EARTHQUAKE PRECURSOR MOBILE NETWORK[*]

Manana Kachakhidze[1,✉]   Nino Kachakhidze-Murphy[2]   Giorgi Khazaradze[3]
Badri Khvitia[2]

[1] *LEPL Institute "OPTIKA", Tbilisi, Georgia*
[2] *Ivane Javakhishvili Tbilisi State University, Tbilisi, Georgia*
[3] *Grup RISKNAT, Institut Geomodels, University of Barcelona, Barcelona*

Abstract   It is known that the VLF/LF radiation existing prior to large earthquakes is recorded in several seismically active countries of the world. The networks of this radiation consist of stationary transmitters and receivers. However, there are cases of large earthquakes, when existing networks cannot detect relevant EM radiation.

In the present paper we focus on the optimal option of a mobile VLF/LF electromagnetic radiation network arrangement to ensure a detection of the upcoming earthquake precursor. We discuss new possibilities of arrangement of the VLF/LF mobile network based on certain physical considerations, which is relatively simplified and completely different from the existing stationary networks. The suggested design, will significantly increase the number of detected/ predicted earthquakes with the relevant EM emissions receivers, strategically placed in the regions of the increased tectonic and seismic activity.

1 Introduction

Studies of earthquake problems in the world were especially intensified from the second half of the last century, since alongside with theoretical studies it became possible to carry out advanced research activities, that included field, laboratory and satellite experiments. All these new activities in the last decades, have revealed various anomalous changes of geophysical fields in lithosphere as well as in atmosphere and ionosphere, prior to the occurrence of earthquake during the so-called preparation process. These different geophysical phenomena may accompany earthquake preparation process and expose themselves several months, weeks or days prior to earthquakes.

Among the observed anomalous geophysical phenomena preceding earthquakes, the specific attention is drawn to earth electromagnetic emissions recorded before earthquakes, because an interesting correlation between seismic activity and disturbances in radiobroadcasts has been revealed by scientists.

Numerous scientific papers were published on this subject that included convincing evidence linking these processes using ground and satellite based terrestrial observations of the Very Low Frequency (VLF), Low Frequency (LF) and Ultra Low Frequency (ULF) EM emissions observed during earthquake preparation period (Bahat et al., 2005; Biagi et al.,1999, 2007, 2009, 2011, 2012, 2013, 2014, 2019; Bleier et al., 2010; Boudjada et al., 2010, 2017; Contoyiannis et al., 2014; Denisenko et al., 2008; Dolea et al., 2015; Eftaxias et al., 2003, 2009; Hayakawa et al., 1994; Hayakawa, 1999; Hayakawa et al., 2002; Hayakawa et all, 2006; Hayakawa et al., 2007; Maggipinto et al, 2015; Mognaschi, 2002; Moldovan et al., 2015; Molchanov et al., 1998; Onishi et al., 2011; Politis et al., 2020; Potirakis et al., 2015; Rozhnoi et al., 2009; Uyeda et al., 2009; Yoshino, 1991; Zhang et al., 2012).

To study the possibility of finding EM disturbance precursors, various networks were established to collect VLF/LF radio signals in order to study EM field variations associated with seismogenic processes. Since the early 2000s, the Japanese researchers have established a VLF radio network (JapanesePacific VLF/LF Network) which has seven receivers to measure the intensity and phase of VLF radio signals from two different transmitters (Hayakawa et al., 2010). In February 2002, in the framework of a scientific cooperation among Japanese, Russian and Italian teams, a radio-receiver was put into operation in the department of Physics at the University of Bari, Italy, which marked the beginning of the development of an Earopean network (Maggipinto et al., 2013).

Since 2009, the network, consisting of VLF (20–60 kHz) and LF (150–300 kHz) radio receivers, is

operating in Europe in order to study the disturbances produced by the earthquakes on the propagation of these signals.

