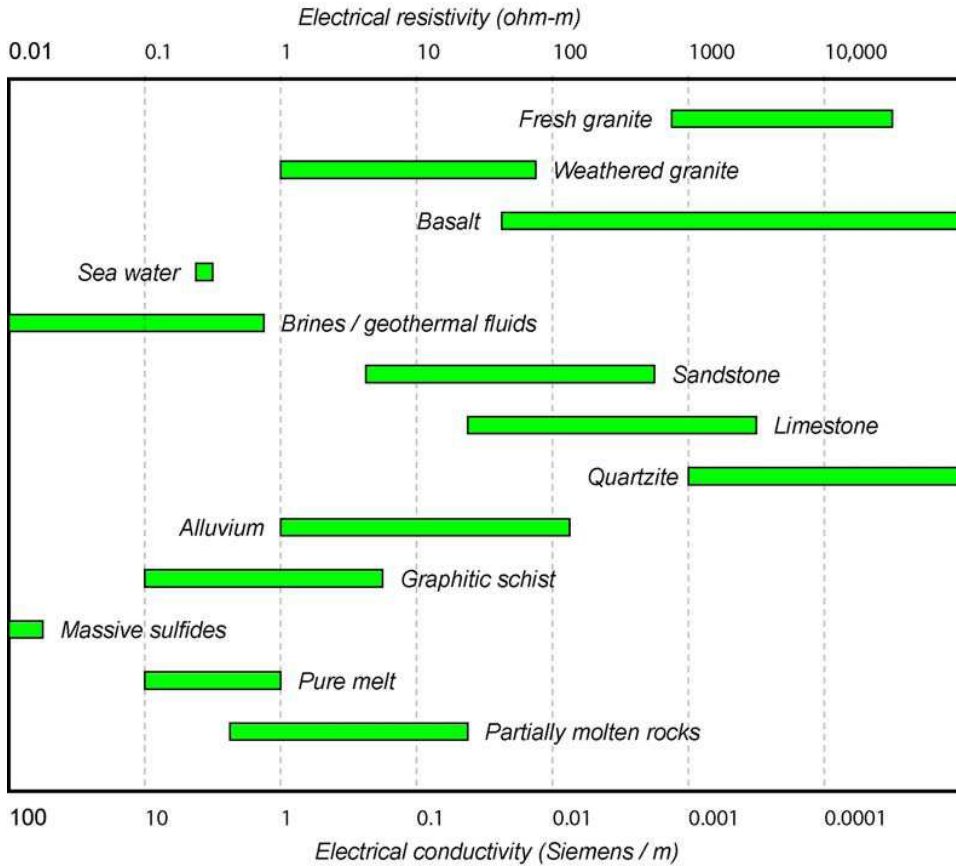

Fig. 10. Electrical resistivity of rocks (Geophysics 2009)

The electric field of the charge q can not produce conduction current through the Earth, but the electric charge is displaced within the Earth generating a polarization charge on the Earth's surface. The polarization charge density at a point P on the Earth's surface is:

$$\sigma_{pol} = q \, \varepsilon_0 \, (\varepsilon - \varepsilon_0) \, d \, / \, 2\pi \, \varepsilon \, (\varepsilon + \varepsilon_0) \, (d^2 + r^2)^{3/2} \tag{4}$$

where ε_0 is the permittivity of free space and approximately that of the atmosphere, and is given by

$$\varepsilon_0 = 8.85 \times 10^{-12} \; C^2/Nm^2 \tag{5}$$

The displacement of the electric charge evidently constitutes an electric current, which is produced as the orbits of the electrons are displaced to some extent under the influence of the electric field of the charge q. This current, however, can only exist until the electric

charges reach the Earth's surface. The electric polarization at the surface of the Earth disappears when the electric charge in the interior of the Earth is removed.
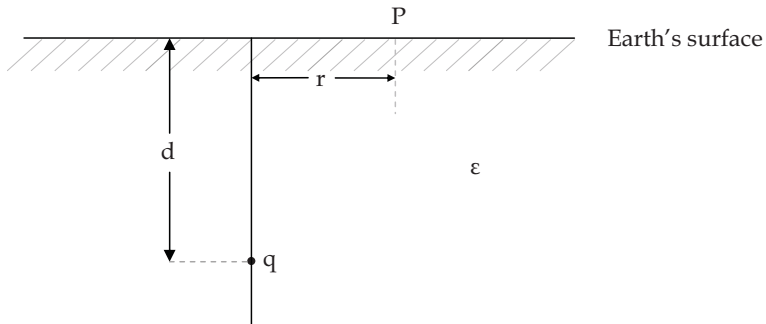
atmosphere

