

## 前駆微小破壊：室内岩石 AE 実験による洞察 Microcracks preceding ruptures: insights gained from laboratory acoustic emission study

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Earthquakes in the crust are caused by the rapid shear fracture of a fault. Thus, understanding the source processes of earthquakes relies on the understanding of shear fracturing in rocks. Abundant experimental evidence shows that macroscopic shear fracturing within rocks and other brittle materials does not occur by the growth of a single shear crack in its own plane. Rather, it is preceded by a very complex pervasive evolution of some pre-failure damage. Therefore, studies focusing on both fracture dynamics and pre-failure damage are a subject of interest in seismology. Fracturing dynamics and the pre-failure damage can be inferred from AE statistics as the number of AE events is proportional to the number of growing cracks, and the AE amplitudes are proportional to the length of crack growth increments in the rock. Therefore, the AE technique, which monitors the spatiotemporal distribution of AE events, is applied to the analysis of the micro-cracking activity inside the sample space, and it can be performed under an artificially controlled pressure, which is very important for the simulation of underground conditions.

The fracture of intact rocks as well as rocks containing natural structures (joints, faults, foliations) under constant stress rate loading or creep conditions is generally characterized by typical stages with different underlying physics. Through an integrated analysis of several AE statistics obtained from AE data collected with the high-speed AE waveform recording system, a three-phase pre-failure-damage model has been proposed and further enforced with new data. The primary phase reflects the initial rupture of pre-existing microcrack population in the sample or in the fault zone. Sub-critical growth dominates the secondary phase. The third phases termed nucleation phase corresponds to the initiation and accelerated growth of the ultimate fracture. In earthquake seismology, researchers have a special interest with the nucleation phase since faulting nucleation governs the predictability of earthquakes.

Lithology, density and size distribution of pre-existing cracks, meso-scale and macro-scale heterogeneities all have an overall role in AEs. There are some cases in which some phases are not clear. In general, homogeneous (both fine-grained and coarse-grained) rocks with pre-existing cracks likely show all phases. Heterogeneous or weak rocks such as S-C cataclasite normally show a lack of the primary phase. Samples with few pre-existing cracks and samples containing optimally oriented weak structures, likely show an unpredictable fracturing behaviour as well as a lack of primary and secondary phases, in addition the nucleation phase has a small number of AEs.

Rules obtained at the laboratory scale are helpful for understanding natural earthquakes on a significantly larger scale. However, we cannot simply bridge laboratory scale to a scale several orders larger. At every step up from a smaller scale to a larger scale, we encountered something different. The difference could be small for each step but, after many steps, we could see something quite different. Studies on all scales are important. Quantitative investigation of rock fracture using AE techniques is still an interesting field for the future. On one hand, it may shed some light on earthquake seismology. On the other hand, it may provide a fundamental technical background promoting applications including: enhanced geothermal systems (EGS), extraction of shale gas and core bed gas, and CO<sub>2</sub> geological storage. The latter of which involves fluids being intensively pumped into the deep Earth under high pressure; injection-induced earthquakes would be a problem that must be well-addressed.

キーワード: AE, 微小破壊, 前駆ダメージ, 断層核形成

Keywords: Acoustic emission (AE), Microfracture, Pre-failure damage, Fault nucleation

## 種々の物質の摩擦・衝突による電波発生状況 Radio wave emission in friction or collision of various materials

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### 1. Introduction

In fracture of rock, radio wave emission was found experimentally [1]. This phenomenon could be used to detect a rock fracture during an earthquake or a volcanic activity [2] [3]. The cause of the radio wave is expected to be micro-discharges, which are generated by an inhomogeneous potential distribution around micro-cracks [4]. However, the theory of emission is not completely understood yet.

In order to clarify the cause of radio wave emission, we carried out experiments to detect the emission in the cases of friction or collision of various materials. This paper describes the experimental results, and a brief explanation of physical process.

### 2. Tested systems and experimental results

We tested the following systems using the manufactured measuring system at 1 MHz, 300 MHz, 2.0 GHz, and 18.8 GHz [5].

#### (1) A lighter using piezoelectricity

This device makes sparkles by knocking a mineral with piezoelectricity. Due to discharges, strong radio wave is emitted, and detected in our measuring system.

