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Earthquake lights and the stress-activation of positive hole charge carriers in rocks

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Abstract

Earthquake-related luminous phenomena (also known as earthquake lights) may arise from (1) the stress-activation of positive hole (p-hole) charge carriers in igneous rocks and (2) the accumulation of high charge carrier concentrations at asperities in the crust where the stress rates increase very rapidly as an earthquake approaches. It is proposed that, when a critical charge carrier concentration is reached, the p-holes form a degenerated solid state plasma that can break out of the confined rock volume and propagate as a rapidly expanding charge cloud. Upon reaching the surface the charge cloud causes dielectric breakdown at the air–rock interface, i.e. corona discharges, accompanied by the emission of light and high frequency electromagnetic radiation.

Keywords: Earthquake lights; Seismo-electromagnetic phenomena; Positive hole (p-hole); P-type semiconductor; Solid state plasma

1. Earthquake lights

Earthquake-related luminous phenomena, also known as earthquake lights, EQLs, have been reported since ancient times (Derr, 1973; Tributsch, 1983). In 1931, based on over 1500 reports from several events in Japan, Musya (1931) stated: "The observations were so abundant and so carefully made that we can no longer feel much doubt as to the reality of the phenomena." Nonetheless, doubts persisted in the scientific community at least until the late 1960s when EQLs were photographically documented during an earthquake swarm near Matsushiro, Japan. Yasui, a seismologist at the Kakioka Magnetic Observatory, studied reports from many people in the surrounding area, including sketches and photographs (Yasui, 1973), and concluded that most of the observations cannot be accounted for by atmospheric lightning, zodiacal light, auroras, meteors or by any other known sources. Similar observations were made in Mexico (Araiza-Quijano and Hernández-del-Valle, 1996) and in many other seismically active regions of the world (Lomnitz, 1994).

St-Laurent (2000) critically evaluated numerous reports of EQLs associated with the $M = 6.5 m_b L_g$ Saguenay earthquake, Québec Province, Canada, on 25 November 1988, which occurred during darkness, at 18:46 local time. The reports confirm the diversity of the observed luminous phenomena. One report that is particularly well supported provides insight into the processes that seem to have taken place in the Saguenay region, close to the 29 km deep hypocenter.

The earthquake was associated with the Saguenay graben, which runs roughly SE–NW and is nearly perpendicular to the St. Lawrence river, meeting it about 150 km northeast of Québec city. The Saguenay graben south wall

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delineates the northeastern edge of the Jacques Cartier block, a horst structure in the 600–900 m high Laurentian Plateau and exceeding it by 100–400 m.

The Saguenay earthquake was remarkable in several respects. First, it occurred outside the previously recognized seismic zones in this part of the Precambrian craton, which forms the Canadian Shield. Second, with a focal depth of 29 km it is one of the deepest intracontinental crustal earthquakes outside of plate convergence zones. Third, the high Lg-wave energy led to prolonged (2 min) and strong shaking in the epicentral region. The relatively low aftershock activity during the next six months (only 84 events, all smaller than $M = 3.6$ except for one $M = 4.1$) implies that a large fraction of the energy stored before the earthquake was released during the main shock.

There is, however, yet another reason for calling the Saguenay earthquake remarkable: A large number of luminous phenomena, reported from a wide area around the epicenter to the INRS, Université du Québec at Sainte-Foy, and to the Université du Québec at Chicoutimi (Ouellet, 1990). The earliest report dates from 25 days before the 25 November 1988 main shock when two individuals driving on Route 175 through the Laurentide Park observed at about 18:30 local time three luminous "masses" that rose from the ground. The area was 15 km from the nearest settlement, but close to the future epicenter. More luminous phenomena were reported during the $m_b = 4.3$ ($m_bL_g = 4.8$) foreshock of 23 November 1988, at the time of the 25 November 1988 main shock and during aftershocks. The phenomena were variously described as globular luminous masses, bands or rays or as intense atmospheric illuminations lasting from several seconds to several minutes. The phenomena were reported from places as far as 205 km from the epicenter, though the majority fell within a 50 km radius. All cases of intense atmospheric illumination were reported from within a radius of 35 km of the epicenter and most were coseismic or nearly coseismic with the $m_b = 4.3$ foreshock of 23 November 1988 (St-Laurent, 2000).

