Luminous Phenomena of Earthquakes: Observations and Theories

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Abstract

Over the past few years, different theories (piezoelectric, positive holes, friction-vaporization, exo-electron emission, tribo- or fracture electrification) have been presented for the interpretation of earthquake lights. Although these theories can interpret earthquake luminous, each suffer from particular problems. There are also ambiguities and questions about the location of the light, the number of light created in an earthquake, the relationship between light and lithology and the different light spectrum. In addition, the proposed theories could not interpret all the observed light (co-seismic and pre-seismic luminous), and it seems that more than one theory is needed to justify the lights. The relationship of the EQLs to active tectonic boundaries suggests all the earthquakes in which light has been seen are located on the active tectonic boundaries and the stress for producing lights should be at its maximum. This study shows that a new theory is needed. A theory that can, above all, explain the relation of light (spectrum and intensity) to lithology, the amount of stress, and active tectonic areas.

Keywords: earthquake lights, co-seismic, tectonic boundaries, lithology, spectrum

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1 Introduction

Earthquake lights or earthquake luminosity is the name of a phenomenon that occurs just before, during, or right after an earthquake. They come in many colors and forms. People have reported seeing them for hundreds of years, but it was not until now that scientists believe they may finally understand why strange lights are seen during an earthquake. As mentioned by Whitehead and Ulusoy (2015) an earthquake light (EQL) is a luminous aerial phenomenon that reportedly appears in the sky at or near areas of tectonic stress, seismic activity, or volcanic eruptions. According to another definition, Earthquake lights are anomalous luminosities associated with and presumably caused by the accumulation and release of stress of the earthquake process, observed prior to or during a seismic event and/or during the aftershock sequence (Derr et al., 2011). Early on, the very existence of EQL was questioned by the scientific community since no really testable data existed and observations were invariably made by untrained observers (Lockner et al., 1983). A transformation in this attitudes occurred when photographs of luminous phenomena were taken during the Matsushiro earthquake swarm in Japan between 1965 and 1967 (Yasui, 1968, 1971). Since then, the continuing reports of EQL (Thériault, 2014), especially the Matsushiro pictures, have led to a general acknowledgement that EQLs do occur. Note that EQL phenomena do not accompany all earthquakes. This paper includes descriptions of the phenomenon, and reviews several theories that have been suggested to explain EQLs and also shows why we need a new theory to explain the relation of EQLs with active tectonic boundaries, faults, lithology and the amount of stress in a single earthquake.

2 Appearance and Observations

The earliest known report of EQLs dates to 373 BCE when the Greek cities Helice and Buris were destroyed by an earthquake accompanied by "immense columns of fire" (Seneca) (Derr et al., 2011). Ancient references will always be questionable, especially when the surviving accounts are written later; however, such references indicate that the people at that time were aware that lights might accompany earthquakes. Many sightings from various countries around the world have since been reported. Seismological studies have also taken into account the historical luminous phenomena, recognizing them as just the darkest chapter in seismology (Sieberg and Lais, 1911). With the beginning of seismology as a science in the 19th century, many scholars devoted time to reporting luminosities (Whitehead and Ulusoy, 2015), like the Irish engineer Robert Mallet, the "founder of seismology", who published a five-part catalog entitled "On the Facts of Earthquake Phenomena" (Mallet, 1851, 1852, 1853, 1854, 1855), in which numerous reports on earthquake luminosities can be found. EQL is mainly flashes of light or glows associated with earthquakes, but because of its transient nature has been treated skeptically by scientists (Whitehead and Ulusoy, 2015). Following capture on film and webcam/security cameras, it is now accepted as real by most seismologists, as judged by the published literature referenced in this paper. There are, by our count, about four useful videos available on the internet. Most show (Table. 1) a white spherical ground-based core surrounded by radiating blue-white light, fading the further it is from the core. However, there have been at least 27 earthquakes in the USA with associated EQL occurrences and about 38 earthquakes in Europe (Thériault et al., 2014). Nonetheless, as noted by Derr (1973), the first known investigations which led to significant interpretations and conclusion were done in the 1930s by two Japanese seismologists, Terada (1931, 1934) and Musya (1931, 1932, 1934) and were described by Davison (1936, 1937). From 1931 to 1934 Musya collected about 1,500 reports of EQL from the Idu Peninsula earthquake of November 26, 1930, at 4:30 a.m. During the year following the Idu earthquake, Musya studied the luminous phenomena attending four other Japanese earthquakes. The reports were most numerous for the South Hyuga earthquake of November 2, 1931. With this earthquake, the lights were usually described as beams radiating from a point on the horizon, as like lightning or a searchlight turned to the sky, and as of blue or bluish color (Derr, 1973). They were seen before the earthquake by 26 observers, during it by 99, and after it by 22 observers (Davison, 1937). Terada (1931) made some calculations on potential differences in the Earth. Nevertheless, he made some perceptive comments about the quality of testimonies of witnesses under stress, which are quite relevant to the problem of collecting subjective data during the earthquake. Another assessment of the problem of EQLs is given by Byerly (1942). In addition to his general description, he documented observations of EQLs observed at sea. If these lights have the same cause as those observed on land, severe restrictions are placed on the mechanism of their generation (Derr, 1973). For example, at the time of the earthquake off the coast of Northern California in January 1922, one observer reported a glow at sea which he at first took to be a ship on fire. At the time of earthquake of October 1926, centering in Monterey Bay, an observer reported a flash at sea that resembled a transformer exploding (Derr, 1973).

