

# Pre-Earthquake Signals at the Ground Level

Jorge A. Heraud P.

**Abstract** Can we really predict earthquakes? Will we be able to do it sometime? The answer to the first question is no, we still cannot predict earthquakes but we seem to be moving in the right direction. At the ground level, several electromagnetic manifestations previous to rupture, are slowly fitting into place.

The main theme in this chapter is luminescence and the prevailing hypothesis in the case described here is the electric origin of the phenomenon commonly known as *Earthquake Lights*, or EQLs. The difficulty of dealing with luminescence nowadays is separating any EQLs from noise arising from artificial lights, electric short circuits, sparks, even fire from electric power lines, from substations, circuit breakers and the like. The San Lorenzo Island off the coast of Lima, Peru has provided three very outstanding cases of pre-seismic and co-seismic EQLs—with geological consistency—spanning 266 years of observation, including two high magnitude earthquakes. In addition there are three cases linked to low magnitude events with close-by hypocenters, about 2 km, which produces pre-earthquake EQLs on the island. In these cases, the high stress resulting from the build-up of a large magnitude earthquake produced a 21-day anticipation of the EQLs, whereas the low magnitude earthquake gave rise to a short 38 hours lead time. New picture evidence collected at San Lorenzo island show rock formations at an old colonial times prison reported to have been the focus of luminescence evidence before the mega earthquake in 1746. In 2007, a strong M8.0 earthquake 160 km away from the island, produced co-seismic lights, probably via the local activation of positive hole carriers by passing seismic waves, specifically S waves, igneous rocks forming vertical dykes in the bay of Lima.

Videos taken by security cameras on the PUCP campus show a very good time correlation with ground acceleration records from a seismometer located on the campus. Videos from an off-campus location show lights that were generated at a hill at the southern end of the city and were confirmed by qualified eyewitnesses. Observations from the San Lorenzo Island point to the possibility that small rocky

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islets in the Bay could have been the points of origin of columns of light seemingly arising out of the ocean.

The deployment of magnetometers, in collaboration with Quakefinder, is currently building up a station network along the seismically very active Southern Peruvian coast. All in all, at least on this side of this subcontinent, luminescence seems to be coupled with the generation and transport of electric charges.

The answer to the question whether it will be able to predict earthquakes sometimes in the future is strongly linked to our ability to (i) understand the physics of rocks under stress and (ii) develop a worldwide network of ground stations to collect and process multivariate data that will allow for meaningful deductions of the data leading to predictions. This is the final quest. Wiring different types of sensors to monitor electromagnetic activity prior to earthquakes is the geophysical equivalent to an electrocardiogram except that is aimed at anticipating impending catastrophic seismic activity. Rather than just sensing the passing of mechanical waves, as cardiologists do by “feeling” the cardiac pulse at the wrist, a worldwide web of monitoring stations, combined with the Internet, might bring us early warning signs pointing at future heart attacks of mother Earth.

## 1 Introduction

Natural hazards mitigation has moved forward in the past years for many types of disasters, through research effort and operating measures derived from space activities, like weather satellites, increased involvement of national and international organizations and many forms of cooperation and funding. This is the case of increasingly reliable weather reports, storms, hurricane watch including path and intensity prediction, Tsunami watch, floods and volcanic activity. What about earthquakes?

One of the most important questions we are now addressing with regards to drastic seismic activity leading to destruction and loss of lives is: Can we really predict earthquakes? Will we be able to do it sometime? Many authors have looked into this issue trying to go beyond the classical research in seismicity and the statistical estimation of future fracture areas with the hope it will lead to a more physical interpretation of what happens to matter subject to great pressures, dynamic forces and other physical interactions leading to seismic rupture and earthquakes. Research could probably lead to new interpretations of the ways nature might have to communicate the advent of a future seismic event, with enough lead time so as to devise operational methods to make life-saving prediction viable.

For over one hundred years, the electrical nature of matter has been recognized through successful theories linked to experimental evidence in physics and chemistry. Astrophysics is finally completing a picture in which we might be able to identify additional ways in which nature sets in motion charges and radiation, its very constituents, to produce a broader spectrum of messengers of telluric consequences. However it is still difficult to accept that, under mechanical stress, electrons in orbitals and the lack of electrons in certain orbitals, so-called positive holes, can set them in motion. Thus, electrons and p-holes and their physical, chemical and elec-

tromagnetic interaction with matter can conceivably set up visible, measurable and recordable ways of tracing, in space and time, activity deep in the Earth's crust in anticipation of the build-up of rupture areas at the onset of an earthquake. The experimental techniques of radio-science can thus be used to study the electromagnetic consequences of the motion, acceleration and deceleration of positive and negative electric charges, the generation of electric currents in the first case and of radio frequency waves in the other two. Besides the production of local magnetic fields and their interaction with the earth's magnetic field, there is accumulation of charges and the build-up of polarization in structures and the rush of huge amounts of electric charges into narrower high points leading to corona discharges, i.e. the burst-like ionization of dielectric air to produce luminescence. In the recombination process, line emissions in the infrared are produced as well as other consequences of the drift and diffusion of charges and the variations of the height of the ionosphere. Some of these phenomena can probably propagate far enough to produce effects at or farther away from the future rupture point or hypocenter, others are probably caused locally, as the seismic wave propagates carrying energy that temporarily stresses appropriate types of rocks with higher igneous content.

In a recent paper, Friedemann Freund [1] covers this issue thoroughly, analyzing the fact that non-seismic signals occurring before earthquakes have been reported but not taken too seriously into consideration for multiple reasons. Among them, we should consider the seriousness of the reports, the uncertainty about their origin and the time correlation between the occurrence of the phenomenon and the onset of the earthquake, perhaps hours, days or weeks later. Several more could be added. The fact that most of these signals are non-linearly related to earthquake magnitude, the location of epicenters and luminous signals in uninhabited areas, the effect of deep geological structures in the propagation of electric charges, the time of the day effect in luminous phenomena for instance, constitute difficulties in their study.

The intention is to give an observational approximation, in this case bridging over centuries, to one of the most ancient records of connections between electromagnetic phenomena and seismic activity. By using an outstanding video recording of co-seismic luminescence at a strategic point in the Peruvian coast during a major earthquake in 2007, an old and curious report of luminescence in a prominent island that occurred over two hundred years ago in the same spot, will be brought into historical perspective. Even more so, in July 27, 2012, a day and a half before an earthquake, pre-seismic lights were observed again in exactly the same spot as in 1746 and 2007. Besides, the possibility of detecting pre-seismic luminescence, opens another way hitherto difficult to be turned into an operational alert method, but at least scientifically possible and desirable as a means to correlate electrically produced luminescence with other methods or prediction.

## **2 Seismic Luminescence: “Earthquake Lights”**

For hundreds, even thousands of years, reports about the luminous phenomena previous to (pre-seismic) or coincidental (co-seismic) with earthquakes have been pil-

ing up since ancient times. Unexpected lights in the sky, rapidly flashing “flames” emanating from the ground, fire-like phenomena or “tongues of fire”, globular gaseous brightness of different sizes, extended white and light blue luminescence in the sky and other shapes and forms of various colors, have all been described. Literature contains vivid descriptions of these phenomena, accounts of word-of-mouth information passed along for decades and even centuries, though most of them associated with religious beliefs related to “divine punishment”.