VLF radio signals span 10 to 60 kHz frequency band. These radio signals are used for worldwide navigation support, time signals and for military purposes. They are propagated in the earth-ionosphere wave-guide mode along the great circle paths. Therefore, their propagation is strongly affected by the ionosphere conditions. LF signals lie in 150 to 300 kHz frequency band. They are used for long wave broadcasting, although its popularity is in decline. These radio signals are characterized by the ground wave and the sky wave propagation modes. The first generates a stable signal that propagates in the earth-troposphere channel and is affected by the surface ground and tropospheric conditions. The second instead gives rise to a signal which varies greatly between day and night, as well as, summer and winter, and which propagates using the lower ionosphere as a reflector; its propagation is mainly affected by the ionosphere condition, particularly in the zone located in the middle of the transmitter-receiver path. The propagation of the VLF/LF radio signals is affected by different factors such as the meteorological conditions, the solar bursts and the geo-magnetic activity. At the same time, variations of some parameters in the ground, in the atmosphere and in the ionosphere, occurring during the preparatory phase of earthquakes, can produce disturbances in the above-mentioned signals. As already reported by many previous studies, the disturbances are classified as anomalies and different methods of analysis as the residual dA/ dP, the terminator time TT, the Wavelet spectra and the Principal Component Analysis have been used (Biagi et al., 2012).

The research of seismic effects on the VLF/LF radio signals is based on the spotting of disturbances in the data. In this framework, a first and fundamental step in the identification of possible disturbances related to non-seismic causes (Biagi et al., 2013). Usually, the daily radio signal is analyzed to detect anomalies and afterwards, a complicated procedure of attributing these anomalies to a specific earthquake is performed, where in the first place, the attempt is made to exclude all other possible causes for the occurrence of the observed anomalies (Biagi et al., 2011; Biagi, 2019). Although, it is true that satellite and terrestrial networks record EM radiation before an earthquake, there are instances of strong earthquakes when radiation cannot be detected (Biagi et al., 2011; Biagi, 2019). This fact raises doubts among the scientific community that the EM emissions may not always exist during the earthquake preparation period. This in some way, contradicts the well-known fact of the EM generation

during the process of crack formation, which has been illustrated both theoretically and experimentally (Bleier et al., 2010; Contoyiannis et al., 2014; Eftaxias et al., 2002, 2007a, 2007b, 2008, 2009, 2010; Freund et al.,2006; Gershenzon et al., 2001; Hadjicontis et al, 2007; Ikeya et al.,1996; Papadopoulos et al., 2010; Politis et al., 2020; Potirakis et al., 2013, 2015; Rabinovitch et al., 2007; Schwingenschuh et al., 2011; Yoshida et al., 1997). Nevertheless, the role of the INFREP (as well as Pacific network and satellite data) is immense in the study of EM emissions existing before earthquakes. The creation of these networks can be considered as the first and the necessary step for further development of the subject of EM emissions prior to the occurrence of earthquakes. The data collected by these networks in Europe and the Pacific basin respectively, has been instrumental to achieve important advances in our knowledge of earthquake generation processes, as well as, raising possibilities for realistic earthquake predictions. Of course, we agree with the position of scientists who have been investigating electromagnetic emissions in the nature and laboratories for years and based on research conclude that the VLF/VHF electromagnetic precursors do exist and that the development of suitable observational techniques and analysis methods is a promising research direction for earthquake precursors study (Eftaxias et al., 2003).

2 Discussion

It is obvious, that the geophysical field, which can be considered as earthquake precursor, has to be precisely expressed the geological model of fault generation in the focus (Mjachkin, 1978). Consequently, a complex process, from the beginning of micro cracks to the main fault formation and the consequent restoration of the equilibrium in the focus of the earthquake, has to be it described analytically. While discussing earthquakes, and especially their prediction, scientist have to be careful, while choosing and applying specific boundary conditions, because it might result in erroneous conclusions.