In the late 60s and early 70s, new research into observations of luminous phenomena in Japan has been done by Yasui (1968, 1971, 1972), who collected and studied pictures, taken by various other observers, of EQLs observed during the Matsushiro earthquake swarm of 1965 to 1967. He has also studied reports of other sightings in Japan. Of the approximately 35 sightings, any pictures which might have recorded unrelated phenomena – Distant lightning, Meteors, Twilight, Zodiacal light, Arcing power lines – were eliminated. At least 18 separate sightings remained unexplained. Afterward, he concluded that luminescence over a mountain area lasting several tens of seconds on a clear and calm winter night is not a known phenomenon. He considered it to be an atmospheric electrical phenomenon, but the earthquake trigger mechanism is unknown. Derr (1973), classified five general characteristics of the phenomenon as observed by Yasui (1968).

i) The central luminous body is a hemisphere, diameter about 20 to 200 m, containing the surface. The body is white, but reflections from clouds may be colored.

ii) The luminescence generally follows the earthquake with a duration of 10 sec to 2 min.

iii) The luminescence is restricted to several areas, none of which is the epicenter. Rather, they occur on mountain summits in a quartz-diorite faulted rock.

iv) Sferics generally follow the luminescence and are strongest in the 10 to 20 kHz range. The luminescence occurs frequently at the time of a cold frontal passage.

There was no indication on the magnetometers at the local observatory.

Table.1. Screenshots of videos on the Internet that were taken right at the time of the earthquakes (co-seismic lights). Most show a white spherical ground-based core surrounded by radiating blue-white light, fading the further it is from the core.

Earthquake	A screenshot of the video
1) The 2016 Kaikoura earthquake was a magnitude 7.8 (Mw) earthquake in the South Island of New Zealand that occurred two minutes after midnight on November 14, 2016 NZDT (USGS).	
2) The 2016 Fukushima earthquake with a moment magnitude of 6.9 east-southeast of Namie, Fukushima Prefecture at 05:59 JST on November 22 (20:59 Nov. 21 UTC), at a depth of 11.4 km (USGS).	
3) The 2017 Chiapas earthquake struck at 23:49 CDT on September 7 (local time; 04:49 on the 8th UTC) in the Gulf of Tehuantepec off the southern coast of Mexico, near state of Chiapas, approximately 87 km (54 mi) south of Pijijiapan, with a Mercalli intensity of IX (Violent). The magnitude was estimated to be Mw 8.2 (USGS).	
4) The 2007 Peru earthquake, which measured 8.0 on the moment magnitude scale, hit the central coast of Peru on August 15 at 23:40:57 UTC (18:40:57 local time) and lasted for about three minutes (USGS).	

In another study, Yasui (1972) has commented on observations of EQL during the October 1, 1969 earthquake at Santa Rosa, California (Engdahl, 1969). The lights were seen extensively over the Santa Rosa area and described in terms of lightning or electric sparks, Saint Elmo's Fire, fireballs or meteors. Some people in Santa Rosa also heard sounds like explosions (Derr, 1973). From the published description, however, the Santa Rosa observations did not include that which was described by Davison (1937) as appearing to be auroral streamers diverging from a point on the horizon, a description which does fit observations, for example, in Chiba prefecture, Japan, January 5, 1968, as sketched by Yasui (1971).

There are a lot of reports of EQLs during both M 7.3 Haicheng earthquake of February 4, 1975, at 7:36 p.m. and the M 7.8 Tangshan earthquake of July 28, 1976, at 3:42 a.m. Based on Yulin and Fuyi (1997), the luminous phenomena were so widespread and the lights were seen to a distance of 100-200 km from the epicenter. The lights lasted for a few seconds and associated with a hissing sound and ground air or fog with ozonic odor and/or smoke. The earthquake lights are considered as the coseismic effect of electromagnetic phenomena in the atmosphere and are a piece of very convincing evidence for energy transfer from earth to air (Yulin and Fuyi, 1997). Although the earthquake lights are mainly occurred at the time of earthquakes, the phenomena were also observed at a very short period of time before and after events. In expelling the ground air from the earth surface and flowing out the water through the surface under pore pressure prior to earthquakes, electromagnetic precursors in the atmosphere can also be caused by electrokinetic effect (Yulin and Fuyi, 1997).

During the Peru earthquake on August 15, 2007 with Mw =8.0, which occurred at 06:40 p.m. local time (LT), hence dark, several EQLs were observed along the Peruvian coast and extensively reported in the capital city of Lima, about 150 km northwest of the epicenter (Heraund and Lira, 2011). These lights were video-recorded by a security camera installed at the Pontificia Universidad Catolica del Peru (PUCP) campus and time-correlated with seismic ground accelerations registered at the seismological station on campus, analyzed and related to highly qualified eyewitness observations of the phenomena from other parts of the city and to other video recordings (Heraud and Lira, 2011). EQLs are also observed in China. A destructive (Mw 7.9) earthquake affected the Sichuan province (China) on May 12, 2008. The seismic event ruptured approximately 270 km of the Yingxiu–Beichuan fault and about 70 km of the Guanxian–Anxian fault. Surface effects were suffered over a wide epicentral area (about 300 km E–W and 250 km N–S) (Chini et al., 2010). EQLs were reportedly spotted by local people (undocumented) in Tianshui, Gansu, approximately 400 kilometers (250 mi) north-northeast of the 2008 Sichuan earthquake's epicenter.

Fidani (2010) reported the EQL of the April 6, 2009 Aquila earthquake, in Central Italy. The study presents the preliminary results of a collection of testimonies about luminous phenomena related to seismic activity in and near Aquila before and after the main seismic event (M=6.3), at 03:32 LT on April 6, 2009. The mainshock caused strong shaking in and near Aquila causing heavy damage and 307 casualties. The earthquake of April 6, 2009 was the strongest event in a sequence of seismic events that started a few months earlier; local seismic activity began to increase in December 2008 (Pondrelli et al., 2010). The most significant prior events occurred on 30 March (M=4.4), at 15:38 LT, April 5 (M=4.2), at 22:48 LT and April 6 (M=3.9), at 00:39 LT (Chiarabba et al., 2009). The mainshock was followed by seven aftershocks within the first week; the moment magnitude (Mw) ≥5, the two strongest ones occurred on April 7 (M=5.6), at 19:47 LT, and on April 9 (M=5.4), at 02:52 LT, (Bindi et al., 2009). About one thousand phenomena were reported of which 241 were luminous phenomena. Several photos included luminous phenomena. At least 99 of such phenomena occurred before the mainshock and other strong events of the seismic sequence, whereas globular lights, luminous clouds, and diffused light were more frequent before the quakes. Luminous events were observed before the mainshock without the ground shaking and were very similar to those reported about two centuries ago (Fidani, 2010). However, the first collection of EQL data compiled in Italy in the early 20th century by the religious naturalist Ignazio Galli contained the first ordering of historical phenomena based on the shapes and time evolutions (Galli, 1910).

