ISSN 8755-6839

SCIENCE OF TSUNAMI HAZARDS

Journal of Tsunami Society International

Volume 37 Number 1 2018

REAL-TIME RADIOACTIVE PRECURSOR OF THE APRIL 16, 2016 Mw 7.8 EARTHQUAKE AND TSUNAMI IN ECUADOR

Theofilos Toulkeridis[1]*, Fernando Mato[1], Katerina Toulkeridis-Estrella[2], Juan Carlos Perez Salinas[3], Santiago Tapia[3] and Walter Fuertes[1]

[1]Universidad de las Fuerzas Armadas ESPE, Sangolquí, Ecuador
[2]Alliance Academy International, Quito, Ecuador
[3]NOVACERO, Lasso, Ecuador

*Corresponding author: ttoulkeridis@espe.edu.ec

ABSTRACT

On the 16th of April 2016, a Mw 7.8 earthquake with a minor tsunami impacted coastal Ecuador, being the most devastating seismic event registered in northern South America in this century so far. Three hours before, an unusual increase of the environmental radiation level was registered at 222 km distance from the epicenter. Trough this study, we have been able to achieve an undeniable relation between such type of anomalies of geological origin and the seismic activity in Ecuador, solving thus the uncertainties presented in related works around this clear earthquake precursor. In this sense, our results demonstrate a full correlation in earthquake detection, reducing also the uncertainty window to less than a few hours.

Keywords: *Earthquake precursors, environmental radiation, geological radioactivity, Early Warning System, Ecuador*

1. INTRODUCTION

The deadliest of all natural hazards by death toll are earthquakes (Kahn, 2005; Anbarci et al., 2005; Raschky, 2008; Marano et al., 2010; Holzer and Savage, 2013). There are, at least one dozen of known earthquakes, which claimed more than hundred thousand lives, reaching up to more than 700 thousand in two single events in China (Butler et al., 1979; Chen, 1988; Gang, 1989; Hou et al., 1998; Gupta et al., 2001). Frequencies of seismic events have been studied by a variety of authors (McGuire, 1995; Shome et al., 1998; Ruff and Kanamori, 1980; McCaffrey, 2008). However, the most accepted data base is of the National Earthquake Information Center of the United States Geological Survey, where there are annually in average more than 1300 seismic events registered being stronger than magnitudes of 5, more than 130 stronger than magnitudes of 6 or higher, and up to 20 earthquakes with a magnitude of higher than 7. Practically all earthquakes with magnitudes higher than 6 being close to settlements or cities leave fatalities. There is a high amount of studies, which attempt to predict earthquakes (Scholz et al., 1973; Rikitake, 1968; Aki, 1981; Smith, 1990; Varotsos and Lazaridou, 1991; Geller, 1997; Keilis-Borok, 2002; Johnston et al., 2006) and try to be able to identify pre-monitoring signals (Allegre et al., 1982; Asteriadis and Livieratos, 1989; Smith, 1998; Sidorin, 2003; Freund, 2007; Cicerone et al., 2009; Freund et al., 2009; Akhoondzadeh et al., 2010; Pulinets and Ouzounov, 2011; Vigny et al., 2011; Yao et al., 2012; Tramutoli et al., 2013; Eleftheriou et al., 2016). Such studies may allow the installation of an early warning system, which in turn facilitates in even short time to take actions and protect life, property and certain infrastructure from incoming destructive seismic waves (Suárez et al., 2009; Rainieri et al., 2011; Satriano et al., 2011; Oliveira et al., 2015).

During the reactivation of the Cotopaxi volcano in central Ecuador (Toulkeridis et al., 2015), observations of the radioactivity determination in the environment lead to the idea, that such data may be able to interpret and predict the nearby occurring volcanic eruptions and also seismic events of certain magnitude. The main aim of our research is to establish a mechanism in which we will confirm a relation between the radiation of the environment and the potential prediction of strong seismic events, like the destructive earthquake of the 16th of April 2016 in coastal Ecuador (Toulkeridis et al., 2017).

There are several studies related to radiation as pre-earthquake sign (Madariaga, 1977; Gokhberg et al., 1982; Dea et al., 1991; Serebryakova et al., 1992; Virk and Singh, 1993; Zeng et al., 1993; Hartzell et al., 1996; Maeda and Tokimasa, 1996; Ouzounov and Freund, 2004; Tronin et al., 2002; Pulinets and Dunajecka, 2007; Ni et al, 2005; Pulinets et al., 2006; Ouzounov et al., 2007). In a particular study, such anomalies were reported for a variety of medium to strong earthquakes such as the M7.9, Bhuj, Gujarat, India in 2001, the M6.8 Boumerdes, North Algeria in 2003, M6.6 Bam Southeastern Iran in 2003 and the M9.0 Sumatra–Andaman Islands, Northern Sumatra, being a mega trust event in 2004 (Ouzounov et al., 2007). The anomalous variation of the radiation has been determined by infrared satellite data and occurred a few days to weeks (4-20 days) prior to the main events (Ouzounov et al., 2007). These anomalies are speculated to have been triggered close or within active tectonic faults due to a complex interaction of the existing stress, electrochemical and thermodynamic processes between the lithosphere, hydrosphere and atmosphere as part of electromagnetic phenomena related to earthquake activity (Ouzounov et al., 2007). Nevertheless, although the relation between radiation in seismic active areas has been observed in a variety of areas, this is the first time documented on ground data and with a more accurate spatio-temporal earthquake location.

2. GEODYNAMICS AND HISTORICAL COASTAL EARTHQUAKES IN THE ECUADOR REGION

Due to its geodynamic situation along the Pacific Rim, the coastal Ecuadorian continental platform is a regularly target of earthquake activity and tsunami impacts (Gusiakov, 2005; Pararas-Carayannis, 2012; Rodriguez et al., 2016). The active continental margin and associated subduction zone between the oceanic Nazca Plate with the continental South American and Caribbean Plates, both separated by the Guayaquil-Caracas Mega Shear (Kellogg and Vega, 1995; Gutscher et al., 1999; Egbue and Kellog, 2010) give rise to tsunamis of tectonic as well submarine landslide origin (Shepperd and Moberly, 1981; Pontoise and Monfret, 2004; Ratzov et al, 2007; 2010; Ioualalen et al., 2011; Pararas-Carayannis, 2012).