Experimental studies in the direction of searching of VLF/LF EM radiation observed before the occurrence of earthquakes have shown that: 1) In the period of large earthquake preparation, EM radiation begins a few weeks before the earthquake; 2) For the spectrum of existing EM emissions the following sequence of frequencies are most common: MHz, kHz; 3) The VLF and LF emissions during the entire processes are accompanied by ULF radiation; 4) In most cases, a few days before the earthquake, so-called "silence" of emissions takes place, when the EM radiation

is either no-existent or drastically reduced; 5) The "silence" of EM emissions is followed by an earthquake (Eftaxias et al., 2009; Eftaxias et al., 2013; Papadopoulos et al., 2010). The existence of this type of VLF/LF field in the epicenter area during the earthquake preparation period and its tendency to change, indicates that: 1) The body responsible for the generation of the observed VLF/LF EM emissions should be located within the earthquake focus; 2) The changes in the frequencies of the observed VLF/LF EM emissions should be caused by changes of length of this body in the focus.

Based on these considerations, the theoretical model of generation of EM emissions observed before earthquakes was developed (Kachakhidze et al., 2015). Consequently, this model was corroborated by the data recorded by the INFREP network and the methods of large earthquake prediction has been developed (Kachakhidze et al., 2019). To summarize these work, it turns out that:

1) About few dozen days prior to the earthquake, it is possible to separate a continuous active frequency channel.

2) By the active channel frequency, about few dozen days before the earthquake, it is possible to determine the length of "cracked strip" on which the cracking process is originated and ultimately, the main fault is formed.

3) The length estimates of the "cracked strip", can be used to determine magnitude of incoming earthquake with certain accuracy about few dozen days prior to the earthquake.

4) After the active frequency channel detection, it becomes possible to determine the future earthquake epicenter with certain accuracy.

5) For short-term prediction of a large earthquake, it is recommended to begin careful monitoring of the frequency data since starting moment of the avalanche-unstable process of fault formation and to follow-up these monitoring throughout the fault evolution dynamics.

6) In case of monitoring of EM emissions preceding an earthquake, it is possible, first to make a long-term prediction few dozen days before, and later a short-term prediction, 2-days before the event.

7) Based on the proposed method, it is easy to separate the foreshock and aftershock series from the main shock.

Finally, we may conclude that EM emissions turned out to be a unique precursor, which is capable of large earthquake short-term prediction. The results of this work confirm above mentioned theoretical model that during the earthquake preparation period, the direct cause of generation of the VLF/LF electromagnetic emissions is the origination and formation of the fault in the earthquake focus (Kachakhidze et al., 2019).

Because the fault, existing in focus, is the radiating body of the VLF/LF electromagnetic field (Kachakhidze et al., 2015), it is obvious, that in order to record the radiated field data, the receiver device of this field must be located to directly see the field radiated from the fault. In order to strengthen the model of generation of EM emissions detected prior to earthquakes with experimental data and to make prognostic conclusions, in the above study we used the retrospective data of the INFREP network which was expected to satisfy the necessary condition of recording a reliable EM emissions data, relevant to earthquakes. Namely, the appropriate receiver must directly "see" and record the electromagnetic emissions. For this reason, we have selected M 5.6 Crete earthquake of 25/5/2016, since it warranted the availability of the VLF/LF EM emissions data from the receiver installed in the town Chania, NW shore of the island of Crete in Greece, some 200 km away from the epicentre of the event (Kachakhidze et al., 2019).

Although the INFREP network receivers get the data from the transmitter, it is possible to assume that the receiver in Crete, besides the data getting from transmitter, recorded the information directly from the radiating body as it "saw" this EM field generated by the fault-generation processes. The study confirmed that, the indeed, the Crete receiver recorded source related data which was used to describe the Crete large earthquake preparation process with high precision, or we had a possibility of description of fault formation process (with quite high accuracy) appeared in the focus and subsequently, it afforded the opportunity to create the large earthquake short–term prediction methods (Kachakhidze et al., 2019).