More recent appearances of the phenomenon, along with video footage of the incidents, happened in Sonoma County of California on August 24, 2014, and in Wellington, New Zealand on November 14, 2016, where blue flashes like lightning were seen in the night sky, and recorded on several videos by local people. On September 8, 2017, many people reported such sightings in Mexico City after an 8.2 magnitude earthquake with epicenter 460 miles (740 km) away, near Pijijiapan in the state of Chiapas.

The most recent report on the observation of EQL was in Iran (Torabi et al., 2018). On November 12, 2017, at 9:18 pm local time, 1:18 pm Eastern Standard Time, a magnitude 7.3 (Mw) earthquake struck Iran near the border with Iraq, where blue flashes like lightning were seen in the night sky, reported by local people.

3 Present Theories and Possible Explanations

Numerous mechanisms for generating and explanation of EQL have been suggested or investigated. However, research into earthquake lights is ongoing.

3.1 Piezoelectric theory

A quartz crystal stressed in the appropriate direction will produce a voltage (Park et al., 1993). This well-established physical phenomenon has been observed for rocks in the laboratory. The effect can occur in the Earth for regions over which there is some alignment or long-range ordering of quartz grains (Finkelstein et al., 1973; Dmowska, 1977; Baird and Kennan, 1985); however, as mentioned by Turk et al. (1977), self-cancellation precludes the development of large potentials. Piezoelectric signals from quartz-bearing rocks are less than 0.1% of those observed for single crystals of quartz (Tuck et al., 1977), even if the crystals are aligned as in a quartzite. However, it has been suggested (Finkelstein and Powell, 1970) that EQLs could be caused by piezoelectric fields produced in surface rocks by seismic waves. As suggested by Finkelstein et al. (1973), the frequency of seismic waves are probably believed to be responsible for these piezoelectric effects was in the low-frequency band from 1 to 10 Hz. Moreover, it was recognized that in order to develop the strong fields required to initiate lightning the resistivity in the surface rocks would need to be of the order of 10^9 ohm m. Finkelstein et al. (1973) have made resistivity measurements directly on rocks located in the immediate vicinity of earthquake activity in the Los Angeles area, where unusual light at the time of the San Fernando earthquake, February 9, 1971, was reported. They have tested the uniformity of resistivity of quartz-bearing rocks (Pacoima Canyon gneiss and Mohave Desert monzonite) at depths of 1-50 meters below the exposed surface of the rocks, by using a four-terminal network system. After the measurements were completed, they realized that the measured resistivities vary only narrowly in the range from 3×10^2 to 3×10^3 ohm m. As a result, they concluded that such low resistivities and low-frequency seismic waves (e.g., 1-10 Hz) would be insufficient to develop electric fields adequate for creating atmospheric lightning. They suggest two ways in which piezoelectricity could conceivably produce sufficiently high fields. Their first suggestion was based on an observation by Brace and Orange (1968), who found that certain granites (e.g., 4.3% saturated Westerly granite) may have a resistivity of 10^6 ohm m at 100 bars. Consequently, earthquakes can release high pressures along or near faults and thus raise resistivities and can at the same time generate high-frequency pressure waves by crack and squeak mechanisms. Their second suggestion was based on the observation by Keller (1971) that rock layers at depths of the order of 10 km may have resistivities of the order of 10^7 ohm m.

Note that Piezoelectric properties depend upon symmetry. All minerals without a center of symmetry may be piezoelectric, except for class 432 in the cubic system owing to its high symmetry (Bishop, 1981). However, very few minerals have been tested and even fewer have any quantitative data (Bond, 1943b; Parkhomenko, 1971).

3.2 Friction-vaporization theory

It has been suggested that during a large earthquake, significant frictional heating will occur near the shear zone (Lockner et al., 1983). As mentioned by Lockner et al. (1983), in proper conditions, this significant frictional heating will lead to vaporization of water in and near the shear zone and a dramatic decrease in electrical conductivity, σ, for saturated or partially saturated rock from about 10^{-1} to $< 10^{-10} S\, m^{-1}$. They have assumed that this continued frictional heating produces increasing σ in the shear zone $(10^{-5}\, S\, m^{-1}\, at\, 500^{\circ}\, C;\ 10^{-4}\, S\, m^{-1}\, at\, 650^{\circ}\, C)$ resulting in a central conductor perhaps a few centimeters wide on the fault axis surrounded by a low σ sheath of rock containing vaporized porewater. Based on their theory, this central conductor will collect charge in the shear zone and because of its specific shape (hundreds of meters deep and only centimeters wide), it will concentrate the charge along its edges, where the curvature is highest. In this hypothesis if the conductor is shallow enough, the charge concentrated along its top edge will produce an intense electric field at the Earth's surface, enhanced by the normal atmospheric potential gradient that will then be strong enough to induce coronal discharge in the atmosphere above the fault. Frictional heating of faults during earthquakes have received much attention (McKenzie and Brune, 1972; Raleigh, 1977; Lachenbruch and Sass, 1980) and also the efficiency of frictional heating during earthquakes and the vertical distribution of stress on active faults are topics of much controversy, Sibson et al. (1979), have shown through identification of pseudotachylytes that significant frictional melting does occur on some faults. According to the theory of Lockner et al. (1983), Frictional-Vaporization theory, EQL would not be expected to occur with all large shallow earthquakes. With laboratory measurements, they have shown with quite reasonable physical assumptions, EQL can be generated and should be expected for at least some earthquakes (Lockner et al., 1983).