Atmospheric events of luminous characteristics associated with earthquakes are commonly known as EQLs for “EarthQuake Lights” and have been described by Richter [2] in 1958, but observationally reported by Terada [3, 4] in 1930 and 1931. One of the first review papers on earthquake lights was written by John Derr [5] in 1973 and it gives a thorough description, with many illustrations, of luminous phenomena associated with earthquakes since one of the first analysis of the problem of considering EQLs in seismology in 1942. As will be recalled further ahead, most of the morphology described by John Derr resembles very closely the luminosities described by qualified witnesses during the M8.0 earthquake in Pisco, Peru and observed extensively in Lima, 150 km away [8]. The statistics of observations seems to be stationary over tens of years in time and thousands of kilometers in space.

In the Mediterranean area, EQLs have been reported since ancient times. Papadopoulos [6] in 1999 collected information from 30 earthquakes and concluded that EQLs were reported from rather shallow and strong earthquakes ( $M \geq 6.0$ ) and epicenters up to about 140 km away. In Quebec, Canada, EQLs were reported by St-Laurent [7] in 2000.

## ***2.1 Signal to Noise Ratio***

One of the difficulties experimental research has to deal with leads to the enhancement of the ratio of signal to noise in any observation, collection of data and data analysis and processing. Seismic luminescence, in a figurative way, is no exception and even at present time, separating cases worthwhile looking into from hoax, is not easy. Electrical flashes associated with the power grid, shorting of power cables, oscillating high voltage transmission lines bouncing against each other, arcing in circuit breakers, corona discharges, open fires and other activities of man-made origin, usually happen. Going back into the past to study the reports of luminescence from time prior to electricity has its advantages since there is no need to mask out non-existent man-made electrical causes. However we have to deal with religious interpretations and superstitious beliefs that greatly increase the number of reports, enhance the atrocity with which the phenomena is perceived, leads to induced opinions that range from the exaggerated intensity of the phenomena to attributed relationships with other occurrences because of assumed divine purpose and control. So ancient reports of luminous phenomena may have no source of confusion with man-made causes but could be highly distorted by subjective personal and collective beliefs.

## 2.2 The Big Earthquake in Lima, 1746

On October 28th, 1746 at 10:30 pm (LT), a 4-minute long mega earthquake hit Lima, the capital city of the Viceroyalty of Peru, then under Spanish rule, and Callao its sea port, about 15 km due west. Without seismometers and modern seismological science, the magnitude of the earthquake cannot be known but estimates place it around 8.6. However, judging by the high percentage of the population killed and reports on the distance reached inland by the sea water of the giant Tsunami, two Spanish “leagues” or around 5 km, some seismologists have estimated a  $M > 9$  event, the largest earthquake ever to strike Peru. The earthquake has been described by different sources, as a major event, much stronger than the great Lima earthquakes of 1582, July 9, 1586, October 10, 1687 or the Cusco 1650, Tacna August 13, 1868 or the Ancash, May 30, 1970, the highest human lives toll earthquake in Peru. In this event, over 75,000 people died as a consequence of the huge induced landslide of a glacier at 6,700 m above sea level that buried the city of Yungay, about 400 km north of Lima.

In 1746, Lima’s population was estimated between 50,000 and 60,000, so the death toll of 7,000 was very high at over 10 %. The port of Callao was about 7,000 people and records account that about only 200 survived, about 23 ships were literally thrown through the air by the tsunami reaching midway into the city of Lima. Diego de Esquivel y Navia [9] and Perez-Mallaina [10] have written good accounts on the events previous, during and after the big earthquake of 1746 and other news from Lima newspapers in 1791, in particular *Mercurio Peruano* [11], have permitted us not only to understand the social events, the fears and disbeliefs surrounding such a tragic event, but from a more scientific point of view, to discover, buried in the noise of fear and superstition, the presence of EQLs, up to three weeks before the earthquake. More recently, Charles Walker [12] a historian steeped in Peruvian culture and history, published a book describing the social events that surrounded the tragic events related to the mega earthquake and tsunami in Lima in 1746.

### 2.2.1 San Lorenzo Island in the Bay of Lima

In central Peru, the bay of Lima is one of the most prominent geographical features on the Pacific coast and spans the capital city of Lima, nowadays with nine million inhabitants. San Lorenzo is the largest of a group of islands, islets and rocks protruding from the ocean, apparently with the appropriate characteristics for propagating electric charges to the surface, as will be shown. San Lorenzo is part of a group of islands together with *El Fronton*, *Palomino*, *Cabinzas* and smaller islets and rocks known as *Horadadas* and is located 4 km from the peninsula at the northern part of the bay. It is 8.3 km long, 2.3 km wide and its highest point rises to 396 m above sea level. It is arid, it has no sources of fresh water and its terrain is rocky and covered by sandy soil. Occupancy has been only temporary along centuries but pre-Columbian ruins found, give a hint that a permanent population might have been established.

**Fig. 1** Old prison and dungeons in the rock at San Lorenzo island. EQLs in the form of tongues of fire were reported coming out of the ground and walls on October 7, 1746, 21 days before the large October 28, 1746 earthquake (Photo credit Maria del Pilar Fortunic)



Nowadays, only a naval base exists as a permanent station but no large electric grid installations as power lines are present so as to suspect man-made electric flashes to be confused with EQLs.

### 2.2.2 Pre-seismic EQLs in San Lorenzo Is., October 1746

Diego de Esquivel y Navia [9], describes a particular incident in which 21 days before the earthquake, strange lights described as “tongues of fire” were seen by the captain of a sloop anchored in San Lorenzo island. They were coming out of the storeroom, the tower and fence walls, made in those days of adobe and rocks and he thought it was a product of his imagination. The old prison, shown in Fig. 1, sits on rock and in an adobe construction, so its walls could not have been the source of real fire, as will be dealt with in the following description. Some of the high security dungeons were caves and holes on the rock with a simple iron gate outside, as can be seen to the right of the building, one of them in white.

When the captain of the sloop met prisoners working at 2–3 am, he learned from the officer in charge of the prison, Manuel Romero, that he had let them out to work because he was afraid the tongues of fire would melt down the prison walls. The captain then realized that what he had witnessed earlier was not the product of his imagination but was corroborated by the prison official. The following translation, with the full account of the pre-seismic EQL event, tries to respect the description and construction of XVIII century Spanish, as contained in the following paragraph:

“On October 7th, 21 days before the sad topic of this letter, don Juan Felix Goycoechea, a man over 50 years old, native of Fuenterrabio in Guipuzcoa, Spain, captain of the king’s sloop in which they were transporting rocks from San Lorenzo island to the prison, between 2 and 3 o’clock in the morning, saw the storeroom, other rooms, towers and fence walls burning; this not only worried him but filled him with horror. A little less than an hour later, he met the prisoners, subject to forced labor on that island, as they were coming to load rocks on the ship and this was a surprise for the captain who did not expect the unusual timing for this job; he asked them for the reasons for their untimely arrival and their answer was that—the island Captain, don Manuel Romero, who was very frightened, released us from prison at about 3 am, so we could watch the prison melt down and there is nobody left there

who is not an eye witness of such flame and fire. With this response Captain Goycochea, confirming what at the beginning he had taken as a false view and presumed as produced by his imagination, made public to the inhabitants of the prison the flames of fire he had seen burning, explaining the reason for the tragic forecast he had issued, saying they had been made in prevention of trouble so they could anticipate the situation with penance”.

It is truly significant that this event could be rescued from the noise level of fantasy that accompanied the great earthquake in Lima in 1746, and becomes significant also in the time difference of 21 days between its occurrence and the seismic event. San Lorenzo island is a mountainous desert island that rises up to about 400m above sea level and at about 5 to 6 km off the tip, as an off shore extension of a small peninsula in the northern end of the bay of Lima. It is made mainly of sedimentary rock but part of it is made of mafic igneous rocks, which resisted erosion. As will be explained, the very intense luminous phenomena video recorded during the 2007 Pisco earthquake and seen co-seismically in Lima, away from the epicenter, occurred among other places, also precisely above San Lorenzo island.