Of course, the most important for earthquake forecasting is to record the parameters of that relevant geophysical field with high accuracy, which is responsible for forecasting.

Because of certain works (Eftaxias et al., 2002, 2009; 2010; Biagi et al., 2009, 2013; Kachakhidze et al., 2015), EM emissions prior to earthquake, turned out like such field, there is no doubt that the receiver of EM field really must "see" and detect the characteristic parameters of the electromagnetic field originated in the focus of the earthquake during earthquake preparation process.

In addition, for recording of M≥5.0 magnitude earthquakes, the receiver must record VLF/LF radiation in (102 kHz–0.377 kHz) frequency range (Kachakhidze et al., 2015). This is one of the essential and necessary requirements, that a modern VLF/LF EM emissions recording network must satisfy. As of today, the existing VLF/LF networks, which consist mainly of stationary transmitters and receivers, record EM emissions in limited frequency bands of 20 to 60 kHz (VLF) and 150 to 300 kHz (LF) respectively, using 10 channels (for example,

INFREP). This design limits the possibilities of recording earthquakes of only certain magnitudes (Biagi et al., 2014; Biagi et al., 2019) and miss others.

It is known that large earthquake (M≥ 5) is being prepared for quite a long time, which means that the process of tectonic stress accumulation takes long time in any seismically active region. For this reason, it's essential that these active regions are in simultaneously monitored using space geodetic GNSS permanent networks, which have a potential of identifying anomalous regions of high tectonic stress accumulation (Banks et al.,1997; Reilinger et al., 2006; Khamidov, 2017; Khazaradze et al., 2019; Sokhadze et al., 2018:2020; Elshin et al., 2020). In the trans-Caucasus, including Georgia, these type of observations are carried out in collaboration with the US scientists, since the end of the last century (Reilinger et al., 2006; Sokhadze et al., 2018; 2020). Combining geodetic, geo-

logic and seismic observations enable multi-disciplinary observations of the ongoing geologic processes of the region (or country). Frequently the identification of these anomalies requires a reevaluation of seismic hazards in this area.