3.3 Positive Holes theory

The first spark of this theory came from the fact that in thermodynamic equilibrium the surface of an ionic crystal will always, as a rule, carry an electric charge resulting from the presence of excess ions of one sign (Frenkel, 1946). The surface charge is then compensated by a space-charge layer of the opposite sign beneath the surface (King and Freund, 1984). King and Freund (1984), who worked on surface charges and subsurface space-charge distribution in magnesium oxides, used the term Positive Holes. As mentioned by King and Freund (1984), the O^- state represents a defect electron or positive hole, sometimes called an Oxygen-associated Hole Center (OHC) (Friebele et al., 1979; Brower et al., 1982). From chemistry, we know that an O^- is a radical and is an oxygen anion with an incomplete valence shell, seven electrons instead of the usual eight.

In 2002, a study was conducted on the generation and propagation of charge in igneous rocks (Freund, 2002). Freund (2002) observed that when a dry granite block is impacted at the higher velocity, 1.5 km/s, the propagation of the P and S waves is registered through the transient piezoelectric response of quartz. He observed that after the sound waves have passed, the surface of the granite block becomes positively charged. He came to the conclusion that observations are consistent with positive holes, e.g. defect electrons in the O^{2-} sublattice, traveling via the O 2p-dominated valence band of the silicate minerals (Freund, 2002). He suggests, before activation, the positive holes lay dormant in the form of electrically inactive positive hole pairs, PHP and concluded this dormant PHP chemically equivalent to peroxy links, $O_3X^{/OO\backslash}XO_3$, with $X = Si^{4+}$, Al^{3+}, etc. He considered the idea that Positive Holes can also be activated by micro fracturing. According to his theory, Positive Holes will form rapidly moving or fluctuating charge clouds that may account for earthquake-related electrical signals and EM emission and wherever such charge clouds intersect the surface, high fields are expected, causing electric discharges and luminous phenomenon or earthquake lights (Freund, 2002). Freund, who became one of the main theorists of the Positive Holes and earthquake lights, describes the physical and chemical nature of these positive holes, how they are introduced into minerals and rocks, and how they become activated. He also argued that once the positive holes are generated, currents propagate through the rocks leading to electromagnetic emission, to positive surface potentials, to corona discharges, to positive ion emission, and to mid-infrared radiation (Freund, 2003).

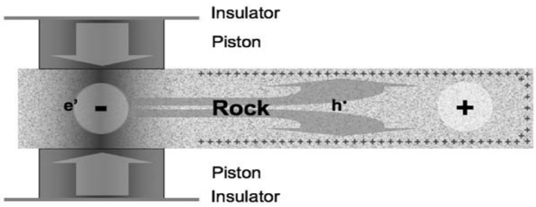


Figure 1. Stress applied to one end of a rock activates electrons and hole, e′ and h˙. The h˙ flow out of the stressed rock volume into the unstressed volume, creating potential difference. The situation is similar to that of an open circuit electro-chemical battery. The stressed volume is negative and the unstressed volume is positive. The h˙ charge carriers become trapped at the surface, leading to a positive surface charge (From Freund et al., 2009).

In another study, Freund et al. (2006), by conducting laboratory studies have shown that when deviatoric stresses are applied to igneous or high-grade metamorphic rocks, electronic charge carriers are activated. Freund et al. (2009), completed the mechanism of the Positive Holes by presenting a Rock Battery model. According to Rock Battery model (Figure 1), when stress is applied to a portion of a rock, the number density of electrons and Positive Holes inside the stressed rock volume increases. Afterward, the $h^{\cdot}$ charge carriers (Positive Holes carriers), can flow out of the stressed rock and into an adjacent unstressed rock, while the electrons, e', stay behind (Freund et al., 2009).

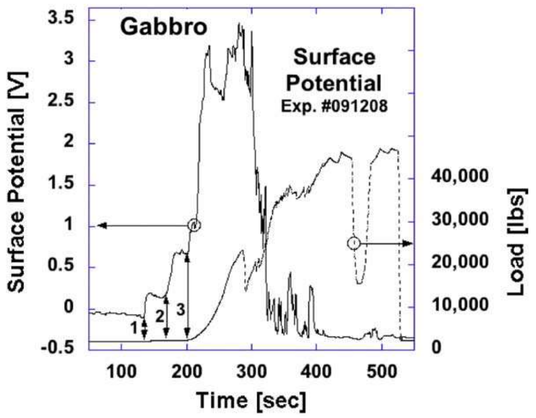


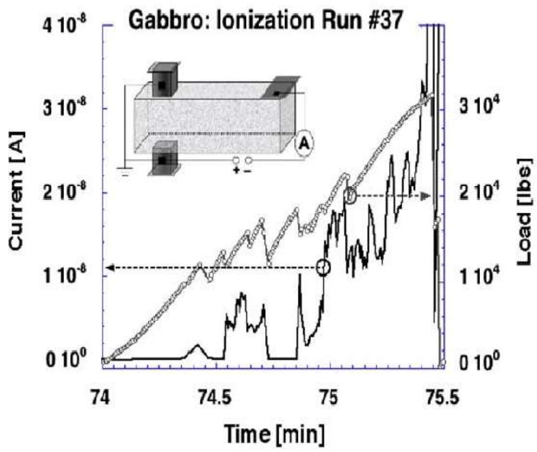
Figure 2. Surface potential. Double arrow1: the surface potential started to build-up as the platen of the press started to rise and caused enough acceleration to activate some charge carriers. Double arrow2: first contact with piston of the press. Double arrow3: start of loading. The rock did not break at the end of this run. The surface potential reached +3.4V, and soon dropped to negative values (- 0.3 V) (from Freund et al., 2009).

