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Shock-Induced Mechanoluminescence of Rocks

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Abstract

Basically the earthquake lights may be caused by the earthquake-shock induced delayed mechanoluminescence of rocks. Following the positive hole theory of earthquakes lights (EQLs) expressions are derived for the shock-induced ML of rocks and the dependence of ML intensity on different parameters, in which a good agreement is found between the experimental and theoretical results.. The present study may be helpful in understanding the pre-earthquake phenomena.

Keywords:* *Earthquake lights, Delayed Mechanoluminescence, Pre-earthquake Phenomenon, Rocks, Positive Holes.

1 INTRODUCTION

The phenomena of light emission related to earthquakes are called earthquake lights (EQLs). EQLs have been reported since ancient times [1,2] and in the past considerable efforts have been made to understand the phenomenon. Various reports confirmed the diversity of the observed luminous phenomena. The study of pre-earthquake phenomena including EQLs is very important and interesting because they may become useful in forecasting earthquakes [3-9]. While there are many observations from many independent sources, a great uncertainty remains about the physics that underlies the emission of light from the earth's surface before or during major earthquakes or during the after shocks. The subterranean stress in an earthquake zone is transformed into a luminous phenomenon in the surroundings. Most of the following theories proposed like piezoelectricity, triboluminescence/triboelectricity, streaming potentials, exoelectron emission radiation and heat, are unconvincing. Mechanoluminescence (ML), generated by the charging of rocks can explain the salient features of earthquake lights.In fact, mechanoluminescence is a type of luminescence induced by any mechanical action on solids [10]. The light emissions induced by elastic deformation, plastic deformation and fracture of solids are called elastico ML(EML), plastico ML (PML) and fracto ML (FML), respectively [11,12] The present paper reports the temporal behavior of the light emission induced by the earthquake shocks on rocks and explores the dependence of EQL intensity on different parameters, in which a good agreement is found between the experimental and theoretical results. It is shown that the present study may be helpful in understanding the pre-earthquake phenomena.

2 THEORETICAL APPROACH TO SHOCK-INDUCED ML OF ROCKS

In fact, the earthquake light is induced by the earthquake shocks onto the rocks. The earthquake shocks produce deformation or strain ε in the rock and subsequently the strain produces movement of dislocations. If $\dot{\varepsilon}$ is the strain rate, then we have $\dot{\varepsilon} = bN_d\ v_d$,
where b is the Burgers vectors, N_d is the density of dislocations and v_d is the average velocity of dislocations[13]. In this case, the rate of sweeping of surface area by the moving dislocations is given by, $g_s = N_d v_d = \dot{\varepsilon}/b$. If τ_p is the pinning time of the moving dislocations, then we can write the following equation for the rate of sweeping of surface area by the moving dislocations

$$\frac{dS}{dt} = g_s - \frac{S}{\tau_p} = \frac{\dot{\varepsilon}}{b} - \alpha S \qquad ...(1)$$

where $\alpha_s = 1/\tau_p$, and S is the area swept by the moving dislocation at any time t.
Integrating Eq.(1) and taking S=0, at t = 0, we get

$$S = \frac{\dot{\varepsilon}}{b\alpha}\left[1 - \exp(-\alpha t)\right] \qquad ...(2)$$

Differentiating Eq.(2) ,we get

$$\frac{dS}{dt}=\frac{\dot{\varepsilon}}{b}\exp(-\alpha t) \qquad \ldots(3)$$

If n_l is the concentration of peroxy links and r_l is the distance from the dislocations upto which activation of peroxy links takes place, then using Eq.(3), the rate of generation g_h of activated p-holes can be expressed as

$$g_h=n_l r_l\frac{dS}{dt}=\frac{n_l r_l\dot{\varepsilon}}{b}\exp(-\alpha t) \qquad \ldots(4)$$

If q is the charge on a p-hole, then the rate of generation g_q of the charges in the deformed region is given by

$$g_q=\frac{qn_l r_l\dot{\varepsilon}}{b}\exp(-\alpha t) \qquad \ldots(5)$$

If a fraction f of the charges in the deformed region is transferred to the surface of the rock and t_o is the delay time, i. e., the time taken for the transfer of charges from the deformed region to the surface of the rock at which ML measurement is done, then the rate of generation G_q of surface charge can be expressed as

$$G_q=\frac{fqn_l r_l\dot{\varepsilon}}{b}\exp[-\alpha(t-t_o)] \qquad \ldots(6)$$

If τ_q is the decay time of surface charges, then using Eq.(6), we can write the following equation

$$\frac{dQ}{dt}=G_q-\frac{Q}{\tau_q}=\frac{fqn_l r_l\dot{\varepsilon}}{b}\exp[-\alpha(t-t_o)]-\beta Q \qquad \ldots(7)$$

where $\beta = 1/\tau_q$, and Q is the effective surface charge at any time t. It is to be noted that the effective surface charge is the charge at which the ML emission is onset.

Integrating Eq.(7) and taking Q =0, at t = 0, we get

$$Q=\frac{fqn_l r_l\dot{\varepsilon}}{b(\beta-\alpha)}[\exp\{-\alpha(t-t_o)\}-\exp\{-\beta(t-t_o)\}]$$

or,

$$Q=\frac{fqn_l r_l\dot{\varepsilon}}{b(\alpha-\beta)}[\exp\{-\beta(t-t_o)\}-\exp\{-\alpha(t-t_o)\}] \qquad \ldots(8)$$

If η is the ML efficiency, then the ML intensity I can be expressed

$$I=\eta\frac{dQ}{dt}=\eta\beta Q$$

or,

$$I=\eta\beta\frac{fqn_l r_l\dot{\varepsilon}}{b(\alpha-\beta)}[\exp\{-\beta(t-t_o)\}-\exp\{-\alpha(t-t_o)\}] \qquad \ldots\ldots(9)$$

Time t_m corresponding to the ML peak can be expressed as

$$t_m=t_o+\frac{1}{(\alpha-\beta)}\ln(\frac{\alpha}{\beta}) \qquad \ldots(10)$$

The maximum ML intensity I_m can be expressed as

$$I_m=\eta\frac{fqn_l r_l\dot{\varepsilon}}{b}\left(\frac{\beta}{\alpha}\right)^{1/(1-\beta/\alpha)} \qquad \ldots.(11)$$

For α>>β, Eq.(11) can be expressed as

$$I_m=\eta\frac{fqn_l r_l\dot{\varepsilon}}{b(\alpha-\beta)} \qquad \ldots(12)$$

The total ML intensity is given by

$$I_T=\frac{\eta fqn_l r_l\dot{\varepsilon}}{b\alpha} \qquad \ldots(13)$$

The fast decay of ML intensity can be expressed as

$$I_{df}=\eta\beta\frac{fqn_l r_l\dot{\varepsilon}}{b(\alpha-\beta)}\exp\{-\beta(t-t_m)\}\exp\{-\beta(t_m-t_o)\} \ldots(14)$$

The slow decay of ML intensity can be expressed as

$$I_{ds}=I_o\exp\left[-\frac{(t-t_c)}{\tau_s}\right]=I_o\exp[-\chi(t-t_c)] \qquad \ldots(15)$$

where t_c is the time at which the fast decay of ML becomes negligible, I_o is value of I_{ds} at t= t_c , and $\chi=1/\tau_s$.

In fact, after the impact of a load on a rock, the ML due to p-holes appears after a certain delay time after the impact. This delay time is related to the transfer of p-holes from the deformed region to the surface of the rock, at which the ML measurement is made.

3 COMPARISON BETWEEN THEORETICAL AND EXPERIMENTAL RESULTS

Although the photographs of earthquake lights have been taken for many earthquakes, the temporal behavior of the light emitted during earthquake has not been recorded. Freund [8] has excited the ML in several rock materials by impact, in which the temporal behavior of the ML has been measured. It is seen from Fig. 1 that when a transient pressure is applied onto a granite sample by impact, then the tribo ML or triboluminescence (luminescence induced by triboelectrification) caused by the friction appears instantaneously at the impact and then a delayed mechanoluminescence associated with the movement of dislocations and subsequent generation of positive holes, appear after a certain time delay t_o. After t_o, the ML intensity initially increases with time, attains a peak value and then it decreases with time.

Fig. 2 shows that when the ML is excited by the impact of a load onto diorite, then initially the ML intensity increases linearly with time, attains a peak value and later on it decreases with time. In this case, the tribo-ML due to the friction could not be observed presumely due to the low value of triboelectrification. In this case, fast decay of ML is followed by the slow decay of ML because of the some content of phosphorescent material in diorite. These results follow Eqs. (9), (10), (12), (13) and (15). Also the slow decay of ML could not be observed for diorite.

4 CONCLUSIONS

The important conclusions drawn from the present investigation are as given below:

(i) Basically the earthquake lights are caused by the earthquake-shock inducd delayed mechanoluminescence of rocks.

(ii) Following the positive hole theory of earthquakes lights (EQLs) expressions are derived for the EQL characteristics and the dependence of EQL intensity on different parameters, in which a good agreement is found between the experimental and theoretical results.

(iii) The EQL intensity should depend on the concentration of peroxy links in rocks, value of the strain rate , value of the radius of interaction of dislocations with peroxy links and on the value of the ML efficiency.

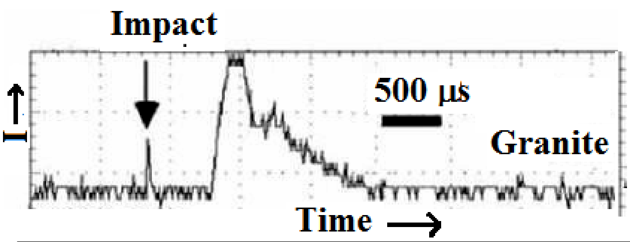

Fig.1: Shock-inuced ML of granite (after Freund, ref. [8]).

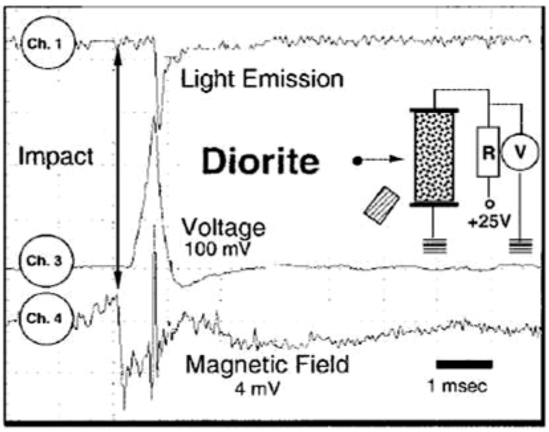

Fig.2: Impact-inuced ML of diorite (after Freund, ref. [8]).

(iv) When a load makes an impact onto a rock, then after a delay time, the ML intensity initially increases with time, attains a peak value and later it decreases with time.

(v) The values of the decay time of the surface charges , pinning time of dislocations , life time of charge carriers in shallow traps and the delay time between the onset of light and the time of impact can be determined from the temporal behavior of the delayed mechanoluminescence (ML) of rocks.

(vi) After the ML peak, the ML intensity decreases exponentially with time, in which the decay time gives the decay time of the surface charge of the rocks.

(vii) The present study may be helpful in understanding the pre-earthquake phenomena.

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