Let us consider the research conducted in Georgia for example. In this study authors present and interpret new GPS observations made during the period 2008 through 2016 for 21 survey-mode sites and 9 continuous stations. The GPS observations are primarily aligned along two roughly range-perpendicular profiles that cross the Lesser–Greater Caucasus boundary zone (Figure 1). Objectives of searching are to determine the rate of active deformation across these two segments of the boundary and use the observed deformation and elastic fault models to constrain the locations and character of active structures in this portion of the Arabia–Eurasia collision zone (Figure 1)
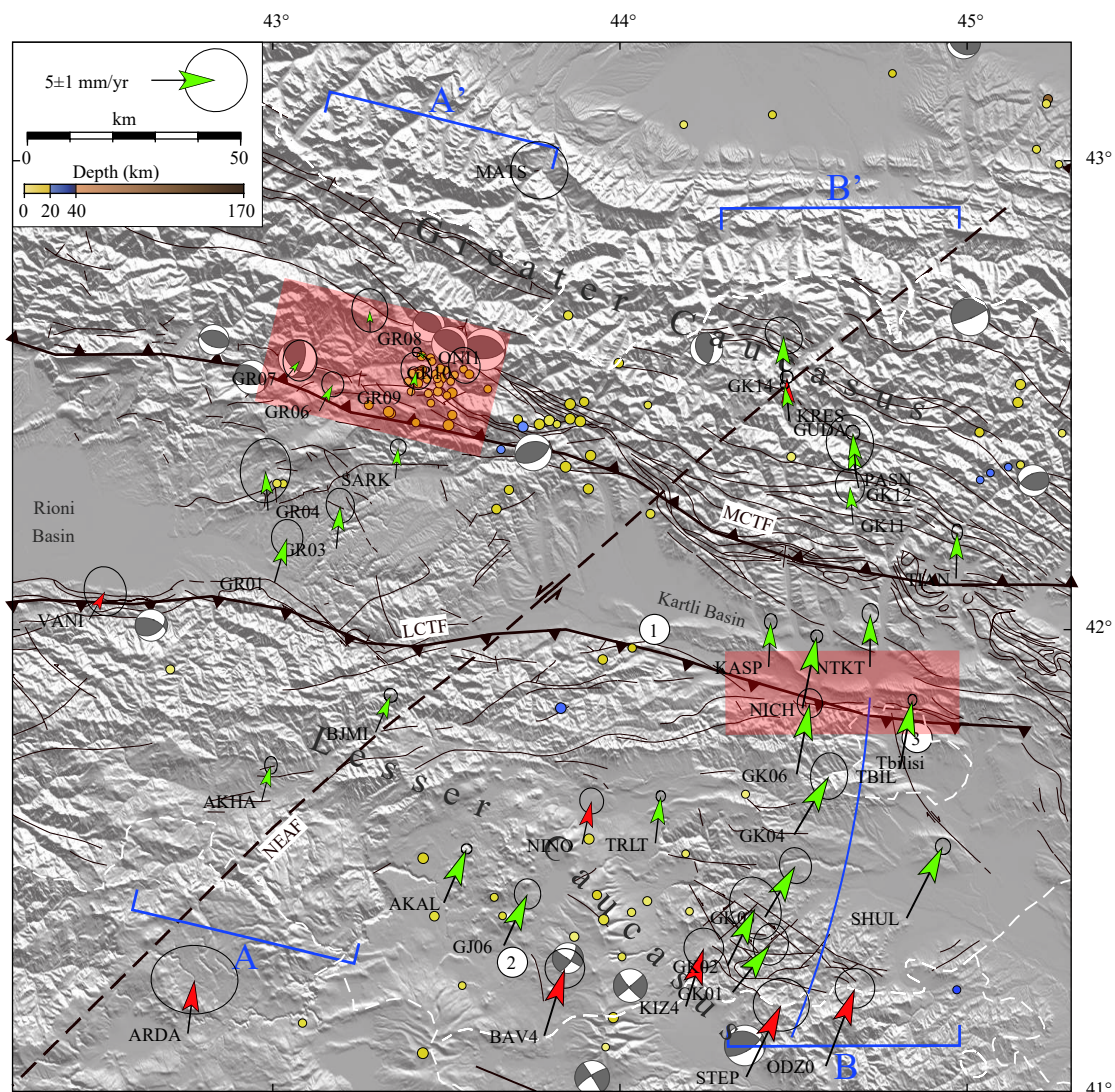

Figure 1

(Sokhadze et al., 2018).

It turned out that convergence between the Lesser and Greater Caucasus along the eastern Rioni Basin is primarily accommodated on a north-dipping fault system along the southern margin of the Greater Caucasus. The geodetically estimated location and dip of the model fault is consistent with the location and fault parameters reported for the 1991 Mw6.9 Racha earthquake, which occurred on the MCTF at depth (Sokhadze et al., 2018).

In contrast, principal convergence between the Lesser and Greater Caucasus across the Tbilisi segment, immediately east of the Rioni segment, occurs along the northern boundary of the Lesser Caucasus. Best-fit fault models involve convergence on a north-or south-dipping thrust fault located near the northern edge of the Lesser Caucasus, approximately 50–70 km south of the MCTF, and near Tbilisi. Authors suggest that the southward offset of the convergence zone is related to the incipient collision between the Lesser and Greater Caucasus. Ongoing seismic, geodetic and tectonic investigations promise to better characterize the source of observed strain and, accordingly, implications for seismic hazards and the tectonic evolution of the LC-GC collision zone (Sokhadze et al., 2018).