To test this model, Freund et al. (2009) used a gabbro from Shanxi, China, a typical deep crustal, igneous rock, chemically identical to basalt, with ~40 modal% plagioclase, ~30% augitic clinopyroxene surrounded by alteration rims to amphibole and chlorite, plus ~25% opaques, a porosity of ~0.3%, and <1% total water, mostly due to hydroxyl-bearing minerals such as amphiboles and the experiments were conducted with $30 \times 15 \times 10\ cm^3$ blocks with one polished surface and all other surfaces saw-cut. They put the block inside an aluminum box ($50 \times 30 \times 30 cm^3$), acting as a Faraday cage and fitted with a steel bellow to apply the load. By doing this experiment, they observed and recorded the surface potentials (Figure 2), positive air ions (Figure 3) and Corona discharges (Figure 4). They showed that, stressing one end of a block of igneous rock such as gabbro leads to a series of processes at the unstressed end:

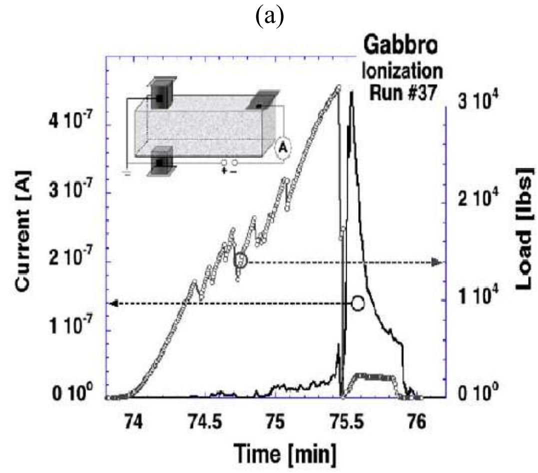
i) Positive surface potentials appear uniformly across the rock surface, increasing rapidly with increasing stress and reaching about +3 V.

ii) Massive amounts of positive airborne ions are collected above the unstressed end of the rock.

iii) Massive amounts of electrons and/or negative airborne ions are collected.



(a)



(b)

Figure 3. (a/b): positive during deformation of gabbro. The discontinuities in the load vs. time curves are caused by a drop in the oil pressure of the hydraulic press when the stainless steel balls are sinking into the rock. (a): Before failure; (b): whole run (from Freund et al., 2009).

As a conclusion, they stated that (Freund et al., 2009) with increasing stress, the following processes occur sequentially at or above the rock surface:

i) Trapping of $h^{\cdot}$ charge carriers and appearance of positive surface charges;

ii) Field-ionization of air molecules and generation of positive air ions; and

iii) Corona discharges with bursts of ion current and flashes of light.

3.4 Exo-electron emission theory

Enomoto et al. (1993) investigated the source mechanism of the seismic geo-electromagnetic activities that occur in a geotribosystem. They have shown that granite generates thermally stimulated exo-electron emission (TSEE) at temperatures ranging from 300 to 400 ºC. They concluded that this emission is released from the trapped levels at intrinsic and extrinsic centers in the minerals. Possible heat sources are discussed in terms of the frictional heating of the precursor slip (Enomoto et al., 1993). Fracture-induced transient electric signals (FTESs), propagated through the rock, could be detected; the intensity of the signals decayed inversely proportionally to the distance from the fracture zone and less FTES was detected for granite annealed at a temperature of 400 ºC, where the piezoelectric effect was unchanged but the exo-electron sites were reset (Enomoto et al., 1993). They concluded that this confirms that the main source of FTES and seismic geo-electric activity is probably the trapped electrons. Their results can be summarized as follows (Enomoto et al., 1993):

i) TSEE from granite was detected in the temperature range 250-400 ºC.

ii) The TSEE peak from quartz appeared at about 380 ºC, probably owing to the release of electrons.

iii) Biotite showed an active TSEE behavior among the constituents of granite.

iv) A temperature rises sufficient to cause TSEE occurs as a result of the frictional heating at the precursor stage of the fracture.

v) When granite bars were subjected to fracture, transient electric signals (FTESs) could be detected at the electrode positioned away from the fracture zone. The FTES decayed inversely proportional to the distance of the detecting electrode from the fracture zone.

Less FTESs were detected for granite annealed at 400 ºC. It was thus confirmed that the main source of the signal is not from the piezoelectric effect but from the trapped electrons.

3.5 Tribo - or fracture electrification theory

To understand the physical mechanism of the anomalous electromagnetic emissions observed before earthquakes, Yamada et al. (1998) carried out some laboratory experiments on electromagnetic and acoustic emission from a rock. They loaded a Granitic sample at a constant strain rate and electromagnetic and acoustic emission were simultaneously recorded during deformation of the sample. They observed that 10 to 20% of the acoustic emissions detected during the experiment are associated with electromagnetic emission. Yamada et al. (1998) then came to this conclusion that, a possible mechanism of electromagnetic emission is electrification of a fresh surface created by subcritical cracking in a rock. They stated that, they do not completely understand how a natural earthquake occurs, it is generally considered to be a result of shear faulting that connects pre-existing small cracks. Therefore, it is reasonable to expect anomalous electromagnetic emission associated with small tensile cracks before an earthquake and to expect that the anomalous electromagnetic emission will be observed only before an earthquake but not at the main shock, which may not be very efficient for creation of a fresh surface (Yamada et al., 1998). Their experimental results can be summarized as follows:

i) EM emissions are observed in association with micro crack growth.

ii) The amplitude spectrum of EM emission is dominated by components with frequencies > 500 kHz, although this may depend on the crack size.

iii) Tensile cracks are more efficient than shear cracks at generating EM emissions.

iv) Large and high-frequency AE events are more efficient for generation of EM emissions than small and low-frequency AE events.