The Ouellet compilation (1990) contains 52 reports, of which 46 were judged to be of sufficient quality to warrant further study. Several of these reports were selected for follow-up contacts with the individuals who had made the observations and for site visits (St-Laurent, 2000).

We shall focus on one particularly well-documented observation made 19 km north of the epicenter, almost coseismic with the main shock. It was reported by Joseph A. Dallaire, a trapper who lives at Laterrière, close to the town of Chicoutimi. On November 25, 1988, Dallaire returned from the nearby forest, where he had inspected his traps. The forest consisted mostly of conifers with a few birches, which had shed their leaves. The wind stood at 5 km/h and the air temperature hovered around −8 °C with a relative humidity of 65%. A few patches of a thin layer of icy snow that had been put down four days earlier remained on the ground. It was around 18:45 and dark, about 2 h 45 min after sunset, about 1 h after moonrise at phase 0.9, with mostly clear sky. Just as Dallaire emerged from the forest, looking NW in the direction of his house across an open field 700 m away, he was startled by a crackling sound approaching fast from behind him.

As soon as the crackling noise had reached Dallaire, he saw a curtain or sheet of bluish light emerging from the forest to his left and to his right. The light was hugging the ground as it moved past him, passed into the open field, and disappeared in a general north-west direction. Dallaire estimated that the sheet of light traveled the distance from the edge of the woods to his house, 700 m, in about 2 s. He reported that the light was bright enough to illuminate his house. As it passed his house, it exceeded the height of its roof, 6 m, and may have been as high as 15 m. At the moment the sheet of light faded and disappeared, he felt the earthquake.

The description contains important details. (i) The event started with a bristling or crackling noise approaching from the direction of the epicenter 19 km to the left as shown in Fig. 1. The noise appears to have been caused by electric discharges off the conifer branches, indicating the buildup of a strong electric field. (ii) The curtain or sheet of light suggests an even stronger electric field that led to a discharge at the ground-to-air interface. (iii) The discharge was traveling from the direction of the epicenter. (iv) The speed of propagation was in the order of 100–300 m/s. (v) The electric discharge and EQL were not coseismic but clearly preceded the seismic wave train.

Tsukuda (1997) reported luminous phenomena observed before and during the $M = 7.2$ January 17, 1995 Hyogo-ken (Kobe) earthquake, which occurred in early morning darkness at 5:46 local time. The light spread rapidly to several kilometers in width and was estimated to reach up to 200 m in height with intensities estimated at 10^3 cd/m^2: "According to most eyewitnesses the luminosity started from ground level on land, suggesting that discharge processes... in near-surface rocks may be the primary driving force".

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 aftershocks. Most efforts to provide a physical explanation of the phenomenon centered on piezoelectricity, a property of quartz to generate electric fields on opposite sides of a single crystal when stressed in certain crystallographic directions (Bishop, 1981; Finkelstein et al., 1973). However, when a rock containing quartz is stressed, the electric fields generated by a large number of individual crystals cancel and the resulting field becomes zero. This is true for random orientations of the quartz crystals as well as for preferentially aligned quartz crystals.[1] Other processes like tribo- or

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[1] Though in texturally aligned rocks the polar axes of the quartz crystals may show a preferred orientation, there is no mechanism in nature that could select their individual +− directions over their −+ directions and thereby create conditions to produce, upon stressing, a net piezoelectric effect.

Fig. 1. Sketch of a luminous phenomenon as reported by J.A. Dallaire.

fracture electrification (Yamada et al., 1989) or exoelectron emission (Enomoto et al., 1993) seem inadequate to produce the large electric fields needed on large scales to account for at least the more powerful and sustained EQLs that have been reported.

2. Dormant electronic charge carriers in rocks

Igneous rocks contain charge carriers, the very existence of which has been overlooked in the past. As described in more detail elsewhere in this Special Issue (Freund et al., 2006), the charge carriers are electronic in nature and seem to be ubiquitous in igneous rocks. Most importantly in the context of EQLs they can be activated by stress.

Fig. 2 shows schematically what happens when we load one end of a 1.2 m long granite slab fitted with Cu electrodes at both ends. Two types of charge carriers appear inside the stressed rock volume on the left: holes and electrons. As indicated by the arrow inside the rock the holes flow from left to right through the unstressed portion of the granite slab. The electrons are unable to flow through the rock. Instead they flow from the source S into the Cu electrode on the left and hence to ground. The electric circuit closes by the electrons flowing through the external wire as indicated by the thin arrow and meeting the holes at the right-hand end of the granite slab.