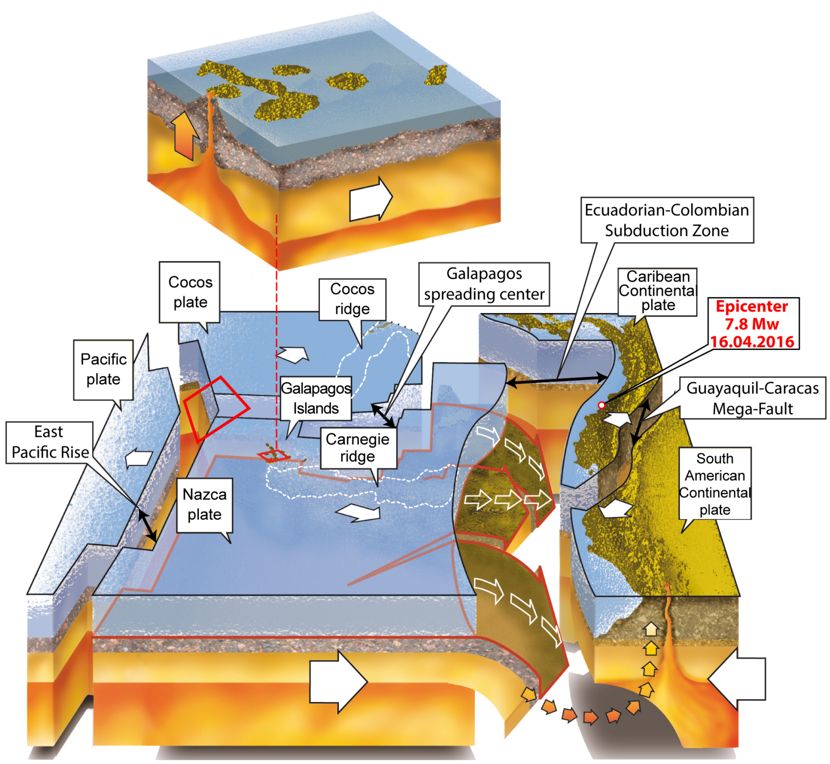


Fig. 1: Geodynamic setting of Ecuador, the Galapagos Islands and the Carnegie Ridge. Adapted from Toulkeridis, 2013 and Rodriguez et al., 2016.

A further origin of earthquakes and tsunamis has been credited to the Galápagos volcanism (Toulkeridis, 2011). The active Galápagos hotspot has produced several voluminous shield-volcanoes, most of which are inactive due to the ESE-movement of the overlying Nazca oceanic plate (Holden and Dietz 1972; Toulkeridis, 2011). The main Galápagos Islands are located south of the E-W-trending Galápagos Spreading Center, east of the N-S-trending East Pacific Rise and some 1000 km west of the Ecuadorian mainland. Due to the volcanic activity and the subsequent plate drifting, two aseismic volcanic ridges were created. The first being the Cocos Ridge is moving to the NE while the second, being the Carnegie Ridge, is moving to the East above the Cocos and Nazca Plates respectively (Harpp et al., 2003). These submarine extinct volcanic ridges are the result of cooling/contraction reactions of magma, as they slowly sunk below the sea surface due to the lack of magma supply, lithospheric movement and strong erosional processes. With time, these submarine volcanic ridges, as well as various microplates, have accreted on the South American continent (Reynaud et al., 1999; Harpp and White, 2001). Nonetheless, such aseismic ridges like the Carnegie Ridge become an obstacle in the oblique subduction process and may generate within the subduction zone a potential valve of marine earthquakes and occasionally tsunamis along the Ecuadorian coast (Pararas-Carayannis, 2012). The Carnegie Ridge collides towards the Ecuadorian continental margin with a velocity of as low as 5 cm per year at a latitude between 1°N and 2°S (Pilger, 1983).

From the known record of the last two centuries, the Ecuadorian shoreline has witnessed a dozen times strong earthquakes and marine quakes, some of which generated tsunamis by mainly local origins with various intensities - one being of up to 8.8 Mw in 1906 (Rudolph and Szirtes, 1911; Kelleher, 1972; Beck and Ruff, 1984; Kanamori and McNally, 1982; Swenson and Beck, 1996; Pararas-Carayannis, 2012), while evidences of paleo-tsunami deposits are scarce (Chunga and Toulkeridis, 2014). Other prominent examples of earthquakes with subsequent tsunamis along the Ecuador–Colombia subduction zone include tsunamis in 1942 (Mw 7.8), 1958 (Mw 7.7) and 1979 (Mw 8.2) within the 600-km long rupture area of the great 1906 event (Collot et al., 2004). While the 1906 event caused the death of up to 1500 persons in Ecuador and Colombia with an unknown financial damage to the existing infrastructure, the 1979 tsunami killed in Colombia at least 807 persons and destroyed approximately 10,000 homes, knocking out electric power and telephone lines (Pararas-Carayannis, 1980; USGS, 2016a).

The evaluation of the last marine quakes, which generated tsunamis, suggests that the probability of a major or great earthquake in this margin region is enormous, especially as there must be substantial strain accumulation in this region (Pararas-Carayannis, 2012). Additionally, given into consideration that the last earthquake in 1979 did not release the amount of energy as the 1906 event, there has been a calculated high probability in the near future, that an earthquake within the Ecuadorian-Colombian trench may generate a tsunami of similar magnitude to that of 1906, which might be even more destructive than the one in the past, particularly if it occurs near high tide (Pararas-Carayannis, 2012). The potential of high losses and damage is given by the fact that the infrastructure of the fishing, tourism and other industries and the movement to live along the beaches, have been highly developed within the last decades along the Ecuadorian coasts. Based on historic known impacts of tsunamis in Ecuador in the last two centuries, the probability of a strike in 2015 has been of about 87% (Rodriguez et al., 2016).

3. THE EARTHQUAKE AND TSUNAMI OF 16 APRIL 2016

In the late afternoon of Saturday, at 18:58:36 (UTC-05:00) local time, a devastating earthquake with a magnitude of 7.8 Mw impacted coastal Ecuador (USGS, 2016b). The seismic event with an epicenter 29 km SSE of Muisne, Province of Esmeraldas (Fig. 1, 2) occurred within a depth of 21 km, killing 663, filling tens of thousands in refugee camps and affecting some two million persons directly. In many aspects, the mentioned earthquake has many similarities with the earthquake of the 14th of May 1942. Nonetheless, the resulting tsunami based most probably on a triggered submarine landslide did not have any remarkable impact (Toulkeridis et al., 2017).

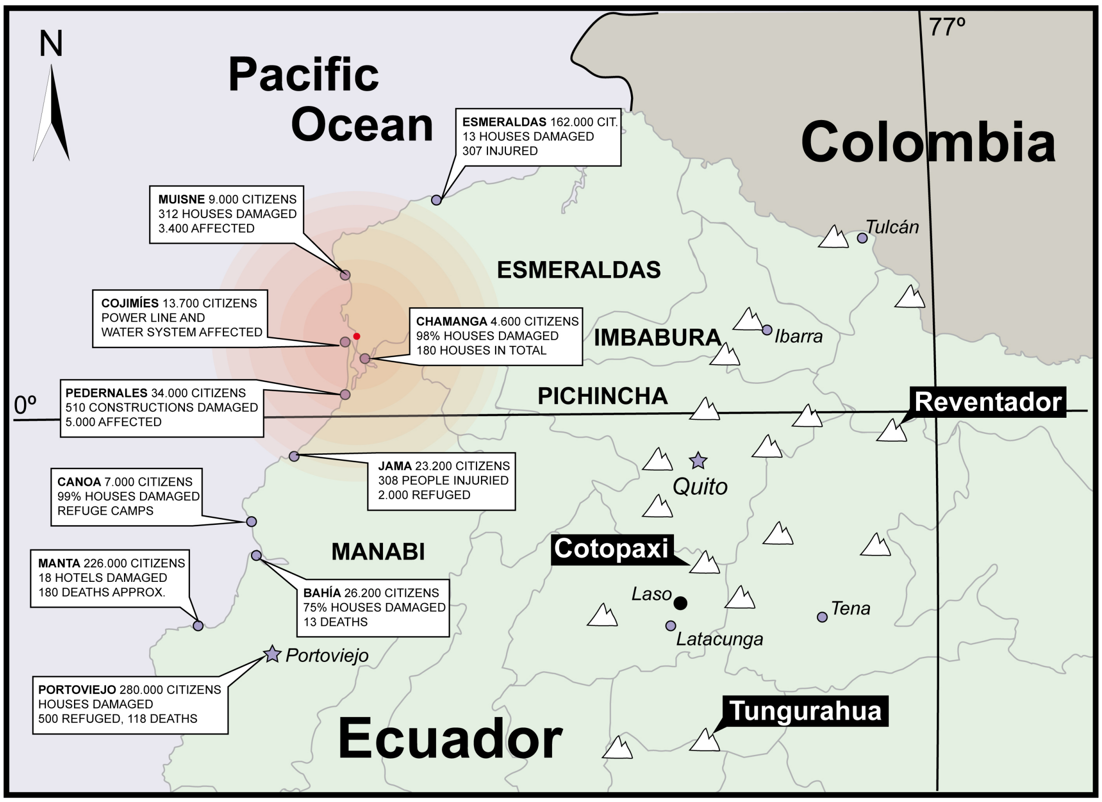


Fig. 2: Epicenter of the 7.8 Mw earthquake (red dot) and a selection of damages in the coastal area. Note location of Reventador, Cotopaxi and Tungurahua volcanoes as well as the station of Laso (black dot), where the radiation of the environment has been determined.

The earthquake impacted a large part of a variety of coastal cities destroying between up to 99% of some close-by villages and cities, Pedernales, Jama, Chone, Portoviejo among others (Fig. 2), in which lines of electricity transmission, infrastructure of water supply, hospitals, schools, private and public buildings, main roads and highways have been severely affected or even completely destroyed. The costs of the damages of the mentioned infrastructure are summing up an approximate loss of some 3.3 billion USD (El Telegrafo, 2016; Toulkeridis et al., 2017).

After the mainshock, 85 aftershocks between 3.8 Mw and 6.8 Mw were recorded by USGS in Ecuador until May 24, last day until we have processed data. The epicenters were localized within a rectangle of coordinates [79.5 W - 81.5 W, 2 S - 1 N], reaching the highest magnitudes around the rupture zone, and 86.05% of them during the first 10 subsequent days.

4. ANALYTICAL PROCEDURES

A LUDLUM MODEL of the 4525 SERIES™ enabled to determine the occurrences of natural and artificial radioactivity in the environment close to the company NOVACERO, which provides a variety of steel products. In order to detect radioactivity especially in vehicles in a pass-through or drive-through scanning modus, the Model 4525 Radiation Portal Monitor (RPM) has been installed in late 2014, some 22 km SW of the Cotopaxi volcano in central Ecuador. The RPM is a system with sensitive gamma and optional neutron detectors for detecting small amounts of radiation. When no vehicle drives through the scanner, the natural background of radioactivity is measured constantly and simultaneously (one measurement per minute). When a radiation alarm occurs, the Supervisor and any Echo stations will sound an audible alert. The system determines if the alarm is a Naturally Occurring Radioactive Alarm (NORM). NORM consists of materials enriched with radioactive elements found in the environment, such as uranium, thorium, and potassium and any of their decay products such as radium and radon. These types of alarms are characterized as having a high background over the entire length of the occupancy rather than the "spike" of a typical gamma alarm.

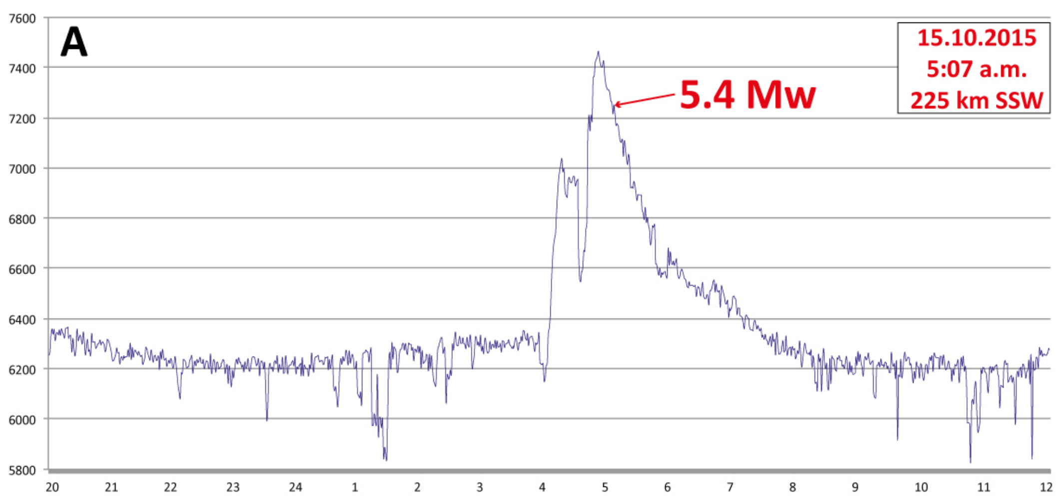
Many factors have to be considered when attempting to do this: (1) Background radiation is not constant. It is continuously changing due to cosmic events, weather (eg. beginning of rainstorms), and other influences. Oilfield pipe, hot water heaters, and industrial piping will sometimes contain scale that is radioactive. Most alarms are the result of NORM; (2) Medical tests that use a radioactive dye or tracer are yet another problem. Patients can be released from the hospital reading several thousand μR/hr or less than 100μSv/hr, and set off RPMs 30 m (100 ft) away; (3) A third problem is that of radiographers and certified welders who use a powerful radiation source to check their material or welds for cracks. This radiation is powerful enough to set off RPMs 3 km away.

5. RESULTS AND DISCUSSION

Radiation of the environment in central Ecuador has been determined almost continuously realizing data at every minute of the day since Mid-January of 2015 up to present day. However, most of the time there has been only the regular day-by-day radiation level of the environment defined as background radiation level (Fig. 3d) with 6200 becs per minute. This radiation of the environment appeared with no significant changes since the beginning of the measurements and has been changed only by the appearance of some seismic events, such originating by volcanic nature or fault-triggered.
Therefore, all the main volcanic eruptions of the close-by Cotopaxi volcano during its visible reactivation in spring of 2015 have been registered by the RPM, prior their occurrences. Other temporal eruptive activity and corresponding environmental radiation inside the same time window originating from the Tungurahua and Reventador volcanoes in Ecuador (Global Volcanism Program, 2016a; 2016b), corresponding craters being in a distance of 73 and 132 km from the RPM

respectively (Fig. 2), were not registered or identified in our data base, most probably due to their low intensity. Additionally, we have been detected a clear pattern in the determination of the environmental radiation of seismic activity in Ecuador since 2015 for all events registered by USGS with magnitudes above 4.9 Mw.

A few hours before an earthquake generation, from 1 hour (Fig. 3a) to 5 hours (Fig. 3b), an unusual high level of radioactivity has been detected by the RPM, reaching levels between 6800 bec/min (Fig. 3b; 3c) and 7465 bec/min (Fig. 3a). This behaviour is related to almost all of the earthquakes recorded. We have also identified the delay in the generation of the earthquake is in almost all cases inversely proportional to the level of radiation reached and to the duration of such anomalies.
According to the general behavior of the precursor anomalies identified, on the early hours of the 16th of April in 2016, an unusual radiation level has been registered by the RPM, which we interpret as a clear pre-monitoring signal of a major seismic event resulting to the most devastating Earthquake of northern South America in this century so far. The alteration of the regular background radioactivity started around 15.30 p.m. and lasted for about almost two hours in which the radiation increased by 650 bec/min, finding a peak level of 6850 bec/min some minutes after the start (Fig. 3c). After reaching this peak level, radiation dropped down to regular level three hours later, sinking down to 6200 bec/min at around 18:45, some minutes prior the Earthquake of 18:58 (Fig. 3c), of which epicenter has been located some 222 km west-northwest of the RPM. This behavior or pattern prior a seismic event has been previously observed with less intense earthquakes as presented earlier (Fig. 3a; 3b).



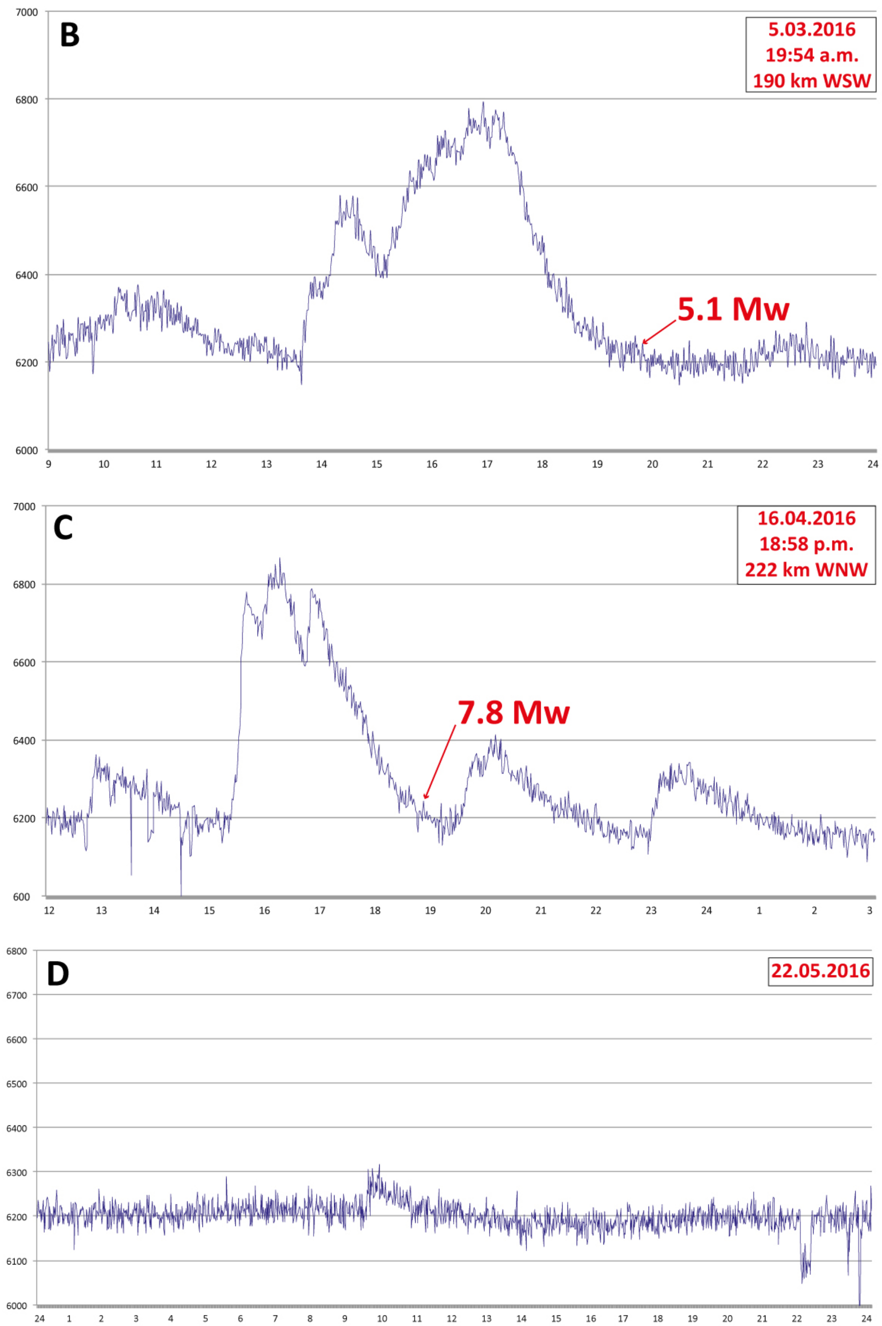


Fig. 3a-d: a) Typical pre-earthquake (5.4 Mw) radiation behaviour of the 15th of October 2015 at 2.50 S, 78.76 W with a depth of 97,1 km (USGS, 2015); b) Typical pre-earthquake (5.1 Mw) radiation behaviour at the 5th of March 2016 at 1.43 S, 80.40 W with a depth of 10 km (USGS, 2016); c) Main 7.8 Mw earthquake of the 16th of April 2016 with different radiation behaviour than regular days. Location of epicenter has been at 0.35 N, 79.93 W at a depth of 21 km (USGS, 2016); d) Regular radiation level of 24 hours of the 22nd of May 2016.

The most plausible origin of such radiation anomalies prior to strong earthquakes might be the result of a complex interaction and coupling behavior of the Lithosphere, Hydrosphere, Atmosphere and Ionosphere (Pulinets et al., 2000; Hayakawa and Molchanov, 2002; Ouzounov et al., 2007). The degree of radiation anomaly certainly depends on the intensity of the earthquake as well as local to regional atmospheric conditions, but will have always a direct link to the magnitude of the earthquake (Ouzounov et al., 2007). As such outgoing long wave earth radiation anomalies and latent increases of temperatures have been noticed prior several strong earthquakes (Dey et al., 2004; Cervone et al., 2005; Pulinets et al., 2006), some of them which even generated severe tsunamis, the application of an early alert system may be applied in a variety of environments such as active continental rims, like the subduction zones around the Pacific Ocean as well as around transform fault zones, like the Guayaquil-Caracas Mega shear in south America or the San Andres fault in the USA, being able to give enough warning time in order to evacuate people from vulnerable places within an adequate period of time.

6. CONCLUSIONS

It has been highlighted the important precursor role of environmental radiation in the precise location of earthquakes in Ecuador. A direct application and benefit of our study may be to achieve an accurate early warning system based on the data presented. The radiation data demonstrate clearly undeniable anomalies, which allow during their development an extremely early warning time towards society and administrators of basic infrastructure to react ahead of a potential catastrophic seismic event. Nonetheless, a more spatial resolution is needed by means of a sensors array, which we propose to be installed based on an efficient and therefore strategic distribution in the entire country of Ecuador. This sensors array will provide then key information for the complex Earthquake Early Warning System, at which we are progressing in Ecuador.

ACKNOWLEGMENTS

We are indebted to the company NOVACERO in Laso, Cotopaxi Province, who generously provided the database for this research. We also thank the Universidad de las Fuerzas Armadas ESPE for logistic and financial support. Fernando Mato acknowledges support from the Prometeo Project of the National Secretariat of Higher Education, Science, Technology and Innovation (SENESCYT), Ecuador.

REFERENCES

Akhoondzadeh, M., Parrot, M. and Saradjian, M.R., 2010. Electron and ion density variations before strong earthquakes (M> 6.0) using DEMETER and GPS data. Natural Hazards and Earth System Science, 10(1), 7-18.

Aki, K., 1981. A probabilistic synthesis of precursory phenomena. Earthquake Prediction, 566-574.

Allegre, C.J., Le Mouel, J.L. and Provost, A., 1982. Scaling rules in rock fracture and possible implications for earthquake prediction. Nature, 297(5861), pp.47-49.

Anbarci, N., Escaleras, M. and Register, C.A., 2005. Earthquake fatalities: the interaction of nature and political economy. Journal of Public Economics, 89(9), 1907-1933.

Asteriadis, G. and Livieratos, E., 1989. Pre-seismic responses of underground water level and temperature concerning a 4.8 magnitude earthquake in Greece on October 20, 1988. Tectonophysics, 170(1), 165-169.

Beck, S.L. and Ruff, L.J., 1984: The rupture process of the great 1979 Colombia earth-quake: evidence for the asperity model. J.Geophys. Res. 89, 9281–9291

Butler, R., Stewart, G.S. and Kanamori, H., 1979. The July 27, 1976 Tangshan, China earthquake—a complex sequence of intraplate events. Bulletin of the Seismological Society of America, 69(1), 207-220.

Cervone, G., Singh, R.P., Kafatos, M., Yu, C., 2005: Wavelet maxima curves of surface latent heat flux anomalies associated with Indian earthquakes. Natural Hazards and Earth System Sciences 5 (27), 87-99.

Chen, Y. ed., 1988. The great Tangshan earthquake of 1976: an anatomy of disaster. Pergamon.

Chunga, K. and Toulkeridis, T., 2014. First evidence of paleo-tsunami deposits of a major historic event in Ecuador. Science of Tsunami Hazards, 33: 55-69.

Cicerone, R. D., Ebel, J. E. and Britton, J., 2009. A systematic compilation of earthquake precursors. Tectonophysics, 476(3), 371-396.

Collot, J.Y., Marcaillou, B., Sage, F., Michaud, F., Agudelo, W., Charvis, P., Graindorge, D., Gutscher, M.A. and Spence, G., 2004. Are rupture zone limits of great subduction earthquakes controlled by upper plate structures? Evidence from multichannel seismic reflection data acquired across the northern Ecuador–southwest Colombia margin. Journal of Geophysical Research: Solid Earth, 109 (B11).

Dea, J.Y., Richman, C.I. and Boerner, W.M., 1991. Observations of seismo-electromagnetic earthquake precursor radiation signatures along Southern Californian fault zones: evidence of long-distance precursor ultra-low frequency signals observed before a moderate Southern California earthquake episode. Canadian journal of physics, 69(8-9), 1138-1145.

Dey, S., Sarkar, S., Singh, R.P., 2004: Anomalous changes in column water vapor after Gujarat earthquake. Advances in Space Research 33 (3), 274-278.

Egbue, O. and Kellogg, J., 2010: Pleistocene to Present North Andean "escape". Tectonophysics 489: 248-257.

El Telegrafo, 2016: http://www.eltelegrafo.com.ec/noticias/ecuador/3/manana-se-daran-a-conocer-cifras-oficiales-del-costo-del-terremoto

Eleftheriou, A., Filizzola, C., Genzano, N., Lacava, T., Lisi, M., Paciello, R., Pergola, N., Vallianatos, F. and Tramutoli, V., 2016. Long-Term RST Analysis of Anomalous TIR Sequences in Relation with Earthquakes Occurred in Greece in the Period 2004–2013. Pure and Applied Geophysics, 173(1), pp.285-303.

Freund, F.T., 2007. Pre-earthquake signals? Part I: Deviatoric stresses turn rocks into a source of electric currents. Natural Hazards and Earth System Science, 7(5), 535-541.

Freund, F.T., Kulahci, I.G., Cyr, G., Ling, J., Winnick, M., Tregloan-Reed, J. and Freund, M.M., 2009. Air ionization at rock surfaces and pre-earthquake signals. Journal of Atmospheric and Solar-Terrestrial Physics, 71(17), 1824-1834.

Gang, Q. The Great China Earthquake. Beijing: Foreign Languages Press, 1989. ISBN 7-119-00565-0.

Geller, R.J., 1997. Earthquake prediction: a critical review. Geophysical Journal International, 131(3), 425-450.

Global Volcanism Program, 2016a. Report on Tungurahua (Ecuador). In: Sennert, S K (ed.), Weekly Volcanic Activity Report, 24 February-1 March 2016. Smithsonian Institution and US Geological Survey.

Global Volcanism Program, 2016b. Report on Reventador (Ecuador). In: Sennert, S K (ed.), Weekly Volcanic Activity Report, 9 March-15 March 2016. Smithsonian Institution and US Geological Survey

Gokhberg, M.B., Morgounov, V.A., Yoshino, T. and Tomizawa, I., 1982. Experimental measurement of electromagnetic emissions possibly related to earthquakes in Japan. Journal of Geophysical Research: Solid Earth, 87(B9), 7824-7828.

Gupta, H.K., Rao, N.P., Rastogi, B.K. and Sarkar, D., 2001. The deadliest intraplate earthquake. Science, 291(5511), 2101-2102.

Gusiakov, V.K., 2005: Tsunami generation potential of different tsunamigenic regions in the Pacific. Marine Geology, 215, 1-2, 3-9.

Gutscher, M.A., Malavieille, J.S.L. and Collot, J.-Y., 1999: Tectonic segmentation of the North Andean margin: impact of the Carnegie ridge collision. Earth Planet. Sci. Lett. 168, 255–270.

Harpp, K. S. and White, W. M. (2001). Tracing a mantle plume: Isotopic and trace element variations of Galápagos seamounts. Geochemistry, Geophysics, Geosystems, 2(6).

Harpp, K. S., Fornari, D. J., Geist, D. J. and Kurz, M. D. (2003). Genovesa Submarine Ridge: A manifestation of plume-ridge interaction in the northern Galápagos Islands. Geochemistry, Geophysics, Geosystems, 4(9).

Hartzell, S., Liu, P. and Mendoza, C., 1996. The 1994 Northridge, California, earthquake: Investigation of rupture velocity, risetime, and high-frequency radiation. Journal of Geophysical Research: Solid Earth, 101(B9), 20091-20108.

Hayakawa, M., Molchanov, O.A. (Eds.), 2002: Seismo Electromagnetic Lithosphere Atmosphere coupling. Terra Scientific Publishing Company (TERRAPUB), Tokyo.

Holden, J. C. and Dietz, R. S. (1972). Galapagos gore, NazCoPac triple junction and Carnegie/Cocos ridges. Nature, 235, 266-269.

Holzer, T.L. and Savage, J.C., 2013. Global earthquake fatalities and population. Earthquake Spectra, 29(1), 155-175.

Hou, J.J., Han, M.K., Chai, B.L. and Han, H.Y., 1998. Geomorphological observations of active faults in the epicentral region of the Huaxian large earthquake in 1556 in Shaanxi Province, China. Journal of structural geology, 20(5), 549-557.

Ioualalen, M., Ratzov, G., Collot, J. Y. and Sanclemente, E. (2011). The tsunami signature on a submerged promontory: the case study of the Atacames Promontory, Ecuador. Geophysical Journal International, 184(2), 680-688.

Johnston, M.J.S., Borcherdt, R.D., Linde, A.T. and Gladwin, M.T., 2006. Continuous borehole strain and pore pressure in the near field of the 28 September 2004 M 6.0 Parkfield, California, earthquake: Implications for nucleation, fault response, earthquake prediction, and tremor. Bulletin of the Seismological Society of America, 96(4B), S56-S72.

Kahn, M.E., 2005. The death toll from natural disasters: the role of income, geography, and institutions. Review of economics and statistics, 87(2), 271-284.

Kanamori, H. and McNally, K.C., 1982: Variable rupture mode of the subduction zone along the Ecuador–Colombia coast. Bull. Seismol. Soc. Am.72 (4), 1241–1253.

Keilis-Borok, V., 2002. Earthquake prediction: State-of-the-art and emerging possibilities. Annual review of earth and planetary sciences, 30(1), 1-33.

Kelleher, J.A., 1972: Ruptures zones of large South American earthquakes and some predictions. Journal of Geophysical Research, 77, 11, 2087-2103.

Kellogg, J.N. and Vega, V., 1995: Tectonic development of Panama, Costa Rica and the Colombian Andes: Constraints from Global Positioning System geodetic studies and gravity. Geol. Soc. Am. Special Paper 295, 75–90.

Madariaga, R., 1977. High-frequency radiation from crack (stress drop) models of earthquake faulting. Geophysical Journal International, 51(3), 625-651.

Maeda, K. and Tokimasa, N., 1996. Decametric radiation at the time of the Hyogo-ken Nanbu Earthquake near Kobe in 1995. Geophysical research letters, 23(18), 2433-2436.

Marano, K.D., Wald, D.J. and Allen, T.I., 2010. Global earthquake casualties due to secondary effects: a quantitative analysis for improving rapid loss analyses. Natural hazards, 52(2), 319-328.

McCaffrey, R., 2008. Global frequency of magnitude 9 earthquakes. Geology, 36(3), 263-266.

McGuire, R.K., 1995. Probabilistic seismic hazard analysis and design earthquakes: closing the loop. Bulletin of the Seismological Society of America, 85(5), 1275-1284.

Ni, S., Kanamori, H. and Helmberger, D., 2005. Seismology: energy radiation from the Sumatra earthquake. Nature, 434(7033), 582-582.

Oliveira, C.S., de Sá, F.M., Lopes, M., Ferreira, M.A. and Pais, I., 2015. Early Warning Systems: Feasibility and End-Users' Point of View. Pure and Applied Geophysics, 172(9), 2353-2370.

Ouzounov, D. and Freund, F., 2004. Mid-infrared emission prior to strong earthquakes analyzed by remote sensing data. Advances in Space Research, 33(3), 268-273.

Ouzounov, D., Liu, D., Chunli, K., Cervone, G., Kafatos, M. and Taylor, P., 2007. Outgoing long wave radiation variability from IR satellite data prior to major earthquakes. Tectonophysics, 431(1), 211-220.

Pararas-Carayannis, G. 1980: The Earthquake and Tsunami of December 12, 1979, in Colombia. Intern. Tsunami Information Center Report, Abstracted article in Tsunami Newsletter, Vol. XIII, No. 1.

Pararas-Carayannis, G., 2012: Potential of tsunami generation along the Colombia/Ecuador subduction margin and the Dolores-Guayaquil Mega-Thrust. Science of Tsunami Hazards, 31, 3, 209-230.

Pilger, R. H. (1983). Kinematics of the South American subduction zone from global plate reconstructions. Geodynamics of the eastern Pacific region, Caribbean and Scotia arcs, 113-125.

Pontoise, B. and Monfret, T. (2004). Shallow seismogenic zone detected from an offshore-onshore temporary seismic network in the Esmeraldas area (northern Ecuador). Geochemistry, Geophysics, Geosystems, 5(2).

Pulinets, S. and Ouzounov, D., 2011. Lithosphere–Atmosphere–Ionosphere Coupling (LAIC) model – An unified concept for earthquake precursors validation. Journal of Asian Earth Sciences, 41(4), 371-382.

Pulinets, S., Ouzounov, D., Ciraolo, L., Singh, R., Cervone, G., Leyva, A., Duna- jecka, M., Karelin, Boyarchuk, K., 2006: Thermal, atmospheric and ionospheric anomalies around the time of Colima M7.8 Earthquake of January 21, 2003. Annales Geophysicae 24, 835-849.

Pulinets, S.A. and Dunajecka, M.A., 2007. Specific variations of air temperature and relative humidity around the time of Michoacan earthquake M8. 1 Sept. 19, 1985 as a possible indicator of interaction between tectonic plates. Tectonophysics, 431(1), 221-230.

Pulinets, S.A., Boyarchuk, K.A., Hegai, V.V., Kim, V.P., Lomonosov, A.M., 2000: Quasi-electrostatic model of atmospherethermo- sphereionosphere coupling. Advances in Space Research 26 (8), 1209-1218.

Pulinets, S.A., Ouzounov, D., Karelin, A.V., Boyarchuk, K.A. and Pokhmelnykh, L.A., 2006. The physical nature of thermal anomalies observed before strong earthquakes. Physics and Chemistry of the Earth, Parts A/B/C, 31(4), 143-153.

Rainieri, C., Fabbrocino, G. and Cosenza, E., 2011. Integrated seismic early warning and structural health monitoring of critical civil infrastructures in seismically prone areas. Structural Health Monitoring, 10(3), 291-308.

Raschky, P.A. 2008. Institutions and the losses from natural disasters. Natural Hazards and Earth System Science 8, 627-634.

Ratzov, G., Collot, J. Y., Sosson, M. and Migeon, S. (2010). Mass-transport deposits in the northern Ecuador subduction trench: Result of frontal erosion over multiple seismic cycles. Earth and Planetary Science Letters, 296(1), 89-102.

Ratzov, G., Sosson, M., Collot, J. Y., Migeon, S., Michaud, F., Lopez, E. and Le Gonidec, Y. (2007). Submarine landslides along the North Ecuador–South Colombia convergent margin: possible tectonic control. In Submarine Mass Movements and Their Consequences. Springer Netherlands, 47-55

Reynaud, C., Jaillard, É., Lapierre, H., Mamberti, M. and Mascle, G. H. (1999). Oceanic plateau and island arcs of southwestern Ecuador: their place in the geodynamic evolution of northwestern South America. Tectonophysics, 307(3), 235-254.

Rikitake, T., 1968. Earthquake prediction. Earth-Science Reviews, 4, 245-282.

Rodriguez, F., DHowitt, M.C., Toulkeridis, T., Salazar, R., Romero, G.E.R., Moya, V.A.R. and Padilla, O., 2016. The economic evaluation and significance of an early relocation versus complete destruction by a potential tsunami of a coastal city in Ecuador. Science of Tsunami Hazards, 35(1). 18-35

Rudolph E. and Szirtes S., 1911: Das kolumbianische Erdbeben am 31 Januar 1906, Gerlands Beitr. z. Geophysik , 2, 132- 275.

Ruff, L.J., and Kanamori, H., 1980, Seismicity and the subduction process: Physics of the Earth and Planetary Interiors, 23, 240–252

Satriano, C., Wu, Y.M., Zollo, A. and Kanamori, H., 2011. Earthquake early warning: Concepts, methods and physical grounds. Soil Dynamics and Earthquake Engineering, 31(2), 106-118.
Scholz, C.H., Sykes, L.R. and Aggarwal, Y.P., 1973. Earthquake prediction: a physical basis. Science, 181(4102), 803-810.
Serebryakova, O.N., Bilichenko, S.V., Chmyrev, V.M., Parrot, M., Rauch, J.L., Lefeuvre, F. and Pokhotelov, O.A., 1992. Electromagnetic ELF radiation from earthquake regions as observed by low-altitude satellites. Geophysical Research Letters, 19(2), 91-94.
Shepperd, G.L. and Moberly, R., 1981: Coastal structure of the continental margin, northwest Peru and southwest Ecuador. Geological Society of America Memoirs, 154, 351-392,
Shome, N., Cornell, C.A., Bazzurro, P. and Carballo, J.E., 1998. Earthquakes, records, and nonlinear responses. Earthquake Spectra, 14(3), 469-500.
Sidorin, A.Y., 2003. Search for earthquake precursors in multidisciplinary data monitoring of geophysical and biological parameters. Natural Hazards and Earth System Science, 3(3/4), 153-158.
Smith, W.D., 1990. Predicting Earthquakes in New-Zealand, Search, 21 (7), 223-226.
Smith, W.D., 1998. Resolution and significance assessment of precursory changes in mean earthquake magnitudes, Geophys. J. Int., 135 (2), 515-522.
Suárez, G., Novelo, D. and Mansilla, E., 2009. Performance evaluation of the seismic alert system (SAS) in Mexico City: a seismological and a social perspective. Seismological Research Letters, 80(5), 707-716.
Swenson, J.L. and Beck, S.L., 1996: Historical 1942 Ecuador and 1942 Peru subduction earthquakes, and earthquake cycles along Colombia–Ecuador and Peru subduction segments. Pure Appl. Geophys.146 (1), 67–101.
Toulkeridis, 2011: Volcanic Galápagos Volcánico. Ediecuatorial, Quito, Ecuador, 364 pp
Toulkeridis, T., Arroyo, C.R., Cruz D'Howitt, M., Debut, A., Vaca, A.V., Cumbal, L., Mato, F. and Aguilera, E., 2015: Evaluation of the initial stage of the reactivated Cotopaxi volcano - Analysis of the first ejected fine-grained material. Natural Hazards and Earth System Sciences, 3, (11), 6947-6976
Toulkeridis, T., Chunga, K., Rentería, W., Rodriguez, F., Mato, F., Nikolaou, S., Cruz D´Howitt, M., Besenzon, D., Ruiz, H., Parra, H. and Vera-Grunaer, X., 2017: The 7.8 M_w Earthquake and Tsunami of the 16th April 2016 in Ecuador - Seismic evaluation, geological field survey and economic implications. Science of tsunami Hazards, 36(4), 197-242.
Tramutoli V, Aliano C, Corrado R, Filizzola C, Genzano N, Lisi M, Martinelli G, Pergola N (2013) On the possible origin of thermal infrared radiation (TIR) anomalies in earthquake-prone areas observed using robust satellite techniques (RST). Chem Geol 339:157–168.
Tronin, A.A., Hayakawa, M. and Molchanov, O.A., 2002. Thermal IR satellite data application for earthquake research in Japan and China. Journal of Geodynamics, 33(4), 519-534.
USGS (United States Geological Service), 2016a: Historic Earthquakes, 1906 January 31st. (http://earthquake.usgs.gov/earthquakes/world/events/1906_01_31.php)
USGS (United States Geological Service), 2016b: M7.8 - 29km SSE of Muisne, Ecuador.http://earthquake.usgs.gov/earthquakes/eventpage/us20005j32#general

Varotsos, P. and Lazaridou, M., 1991. Latest aspects of earthquake prediction in Greece based on seismic electric signals. Tectonophysics, 188(3), 321-347.

Vigny, C., Socquet, A., Peyrat, S., Ruegg, J.C., Métois, M., Madariaga, R., Morvan, S., Lancieri, M., Lacassin, R., Campos, J. and Carrizo, D., 2011. The 2010 Mw 8.8 Maule megathrust earthquake of Central Chile, monitored by GPS. Science, 332(6036), 1417-1421.

Virk, H.S. and Singh, B., 1993. Radon anomalies in soil-gas and groundwater as earthquake precursor phenomena. Tectonophysics, 227(1), 215-224.

Yao, Y., Chen, P., Wu, H., Zhang, S. and Peng, W., 2012. Analysis of ionospheric anomalies before the 2011 M w 9.0 Japan earthquake. Chinese Science Bulletin, 57(5), 500-510.

Zeng, Y., Aki, K. and Teng, T.L., 1993. Mapping of the high-frequency source radiation for the Loma Prieta earthquake, California. Journal of Geophysical Research: Solid Earth, 98(B7), 11981-11993.