The physical mechanism for EM emissions associated with rock deformation is not likely to be piezoelectric, but is probably related to the electrification by contact and separation of the fresh surface.

EQLs theories, although each one looks perfect, they also have weaknesses. The basic questions posed in the next section are the most unanswered and fundamental questions that these theories cannot answer.

4 Results and Discussion

4.1 Weaknesses and fundamental questions about present theories

Although the theories of earthquake lights seem to be perfect, there are some questions that have not yet been addressed. First of all, we think that none of the proposed theories can cover all the observed lights. This does not mean that these theories are wrong or cannot be used to justify this phenomenon. However, none of these theories can explain the observed EQLs at sea and inland. The number of these EQLs in a single earthquake and the exact location of these lights is not mentioned in any of the theories. As a fundamental question

Table 2. Summary of present theories for explanation of EQLs.

Theory	Physical process	Laboratory / Field study	Reference
Piezoelectric	Piezoelectric effect: results from the linear electromechanical interaction between the mechanical and electrical states in crystalline materials with no inversion symmetry.	Resistivity measurements directly on rocks located in the immediate vicinity of earthquake activity in the Los Angeles area.	Finkelstein et al. (1973)
Friction-vaporization	Frictional heating: will occur near shear zone then this heating will lead to vaporization of water in and near the shear zone and a dramatic decrease in electrical conductivity, σ, resulting a central conductor that collect charges and transfer to the earth's surface.	Study of conductivity against temperature for granite and conductivity of rocks for various earthquake.	Lockner et al. (1983)
Positive Holes	Ionization of oxygen to oxygen anions: by breaking of peroxy bonds in some types of rocks (dolomite, rhyolite, etc.) by the high stress before and during an earthquake the ions travel up through the cracks in the rocks. Once they reach the atmosphere, these ions can ionize pockets of air, forming plasma that emits light.	Impacting a dry granite block at higher velocity, 1.5 km/s, the propagation of the P and S waves was registered through the transient piezoelectric response of quartz and measurements of positive ion current during deformation of gabbro.	Freund (2002, 2003, 2011), Freund et al. (2009) Freund and Freund (2015)
Exo-electron emission	Thermally stimulated exo-electron emission: this emission is released from the trapped levels at intrinsic and extrinsic centers in the minerals. Possible heat sources is the frictional heating of the precursor slip	Granite generates thermally stimulated exo-electron emission (TSEE) at temperatures ranging from 300 to 400 ºC due to the release of electrons.	Enomoto et al. (1993)
Tribo - or fracture electrification	Electrification: anomalous electromagnetic emission associated with small tensile cracks before an earthquake.	Granitic samples were loaded at a constant strain rate and electromagnetic and acoustic emission were simultaneously recorded during deformation of the sample.	Yamada et al. (1988)

that has not been answered in any theory, we can ask, why EQLs are seen in a small number of earthquakes? None of the theories have been able to interpret the observed light spectrum. Only IR emission have been noted during the laboratory study (Freund and Wengeler, 1982; Freund and Freund, 2015). Two colors, blue-violet and orange (Figure 5), reported in a laboratory study (photographic evidence of luminescence during faulting in granite), which was done on a granite sample (Kato et al., 2010). However, different spectrum of observed EQLs is not interpreted by any theory.

In the meantime, we think that none of the theories can be used alone to explain the pre-seismic and co-seismic lights, which pre-seismic lights have been observed in the sky and atmosphere, and co-seismic lights have been observed near the earth's surface and illuminate the night sky, like a flashlight that is placed across the surface of the earth.

The basic questions that theories have failed to answer are:

i) Is there a connection between the different spectrum of EQLs and the lithology of a region?

ii) Where is the exact location of these lights?

iii) How many of these lights occur in an earthquake and why?

iv) Why EQLs occur in a small number of earthquakes and more on active tectonic boundaries?

v) Basically, why can light be seen during an earthquake?

The main weaknesses of each theory is explained in the following sections.

4.1.1 Piezoelectric

The main problem of the piezoelectric theory is the fundamental dependence of this theory on quartz crystals. Since electrostatic production in this method is unique to quartz and minerals having similar properties of quartz, it cannot practically be accepted to justify the light observed during earthquakes. Because in some cases, EQLs have been observed in areas with limestone lithology (and other lithology in other areas).

4.1.2 Friction-vaporization

The weakness of this theory is about the central conductor that is defined. As mentioned by Lockner et al. (1983), the source of electric charge for this conductor is the quartz-bearing rocks. Therefore, although this theory seems more complete than piezoelectric theory, it will have the same problem. What about other rocks?

Another problem is that in laboratory studies on this theory, only the electrical conductivity of granite samples is measured. No light is seen in the laboratory studies.

4.1.3 Positive Holes

Among the proposed theories, this theory appears to be the most complete. A lot of laboratory studies have been done over a decade on this theory. In this theory, Positive Holes are defect electrons in the O^{2-} sublattice that traveling via the O 2p-dominated valence band of the silicate minerals (Freund, 2002). Therefore, this is the first limitation of this method. Freund suggests that, before activation (before earthquake) the positive holes lay dormant in the form of electrically inactive Positive Hole Pairs (PHP), and concluded that this dormant PHP chemically is equivalent to peroxy links, $O_3X^{/OO\backslash}XO_3$, with $X = Si^{4+}$, Al^{3+}, etc (Freund, 2002). Thus, we need minerals with peroxy links $O_3X^{/OO\backslash}XO_3$ that are mainly silicates. It seems that there is also a lithology problem in this theory.

Another weakness of this theory is the spectrum of light. Despite all the efforts made on this method, only IR emission have been reported during the laboratory studies (Freund et al., 2007). While the videos and photos available from EQLs show that the lights are in the range of 350 to 600 nm. Besides, the relationship between the light spectrum and various lithologies cannot be justified.

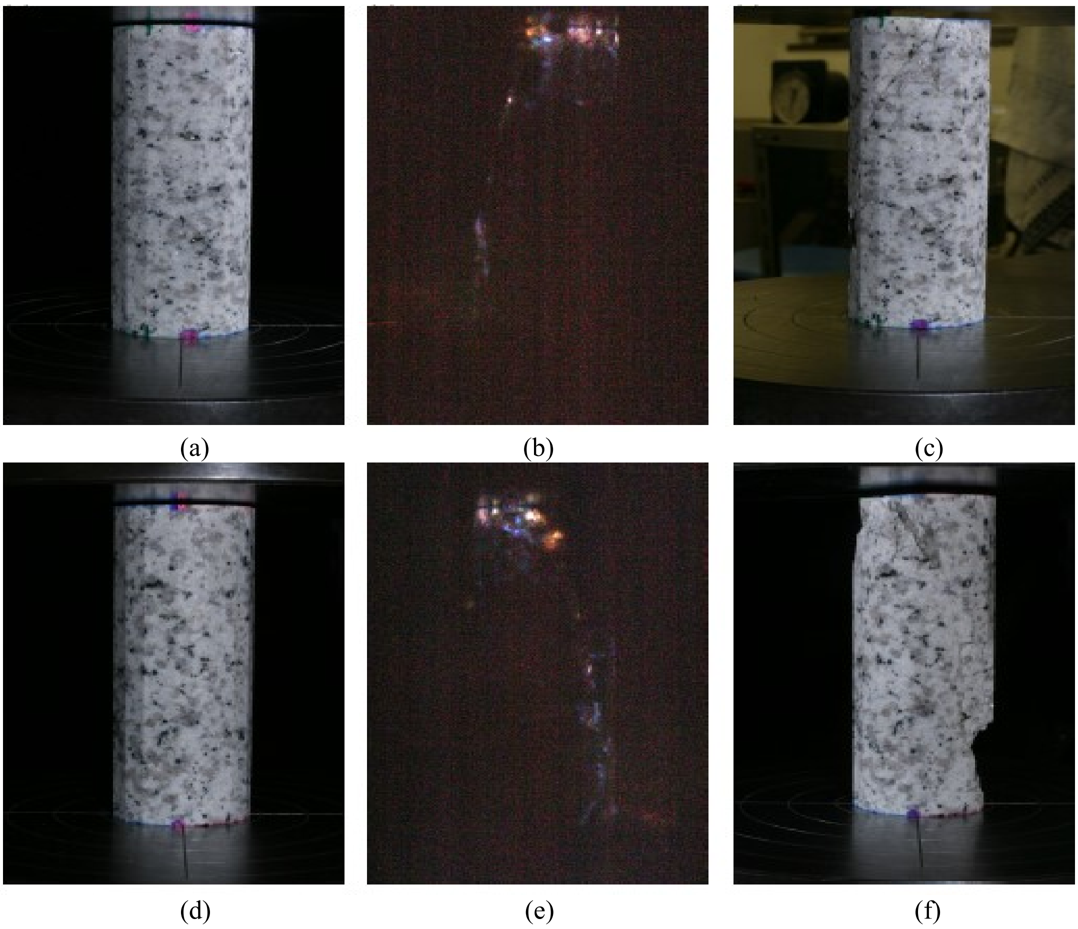
4.1.4 Exo-electron emission

In this theory, the problem of three other theories can be seen. Theory's experiments are done only on granite samples. Granite generates thermally stimulated exo-electron emission (TSEE) at temperatures ranging from 300 to 400 ºC. Like Friction-vaporization theory, the source of heat is frictional heating of faults. Moreover, laboratory observations showed no light in the range of 350-600 nm.

4.1.5 Tribo - or fracture electrification

Tribo- or fracture electrification theory has some weaknesses like other theories. The first one is lithology. All the experiments only have been done on granitic samples, and no light has been observed during the experiments. This theory seems to be somewhat similar to the theory of Positive Holes.

In all of these theories, only some of the physical properties of rocks are addressed and investigated (resistivity measurements in the piezoelectric theory, conductivity measurements in the friction-vaporization theory, different ion current measurements in the positive hole theory, fracture-induced transient electric signal measurements in the exo-electron emission theory, and acoustic emission measurements in the tribo- or fracture electrification theory). What should these experiments respond to is the spectrum of light and its different intensity, their



(a) (b) (c)

(d) (e) (f)

Figure 5. A typical image of bright luminescence for a coarse grained granite specimen, illuminated bright spots align diagonally from the upper left corner to the lower right corner on the specimen. This alignment is on the fault plane that is spontaneously developed during its fracture (e, f)), which demonstrates that bright luminescence occurs on the fault plane (from Kato et al., 2010).

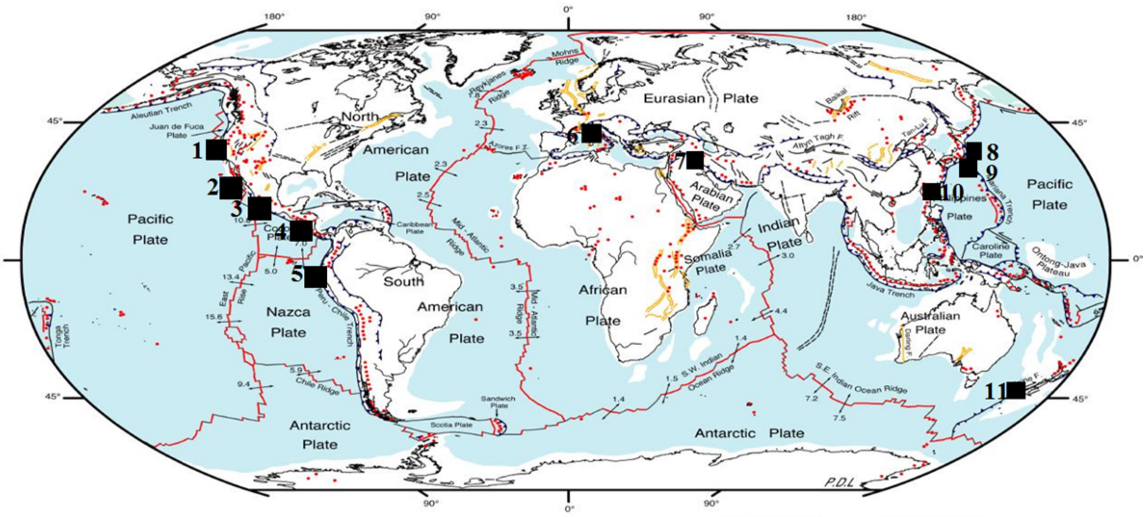


Figure 6. Digital tectonic activity map (DTAM) of the earth including tectonism and volcanism of the last one million years (From NASA). We marked the locations of 11 EQLs and related earthquakes by black squares. (1) off the coast of northern California earthquake, 1922 (Mw 7.3) (Derr, 1973), (2) 1926, Monterey Bay, Intensity VIII in Santa Cruz (Derr, 1973), (3) 1969, Santa Rosa, Mw 5.6 & 5.7 (Yasui, 1972), (4) 2017, Chiapas, Mw 8.2, (5)Peru, 2007, Mw 8.0 (Heraud and Lira, 2011), (6) 2009, L'Aquila,Mw 5.8 & 5.9 (Fidani, 2010), (7) 2017, Ezgeleh Earthquake, Mw 7.3 (Torabi et al., 2018), (8) Idu Peninsula, 1930 (Musya, 1931), (9) Matsushiro, 1965 (Yasui, 1968), (10) Haicheng ,1975 , 7.3 (Yulin and Fuyi , 1997), (11) 2016, New Zealand,Mw 7.8. All the EQLs location is exactly at the most active tectonic boundaries.

relationship to different lithologies and the amount of stress in an earthquake, which has not been done or discussed carefully. With all these explanations, all these theories and efforts are respected and also necessary to achieve the best possible theory.

4.2 Relation between EQLs and active tectonics boundaries

For a better understanding of the location of the observed lights, they are marked on an active tectonic map.

As shown in Figure 6, earthquakes in which light has been seen are all located on the active tectonic boundaries. This suggests that the earthquakes which produce light should be in areas where stress is at its maximum. This point may also indicate that the source of light is associated with fault zones or rupture areas. On the other hand, if the light is related to fault and surface ruptures, lithology will also affect the production of light. All of the above theories have attributed light production to a particular mineral or rock. However, in nature, we are faced with a variety of rocks and minerals. The role of stress in light intensity should also be considered. Placing earthquakes (with EQLs observation) in active tectonic areas does not mean that all of them will produce the same light with the same intensity. The larger the earthquake seems, the more intense the light will be produced.

4.3 Magnitude range of earthquakes

To study the magnitude of earthquakes that accompanied with EQLs, all reports that included earthquake magnitudes have been reviewed. Thériault et al. (2014) have provided a list of 27 earthquakes in the Americas and 38 in Europe with associated EQL occurrences based on date, depth, magnitude, geological location, and the area in which light is being seen. By analyzing their data for the Americas, we found that 20.83% of the magnitudes were less than 5.0, 20.83% were between 5.0 and 6.0 and 58.33% were greater than 6.0 (e.g. 1960 Valdivia earthquake, Central Chile, Mw 9.5 and 2007 Peru earthquake, Mw 8.0. see Table 1). For Europe, we found that 24.13% of the magnitudes were less than 5.0, 27.58% were between 5.0 and 6.0, and 44.83% were greater than 6.0.

Most of the earthquakes with which light has been observed have magnitudes above 6.0 (58.33% in Americas and 44.83% in Europe). One of the cases that theories have not yet been able to explain is the relationship between the different magnitudes and the intensity and spectrum of light. Because it seems that, the larger the magnitude of the earthquakes is, the light will be more intense and shorter in the spectrum.

5 Conclusions

Despite all the theories proposed for the explanation of EQLs, our review of these theories suggests that these theories have not succeeded in interpreting the phenomena associated with EQLs such as light spectrum and intensity, lithology, relation with active tectonic boundaries and amount of stress. All five theories (see sections 3 and 4) have the same weaknesses. In all of these theories, only some of the physical properties of rocks are addressed and investigated (resistivity measurements in the piezoelectric theory, conductivity measurements in the friction-vaporization theory, different ion current measurements in the positive hole theory, fracture-induced transient electric signal measurements in the exo-electron emission theory and acoustic emission measurements in the tribo- or fracture electrification theory). These theories cannot explain the role of different lithologies in the production of light and its different spectrum. However, the theory of positive Holes seems to be more complete than the rest. This is the only theory that led to the production of light in the laboratory studies (only IR emission have been reported (Freund et al., 2007)).

We also examine the relationship of the EQLs to active tectonic boundaries. All the earthquakes in which light has been seen are located on the active tectonic boundaries. This suggests those earthquakes that produce light should be in areas where stress is at its maximum. Therefore, the role of stress in producing light (different spectrum and intensity) can be very determinative and should be considered in the future.

According to available reports of earthquakes in which EQLs was observed, earthquakes with magnitude greater than 6.0 often result in EQLs. It is noteworthy that all these earthquakes are located in the most active tectonic areas.

As a final conclusion, there seems to be a need for a more comprehensive theory for the interpretation of EQLs. The theory that can, above all, explain the relation of light (Spectrum and intensity) to lithology, the amount of stress, and active tectonic areas.

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