### 2.2.3 Pre-seismic EQLs in San Lorenzo Is., July 2012

Mr. Diego E. Menendez, an engineer and the brother of a research assistant at our Institute, is quite familiar with our 2007 EQLs video since he helped us reformatting it. Hence he is a qualified observer for this matter. On July 27, 2012, he alerted us of outstandingly similar but brief lights he saw in the direction of San Lorenzo, the evening of July 27, 2012 at 10:30 pm LT. It was quite a welcomed coincidence but there was no hint as when the seismic event would occur, however the fact that San Lorenzo was precisely under the observed luminescence led us to think of the likelihood of a nearby event. Thirty eight hours later, on July 29, 2012 at 12:36 pm LT, a  $M_L$  4.5 earthquake occurred just about 2 km NE of San Lorenzo Island at a depth of 58 km, corroborating the pre-seismic nature of the luminescence, reported to us ahead of the event. The scenario of these pre-seismic sightings in the bay of Lima is shown on Fig. 2. It has been estimated that the 1746 earthquake epicenter probably occurred around the same place.

## 2.3 *The Pisco, Peru, 2007 Earthquake*

Most earthquakes in Peru are caused by convergent plate tectonics, as a consequence of the subduction of the Nazca plate under the South American continental plate, one of the most active regions in the world, resulting in the rise on the Andean cordillera. According to Tavera and Bernal [13], the  $M_w = 8.0$  earthquake off the coast of Pisco on August 15, 2007, was the largest shallow earthquake in Central Peru during the last 250 years. Tavera et al. [14] have covered the earthquake which produced extensive damage to property and infrastructure in the cities of Ica, Pisco, Chincha, El Carmen and many smaller towns. Total death toll was 520 people, about 1500 wounded, 59,000 houses destroyed, and Pisco was the hardest hit with 85 % of its houses destroyed.

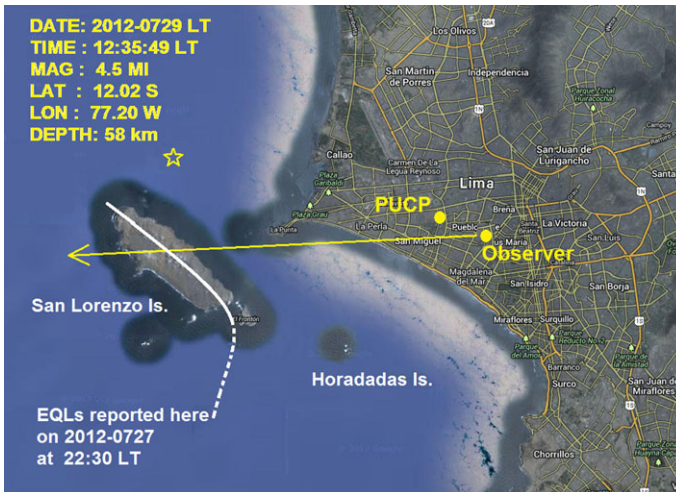


Fig. 2 Scenario of Pre-seismic EQLs in San Lorenzo island, Lima, Peru, July 27, 2012

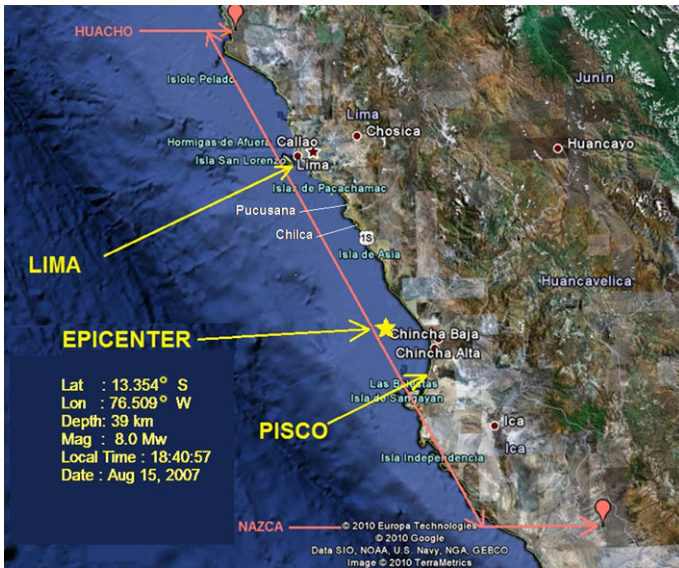
### 2.3.1 Co-seismic EQLs Along the Peruvian Coast

According to Ocola and Torres [15], co-seismic luminosity has been reported by hundreds or thousands of people along the coast, almost as far south as Nazca and as far north as Huacho, especially in small towns and beaches. Most places and small islands along the central Peruvian coast (with green captions) and referred to here, are depicted in Fig. 3, which shows the zone spanning from Nazca to Huacho. In the capital city of Lima, about 160 km north of the epicenter, thousands of people reported seeing the lights in various forms: quick, moving flashes of different colors but predominantly bright white or light blue in the direction of the coast, over the ocean, over the top of islands and some hills. Ocola describes very important evidence of lights reported by people who were on the beach at the time. They observed lights over the uninhabited islands off the coast of Chincha and hence strongly enhancing the fact that no man-made electric sources could have been responsible for the luminous phenomena. My personal experience during several interviews with eyewitnesses in two towns along the coast about 60 km south of Lima, Chilca and Pucusana, has been very similar. Observers were very emphatic in describing the luminous phenomena in the direction of the ocean and those in Pucusana (see Fig. 3) all pointed to the top of a close-by island as the origin of most EQLs.

### 2.3.2 Co-seismic EQLs in the Bay of Lima: Witnesses' Accounts

Complete video evidence of co-seismic luminescence was recorded at the PUCP campus by a stationary security color camera, pointing at a fixed direction with time stamp in milliseconds [16]. Using another video, recorded in a shopping center



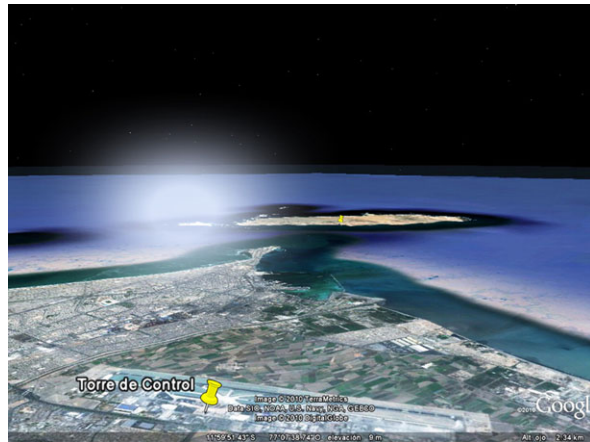


**Fig. 3** Scene of reported EQLs from areas south to north of the epicenter in central Peru. Islands are shown in green, locations in white

overlooking the ocean, ray tracing could be performed to analyze the direction of the captured lights. With the additional participation of several qualified eyewitnesses, a fairly good layout of the EQLs along the Lima skyline was reconstructed.

On August 15, 2007 at 18:41:00 LT, Mr. Giancarlo Crapesi a Peruvian private pilot was landing a twin engine turbo prop plane at “Jorge Chavez” international airport in Lima. At an altitude of 1500 ft (~300 m) on his final approach, he reported to the control tower the presence of rapidly moving, flickering lights in different parts of the bay, especially on the top of islands and hills. He was told an earthquake was underway at that very moment. Mr. Crapesi decided to check the status of the landing strip before committing to landing. However he decided to land instead of continuing to the only alternate airport, that of Pisco. At the time, it was not yet known that the epicenter of the  $M_w = 8.0$  earthquake had actually started near Pisco so that landing there would have been impossible. In a follow-on interview Mr. Crapesi described with great detail the shapes, colors and timing of the lights, and he was present as an art student transferred his description to a Google earth map for his approval. Mr. Crapesi emphasized the lights on top of the hills along the landing path well known to him under the names “La Regla” and “La Milla”. He also mentioned EQLs emanating from the top of San Lorenzo island and from “Morro Solar”, a well known 350 m high hill in the southern part of Lima. From his flight experience, he described the lights as rapidly moving, similar to those produced by electrostatic discharges from wing tips of aircraft. A comprehensive image of this witness description, together with a general overview of the scenario is given later in Fig. 9.

**Fig. 4** View of EQLS over San Lorenzo and El Fronton islands, and the ocean between them and the coast, as described by air traffic controller at the Lima airport



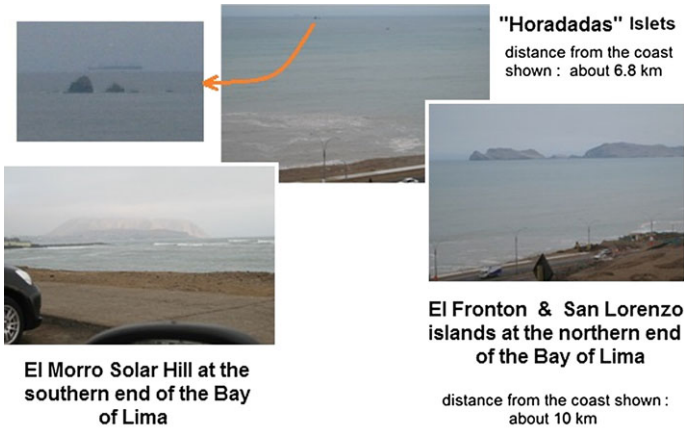
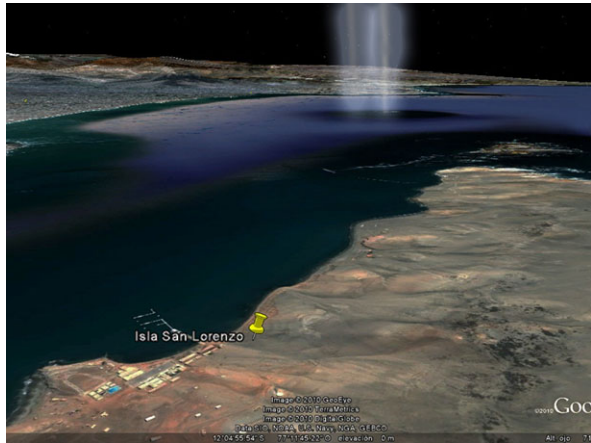
Our second eyewitness was Mr. Jorge Merino, an air traffic controller from CORPAC, the aeronautical authority in Peru, who was on duty at the control tower at “Jorge Chavez” international airport at the time of the earthquake. Mr. Merino described the lights as “coming out of the ocean” from the strait between San Lorenzo and Fronton islands as being round in shape and somewhat diffused. His description was drawn by an art student and later reproduced on a Google earth map for his approval, as shown on Fig. 4.

The third eyewitness was the chief security officer at the Lima international airport, Mr. Juan Salas, who was near the parking ramp when the earthquake started. As he paced back to the main airport building, he saw white and light blue lights reflected off the large glass windows of the terminal. The lights were coming from the west, i.e. from the direction of the ocean. Mr. Salas saved the videos from the outside security cameras, which were compared with videos of updated cameras installed later, in order to determine the exact direction the cameras had been pointing at the time of the earthquake.

Our fourth eyewitness, second lieutenant Guillermo Zamorano from the Peruvian Navy, was at San Lorenzo Island at the time of the earthquake. He described seeing “columns of light” emanating from the ocean as he looked towards the Lima coast line. The lights were rising at four consecutive times during the earthquake, consistent with the time capture on the video at the PUCP campus. The lights were white and light blue with some spiral stripe structure. At first this witness account seemed difficult to fit since it would be difficult to understand how a column of light would rise off the ocean. However, upon further examination, a group of pointed rocks or islets was identified, low above the water line and difficult to see, but definitely above water in the precise area described by our witnesses and known as “Horradadas” Islands. The image, recreated with the help of our Art student, is shown in Fig. 5.

Three specific views of the southern (Morro Solar) and northern (islands) parts of the bay of Lima are shown in Fig. 6.

**Fig. 5** Columns of light emerging from little islets (Horadadas Is.) on the ocean, as described by an observer on the San Lorenzo Island

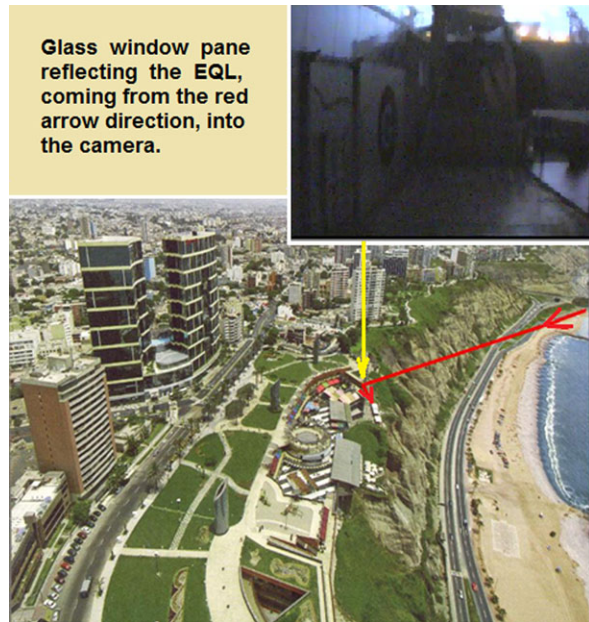


**Fig. 6** Southern part (*left*) and northern part of the bay (*right*)

### 2.3.3 Co-seismic EQLs in the Bay of Lima: Video Evidence

The fifth evidence comes from a security video provided by the “Larcomar” shopping center, a recent development right at the edge of the cliff overlooking the bay of Lima. The video was one of twelve kept for years by the security officer of the shopping center and generously made available to us for our research. Almost all the cameras were inside buildings and stores but one of them pointed towards the large glass window of the discotheque facing the ocean. Knowing the direction into which the fixed camera was pointing we could deduct by simple ray tracing the origin of a strong and sudden luminescence that was present in two of the video frames. Figure 7 shows the large glass window illuminated by an intense white and light blue flash of light on one of the frames and located as shown on the aerial view

**Fig. 7** Luminescence reflected on a glass window pane of a discotheque at *Larcomar* shopping center, Lima and the ray tracing identifying the direction

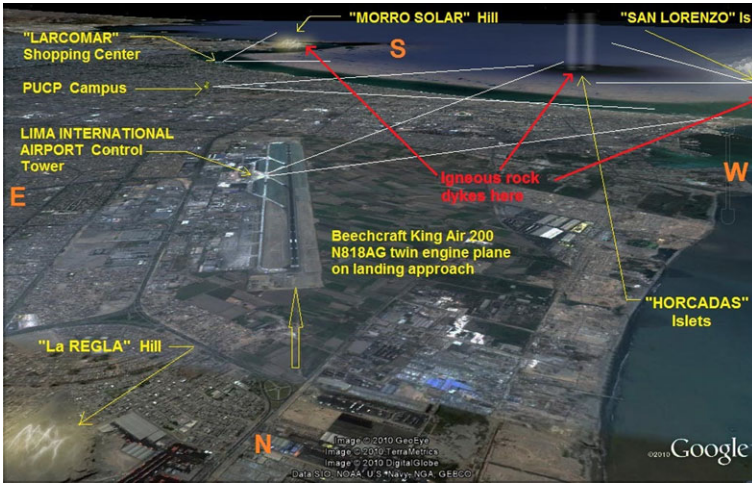


**Fig. 8** Security camera #3 at the PUCP campus. Notice the position of camera (*white dot*) and its pointing direction (*black arrow*) towards the west and San Lorenzo Island



of the *Larcomar* shopping center overlooking the ocean. The ray tracing identified the ridge known as “*Morro Solar*” as the direction from where the EQLs arrived.

The sixth and most important graphic evidence comes from security cameras around the campus at PUCP. One of them, camera #3 was fixed, pointing due west at the time of the earthquake. Figure 8 shows the direction (black arrow) of the camera (white dot), looking directly at San Lorenzo Island. This evidence will be further analyzed in the next section.



**Fig. 9** Overall scenario of the bay of Lima showing the EQLs studied, observation points and geographical features

Figure 9 shows a compendium of the eyewitness reports and video records of the observations in the bay of Lima. The Google Earth-based view shows the bay of Lima looking south, hence West is to the right in this image, where San Lorenzo and surrounding islands are barely perceptible. This view should be compared with the map shown in Fig. 14, in rather the opposite direction, but the map complements the observed coincidence of the spots where luminescence occurred vs. the geological structures that support the generation of local electric charges.

### 2.3.4 Analysis of the Observations

The digital video, recovered from storage after almost three years, displays vivid colors, frame numbers, date and timing in milliseconds. It represents a valuable document to the luminous phenomena in the bay of Lima during the Pisco 2007 earthquake. It is also significant in that the direction in which the camera points is easily deductible and coincides with that of the San Lorenzo—El Fronton islands, as seen from the PUCP campus. Four of those frames are shown in Fig. 10 and correspond to the last and most intense EQL.

The intensity of the luminescence was determined by delimiting the area for each of 13 colors, establishing a linear scale and counting square pixels for each frame in the portion of interest with specific software, as depicted in Fig. 11.

A weighted area count gives a sufficiently accurate measure of the intensity of the light versus time. In this way four main time groups were identified. An additional group, group #2, due to light coming from a different direction, was identified. The time, duration, and intensity distribution for each EQL event are summarized in Fig. 12.



**Fig. 10** EQLs in Lima during the 2007 Pisco earthquake as recorded by a stationary security video camera. The frame number is on the *upper right corner* and local time on the *bottom central line*

In order to correlate the times of the EQLs with the earthquake, we took the 3-axis ground acceleration records of the PUCP campus seismometer. Disregarding details of the luminous phenomena, the timing of the EQLs is depicted in Fig. 13, together with the magnitude of the ground acceleration and the time difference correlation of both. We can identify two seismic wave trains corresponding to the two hypocenters that fractured during the Pisco earthquake, approximately 75 seconds apart.

The first wave train started at about 10 sec with the arrival of the first P wave, followed about 20 sec later by the arrival of the first S waves, characterized by significantly higher ground acceleration values. The arrival time difference, about 20 sec, is consistent with the travel time difference between P waves (about 6 km/sec) and S waves (about 3.4 km/sec) and the distance from the earthquake center, 150 km. Excellent correlation is found between the timing of the EQLs and the passage of the S waves leading to peaks in the ground acceleration. The timing of the EQLs with the passage of the S waves is consistent with the observations of voltage pulses recorded by Takeuchi et al. [17].

It is obvious that, for the Pisco earthquake, the EQLs coincide with the arrival of the S waves. This confirms the hypothesis that these luminous phenomena are locally produced, triggered by the extremely rapid, high-amplitude compression and shearing of the rocks during the passage of the S waves.

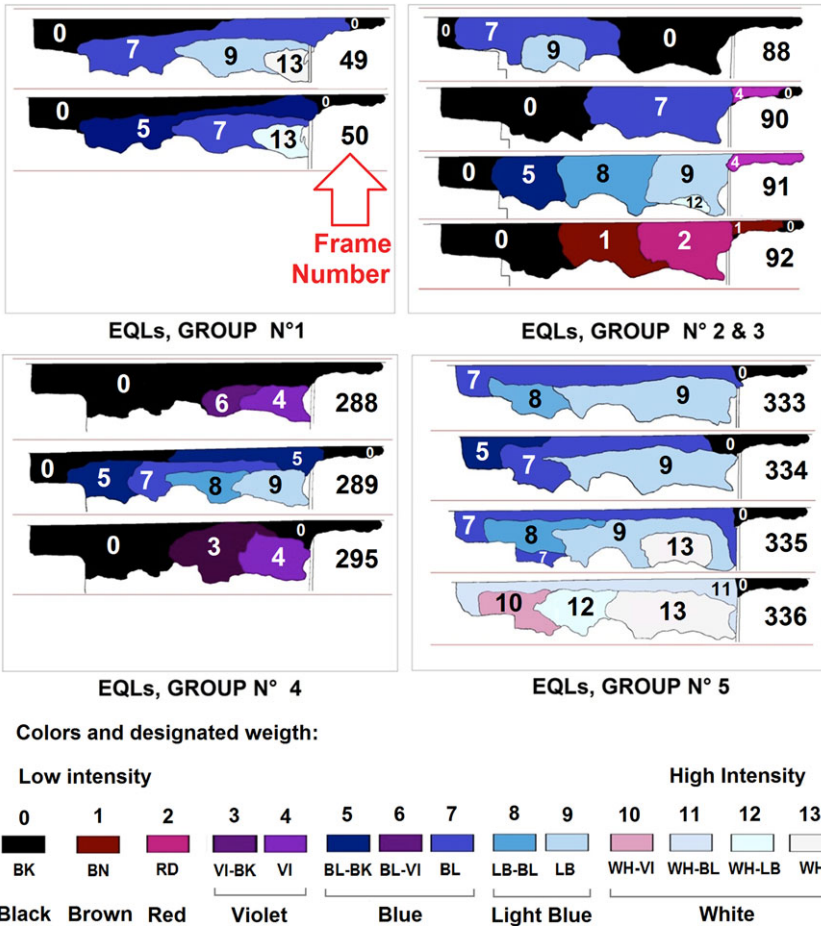
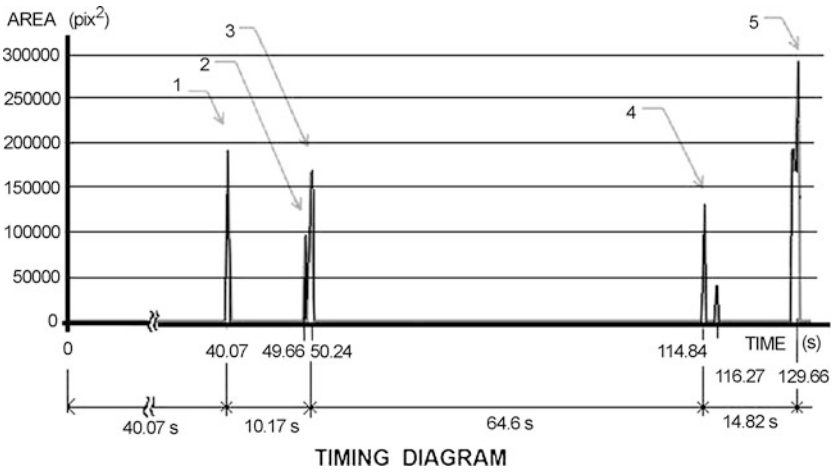


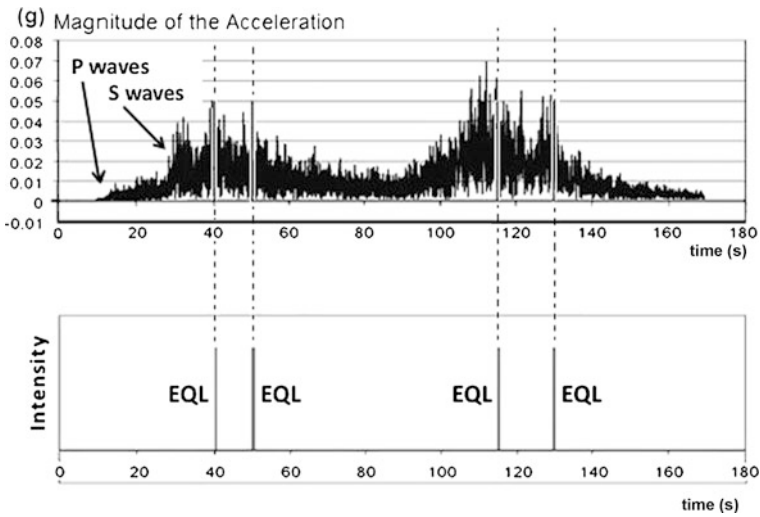
Fig. 11 Luminescence by time frames, colors and areas

### 2.3.5 Overall View of the Luminous Phenomena

In order to significantly improve the “signal to noise ratio” of the observation, we focused on the phenomena described by witnesses and cameras, across the hills close to the ocean and towards the islands. The observational directions are shown in Fig. 14, with special emphasis on directions, angles of coverage from different observation points from where we have credible reports and video recordings. Additionally, shaded in green, we observe a high coincidence between the areas where the EQLs were video-recorded and reported by qualified witnesses and the geological formation in the bay with mafic igneous rocks of Jurassic and Cretaceous age, a condition that appears to be a prerequisite to the activation of electric charges in the rocks during the sudden compression and shearing during the passage of the S waves.



**Fig. 12** Resulting morphology and timing diagram for the EQLs



**Fig. 13** Time Correlation between the EQLs and the magnitude of the ground acceleration  $g$  at the PUCP Campus—August 15, 2007

### 3 Generation and Transport of Charges

#### 3.1 Generation of Electric Charges Connected to Seismic Activity

Understanding the generation of electric charges in rocks traces back to work done in the late 1980s and early 1990s, when Minoru Freund [18], his father Friedemann Freund and his post-doc François Batllo demonstrated, in a series of elegant labora-



**Fig. 14** Map showing the location of the eyewitnesses (airplane pilot, airport control tower observer, officer at naval base on San Lorenzo Island) and of the security video cameras

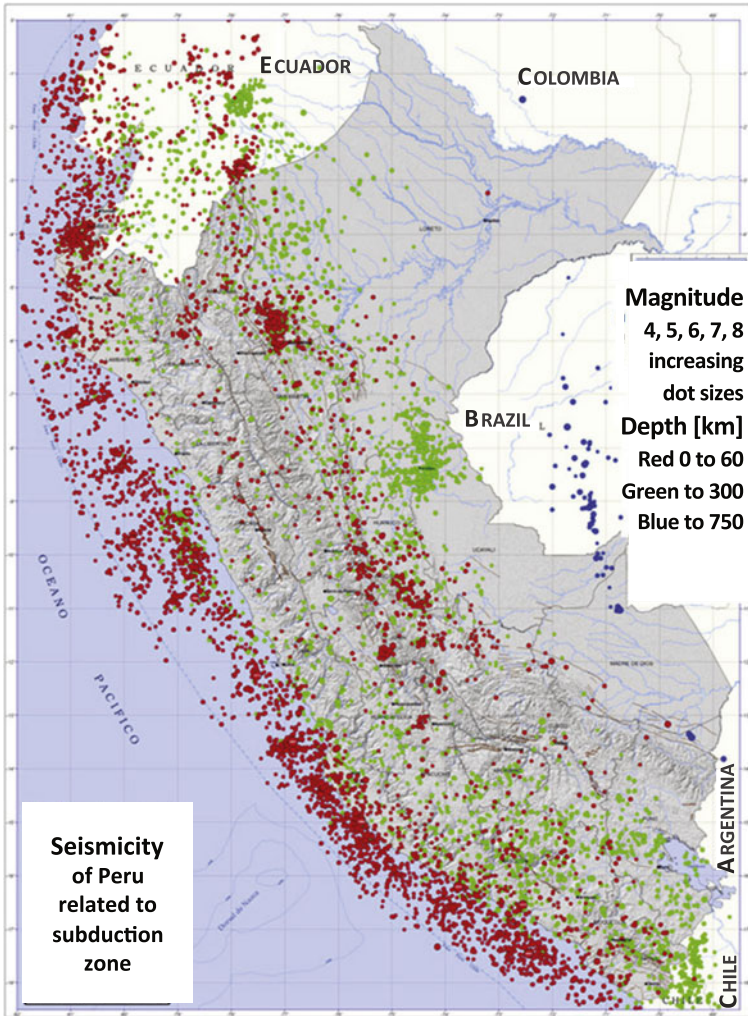


tory experiments, the activation of positively charged electronic charge carriers, first in oxide single crystals, later in silicate minerals. Mino's familiarity with high  $T_c$  oxide superconductors, just discovered around this time by Mino's Ph.D. co-advisor Nobel Laureate Alex Müller, helped lay the foundation for the characterization of these remarkable electronic charge carriers, which normally exist in an electrically inactive state. They are now known as positive holes.

The broader geophysical implications of this early work became apparent when, in the early 2000s, Freund [19] and Freund et al. [20] showed for the first time that, when stresses are applied to a slab of rock, granite or gabbro or anorthosite, these same electronic charge carriers become activated as previously identified in single crystal studies. In rocks the positive holes produce a continuous electric current flowing out the stressed rock volume, spreading into and through unstressed rocks, traveling fast and far.

In the previously cited work, Friedemann Freund [1] presents a well-balanced formulation of a solid state theory towards a comprehensive understanding of the generation and transport mechanisms of electric charges in rocks subject to stress. He showed that positive-holes, or p-holes, pre-exist in an electrically inactive, dormant state as peroxy links and that they become activated when stresses are applied. Flowing out of the stressed rock volume the p-holes constitute electric currents. Those currents create electric and magnetic fields, emit ultralow frequency electromagnetic waves, and produce multiple electric phenomena including locally extremely high electric fields capable of ionizing the air, causing dielectric breakdown and bursts of light.

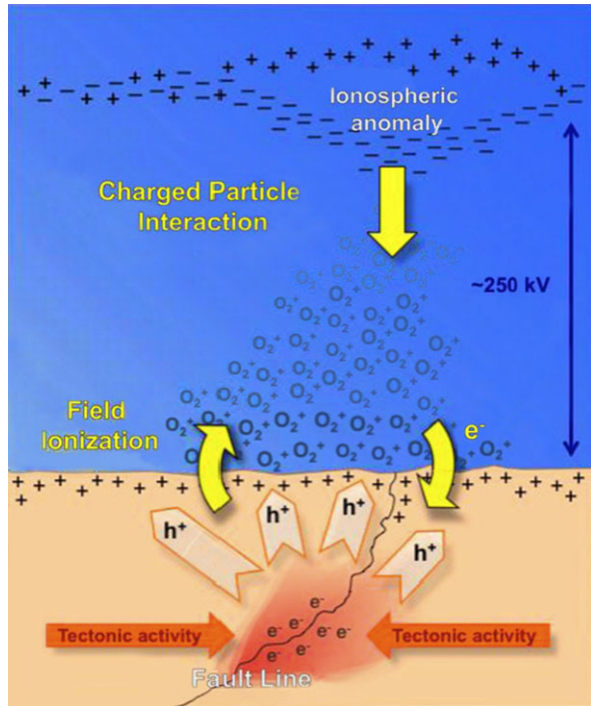
In the earth's crust, the various movements of tectonic plates relative to each other produce great stress levels down to depths of tens of kilometers to hundreds of kilometers. In the Peruvian case, the subduction of the Nazca plate under the continental plate starts at the Peru-Chile trench about 50 km offshore and dips under the continent producing the rise of the Andean ranges along the Pacific coast of the South American subcontinent, from the southern tip of Chile to northern Colombia. Seismic activity is considered "shallow" for hypocenters up to 60 km deep, occur-



**Fig. 15** Seismic activity in Peru plotted by depth and magnitude, 1964–2008

ring mostly along the Peruvian coast, a strip of land that stretches about 100 km from offshore to the rising line of the Andes. Earthquakes occurring between 60 km and 300 km deep in the Peruvian highlands are considered “medium depth” and those from 300 to 750 km occurring in the Peruvian Amazon jungle are considered “deep”. Seismic activity from 1964 through 2008 has been plotted by the *Instituto Geofísico del Perú* in these three depths according to their red, green and deep blue color and magnitude according to diameter, as shown in Fig. 15.

**Fig. 16** Generation and local transport of p-holes by Friedemann Freund



### 3.2 Transport of Electric Charges Connected to Seismic Activity

Freund [1] considers that the generation of p-holes in great quantities produces a migration of these positive charges along the rock, beyond the volume under stress and into the unstressed rock, constituting an electric current of positive carriers subjected to recombination with free electrons. Additionally, this would give rise to emission of infrared radiation and accumulation of surface charges leading to air ionization and to corona discharges due to dielectric breakdown of the air and EQLs. His model is depicted in Fig. 16.

In general, there are several mechanisms by which electric charges will move in a solid:

- (a) Drift, i.e. the motion of charges subject to electric and magnetic fields.
- (b) Diffusion, caused by the number density gradient of the charges between contiguous volumes of the solid.
- (c) Recombination, caused by electrons achieving a lower energy state.
- (d) Combined motion of charges in magnetic fields, leading to the Hall effect in semiconductors.

In the case of drift motion of charges, at the presence of an electric field ( $\vec{E}$ ) the lattice should produce a free electron to respond with an acceleration ( $\vec{a}$ ) proportional to the field:

$$\vec{a} = \frac{-q}{m^*} \vec{E}$$

where  $q$  is the electron charge and  $m^*$  the effective mass. However accelerated motion pertains only to a perfect crystal so in most cases with collisions, charges move with a drift terminal velocity proportional to the electric field and its constant of proportionality is the electron (or hole), mobility:

$$\vec{v}_n = -\mu_n \vec{E}$$

Motion of charges by drift requires the presence of an electric field and motion is limited by lattice and impurities collisions or scattering.

Motions of charges by diffusion is the consequence of a statistical case of a 3-dimensional random walk problem. For a one-dimensional number density distribution along  $x$ ,  $n(x)$ , the resulting current density is given by:

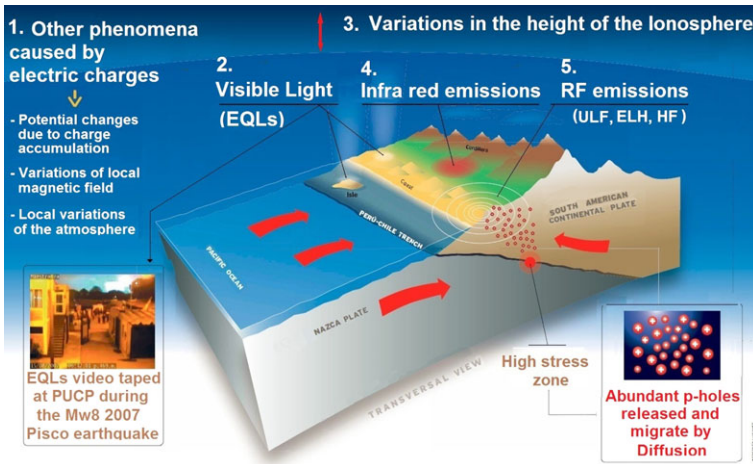
$$\vec{j} = -D \frac{\partial n(x)}{\partial x} \vec{e}_x$$

where  $D$  is the diffusion constant given by the ratio of the particle mean free path squared to the mean free time,  $n(x)$  is the number density of electrons (or p-holes) and the partial derivative with respect to  $x$  denotes a one-dimensional case. In other words, the current density is a vector proportional to the vector gradient of the number density distribution and the negative sign accounts for the fact that charges will diffuse from higher density regions to lower density regions. Hence the presence of an electric field is not needed. Diffusive flow of both negative and positive charges, requires then a density gradient, like a sudden generation of broken peroxy links in great quantities as stated by Freund, to set up high currents of charges rushing to a liberating pointed end. Thus and in a simple way, we can think of diffusion as the transport mechanism for the generation of EQLs.

### 3.3 A Simple Model for the Peruvian Coast

A simple model that includes the generation, transport and luminescence release is shown on Fig. 17. For EQLs near the epicenter, locally produced charges at the subduction zone where the future hypocenter or rupture point is building up, are responsible for EQLs. As the seismic wave propagates, the local pressure of the S waves leads to the activation of very high concentrations of p-holes, which would then cause the outburst of light from the surface of the Earth due to the dielectric breakdown of the air.

Preliminary analysis of the possibility of generating EQLs with charges that propagate all the way from the epicenter, 160 km away in the case of the Pisco,



**Fig. 17** Subduction plate tectonics along the Peruvian coast and the generation of p-holes giving rise to luminescence at and away from the epicenter stress driven by a seismic wave

Peru earthquake, show that the timing is not compatible with our observations. According to Freund [1] positive holes propagating outward from a source correspond to electrons hopping in the opposite direction from 2-electron ( $O^{2-}$ ) to 1-electron deficient oxygens ( $O^-$ ). The maximum speed of propagation is limited by the frequency  $f$  of thermal phonons,  $\sim 10^{12} \text{ sec}^{-1}$ , and the inter-atomic O–O distance  $d$ ,  $2.8 \text{ \AA}$  or  $2.8 \times 10^{-10} \text{ m}$ :

$$v_{h'} = fd = 10^{12} \text{ Hz} \times 28 \times 10^{-10} \text{ m} = 280 \text{ ms}^{-1}$$

This relatively high speed may be applicable for EQLs produced very near the epicenter. However, as the cloud of p-holes spreads further out, it dilutes. Therefore its speed of propagation must slow down. Even considering elevated temperatures deeper in the earth’s crust along the propagation paths, providing for a higher conductivity, the speed of p-hole propagation will remain far below the speed of propagation of seismic waves, typically about 4 to 7  $\text{km sec}^{-1}$  typically in the Peruvian coast for P-wave and about 3.4  $\text{km sec}^{-1}$  for S-waves. Thus, far from epicenters, it is not possible to justify co-seismic EQLs as being produced by p-holes propagating directly from the point of rupture. Therefore, local generation of charges by similar mechanisms must be considered for EQLs coincident with the arrival of the seismic waves. In other words, EQLs must be produced locally, synchronized with the arrival of the seismic waves, specifically S-waves, passing through igneous rock formations close to the surface. Abundant p-holes suddenly formed and creating a strong density gradient, travel by diffusion to pointed formations on the surface, increasing the chances of corona breakdown near the ground and illuminating the surroundings with a fuzzy and rapidly moving flame-like luminescence.

One question that quickly comes up is the reason for the observed time difference between observable electromagnetic precursors and seismic activity, as reported for both EQLs and variations in the local earth’s magnetic field in magnetometer

**Table 1** Observed EQLs and their relations to earthquakes, for San Lorenzo Is.

EQLs observed			Earthquake			Timing and distance	
Date	Local time	Type	Date	Local time	Mag.	Lead time	Epicenter
1746–1007	02:30	Pre-seismic	1746–1028	22:30	8.6 (est.)	21 days	~2 km NE
2007–0815	18:41	Co-seismic	2007–0815	18:41	8.0	None	~160 km SSE
2012–0727	22:30	Pre-seismic	2012–0729	12:30	4.3	38 hours	~2 km NE

records. As discussed in the next session, up to 2 weeks have been observed in Alum Rock, California and in Tacna, Peru in the case of magnetometers. In the case of EQLs, three distinct cases above San Lorenzo Island have been studied: two pre-seismic and one co-seismic. Table 1 shows these three cases including the lead time.

As can be noticed, pre-seismic EQLs are connected to nearby epicenters, almost precisely in the same place, the oldest one corresponding to the 1746 mega-earthquake (estimated at M8.9 when no seismometers were available, but considered by many seismologists as a M9+ event). We are tempted to conclude that very close to the epicenter, pre-seismic EQLs are observed with short lead-times, of the order of hours, for lower magnitude earthquakes, whereas large magnitude to-be earthquakes show precursor EQLs with lead-times of the order of weeks. This “vicinity condition” to the future epicenter seems to determine the rather proportional factor or lead-time to earthquake magnitude. In the case of the July 29, 2012 earthquake, even though we had the qualified eyewitness report of the EQL observed 38 hours ahead of the earthquake and suspected a possible rupture was in progress, we had no way of determining the time the earthquake would occur. For distant epicenters, tens or hundreds of kilometers away, the effect is still local, produced by p-holes activated in rock volumes that undergo rapid stress build-up without, however, rupturing. The Earth crust is a dynamic system with stresses waxing and waning all the time at different locations, especially in parts of the crust, where seismic activity will eventually occur. Not every local stress build-up leads to catastrophic rupture, hence an earthquake, but episodes of locally high stresses can lead to co-seismic EQLs.

#### 4 Low Frequency Micropulsations in the Local Magnetic Field and Future Research

In 2009, through a cooperative agreement with Quakefinder of Palo Alto, California, deployment of a network of magnetometers, sensitive to ultralow frequency (ULF) electromagnetic (EM) emissions, was started. Dunson et al. [21] have described a similar lead time of about 14 days between ULF pulses and earthquakes, both in Alum Rock, California and in Tacna, Peru. Ten of such induction coil magnetometers have been installed in selected parts of the Peruvian coast, clustered in

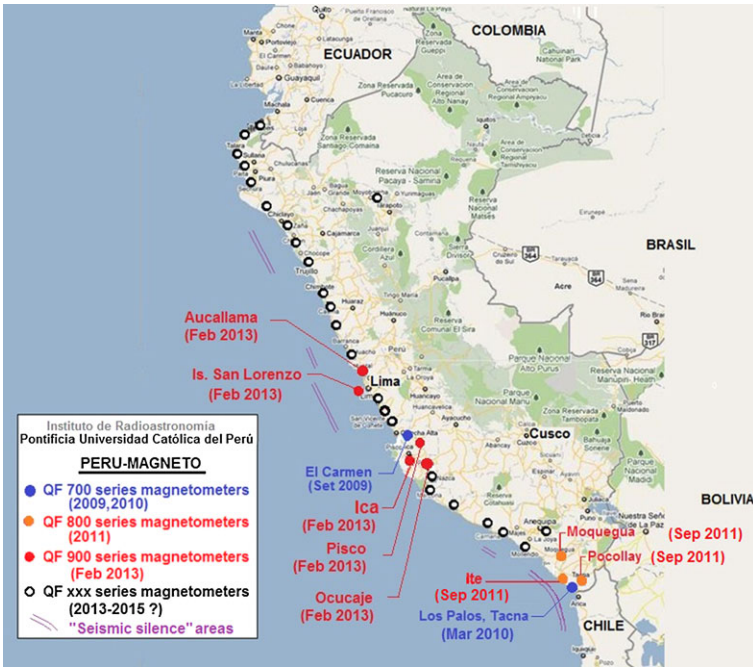


Fig. 18 The proposed Peru-Magneto network, showing the existing magnetometer sites (solid colors: blue, orange, red) and the future installations (black circles)

order to take advantage of additional triangulation capacity with trustable azimuth observations of sources of ultra low frequency pulsations. One of them has been, just recently, installed at San Lorenzo island, not too far away from the centuries old prison mentioned, with the purpose of studying the propagation of charges and generation of ULF signals. Next to it, automatic recording cameras and other experiments will be deployed shortly. On Fig. 18 the “Peru-Magneto” network is shown, with future stations in black circles and the already installed sites in color-coded solid circles.

### 5 Concluding Remarks

Luigi Galvani was proven right in interpreting that the muscles of the frog generated electric currents. Over a century later, currents generated by heart muscles were sensed remotely to diagnose heart disease rather than by pressure waves obtained by pressing arteries against bones. Let’s be confident that remote sensing of electromagnetic phenomena can provide us with new clues and means to anticipate the *tantrums* of planet Earth.

**Acknowledgements** I want to express my recognition to the late Mino Freund, whose dedicated work in various areas of his scientific interest, brought all of us together in this book. From the

multidisciplinary symposium held in NASA Ames Research Center on August 10, 2012, it was clear that the broad view Mino had and his enthusiasm for science was the catalyst for a group of scientists in discussing together topics that mixed and matched superbly. My thanks to Friedemann Freund for the honor of being invited to participate.

Part of this work, pertaining to the co-seismic observations in Lima in 2007, was published together with Juan A. Lira. My thanks to Carlos Sotomayor of PUCP for providing me the video recording obtained on the PUCP campus, to CORPAC, the Peruvian Aeronautical Authority and qualified witnesses like air traffic controller Jorge Merino and pilot Giancarlo Crapesi, lieutenant Guillermo Zamorano of the Peruvian Navy, Juan Salas, chief security officer of LAP, the Lima Airport operators and the Larcomar shopping center. I would also like to thank seismologists Daniel Huaco of CERESIS (Regional Seismology Center for South America) and Leonidas Ocola, professor at San Marcos University in Lima. My thanks to Silvia Rosas, Professor and head of the Mining and Geology area at PUCP for her interpretations of the geological maps of the bay of Lima, as well as INRAS research assistants Neils Vilchez and Daniel Menendez for their participation in the experimental work and Victor Centa for the programming and signal processing. Useful discussions were also held with Thomas Bleier of Quakefinder and Friedemann Freund of the SETI Institute, France St-Laurent and Robert Theriault. Pictures of the San Lorenzo prison were taken during a trip to the island supported by the Peruvian Navy. We are indebted to Quakefinder for providing us with magnetometers and to Telefonica del Peru for the donation of the magnetometer now installed at San Lorenzo island, modems and indefinite airtime for getting the data from our magnetometers via cellular 3G data links.

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