This type of studies will enable us to identify specific territory (or territories) in the region where tectonic stress is being actively accumulated, and where potentially, important EM emissions anomalies can be revealed before the occurrence of future earthquakes. In the case of Georgia, according to the geological interpretation, because of increased geodetically detected tectonic strain rates near Tbilisi, it seems to be necessary to re-evaluate the seismic hazard estimates for this area, where more than a million people live.

The fact that earthquakes occur in areas where tectonic stress is accumulated and that also, the same areas are responsible for the generation of the faults that start the EM emissions a few months or years before the earthquake (Sokhadze et al., 2018; Elshin et al., 2020), gives us the opportunity to think about modernization of the modern networks of electromagnetic radiation. Specifically, in order to predict an earthquake, the network of mobile receivers of VLF/LF electromagnetic emissions, without transmitters, must be purposefully installed on the specific tectonic stress anomaly of the region (or country). Such a network may be called an "earthquake precursor mobile network" (EPMN).

It should be noted that, before arrangement of earthquake precursor mobile network, after numeric estimation of tectonic stress area (even in the case when it changes constantly) it is possible in advance, step by step, to determine an approximate value of the incoming earthquake magnitude using the Dobrovolsky et al. (1979) formula:

$$R = 10^{0.43M}$$

where R is the "strain radius" in km and M is an earthquake magnitude.

In such a case, by monitoring of incoming earthquake magnitude, it is also possible to estimate approximate changes of the fault lengths in the focus of incoming earthquake (Kachakhidze et al., 2015). Therefore, the "area of vision" of the earthquake precursor mobile network of VLF/LF EM emissions existent prior to the earthquake, in the case of different magnitudes, obviously, will be different. These works can be carried out at any early stage of tectonic stress accumulation and in order to control the process of inter-seismic tectonic stress accumulation, which can last for quite long time. In case of reaching a certain limit of tectonic tension, it can become necessary to initiate earthquake prediction procedures and consequently, the earthquake precursor mobile network has to be installed in a specific seismogenic area. Our previous research allows us to determine the required number of EM emissions receivers and precisely select a location where the best reception of VLF/LF EM radiation from the earthquake focus will be guaranteed.

The arrangement of stationary networks throughout the whole region (or country) is justified for areas where geodetic surveys are not conducted in order to detect active tectonic anomalies. In addition, it should also be noted that stationary EM networks, except for the receivers, also consists of transmitters, which are quite expensive.

Thus, in order to obtain complete records of electromagnetic emissions existent before an earthquake, it is necessary first of all to conduct geodetic surveys to detect tectonic anomalies in any region (or country), complemented with permanent GNSS networks and afterwards, followed by the installation of an earthquake precursor mobile network at the specific sites of tectonic anomalies.

"Earthquake precursor mobile network" proposed in this study, has some specific advantages compared to the existing stationary networks, such as INFREP. These advantages include:

1) "Earthquake precursor mobile network" does not need costly transmitters and only consists of mobile EM radiation receivers.

2) Since the receivers are designed to be mobile, their transportation and installation is easy and provides a possibility of establishing a new survey site(s) when new tectonic anomalies are detected.

3) Earthquake precursor mobile network provides a possibility, depending on a specific upcoming earthquake, to change the number of deployed receivers, depending on the length of the specific fault involved.

It must be kept in mind that the perfect recording of radiated electromagnetic emissions depend on the orientation of the main fault, generated in the earthquake focus, towards the receiver, which may be determined with certain accuracy during long time observation. According to our previous work, the active fault, where the earthquake preparing process is taking place, may be detected some dozen days before an upcoming earthquake and the involved fault length in the focus area can also be determined with certain accuracy (Kachakhidze et al., 2015; 2019). It means that in order to obtain the best and the most meaningful data of electromagnetic emissions, the spatial distribution and configuration of the EM mobile receivers must be chosen to optimize the obtained data. It is desirable to determine approximate location of the earthquake focus in advance based on the data of the tectonic anomalies (Elshin et al., 2020). Since the EM receivers should be located in the vicinity of the probable epicenter of the upcoming earthquake, will detect the full spectrum of electromagnetic emissions (with some accuracy, of course) which will be radiated by fault. To control the full spectrum of radiation means to measure EM emissions in 102 kHz to 0.377 kHz frequency band, which is necessary to predict $M \geq 5.0$ magnitude earthquakes.

We believe that, the deployment of the suggested earthquake precursor mobile networks, in conjunction with the establishment of the continued space geodetic observing networks, will make earthquake prediction research using EM emissions, much more wide-spread and with significantly smaller economic costs.

3 Conclusions:

In the present work, the considerations about expediency and benefits of arrangement of an Earthquake precursor mobile network of VLF/LF electromagnetic emissions receivers, capable of detecting EM radiation preceding earthquakes are offered.

In any seismically active region (country), where the general tectonic stress field is studied in advance by geodetic monitoring, the following possibilities arise:

To arrange purposefully the Earthquake precursor mobile network of EM emissions receivers in areas of pre-identified specific geotectonic anomalies, according to a preliminary rough calculation of the expected magnitude

of the incoming earthquake. The high precision measurements of VLF/LF EM emissions for earthquakes with $M \geq 5.0$ magnitudes in 102–0.377 kHz frequency bands must be carried out.

Earthquake precursor mobile networks will be organized with much smaller financial cost, which is due to the fact that this network consists only of EM emissions receivers, the location of which can be easily changed according to changing location of geotectonic anomalies; This will allow us to optimally use human resources as well as the necessary material and technical base.

As for already existing networks, the suggested methodology can also be used in conjunction with a permanent. Stationary observations, which can time-to-time complemented with several mobile receivers to increase their sensitivity and target specific regions that show increased tectonic and/or seismic activity.

Acknowledgements

References

Banks CJ, Robinson AG, Williams MP (1997) Structure and regional tectonics of the achara-trialet fold belt and the adjacent rioni and kartli foreland basins, Republic of Georgia. In: Robinson AG (ed) AAPG Memoir, AAPG STUDI. American Association of Petroleum Geologists (AAPG), pp 331–346

Bahat D, Rabinovitch A, Frid V (2005) Tensile fracturing in rocks: Tectonofractographic and electromagnetic radiation methods

Biagi PF (1999) Seismic effects on LF radiowaves. In: Hayakawa M (ed) Atmospheric and ionospheric electromagnetic phenomena associated with earthquakes. Terra Scientific Publishing Company, Tokyo, Japan, pp 535–542

Biagi PF, Castellana L, Maggipinto T, et al. (2007) Decrease in the electric intensity of VLF/LF radio signals and possible connections. Nat Hazards Earth Syst Sci 7: 423–430

Biagi PF, Castellana L, Maggipinto T, et al. (2009) A pre seismic radio anomaly revealed in the area where the Abruzzo earthquake (M=6.3) occurred on 6 April 2009. Nat Hazards Earth Syst Sci 9: 1551–1556

Biagi PF, Maggipinto T, Righetti F, et al. (2011) The European

VLF/LF radio network to search for earthquake precursors: setting up and natural/man-made disturbances. Nat Hazards Earth Syst Sci **11**: 333–341

Biagi PF, Righetti F, Maggipinto T, *et al*. (2012) Anomalies Observed in VLF and LF Radio Signals on the Occasion of the Western Turkey Earthquake (Mw 5.7) on May 19, 2011. Int J Geosci **03**: 856–865

Biagi, P.F., Magippinto, T., Schiavulli, L., Ligonzo, T., Ermini, A. (2013) European Network for collecting VLF/LF radio signals (D5.1a). DPC- INGV - S3 Project. "Short Term Earthquake prediction and preparation".

Biagi PF, Maggipinto T, Ermini A (2015) The European VLF/LF radio network: current status. Acta Geod Geophys **50**: 109–120

Biagi PF, