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Co-seismic luminescence in Lima, 150 km from the epicenter of the Pisco, Peru earthquake of 15 August 2007

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Abstract. The first photographs of Co-seismic Luminescence, commonly known as Earthquake lights (EQLs), were reported in 1968 in Japan. However, there have been documented reports of luminescence associated with earthquakes since ancient times in different parts of the world. Besides this, there is modern scientific work dealing with evidence of and models for the production of such lights. During the Peru 15 August 2007 $M_\mathrm{w} = 8.0$ earthquake which occurred at 06:40 p.m. LT, hence dark in the southern wintertime, several EQLs were observed along the Peruvian coast and extensively reported in the capital city of Lima, about 150 km northwest of the epicenter. 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. We believe the evidence presented here contributes significantly to sustain the hypothesis that electromagnetic phenomena related to seismic activity can occur, at least during an earthquake. It is highly probable that continued research in luminescence and the use of magnetometers in studying electromagnetic activity and radon gas emanation detectors will contribute even more towards determining their occurrence during and probably prior to seismic activity.

1 Introduction

Co-seismic Luminescence, which hereafter will be called “Earth Quake Light” (EQL) for reasons of brevity, is a secondary effect of a seismic event, which can take place in the atmosphere during a particularly strong earthquake, as described by Richter (1958). In Japan, EQLs were systematically reported as early as the 1930s by Terada (1930, 1931) and the first photographs of EQLs were published by Yasui (1968). Features of EQLs were reported in Japan after the Kobe earthquake of 17 January 1995 ($M = 7.2$) and their features studied by Tsukuda (1997). In the Mediterranean Sea region, EQLs were reported in association with earthquakes occurring from ancient times until recently. In well-documented research, Papadopoulos (1999) worked with data from 30 earthquake events and concluded that EQLs were reported only in association with strong ($M \geq 6.0$), shallow earthquakes and at epicentral distances up to about 140 km. No EQLs were reported to accompany intermediate-depth earthquakes. EQLs were also reported in NW Turkey by Stothers (2004). St-Laurent (2000) reported EQLs associated with earthquakes as small as $M = 4.8$ in Quebec, Canada. Omori et al. (2007) have researched on anomalous radon gas emissions associated with electromagnetic phenomena previous to large earthquakes, which could be the case in the large earthquake of 2007 in Pisco, Peru. Recently, Fidani (2010) published a comprehensive study of EQLs associated with the 6 April 2009 Aquila earthquake in Italy in which 241 EQL reports were considered out of 1057 phenomena. Some have coincidental characteristics with the lights described here, and will be discussed in Sect. 4. The EQLs can be seen from a distance of a few kilometers and have been reported to show usually white, light-blue and blue colors, although reddish and darker colors also occur and may last from a fraction of a second to several seconds.

Some theories (Mizutani et al., 1976; Lockner et al., 1983; St-Laurent et al., 2006) have been proposed to explain EQLs accompanying earthquakes. A model has been proposed by Liperovsky et al. (2005) that considers the injection of radon gas and aerosol gases into the atmosphere and ionosphere to explain the enhancement of electromagnetic activity previous to earthquakes. Later, Liperovsky et al. (2008) considered a model for the generation of electric fields with time scales

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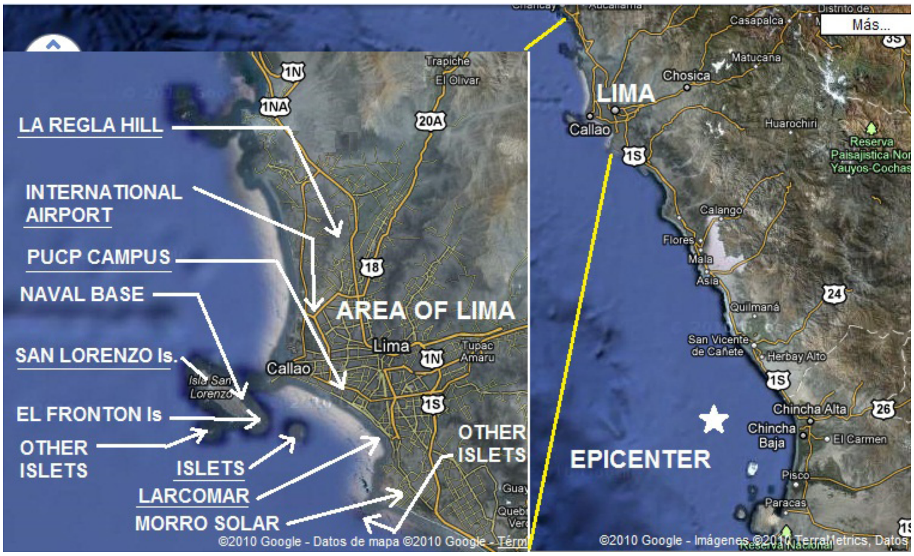


Fig. 1. To the right, the map of central Peru and the location of the epicenter. To the left, the area of Lima showing referenced locations.

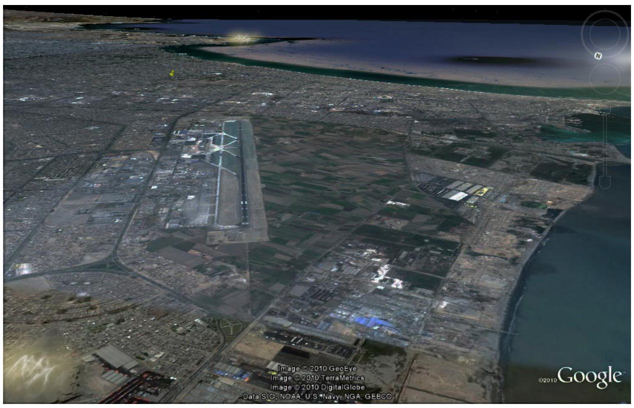


Fig. 2. View from the cockpit of a Beechcraft plane on its landing approach.

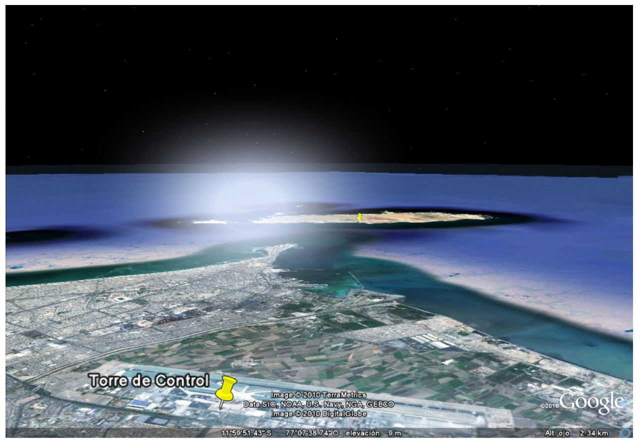


Fig. 3. View from the Control Tower at the Lima International Airport. Although this view corresponds to a higher altitude position, it illustrates the diffused nature and broad view of the lights reported as coming from the ocean between the coast and the islands.

from 1 to 100 min and infrared radiation in aerosol clouds caused by radon in the atmosphere, before strong earthquakes and near the fracture areas. Freund (2010) proposes a thorough solid state theory to explain pre-earthquake signals based on phonon-assisted electron hopping or positive hole propagation of charge carriers. An important compendium on luminescence related to seismicity will soon be published by Derr et al. (2011), in the Encyclopedia of Solid Earth Geophysics.

On the experimental side, Brady and Rowell (1986) carried out the first laboratory experiments trying to explain the origin of EQLs. They observed light emission by rocks that were subject to high pressure. Recently, Bleier et al. (2010), performed pertinent rock fracturing experiments on the field and confirmed the existence of electromagnetic activity prior to the actual fracturing.

Historically, there are several references to flame-like lights related with seismic activity from the colonial times in Peru. Even though they do not constitute scientific evidence, it is worth mentioning some of them in relation to the scenarios described in this research. Esquivel y Navia (1980) refers to the earthquake of 9 July, 1586, which was felt between Lima and Cusco "along 150 leagues" and to the chronicles of the great earthquake of 31 March 1950 in Cusco during which people saw "fire volcanoes burst" and the reference was obviously to volcano-like activity since there are no actual volcanoes there. But the most interesting chronicle he has refers to the great earthquake in Lima on 28 October 1746, the largest reported in this city, accompanied by a

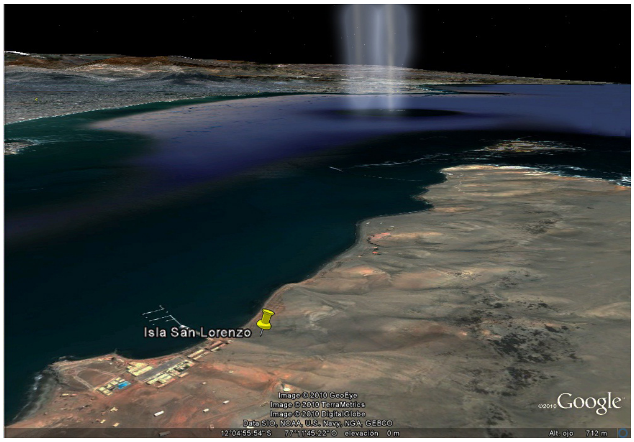


Fig. 4. The continental coast from "San Lorenzo" island, looking SSE. The witness was located by the pier, close to the yellow thumbtack. The image is a computer recreation approved by the witness. The striped light columns appeared to be coming out of the ocean but rocky islets have been identified in that area.

Fig. 5. Position and orientation of the security camera at the PUCP campus, looking west. In the background is the Pacific Ocean and San Lorenzo Island. An eyewitness described the luminescence he observed from the island, as coming out of the ocean, in a southeast direction, towards the coast.

very large Tsunami that washed the coast up to two leagues (about 5 km) inland. It describes the flame-like phenomena that occurred between 02:00–03:00 a.m. LT on 7 October 1746, twenty one days before the earthquake on the island of San Lorenzo, 5 km west of the Lima coast (referenced in this research). Captain Manuel Romero, in charge of the prison at the island, decided to temporarily free the prisoners at that time so they could watch the phenomena and testify to having seen it. Perez-Mallaina (2001) cites a chronicle archived at the Madrid National Library that describes the Lima earthquake in 1746 in which Juan Felix Goicochea refers to have seen "flames" close to the people. Finally, the Lima newspaper "Mercurio Peruano" (1791) refers to the earthquake in Pasco on 14 October 1791, at 09:17 p.m. LT, during which "discharges like those of a marching regiment" were observed, in obvious reference to St. Elmo's fire.

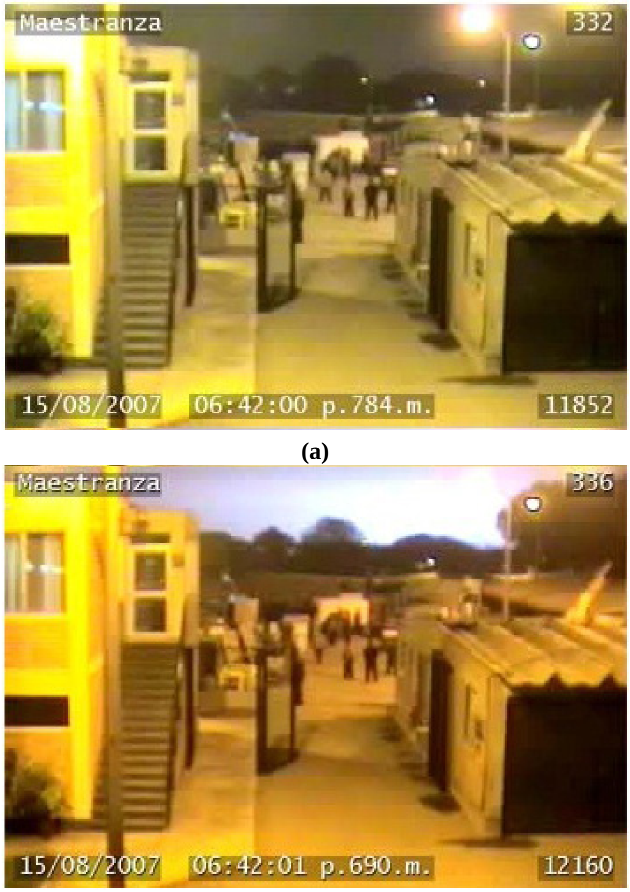
During the Peruvian earthquake of 15 August 2007, a significant number of EQL observations were reported along the Peruvian coast and stretching from Ica, about 100 km south of the epicenter, to Huacho about 260 km north of the epicenter, by Ocola and Torres (2007). A map of central Peru including the epicentral area to the Huacho area as well as the amplified Lima bay area, is shown in Fig. 1. Several impressive and extended lights were seen in different parts of the city of Lima, mostly coming from the direction of the Pacific Ocean and some of them have been identified as originating on surrounding hills and islands on the ocean. This was the first night time event in a highly populated area; all of the stronger earthquakes felt in the Lima area, at least during the last 70 years (1940, 1966, 1970, 1974), had occurred in the daytime. Hence, a smaller number of witnesses in other parts of the country during night time earthquakes had reported EQLs before the 2007 earthquake in Pisco. Video evidence of the luminescence in the Lima area, about 150 km NW of the epicenter, has been posted by individuals in popular video sites on the Internet. Besides the access to videos from security cameras at PUCP, two more security cameras, one at the Lima airport and the other at a sea-side open air shopping mall (Larcomar) have been analyzed. We have also conducted extensive follow-up interview sessions with four highly qualified eyewitnesses: an air-traffic controller on duty at the control tower of the Lima airport, an airplane pilot on his landing approach at the Lima airport at the time of the earthquake, the chief security officer of the Lima airport and a Peruvian navy officer on San Lorenzo Island overlooking the Lima coastline. The description of what they saw has been analyzed as far as determining the angle of arrival, extension, morphology, color and duration of the lights, as well as determining the coincidental areas of some of the light sources. Their testimonies have been translated into computer-generated images with their participation and approval, as shown in the following figures.

The lights reported here were observed at the PUCP campus in the city of Lima (see Internet links to INRAS-PUCP[1]). A fixed security camera installed there and pointing west towards the ocean registered the lights during the whole event, capturing colors, extension and comparative intensity of the lights as well as relative sequential timing in seconds, available frame by frame. The location of this camera is shown in Fig. 5. The video evidence had been diligently saved but remained forgotten in storage until last May 2010 when it was made available for our research. In order to discard possible short circuits from the power supply network as the cause of the lights, we have searched the area from

[1]Institute for Radioastronomy (INRAS-PUCP) (2010), Video of Earthquake Lights at the PUCP campus, (available until 31 December 2012), http://www.pucp.edu.pe/inras/peru-magneto/mod-3cam-3.exe, 15 August 2007.

Table 1. Pisco, Peru 15 August 2007 earthquake parameters.

Parameter	Value
Magnitude	8.0 M_w [7.9 M_w, 7.0 ML according to IGP]
Date/Time (at epicenter)	15 Aug 2007/18:40:57 LT
Date/Time (UTC)	15 Aug 2007/23:40:57 UTC
Location	LAT: 13.354° S, LON: 76.509° W
Location uncertainty	±5.2 km
Depth	39 km
Region	Near the coast of central Peru
Distances	50 km W of Chincha Alta, 150 km SSE of Lima
Parameters	NST = 275, Nph = 275, Dmin = 155 km Rmss = 0.84 s, Gp = 29°
Mtype	Centroid moment magnitude (M_w) version = 9
Source	USGS NETC (WDCS-D)
Event ID	us2007gbcv



(a)

(b)

Fig. 6. The EQL, at 06:42:1.690 p.m. LT **(a)** Before the EQL, at 06:42:0.784 p.m. LT **(b)** During the EQL, at 06:42:1.690 p.m. LT

the PUCP campus to the Pacific Ocean. This is an urban area without major electrical substations. There are electrical power distribution lines, but neither the electrical power company nor the fire department reported any specific arcing or fires in the adjacent areas during the earthquake. The weather conditions during the earthquake were registered at the meteorological station at the PUCP campus: Air temperature = 15°C, relative humidity = 82%, pressure = 1002 mb, wind SW 15 km/hr, 75% of the sky was clear and visibility from 1500 ft high as reported by our pilot witness, was very good with no atmospheric electrical activity. Moreover, Lima is located in an arid coastal zone without thunderstorms or rain during the entire year; the yearly average precipitation for the period 1973–2007, measured at the campus weather station, was 7.4 mm. The unequivocal lights reported by our qualified witnesses in the areas of observation and large areas of luminescence shining from hill tops without electric transmission lines and video-taped lights from the direction of the ocean, led us to the conclusion that the lights reported here are most probably a real phenomenon, independent of man-made electrical installation problems, fires or thunderstorms.

2 The Pisco, Peru 2007 $M_w = 8.0$ earthquake

As a result of the subduction of the Nazca Plate under the South American Plate, converging plate tectonics produces intense seismic activity in the Andean region on the west side of the South American subcontinent. This region is one of the most active areas in the world with 15% to 20% of the total seismic energy released in our planet, according to Giesecke et al. (2004). Peru has suffered very strong earthquakes throughout its history and repeated seismic activity has been reported frequently. The Pisco earthquake of 2007, first covered by Tavera et al. (2007), was the largest shallow (depth from 0 to 60 km) earthquake in Central Peru in the last 250 years according to the description by Tavera and Bernal (2008). Extensive damage occurred in the port and city of Pisco, Chincha, El Carmen, Ica, Cañete and smaller towns. The event was felt along the Peruvian coast and very strongly in Lima, Peru's capital city harboring nine million people. At the time, most inhabitants in Lima were in the streets, leaving work and witnessed previously unseen rapidly moving flashes of light of short duration in the city skies, white and bluish lights, mostly in the direction of the ocean and on the top of some hills. But light activity was reported also by hundreds of people along the coastal towns and beaches, especially within a hundred kilometers from the epicenter. Some video and photographic evidence was quickly accumulated, even by professional TV cameramen but mostly without precise direction or time reference. Table 1 shows the main earthquake parameters.

Table 2. Evidence by witnesses and scenarios.

#	Location of witness	Scenario	Type of observation
1	Airplane on landing approach	A, B, D	Verbal report, image drawn
2	Lima Airport Control Tower	B, C	Verbal report, image drawn
3	Lima Airport installations	B, C	Verbal report
4	San Lorenzo island	C	Verbal report, image drawn
5	PUCP	B	VIDEO #2, analysis of video
6	Larcomar shopping center	D	VIDEO #1

sites: A – "La Regla" Hill B – "San Lorenzo" Island
C – Group of Islets D – "Morro Solar" Hill

3 The evidence

Collected evidence for the luminescence in the Lima area has been organized according to Table 2 and Fig. 7. Witnesses were interviewed and with their interactive help, their testimonies were transferred to images by an art student with the aid of computer graphics. The witnesses gave indications and approved the results. Videos at PUCP and Larcomar were extensively analyzed and will be covered later on.

3.1 Analysis of witness reports

3.1.1 Eyewitness #1: private pilot on landing approach at Lima International Airport

On 15 August 2007 at 18:41:00 LT, Giancarlo Crapesi, a Peruvian private pilot, was on his final landing approach at "Jorge Chavez" Lima International Airport, at an altitude of about 1500 ft on board a twin engine turboprop plane. He saw unusual white and light blue lights flickering on top of the hills surrounding Lima, especially on the top of "La Regla", a well-known hill to the left of the landing strip with absolutely no transmission lines or any other construction or infrastructure. His impression was that of St. Elmo's fire, well known to him from his flight experience, as luminescence produced by electrostatic discharges from the wing tips. To the right, "San Lorenzo" island also showed luminescence; the island has only a Peruvian Navy training base, no transmission lines or large installations and its hilly center rises 398 m a.s.l. At the end of the Lima Bay, "Morro Solar", a prominent hill 274 m high, also showed lights rising from its top. The hill has television transmission towers but no exposed power lines. A few other hills to the left of "La Regla" showed some similar luminous activity, too (see Fig. 2). Mr. Crapesi asked the control tower about the phenomenon he was observing and the reply was that a strong earthquake was striking Lima at that precise time. After considering to proceed to the alternate emergency airport at Pisco, much closer to the still unknown epicenter location, he decided to land in Lima.

3.1.2 Eyewitness #2: air traffic controller on duty at the Lima Airport tower

On the late afternoon of 15 August 2007, air traffic controller Jorge Merino from CORPAC, the aeronautical authority in Peru, was on duty at the control tower of the Lima International Airport when the earthquake started. He was in radio contact with our first witness, Mr. Crapesi, who was on his landing approach and remained on duty taking care of ground to aircraft communications. He did see luminescence coming out of the ocean, half way between the coast and the "Fronton" island south of "San Lorenzo" island, which he vividly described as round, high and somewhat diffused, during the visit he hosted for us to the airport control tower. Mr. Merino pointed out the azimuth of the luminescence from his vantage point at his work station high above the airport runway and described the shape, height and duration of the flashes of light over the ocean and "El Fronton" island, while an art student made a drawing of his observations. Later, his descriptions were converted to images on a computer for his approval and are depicted in Fig. 3.

3.1.3 Eyewitness #3: chief security officer at the Lima Airport

When the earthquake started, Chief Security Officer at the Lima International Airport Mr. Juan Salas was near the airplane parking ramp and he walked towards the airport building. Reflected on the large glass walls at the main airport tower facing west toward the ocean, he saw white and light blue lights produced in that same direction. Black and white analog video tapes used at the time, were stored by the security office and at our request were located and played back for us to see and compare with a view from a present day digital color camera pointing in exactly the same direction, in order to accurately estimate the original camera pointing direction. However the video has not been released yet by the airport authorities.

Fig. 7. Partial view of the city of Lima from the air: the whole scenario. Letter locations denote sources of luminescence, number locations denote position of observers and the white lines show the view angle of video cameras and visual observations reported.

3.1.4 Eyewitness #4: navy officer at "San Lorenzo" Island

At the time of the earthquake, second lieutenant Guillermo Zamorano was at the naval base in the island. As he looked east towards the coast of Lima, he saw "columns of light" rising out of the ocean between the "Fronton" island and the continental coast, southeast of his location. The columns rising up at four instances were mainly white and light blue and seemed to have some structure, somewhat like slightly brighter spiral stripes. His impression has been superimposed on a Google Earth image by an artist and approved by the witness as coinciding with his description of the scene, as shown in Fig. 4.