The outflow of two currents from the stressed rock volume in opposite directions indicates that the boundary between stressed and unstressed rock acts as a diode. The diode lets the holes pass but blocks the electrons. Note that the two currents flow without externally applied voltage. They represent a self-generated battery current. The driving force is provided by the stress gradient. As the holes flow out from the stressed rock volume into the unstressed rock, they set up an electric field. This electric field pulls the electrons out of the stressed rock volume and causes them to flow through the external circuit to meet the holes at the right end of the slab. This electric field tightly couples the two currents and forces them to synchronize (Freund et al., 2006).

Next we discuss the nature of the charge carriers involved in the generation of these currents.

The holes are defect electrons in the O 2p-dominated valence band of the silicate minerals, i.e. that consist of electronic states that can best be described as a change of the valence of oxygen anions from their usual 2- to the

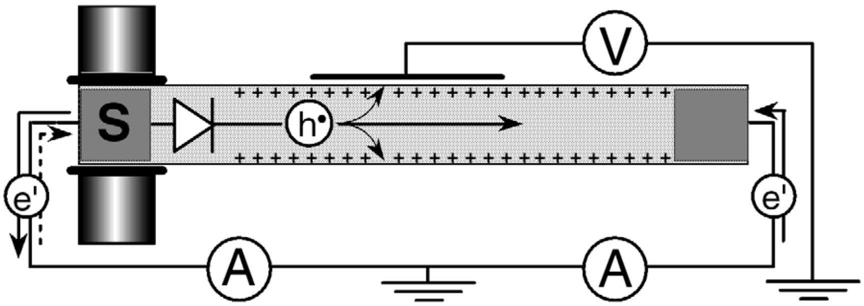

Fig. 2. Two self-generated currents flow out of the stressed rock volume, the source S, a hole current ($h^{\bullet}$) and an electron current (e'), while a positive surface potential builds up. The boundary between stressed and unstressed rock is indicated by the symbol for a diode.

1-state. They are equivalent to O^{-} in an O^{2-} matrix. We call them "positive holes" or p-holes for short, symbolized by $h^{\bullet}$. The presence of these charge carriers in (otherwise insulating) oxide and silicate materials has been established through studies involving single crystals and rocks summarized in Freund (2003). Normally the p-holes are inactive, i.e. dormant in the form of positive hole pairs, PHPs, chemically equivalent to peroxy links of the type $O_3Si–OO–SiO_3$ (Freund, 2002). When rocks are placed under stress, mineral grains begin to plastically deform. This deformation causes dislocations to move and new dislocations to be generated. The moving dislocations intersect the peroxy links and cause them to momentarily break. The higher the rate of deformation, the more dislocations appear and the more p-holes are activated per unit rock volume. We can represent this generation process as a two-step process:

$$\boxed{\underset{\text{PHP}}{O_3Si{-}OO{-}SiO_3} = \underset{\text{broken PHP}}{O_3Si{-}O^{\bullet}{}_{\bullet}O{-}SiO_3} = \underset{\text{loosely bound electron}}{[O_3Si{-}OO{-}SiO_3]'} + \underset{\text{mobile p-hole}}{h^{\bullet}}}$$

where the dots $^{\bullet}$ signify O^{-} states of the broken peroxy link, the superscript $'$ an electron that has moved in, and $h^{\bullet}$ a p-hole that has moved out.

The electrons are co-activated alongside with the p-holes. They are loosely bound and, hence, mobile. A stressed rock volume becomes a "source" which can release both p-holes and electrons.

The p-holes have the unusual property that, being electronic states in the valence band, they are able to spread out of the source into the surrounding unstressed rock. To travel they use the O 2p-dominated upper edge of the valence band, which provides for a small but finite p-type conductivity. The p-holes can therefore propagate through unstressed rock and even cross different rock types (Freund, 2002).

The electrons are unable to flow from the stressed rock into the unstressed rock. The reason is that they need an n-type conducting pathway. In the experiment sketched in Fig. 2 we artificially provided this n-type connectivity by applying one of the Cu electrodes directly to the source volume. In nature, in the Earth's crust, n-type conductivity becomes available at high temperatures, viz. at greater depth along the geotherm.

3. Geophysical scenario

Fig. 3 translates the geometry of the laboratory experiment shown in Fig. 2 into a geophysical scenario, presenting a cross section through the crust down to the hot mid- to lower crust. We assume the crust to be pushed by tectonic forces from the left to the right causing p-holes and electrons to be activated. We further assume that p-holes can flow out horizontally through the p-type conductive cool upper portions of the crust, while electrons connect downward to the n-type conductive, hot mid- to lower crust. However, there may be situations where the outflow currents do not keep up with the production rate of p-holes and electrons in the stressed volume.

This situation can arise when the concentration of charge carriers increases very rapidly due to rapid stress increase. At some point the charge carrier concentration then reaches a point at which they form a degenerate charge cloud. Such a state can become unstable and break

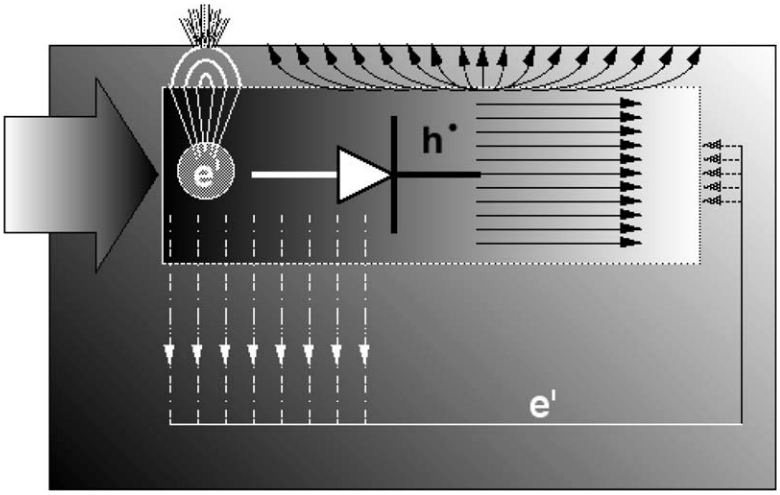

Fig. 3. Schematic cross section through the crust from the p-type conductive upper crust to the n-type conductive, hot lower crust. If, due to very rapid increase of stress in a given volume, more charge carriers are activated than can be dissipated (dashed arrows), a solid state plasma may form. It breaks out and bursts through Earth's surface, causing an electric discharge and attendant luminous phenomena.

out of its confined volume as a solid state plasma propagating outward explosively in the form of a p-hole cloud. When the plasma crosses the surface, it causes ionization of the air, a corona discharge and, hence, light emission.

4. Electrical discharges in laboratory experiments

In fact there are already laboratory observations that suggest some kind of solid state plasma formed in highly stressed rock volumes by p-hole charge carriers and their burst-like expansion, though these observations had not previously been analyzed in this physical context. An example is shown in Fig. 4a. We took a granite plate, approximately $30 \times 20 \times 2\ \mathrm{cm}^3$, and loaded one inner portion of it at a constant stress rate up to failure. During loading but before failure several cracks formed inside the stressed rock volume. We recorded their acoustic signals with a microphone placed about 5 cm from the edge of the piston. In addition, as sketched in the inset in Fig. 4a, we had installed a capacitive sensor placed about 20 cm from the edge of the piston to record the surface potential.

Several cracks spread over several minutes before failure of the rock triggered the data acquisition system. During each crack we recorded at the location of the capacitive sensor a burst of positive voltage, lasting less than 50 μs and followed by a longer-lasting negative voltage. However, as shown in Fig. 4a for crack #11, the burst-like positive signal arrived about 1 ms before the microphone recorded the acoustic signal of the crack itself. The amplitude of the voltage burst, +3 V but occasionally up to +12 V, was significantly higher than the steady state surface potentials, less than +100 mV, observed during loading (Freund et al., 2004). Takeuchi and Nagahama (2001) observed similar positive voltage signals during strike-slip faulting experiments and Enomoto et al. (1993) reported pulses up to +17 V. The positive sign, high amplitude and shortness of the signal are all consistent with a p-hole charge cloud that expanded rapidly from inside the severely stressed rock volume, presumably from the microvolume which was about to crack. From this we can infer that the rate of generation of the charge carriers in the stressed rock volume must reach its maximum shortly before fracture.

Why this is so has to do with the mechanism of deformation of mineral grains. Deformation occurs via the generation of dislocations. As illustrated schematically from left to right in Fig. 4b the density of dislocations increases with increasing stress. Eventually, the number of dislocations per unit volume becomes so large, on the order of 10^{10}–$10^{12}\ \mathrm{cm/cm}^3$, that saturation is reached. From this point onward few new dislocations are formed and most existing ones begin to entangle. They coalesce to form microcracks, which rapidly evolve into larger cracks and eventually into fractures. If dislocation movement is the mechanism by which charge carriers are activated as suggested above, the rate at which p-holes are generated must reach a maximum before fracture.

We can take it one step further and look at the timing of the positive voltage burst relative to the fracture event. From impact experiments we know that p-hole charge clouds propagate at speeds between 100 and 300 m/s (Freund, 2002). These speeds are consistent with the concept of p-holes propagating via electrons hopping in the opposite directions from O^{2-} to O^{2-} sites at the frequency of the lattice phonons. The jump distance is on the order of 3 Å (3×10^{-10} m). The phonon frequency is on the order of $10^{12}\ \mathrm{s}^{-1}$. Hence, $3 \times 10^{-10} \times 10^{12} = 300$ m/s. Acoustic signals propagate through granite at 6 km/s for compressional

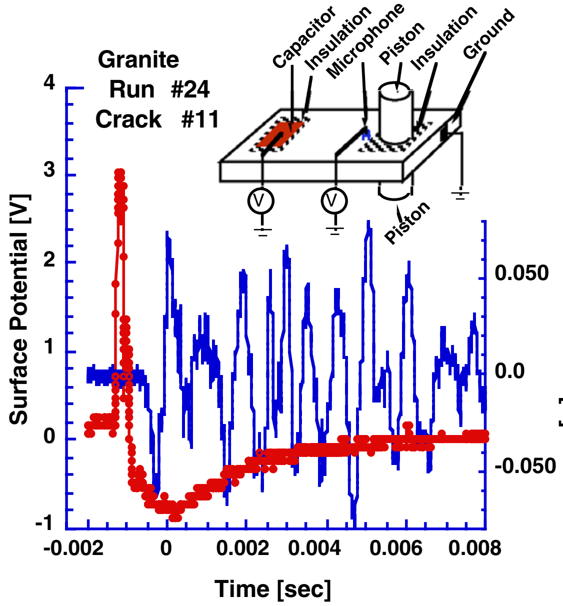

Fig. 4a. Surface potential and acoustic signal recorded during crack formation in a granite plate placed under load. Note the early arrival of the voltage pulse (Freund et al., 2004).

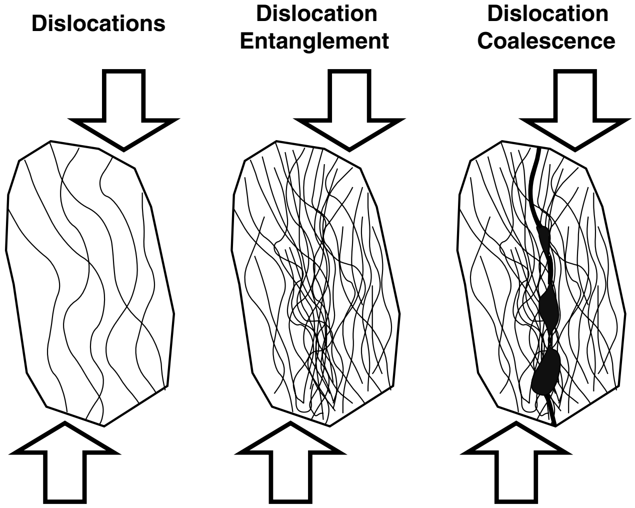

Fig. 4b. Schematic representation of the number of dislocations generated during plastic deformation, their entanglement and eventual coalescence into microcracks, initiating fracture.

(P) waves and at 3.4 km/s for transverse (S) waves. Hence, the acoustic signal of the crack event would reach the microphone in about 10 μs, while the voltage pulse takes 100 times longer, about 1 ms, to reach the capacitive sensor at the location shown in Fig. 4a. Since the voltage pulse arrived 1 ms before the acoustic signal, it must have been generated at its starting point, in the aforementioned microvolume, 2 ms before the crack.[2]

During the experiment depicted in Fig. 4a we did not simultaneously measure the light emission or the emission of kHz electromagnetic (EM) radiation that is characteristic of electric discharges. However, the shape of the positive voltage burst and its subsequent broader negative voltage are very similar to the voltage pulses recorded during low-speed (100 m/s) impact experiments. In these experiments a positive charge cloud was generated by the sudden stress to rock volume around the impact point. The charge cloud spread through the rock samples and arrived at the surface, causing the voltage signal to increase. The increase of the positive surface potential was interrupted above 400 mV by a sudden emission of light. The light came from the edges of the rock where the electric field is highest. At the same time a burst of 10–20 kHz EM radiation was recorded. Light emission and a burst of radio-frequency radiation are both clear indicators of a corona discharge.

Taking these various observations into account we can confidently say that the +3 V voltage burst recorded about 1 ms before cracking and shown in Fig. 4a must have been accompanied by a corona discharge due to the high electric field that built up at the rock surface upon arrival of the p-hole charge cloud. Hence, the experiment depicted in Fig. 4a must have produced a small, artificial EQL.

5. Saguenay earthquake light observations

We now return to the field observations, specifically to the reports on EQLs associated with the Saguenay earthquake (St-Laurent, 2000). The wide distribution of reported EQL sightings during the time leading up to the Saguenay event and the fact that the earliest report came in 25 days before the main shock indicates that the entire region was building up stress to a critical level. Intersecting faults, buried plutons, rift pillow and other deep structures are capable of localizing stresses (Zoback and Richardson, 1996) and of acting as "stress concentrators" (Gangopadhyay and Talwani, 2003). According to Du Berger et al. (1991) "plutons in the region span an area of few hundred square kilometers and extend to middle and lower crustal depths and are mostly composed of granite, mangerite, mafic dikes and gabbro". Small volumes within this crystalline basement presumably became critical in the sense that, by accumulating localized stresses, they produced p-hole concentrations high enough to initiate an outburst of a charge cloud. The outbursts led to electric discharges at the Earth's surface but were not necessarily accompanied by foreshocks. In some ways these local stress concentrators behaved like the microvolumes in our rock deformation experiment depicted in Fig. 4a. These microvolumes became critical one after the other and cracked, while the overall stress increased. In the case of the Saguenay event, each of the local stress concentrators released stresses at depth or transferred them laterally onto the remaining asperity, which eventually broke catastrophically during the main shock.

Fig. 5(top) shows a vertically exaggerated cross section of the Saguenay graben, ~40 km wide. Indicated from right to left are the North Wall, the Saguenay River, the location of the observer (J.A. Dallaire), the South Wall, and the epicenter. The Saguenay earthquake was initiated at a depth of 29 km near the south rim of the Graben (Roy et al., 1993). Fig. 5(bottom) depicts a section through the crust with the hypocenter marked by a star where t_1 and t_2 are, respectively the epicenter and the location of the observer J.A. Dallaire at a distance of 19 km. The hypocenter is shown as a source of a charge cloud expanding at ~300 m/s.

We assume that the hypocenter was the last asperity where the stresses accumulated and reached their highest values shortly before the main rupture. The volume of this asperity can be considered analogous to the microvolume in the stressed laboratory rock sample shortly before a crack forms. As in the case of the laboratory experiment, when stresses build up, dislocations are generated in increasing numbers on the scale of the individual mineral grains, thereby activating an ever larger number of p-holes and electrons. Assuming a constant rate of deformation, the stresses increase very rapidly as the system moves closer to catastrophic failure. The consequences will be that the rate at which p-holes and electrons are generated will eventually exceed the rate at which the charge carriers can be dissipated. It is therefore conceivable that, shortly before rupture, a cloud of charge carriers, presumably p-holes, will burst out of the confined volume of the asperity and expand outward as depicted in Fig. 5(bottom). On intersecting the surface above, this massive charge cloud will induce a large electric discharge at the air–rock interface and a luminous corona discharge similar to the corona discharges produced during the impact experiments (Freund, 2002).

Assuming a speed of propagation of the charge cloud in the range of 100–300 m/s and knowing from Dallaire's report that the rapidly moving curtain of light arrived at his location before the first seismic wave train, we can estimate the time at which this outburst must have started at the asperity which we identify with the hypocenter. The distance from the hypocenter to Dallaire's location is ~36 km. The P waves take ~6 s to travel this far at 6 km/s. A p-hole

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[2] If the voltage pulse were not due to a propagating charge cloud but to the electric field generated by piezoelectric quartz crystals, its speed of propagation would be the speed of light divided by the dielectric constant, ~50,000 km/s. In this case, given the limited time resolution of the experiment, the arrival time of the voltage pulse would be coincident with the acoustic signal.

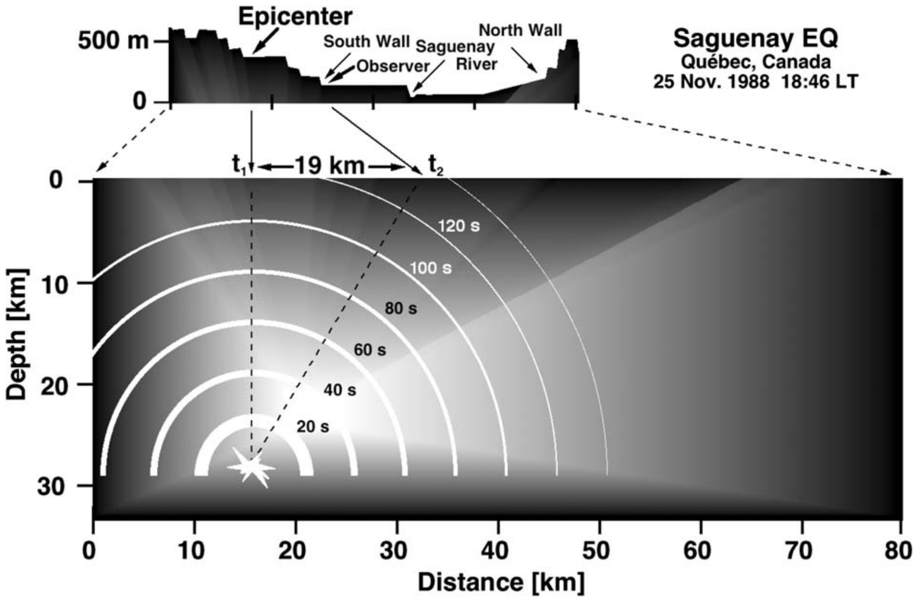

Fig. 5. Top: schematic, vertically exaggerated cross section through the Saguenay graben. Bottom: hypocenter at 29 km depth and outburst of a charge cloud assumed to travel at ∼300 m/s.

charge cloud travelling at 300 m/s would cover the same distance in 120 s. Hence, in order to arrive at Dallaire's location before the fastest seismic wave train, the charge cloud must have burst out of its confinement near the hypocenter about 130 s before the rupture. This implies that the maximum of the charge carrier generation process in the source volume was reached about 130 s before rupture. The estimated 2 s which the light curtain needed to traverse the 700 m wide open field in Dallaire's view agree with a speed of p-hole propagation on the order of 300 m/s. The relatively low speed of propagation of the charge cloud is echoed in many other reports that the luminous flashes associated with earthquakes are short-lived but longer-lasting than lightning strikes (Enomoto and Zheng, 1998; Tsukuda, 1997; Yoshida et al., 1995).

6. Conclusions

On the basis of the foregoing discussion we propose that the luminous phenomena associated with earthquakes, often called earthquake lights, EQL, are caused by electric discharges. The source of these discharges lies in the Earth's crust, in confined rock volumes that represent asperities and build up high and rapidly increasing stresses as part of the earthquake preparation process. Such stresses activate electronic charge carriers that lie dormant in the rocks. These charge carriers are p-holes and electrons, of which the p-holes have the unique property that they can propagate through otherwise insulating rocks.

If the rate at which the p-holes and electrons are activated exceeds the rate at which they can be dissipated, a situation may arise where the p-holes form a degenerate solid state plasma that can burst out of its confined rock volume and propagate at relatively high speed through the overlying rocks. When this charge cloud intersects the Earth's surface, it causes ionization of the air and, hence, corona discharges, which are accompanied by the emission of light. The many different forms and shapes of EQLs that have been reported suggest that the conditions of the solid state plasma and its discharge through the Earth's surface can be highly variable.

Our conclusions seem to be consistent with not only the observed luminous phenomena but also with the reported emission of radio-frequency electromagnetic radiation and other effects.

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