Fig. 11. Point charge q embedded in the interior of the Earth

A negative point charge –q embedded in the interior of the Earth would induce a negative charge distribution on the Earth's surface, as shown in Fig. 12. The lines of force are shown qualitatively in Fig. 13. The electric field strength on the Earth's surface is:

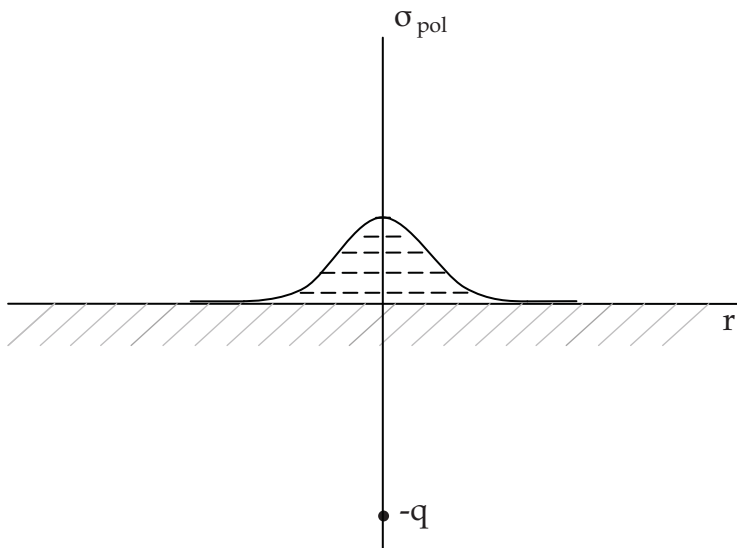$$E = q \, / \, 4\pi \, \varepsilon_0 \, (d^2 + r^2) \tag{6}$$

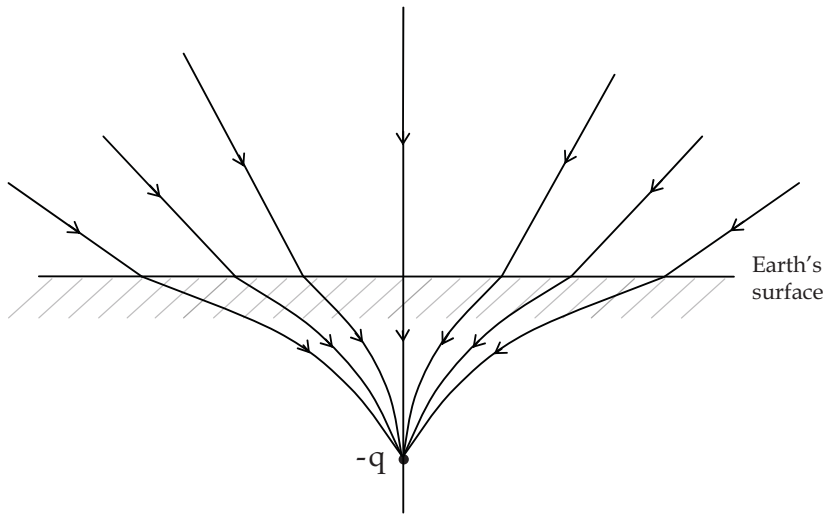Fig. 12. The distribution of polarization charge on the Earth´s surface due to a point charge -q in its interior

Fig. 13. Lines of force for a point charge -q in the interior of the Earth

Then σ_{pol} and E have their maximum values on the Earth's surface directly above the charge –q for r=0. The electromagnetic emission in the atmosphere is produced if at any point of the Earth's surface a limit of the electrical potential is reached at which a sudden electrical discharge through the atmosphere occurs.

6. Experiments on the electric displacement of soil, water and granite

Here, we report experimental research to explain how electric charge can be generated on the Earth's surface by earthquakes.

In the first experiment a dry soil block, 4 centimeters high, 10 centimeters wide and 8 meters long, is perfectly discharged. Then, one end of the block is charged with an electrical induction machine, as shown in Fig. 14. We could detect with an electroscope a polarization charge at the surface of the block until a distance of 5 meter.

Fig. 14. A polarization charge is induced at the surface of a dry soil block

In the second experiment a vessel, 14 centimeters high and with a diameter of 25 centimeters, filled with distilled water is perfectly discharged. Then, the bottom of the vessel is connected by a wire to the machine and charged, as shown in Fig. 15. With the electroscope we found a polarization charge at the surface of the water.
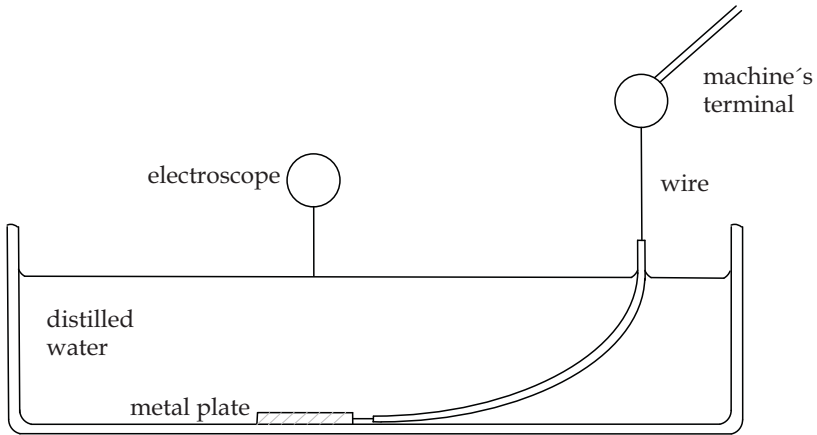
Fig. 15. A polarization charge is induced at the surface of distilled water

In the third experiment a red granite block, 2 centimeters high, 10 centimeters wide and 16 centimeters long, is perfectly discharged. Then, the upper surface of the block is connected by a wire to the machine and charged, as shown in Fig. 16. Again, we could detect a polarization charge at the lower surface of the block with the electroscope.
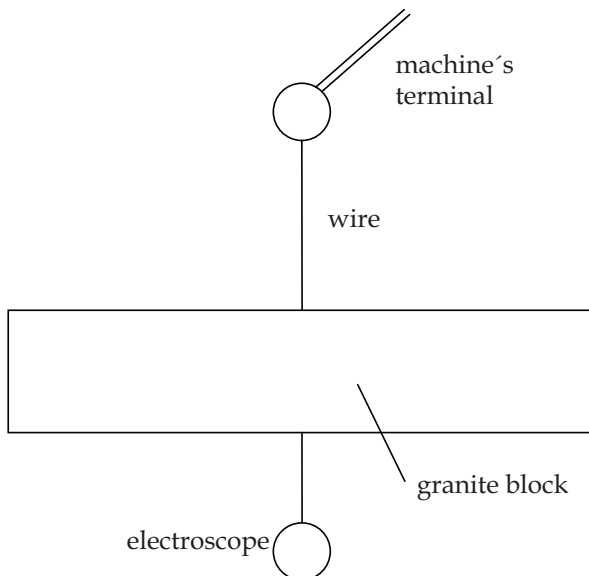
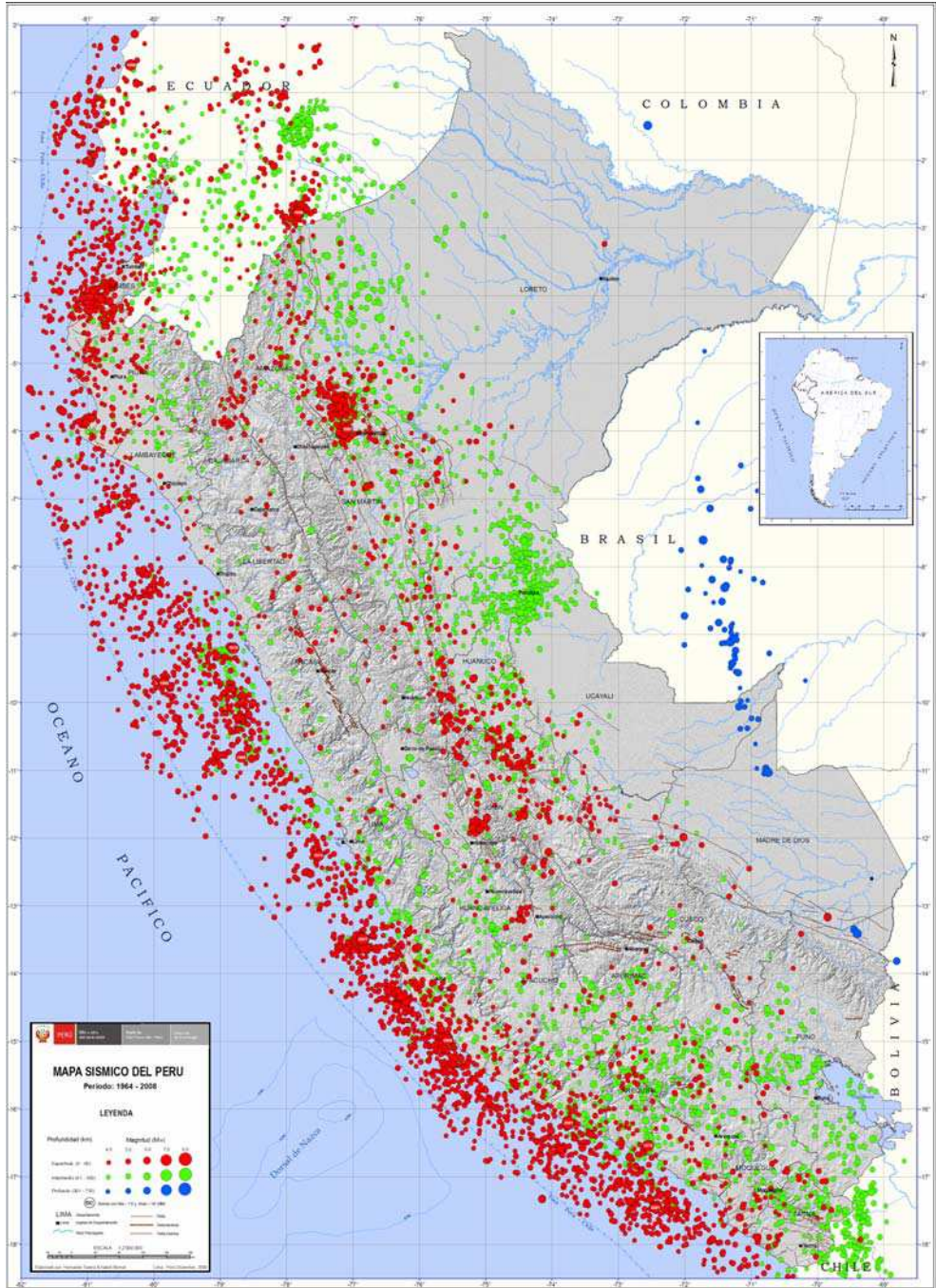Fig. 16. A polarization charge is induced at the lower surface of the granite block

Fig. 17. Seismicity of Peru (Tavera and Bernal 2009)

7. Conclusions

Table 1. gives the dielectric constants of soil, water and granite. Using these, we would expect a surface polarization charge under the action of an electric field in these materials. In all studied cases our experimental researches confirmed this.

	Dielectric Constant, $\kappa = \varepsilon / \varepsilon_0$
Dry soil	14
Distilled water	81
Red granite	5

Table 1. Material characteristics

Using the relation (6), we could expect electrical discharge through the atmosphere if the interior of the Earth is charged with electricity according to

$$q / 4\pi\varepsilon_0 d^2 \geq 3 \, (10^6) \, \text{V/m} \tag{7}$$

Using the relation (4), we would also expect electrical discharge through the atmosphere if the polarization charge at the Earth's surface is

$$\sigma_{pol} \geq [0.53 \, (10^{-4}) \, \varepsilon_0 \, (\varepsilon - \varepsilon_0) \, / \, \varepsilon \, (\varepsilon + \varepsilon_0)] \, \text{C/m}^2 \tag{8}$$

Although the upper crust of the Earth can contain an insulator stratum, it is possible to have electric currents due to induction phenomena. A polarization charge can therefore be generated at the Earth's surface, it is only necessary that somewhere in the interior of the Earth is charged with electricity, and this can occur with an earthquake.

8. Future research

Considering the seismicity of Peru (Fig. 17.), we observe that the shallow earthquakes (depth < 60 km) take place near the coast (red dots). Light emissions during the Peruvian earthquake of 2007 were also observed in this area. These facts may be correlated in so far as the nearer the electric charge q is to the Earth's surface, the bigger is the polarization charge density as well as the electric field strength on the Earth's surface.

One next step is to conduct an experiment, that connects a grounded rod to an electroscope in order to detect the surface polarization charge during an earthquake at the San Lorenzo Island (situated 4 km in front of Lima's coast), where pre-seismic and co-seismic luminescence have been reported.

9. Acknowledgment

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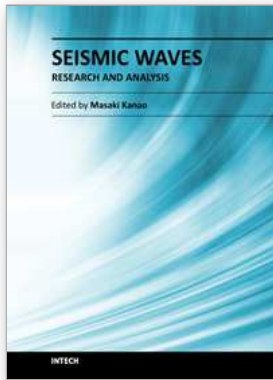
Seismic Waves - Research and Analysis

Edited by Dr. Masaki Kanao

The importance of seismic wave research lies not only in our ability to understand and predict earthquakes and tsunamis, it also reveals information on the Earth's composition and features in much the same way as it led to the discovery of Mohorovicic's discontinuity. As our theoretical understanding of the physics behind seismic waves has grown, physical and numerical modeling have greatly advanced and now augment applied seismology for better prediction and engineering practices. This has led to some novel applications such as using artificially-induced shocks for exploration of the Earth's subsurface and seismic stimulation for increasing the productivity of oil wells. This book demonstrates the latest techniques and advances in seismic wave analysis from theoretical approach, data acquisition and interpretation, to analyses and numerical simulations, as well as research applications. A review process was conducted in cooperation with sincere support by Drs. Hiroshi Takenaka, Yoshio Murai, Jun Matsushima, and Genti Toyokuni.

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