3.1.5 Video #1 from a security camera at the Larcomar Shopping Center

The Larcomar shopping center is located by the oceanside. Built on a cliff about 40 m high above the ocean, it is an open Mall with galleries, food courts and restaurants that overlook the Pacific Ocean. From its sidewalks towards the west, there is nothing but the open sea and hence no possibility of any man-made electrical phenomena. Security cameras are mainly located pointing towards the galleries and boutiques, that is, not in the direction of the ocean. The Control and Security Office at the shopping center was very cooperative and provided us with twelve video clips from each of their cameras captured during the earthquake, which also had been stored since 2007. Almost all of them just showed scared people running around in food courts and sidewalks. However one camera recorded a large flash of white and blue light reflected from a large window wall facing the ocean. Simple geometric ray tracing provides an angle of view pointing towards the ocean and the "Morro Solar" hill at the southern end of the city. There cannot be any other explanation for it, except for an explosion inside the building, which of course never happened. The video, released for our research, can be seen in the university website (see Internet link to Lacomar[2]).

3.1.6 Video #2 from a security camera at the PUCP campus

The video from PUCP contains a continuous recording of the event, from beginning to end as provided by a color digital camera pointing in a fixed direction. Images were captured from the video, frame by frame and analyzed in time, morphology and color. Further discussion and analysis of the recorded information from this camera at PUCP is presented below in Sect. 3.2.

3.1.7 Summary of observations

A general view of the complete scenario is shown in Fig. 7 from the vantage point of a landing airplane (observer 1), where sources of lights (A, B, C, D) and positions of eyewitnesses (1, 2, 3, 4) and of the two video cameras (5, 6) are

[2] Larcomar Shopping Center, Miraflores, Lima, Peru, Video of Earthquake Lights at Larcomar, (available until 31 December 2012) http://www.pucp.edu.pe/inras/peru-magneto/1841090.avi, 15 August 2007

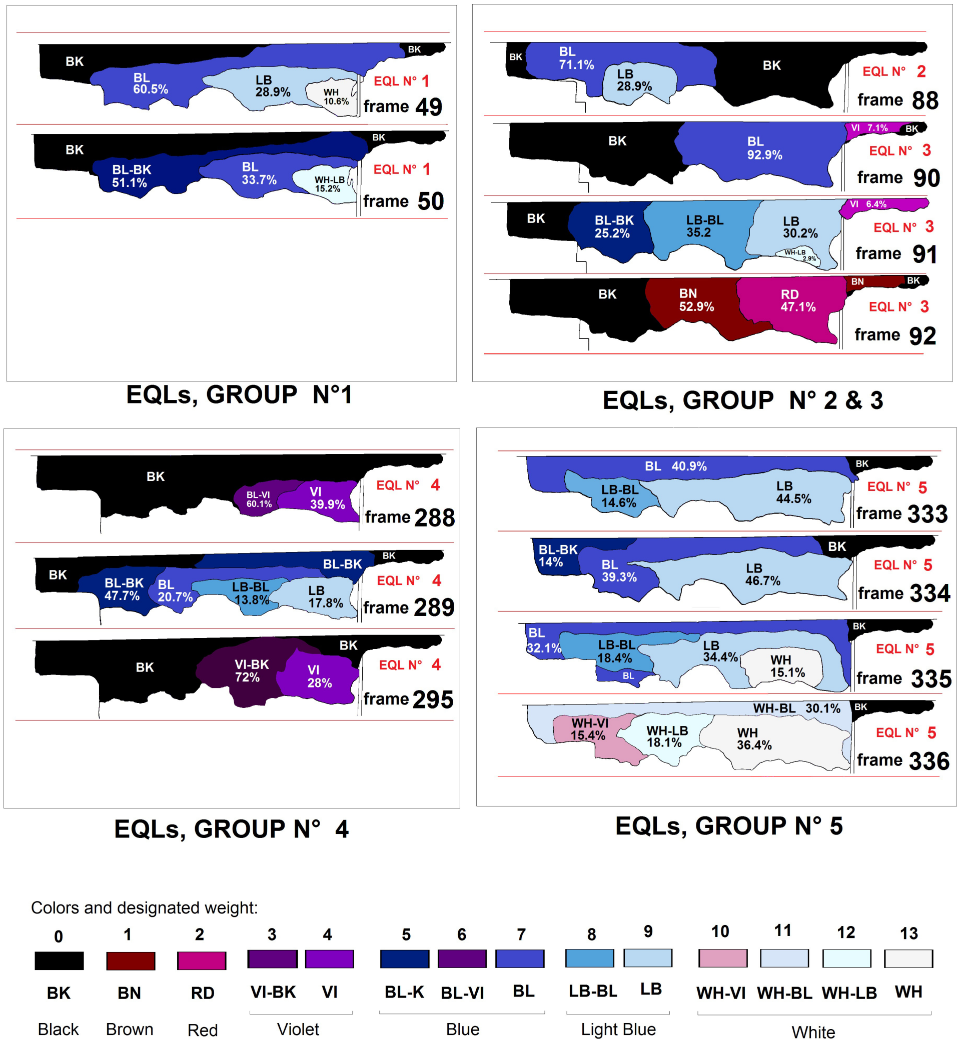


Fig. 8. Colors of the Lights. These four groups depict the five main lights shown in Fig. 9, analyzed frame by frame. Groups 2 & 3 are together since they occurred almost simultaneously, but arriving from slightly different directions. A color scale is also provided.

shown. The landing approach is from the north, hence “San Lorenzo” island is to the right, but not shown in the image. A complete view of the Lima bay in the central coast of Peru and its location in relation to the epicenter is shown in Fig. 1.

3.2 The PUCP video evidence

The analyzed video from one of the security cameras on campus contains a continuous recording of the whole event. The camera remained fixed in a westward direction during the event and shows vertical, horizontal and circular motions produced by the Earth shaking. Two of the frames are shown in Fig. 6. The video was analyzed frame by frame, camera shaking motion starts at frame #25 in the video, but the start of the accelerometer records has been taken as the initial time for the time base, as shown in Fig. 9. Since the time axis is not absolute, it represents the origin for relative timing and because short-term stability is high, the horizontal axis represents a good relative time base. Five main flashes were registered, looking to the west, from mainly three directions within the 25 degree camera view angle. Three came from the same direction and two from directions slightly to the south of the other three. The five light flashes depicted in Fig. 9 are further described in duration and time of occurrence in Table 3 and the average time between frames is about 0.23 s or about 4 frames/s.