#### (2) A lighter using friction of OL metal

Formerly, this type of a lighter was widely used for igniting cigarettes. The alloy metal of cerium and iron rubs a revolving drum so that sparkles are made changing the friction power to thermal energy. Despite significant sparkles, radio wave could not be detected in this case.

#### (3) Igniter using a flint stone

A flint stone is struck against iron pyrites so that small flakes of iron are scattered being made hot. The flint stone is mostly chert in Europe, and quartz, sanukite, or obsidian in Japan. Sparkles cannot be made by striking two bulks of flint each other. Radio wave is not emitted in this case.

#### (4) Striking a steel lump with a steel hammer

Radio wave is emitted in this case. Probably, the kinetic energy is converted not to thermal energy but to the excitation of electrons or atoms so that inhomogeneous potential distribution is realized.

### 3. Conclusions

In general, sparks are not the origin of radio wave emission. This emission is esteemed a non-thermal phenomenon. An inhomogeneous potential distribution makes micro-discharges that emit radio waves. In some cases, the cause of an inhomogeneous potential distribution makes the sparks.

Further study is needed to clarify the mechanism of the energy transfer to electron excitation.

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Keywords: radio wave, friction or collision, various materials, electrical discharge, micro-crack, non-thermal phenomenon

## Seismoelectric phenomena of electrokinetic nature associated with the formation of cracks in porous media

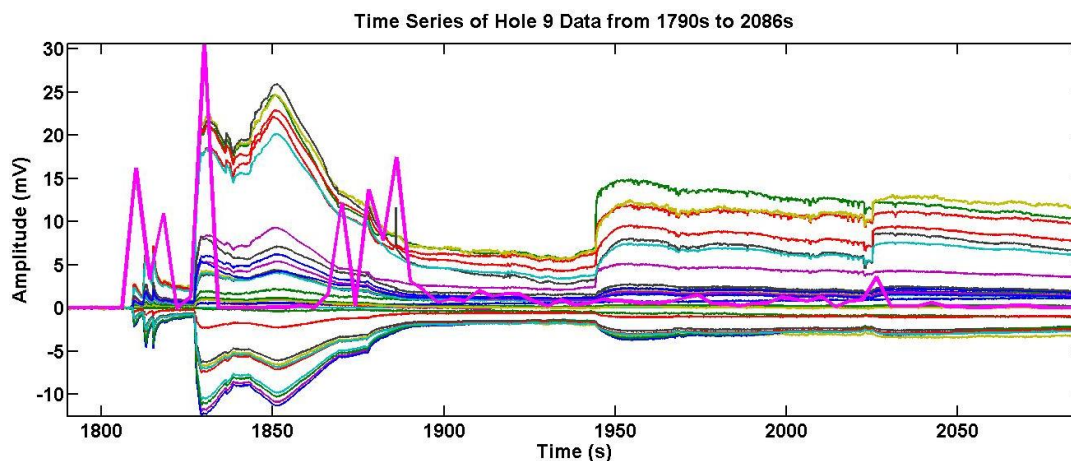
### Seismoelectric phenomena of electrokinetic nature associated with the formation of cracks in porous media

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I will describe the physics of the generation of electromagnetic disturbances associated with the formation of cracks in porous media. The mechanism is electrokinetic in nature (i.e., associated with the flow of the pore water with respect to the solid phase of a porous material). I will describe the occurrence of these electromagnetic signals and how they can be inverted jointly with seismic signals to determine the position of the hydromechanical disturbance and its moment tensor. I will also demonstrate that electrical fields of electrokinetic nature are associated with the formation of crack through a set of laboratory experiments (see figure below showing the fluctuation in the electrical potential on the surface of the block and the amount of recorded acoustic emissions). The associated electrical field fluctuations can be remotely monitored and the resulting signals used to localize their causative source. The technique is similar to what is performed in electroencephalography (in the medical world) in which an electrical field (associated with the opening of ionic channels at the synapses between the neurons) can be measured on the scalp of a patient and inverted to localize and monitor brain activity. A laboratory experiment shows how these electrical fields can be recorded at the surface of a cement block during the fracking of the block. The measurements are performed with a research-grade medical electroencephalograph and inverted using the genetic algorithm to localize the causative source of electrical current and therefore localize the evolution of the crack. Two snapshots of electrical signals are used to show how the breakage evolves over time. A second experiment is performed to see if we could localize a pulse water injection from a shallow well in field conditions and in the case of a heterogeneous subsurface.

キーワード: electrokinetic, streaming current, self-potential, moment tensor, source localization, electromagnetic phenomena  
Keywords: electrokinetic, streaming current, self-potential, moment tensor, source localization, electromagnetic phenomena



## Waveform analysis of seismo-magnetic signals in Boso, Japan Waveform analysis of seismo-magnetic signals in Boso, Japan

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To clarify the seismo-magnetic phenomena, it is essential to establish theoretical models to explain how the phenomena come out. A reliable model should coincide with field observations. Thus, the fundamental part is to find out what are the signals associated with earthquakes. Therefore, in this study we have checked detailed waveform of seismo-magnetic signals observed in Boso, Japan. Our preliminary results indicate that there are mainly two kinds of seismo-magnetic signals: one is noise-like signals; the other is transient/quasi-rectangular signals. The former are mainly detected before the 2005 M6.1 Boso earthquake; the latter is observed mainly during slow slip events.

キーワード: ULF seismo-magnetic phenomena, waveform analysis, slow slip events

Keywords: ULF seismo-magnetic phenomena, waveform analysis, slow slip events

## Quantitative evidence of the coupling between seismic and electromagnetic signals Quantitative evidence of the coupling between seismic and electromagnetic signals

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There are some reports of the coupling between seismic and electromagnetic signals from both the natural earthquakes and the active field experiments. Such coupling effect may provide some useful information of earthquake process and/or oil exploration. Although the coupling mechanisms are not well understood at the current stage, there are some candidate mechanisms, such as the electrokinetic effect and piezoelectric effect. We focused this study on seismic and electromagnetic coupling for the data observed during earthquakes or synthesized from our numerical simulation method based on electrokinetic effect and earthquake models. We presented a quantitative analysis method of the correlation between seismic and electromagnetic signals. As an example of the field data, we investigated the data recorded during the Ms5.7 Ningqiang earthquake, China. The results indicated that there is a clear coupling between seismic and electromagnetic signals. As a further example of the synthetic data of seismic and electromagnetic signals, we obtained the synthetic seismic and electromagnetic signals using our numerical simulation method and confirmed the existence of coupling between the seismic and electromagnetic signals in the synthetic data.

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キーワード: Co-seismic electromagnetic signals, Rupture model, Source time function, Electrokinetic effect  
Keywords: Co-seismic electromagnetic signals, Rupture model, Source time function, Electrokinetic effect

## 地表自然電位観測による地下水動態の推定 The Development of self-potential tomography to estimate the ground water condition

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近年、集中豪雨の頻度が増加するにつれて、斜面崩壊の発生件数も増加する傾向にある。降雨に起因する斜面崩壊の過程を解明し、斜面の監視や崩壊発生時刻を予測することは重要な課題である。そのために我々は、斜面崩壊の早期予測システムの開発を目的とし、自然電位法によるアプローチを試みている。この手法は、間隙水圧計を用いた観測に比べ、コストが安く、広範囲にわたり観測を行えるという利点がある。これまでの室内実験の結果から、水の動きや土層の変位と自然電位との間に関係性があることが確認されてきた。しかし、現段階では自然電位から地下水動態を推定するまでには至っていない。そこで本研究では、自然電位から地下の電荷分布を推定し、地下水動態を推定する手法の開発を行った。

地下の電荷分布は、測定された自然電位とクーロンの法則によって結びついている。したがって、電荷分布の推定は逆問題となる。この逆問題を解くために本研究では、線形正則化法であるフィリップス・ティホノフ正則化法を用い、最適解を選択するための客観的評価量として、GCV(Generalized Cross Validation)を使用した。また、推定した電荷分布の評価と地下水動態の関係性を調査するため、小型水槽実験システムを用いてシミュレーションと実験を行った。

結果として、開発されたアルゴリズムは数値シミュレーションにおいて有効であることがわかった。小型水槽実験システムを用いた実験は、電荷分布の評価と地下水動態の関係性の解明に良い結果をもたらしたが、一方でいくつかの改善点を示した。詳細は講演時に述べる。

キーワード: 斜面崩壊, 自然電位

Keywords: landslide, self-potential

## Induced seismicity due to fluid injection at a deep well in Youngstown, Ohio, USA Induced seismicity due to fluid injection at a deep well in Youngstown, Ohio, USA

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Over 100 small earthquakes ( $M_w$  0.4-3.9) were detected during January 2011- February 2012 in the Youngstown, Ohio, USA area, where there were no known earthquakes in the past. These shocks were apparently close to a deep fluid injection well, and hence, were immediately suspected as induced by the fluid injection. This 14-months seismicity included a half-dozen felt earthquakes and culminated with a  $M_w$  3.9 shock on 31 December 2011, about 24 hours after the fluid injection ceased in the deep well in Youngstown. Among the 109 shocks, 12 events greater than  $M_w$  1.8 were detected by regional network, whereas 97 small earthquakes ( $0.4 < M_w < 1.8$ ) were only detected by using the waveform correlation detector.

Among these shocks, 21 earthquakes were accurately located by using the local portable station data. All of the accurately located earthquakes were distributed along a set of subsurface faults striking N265 (due East-west) and dipping steeply to the north – consistent with the focal mechanism of  $M_w$  3.9 mainshock on 31 December 2011. All of the well-located earthquakes have occurred at depths ranging from 3.5 to 4.0 km in the Precambrian crystalline basement.

We conclude that the recent earthquakes which occurred during 2011 - 2012 in Youngstown, Ohio were indeed induced by the waste fluid injection at a deep injection well due to increased pore pressure along the preexisting East-west trending faults located close to the wellbore in the Precambrian basement. We found that the earthquakes are located along a 1.2 km-long, East-west trending subsurface en echelon fault, and that the seismicity initiated at the eastern end of the subsurface fault – close to the injection point, and migrated toward the west – away from the wellbore, indicating that the expanding high fluid pressure front increased the pore pressure along its East-west trending path and progressively triggered the earthquakes. Further, we observe that the occurrence of these earthquakes is generally correlated to the total daily injection volume and that several sharp peaks in the daily injection volume correlate with the occurrence of earthquakes. We observed that several periods of quiescence of seismicity follow gaps in surface injection volumes and pressure (sudden drops in injection pressure followed by prolonged low pressure), which may indicate that the earthquakes were directly caused by the pressure buildup in the fractured Precambrian basement and stopped when pressure dropped. Geohydrologic properties of the Youngstown, Ohio area behaved as a fractured Precambrian rock similar to the Rocky Mountain Arsenal, Colorado, USA site of induced earthquakes during 1960s.

キーワード: Induced seismicity, Fluid pore pressure, Shale gas extraction, Space and time migration of earthquakes  
Keywords: Induced seismicity, Fluid pore pressure, Shale gas extraction, Space and time migration of earthquakes



## 地震発生直前の微小クラックの特性 Characteristics of Microcracks in the Nucleation Stage of Natural Earthquake

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At the last JpGU meeting we reported that a deep underground electric field measurement using special antenna could detect micro-cracks appearing in the nucleation stage of the Tohoku Earthquake (Fujinawa et al., 2013). Here we report several results of further analysis on the characteristic pulse-like phenomena.

### 1) Detection Distance:

Some events of B-type variation have clear first and second phases (Figure 1). The S-P time is 25ms corresponding to about 180m of the epicentral distance. Majority of events have no apparent P phases due to the small strength of the P phase and/or large dissipation. The detection distance of P phase is about 200m. On the other hand the S phase of the frequency of some 100Hz and amplitude of 2mV suggests detection distance of some 10km, much larger than that of the acoustic emission signal of order several hundred meters by elastic observation.

The characteristic electric field variation induced by crack through electro-kinetic mechanism have been discussed by systematic formulations (Pride, 1994; Revil and Leroy, 2004). As to the wave mode, there are four kinds of wave, slow P and fast P wave (ordinary p wave), S-wave (ordinary S wave) and electromagnetic wave (EM). Events containing P phase have occasionally small forerunners at about the origin time possibly corresponding to (see Fig.1).

### 2) Correspondence to main shock:

The seismological approaches (e.g., Kato et al., 2012) showed that there were two slow seismic slip events from mid-February to the Tohoku Earthquake and microearthquake activities around the foreshocks and mainshocks. Those activities were whole around the epicentral zone, about 300 km northeast from the observation site. The detection distance of the electric field change by the borehole antenna is at most 100 kilometer. Our observational evidence including temporal evolution of the microcrack activity and b value of 0.7 suggest that the micro-cracks of B-type are related to the nucleation process of the main shock, though they occurred at the edge of the giant rupture area. We propose that the nucleation process is not limited at around the asperity, but extends to whole rupture zone. More extensive monitoring of the microcrack of magnitude less than -5 can provide clue to this question.

### 3) Intermittent Criticality

There appeared undulation of microcrack activity after the most active period around 9th March, 2011. The undulation has been suggested to reflect the intermittent criticality indicating another phase of nucleation (Sornette and Sammis, 1995; Kaporis et al., 2005). As approaching to the main shock there appeared two kinds of events. One kind is a superposition of several smaller events. It is interpreted that small events substantially increased with the result of picking up more smaller events in the time interval of data length of 100ms. The second kind is like a long chain of small events. These feature suggest that microcrack activity has changed at the last stage of nucleation stage.

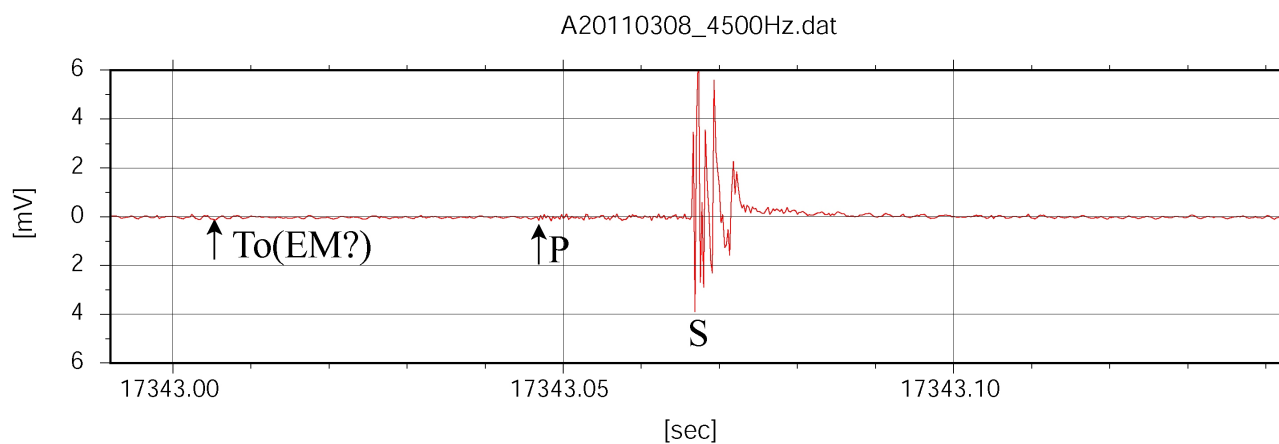
4) It is well known that the crust of the earth is elastic-porous medium filled with fluid as water. The research on the rupture of such kind of medium had a remarkable development in early 1990 contributing to interpret the mysterious seismo-electric phenomena associated earthquakes enabling systematic treatment and suggesting new method of geophysical prospecting. The formulation of Pride and Revil have been used to interpret the phase of faster propagation of EM signal with velocity much larger than the p-wave speed (Fujinawa et al., 2011), the ULF band anomalies associated the slow-slip (Han, 2013). And, our electromagnetic method has been suggested to detect micro-cracks preceding natural earthquakes to identify the nucleation stage providing a break-through for the short term prediction method. The converted electromagnetic mode at the material contrast from elastic seismic wave has been proved to be profitable means to survey for oil and gas.

Keywords: Microcrack, Earthquake Prediction, Nucleation Stage, Seismo-electric- signal, Electrokinetic effect, Tohoku Earthquake

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## 半導体鉱物の破壊に伴う電磁放射 Electromagnetic emissions from fracture of semiconductor pyrite

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はじめに

弾性波が鉱体に伝搬するとラジオ波と呼ばれる電磁波が発生する。ラジオ波は弾性波の周波数の10~100倍という高い周波数を持ち、その発生は半導体鉱物を含む鉱体での発破実験や、室内での鉱体サンプルを用いた実験で観測されている。こうした観測によるとラジオ波の発生は半導体鉱物を含む鉱体の持つ整流性が強く関係していると示唆されている。半導体鉱物はn型、p型と2つに区別する事ができ、n型、p型が組み合わせると整流性を持つp-n接合を作る。鉱体内部には半導体鉱物のp-n接合が、並列および直列に多数つながって存在するため、鉱体全体で整流性を示す。過去の研究ではラジオ波の発生メカニズムを明らかにするために、鉱体全体の巨視的なスケールの整流特性を測定した。しかし、半導体鉱物における1つ1つの微小なp-n接合の整流特性の評価がされていなかったため、鉱体の整流性の定量的な評価は困難であった。

半導体鉱物の鉱物組成は、微量元素や欠陥の存在により不均質性を持つ。整流性は組成に強く依存するので、整流性の定量的な評価には、微小部位ごとの組成解析が必要である。本研究では、半導体鉱物の黄鉄鉱の組成と整流性を測定する。そして、鉱体における電磁放射の可能性について議論する。

手法

半導体鉱物試料として宮城県和賀仙人鉱山産の黄鉄鉱を用いた。試料は厚さ0.38 cm、表面積1.4 cm<sup>2</sup>の大きさに切断し、測定を行った。

電解法とSEM-EDSにより試料の組織観察、組成測定を行った。そして、プローブ試験機による熱起電力測定、電気特性測定を行った。熱起電力測定により半導体鉱物のp型、n型の判別をし、電気特性測定において整流性の定量的評価を行った。

結果

電解の結果、試料表面の組成の不均質性は溶解度の違いとして現れた。そのため、試料表面に腐食像が現れ、一部は累帯構造を成した。累帯構造の各ゾーンの幅は数十~数百μmである。熱起電力測定によると、こうした腐食によって得られた累帯構造はp型とn型の存在領域の違いを反映している事が分かった。p型の領域はn型の領域に比べ溶解度が大きかった。SEM-EDSの解析によると、p型の領域に約1.0 wt.%のPbの微量元素が結晶面に平行に存在する事が明らかにされた。

プローブによる電気特性測定では、試料のp-n接合部で整流性が確認された。整流性の特性はp-n接合部の電流-電圧特性を測定することで明らかにされ、pn接合の順方向降伏電圧は $V_{FM} = 0.3$  V、逆方向降伏電圧は $V_{RB} = 1.5$  Vであった。

議論・結論

2つの種類の岩石が接触する際、岩石表面間で電子の移動が起こり、電位差が生まれる。この接触による帯電は岩石の剥離時の電磁放射の原因となりうる。もし、2種類の岩石をp型とn型の半導体鉱物と考えると、接触による帯電電圧はp-n接合の順方向降伏電圧で与えられる。接合部はコンデンサーを形成していると見なせる。接合部の剥離の際、表面の帯電密度により極板間の電圧がパッシェンの法則における極板間気体の降伏電圧に達するとコロナ放電が生じる(空気の場合、コロナ放電を引き起こすのに $5.0 \times 10^{-5}$  C/m<sup>2</sup>の帯電密度が必要)。実験結果より、黄鉄鉱のp-n接合の剥離面に生じる帯電密度は $2.7 \times 10^{-4}$  C/m<sup>2</sup>と見積もられる。誘電緩和による剥離面の帯電の減衰の影響を加えると、接触面同士が剥離される速度を考慮する必要がある。この場合、コロナ放電を引き起こすのに必要な剥離速度は2.0 km/sと見積もられる。この結果より、黄鉄鉱の破壊が破壊伝搬速度2.0 km/s以上の剪断破壊により引き起こされる時、コロナ放電による電磁波の発生が期待される。

以上のように、黄鉄鉱の破壊は電磁放射の原因となりうる、鉱体から発生する電磁波の周波数等の特性を明らかにするために、更なる研究が求められる。

キーワード: 地震電磁気現象, 半導体鉱物, ラジオ波, p-n接合

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SCG10-P01

会場:3 階ポスター会場

時間:5 月 2 日 16:15-17:30

Keywords: Seismic electromagnetic signals, Semiconductor minerals, Radio wave, P-n junction