3.2.1 Luminescence morphology and intensity estimation

In order to estimate the luminescence intensity, different colors were delimited in the pictures captured from the video and their areas measured with square-pixel estimation software. An arbitrary linear, relative intensity scale was created,

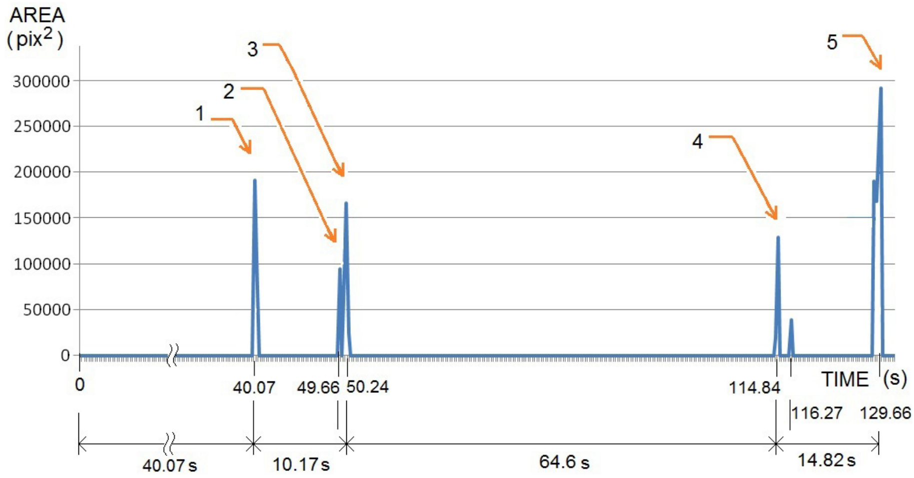


Fig. 9. Morphology of the lights observed. The horizontal time axis shown represents seconds as measured from the start of the accelerometer records. The areas represent the colors and intensity of the flashes observed, as explained in the text and shown in Fig. 8.

Table 3. Time of occurrence and direction of the EQLs.

EQL-No. (see Fig. 9)	EQL time (LT) [hh]:[mm]:[ss.sss]	# of Frames	EQL time difference (s)	Direction	Seismic peak time (s)	Seismic peak time difference (s)
1	06:40:32.092	2	0.000	W 12° N	40.065	0
2	06:40:41.685	1	9.593	W	48.255	8.19
3	06:40:42.269	3	10.177	W 12° N	48.255	8.19
4	06:41:46.871	3	74.779	W 12° N	112.14	72.075
5	06:42:01.690	4	89.598	W 8° N	129.14	89.075

relating the apparent color of the area with intensity, ranging from 0 (black) to 13 (white). In ascending brightness, first black is followed by brown, red, violet, blue, light blue and white and some of their combinations. The scale of colors chosen resembles the colors observed but they are not necessarily identical, since this is not a spectral study but rather a means of estimating the intensity as a weighted sum of the areas observed. The resulting diagrams, shown in Fig. 8 for each of the groups of lights, give a fair and uniform estimate of the relative intensities for each area and color in each flash, as well as their duration. The linear color scale with letter designations for the colors is also shown.

The intensities obtained by the method described are plotted vs. time in Fig. 9, giving the resulting intensity of the luminescence observed in each of the video frame groups, in the vertical scale. As explained, this scale is not necessarily representative of the energy released.

3.2.2 Relationship between EQLs and seismic ground accelerations

The acceleration records of the earthquake (see internet links INRAS-PUCP[3]) were registered by the Seismic-proof Structures Laboratory at the PUCP campus. To determine the relationship between EQLs and seismic ground accelerations, we analyzed both the video and the accelerometer records. Traces A, B and C in Fig. 10 show the vertical, N-S, and E-W components of the acceleration, respectively. Trace D shows the calculated value of the ground acceleration, that is the magnitude of the acceleration vector regardless of its direction in three dimensional space. We can observe two seismic wave trains with large accelerations that correspond to two different hypocenters belonging to the same fracture. The EQLs were video-recorded during both seismic wave trains. The camera and the accelerometer were not synchronized.

[3]Institute for Radioastronomy (INRAS-PUCP) (2010), Earthquake acceleration records at the PUCP campus, (available until 31 December 2012) http://www.pucp.edu.pe/inras/peru-magneto/Aug-15-2007-Accelerograms-PUCP.xls15 August 2007.

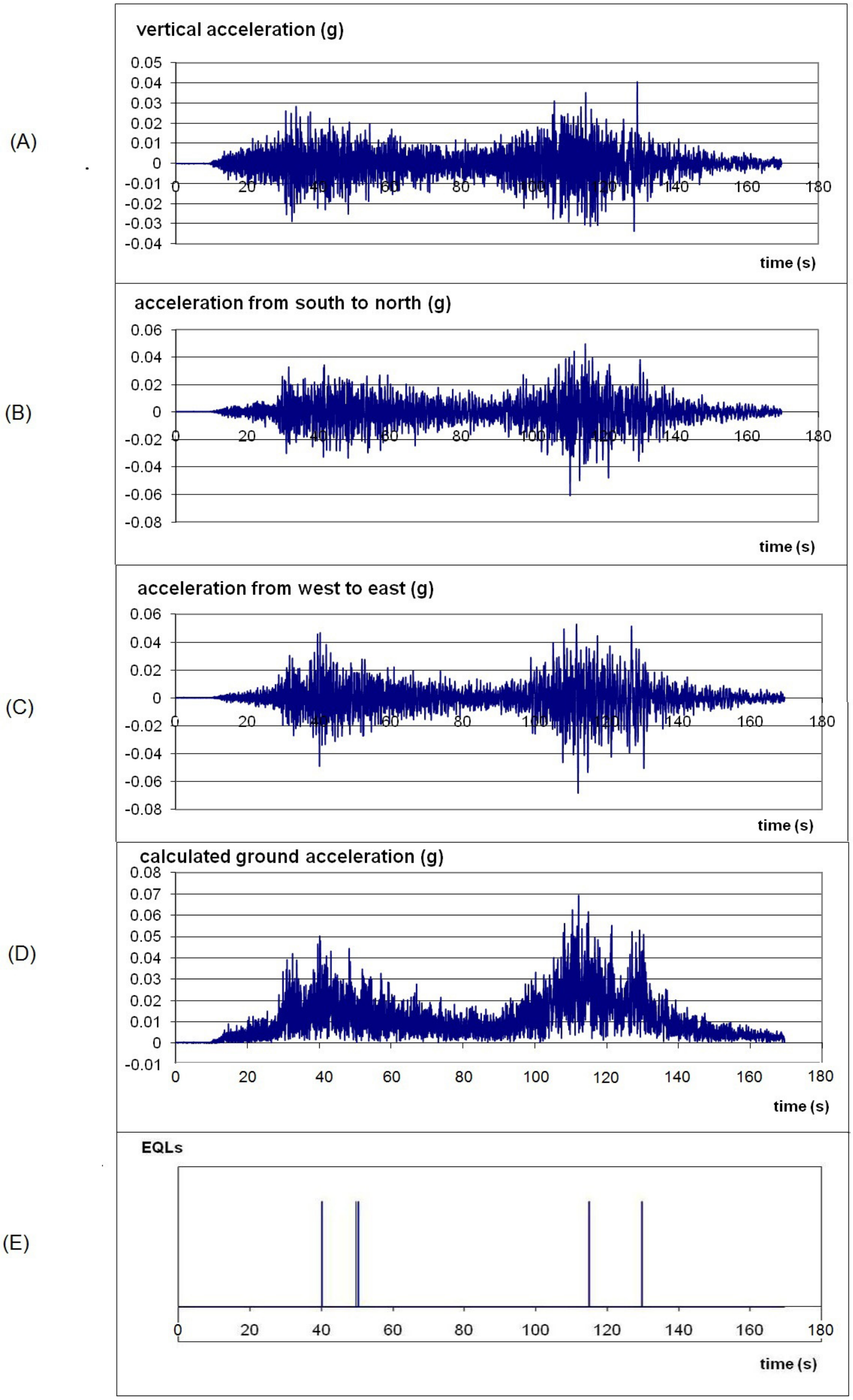


Fig. 10. The acceleration records registered at the PUCP campus (**A**, **B**, and **C**), only 500 m away from the video camera that registered the EQLs. **(D)** shows the value of the ground acceleration vector. **(E)** shows the time difference of the EQLs obtained from the video.

To discern a time relation between the EQLs and seismic ground accelerations, it is important to consider only the time differences between the first and the subsequent EQLs (Table 3) and to fit these with the time differences of the seismic ground accelerations. Trace E in Fig. 10 shows the EQL time differences. A good time difference correlation was found between the EQLs and the main peaks of the ground acceleration. In Table 3 we can see that the direction of the reported EQLs fitted into some directions only, although seismic waves pass through the entire Earth crust, which leads us to suggest that the EQL generation process can only start at certain points in the Earth's interior.

4 Discussion

There are several points we would like to stress, as answers to obvious questions:

The Lima scenario of an earthquake that occurred three years ago could be reconstructed as far as the observed luminescence is concerned. This was possible due to the availability of video footage of the 2007 earthquake from three different sources almost three years after the earthquake. This was also due to the active participation of qualified witnesses. Their vivid memories and the recovered videos fit well as far as morphology, direction of observation and location is concerned. The observations cover most of the lights observed by the pilot witness and hence the scenario could be reconstructed in spite of the time delay.

The reported luminous events correlate well with seismic activity that occurred 150 km from the epicenter, as shown in the time correlation (Fig. 10) with the accelerometer records and it is hard to explain that charge migration all the way from the epicenter is directly responsible for this phenomenon. Then, we put forward the hypothesis that locally-generated electric charges could be responsible for local luminescence through a process of stress on rocks produced by seismic waves as they propagate towards the surface. Local enhancement by radon gas emanations, in this particularly shallow depth earthquake, is still an unexplored possibility. In this way, local rock conditions and the particular geometry of islands and hills could intervene. However, there is a time delay of several seconds between the incidence of the stress-carrying seismic waves and the occurrence of the lights. From the accelerometer records in Fig. 10, we have estimated this delay to be about 30 s from the arrival time of the P-wave and about 18 s from the arrival of the S-wave, estimated from the work by Tavera et al. (2007). We should bear in mind an experiment reported by Takeuchi et al. (2004), in which the arrival of the S-wave was found to coincide in time with sudden changes in the potential difference between a large plate electrode and ground in a mine gallery in Japan.

Since most of the lights were reported to be emitted by rocky or sand- covered rock surfaces on the top of hills, lights emerging from the ocean, as reported by one witness, were not found to be strictly consistent with the hypothesis. So we checked the area both physically from the coast and in maps and located a group of known islets located in the general area where our witness saw the light columns rising from the ocean. The rocks protrude from the ocean there. However, three of them are particularly prominent and have pointed surfaces capable of producing a leakage point effect for electric charges. Connected to the ocean floor in the shallow waters near the coast, these rocks can conduct electrons and leak them into the atmosphere.

All of the witnesses interviewed clearly reported luminescence emerging "from the ocean" or from hills and islands either completely deprived of man-made installations or, in one case, without open electric transmission lines. Hence, artificially induced phenomena can be discarded. Besides, when the videos from three security cameras were reviewed, it was found that they point toward the ocean and one of them is precisely located at the oceanside.

The work by Papadopoulos has some coincidental historical reports in colonial Peru in the past 450 years, as far as the fiery luminescence observed. It shows that the strong earthquakes analyzed ($M \geq 6$) and those with shallow focal depths, even up to 140 km from the epicenter, are connected to luminescence in the scenarios described. The M8.0 Pisco earthquake described in this work, with a focal depth of 39 km, produced luminescence at least 150 km from the epicenter and hence seems to fit into the set of his observational characteristics.

It is interesting to consider the work by Fidani, cited in the Introduction because of the morphological and location similarities between some of the lights reported in Aquila, Italy and in Lima, Peru. About 55% of the epicenters considered by Fidani in the precursors and after-shocks, including the main $M = 6.3$ earthquake, were 10 km deep or less, and that is about a quarter of the depth of the main Pisco, Peru earthquake. However, shapes and colors are coincidental in some case, like the *thin strips* of light of short duration, white and clear blue, bright and high in the sky, or the *columns* observed during the main shock in Bagno, Bazzano and Pile are similar to the columns observed from San Lorenzo Island in Lima or even the *flame-like* lights reported in San Lorenzo, three weeks before the large 1746 earthquake. Other similar lights are the white and different shades of blue *flashes* reported to last fractions of a second to a few seconds in Aquila and the lights observed in the Peruvian earthquake, coincidental with the activity that seems to have happened, mostly on mountain tops and islands, around Lima.

If we try to fit the models of Liperovsky et al. (2005 and 2008) and Omori et al. (2007) cited in the Introduction section into the observations in this research, we have the limitation that no radon gas monitoring has been performed in Peru. Mainly because most earthquakes in the country are related to medium depth (in Peru considered from 61 to 300 km) and deep (301–750 km) hypocenters, so far they have not been considered to produce radon gas emanations. We have not been able to get experimental evidences of this kind and hence, cannot say much about the incidence of radon gas emanations in the luminous phenomena described here. However, the interaction of local charge migration with emanations of radon gas, hitherto not experimented with, in shallow depth earthquakes is a possibility and we have to conclude that radon gas monitoring is something we should look more into with future work. Besides, regarding the incidence of pre-seismic, co-seismic or post-seismic luminous activity in this work, no reports have been registered of lights previous or after the earthquake, but of course the absence of reported evidence is no definitive evidence of absence. In this particular observation, reconstructed three years after the earthquake, we can only say that the reports of luminescence have been co-seismic.

5 Future work

The Institute for Radio Astronomy at the Pontificia Universidad Catolica del Peru conducts research in several areas related to radio science and space science and engineering, including development of small satellites as well as the relationship between electromagnetic phenomena and seismic activity. In our association with QuakeFinder of Palo Alto, California, a joint cooperation program was established and followed by the installation of two QF1007 magnetometers in El Carmen, Chincha and in Tacna. The first one is located near the coast, close to the epicenter of the Pisco 2007 earthquake, in order to gather data from a still active area and with about three times the average seismic activity in the country. The second one is located in southern Peru, in an area known for seismic quiescence where a large earthquake is probably overdue. Our future research in this area is being directed to trying to establish a connection between luminous and infrared phenomena with pulses sensed by the magnetometers, prior to and during seismic activity. With student participation, the development of a continuous recording wide-angle camera (fish-eye type) for night surveillance of the skies is being developed, in search for possible precursor EQLs associated with electromagnetic activity in areas covered by QuakeFinder's QF-series magnetometers. This will allow us not only to register sky luminosity and correlate it with seismic activity from a co-seismic point of view but also to detect possible pre-seismic luminous activity occurring inadvertently and possibly correlated with magnetometer data and air conductivity records in our two sites in Peru. Furthermore, the installation of new magnetometers and cameras in the Lima area is being planned. In addition to the deployment of new instrumentation and data gathering in future work, we also plan to investigate the geology of the rocky terrain in the Lima area.

Radon gas emanations before and during the 2007 earthquake have not been explored, as explained, due to the medium and deep hypo-central earthquakes in Peru. However, radon gas has been studied by several researchers as a very probable cause of enhancing electric field intensity as previously mentioned, so we will pursue efforts in order to incorporate such observations, especially in southern Peru, where existing tunnels and caves can be used to monitor enhanced concentration of gases previous to earthquakes. Probable locations close to the magnetometer sites where we can monitor charge migration-induced magnetic field pulsations are being considered, along with automated telecommunications facilities. This work should also be complemented with infrared observations from satellites.

6 Conclusions

A systematic investigation of the lights reported in the Lima area during the Peruvian earthquake of 2007 in Pisco, Peru, has led us to the conclusion that there is probably a real phenomenon, independent of thunderstorms and electrical system's failures and associated with seismic activity during this large earthquake. The incoming direction of the reported lights fitted into a recognizable pattern as described by highly qualified witnesses and reconstructed in approved images that, according to the witnesses, reflect well their experience on the evening of 15 August 2007. Additionally, the analysis of a fixed camera video, from which areas and intensities can be estimated, leads to a good differential time correlation of the observed luminescence with accelerometer records obtained at the same area. A time difference correlation between the lights and the main peaks of the ground acceleration was found. All this evidence points in the direction of establishing a close relationship between local charge migration events in underground activity in the observed areas with probable electron leakage into the atmosphere that derives in air luminescence with co-seismic implications. Future work will try to explore the possible correlation between pulses from the two magnetometers operating in southern Peru and future sites with pre-seismic luminescence as well as incorporating optical, infrared and radon gas observations. In this way, we expect to close the gap in understanding the relationship between very distant seismic hypo-central fracture and seemingly local causality.

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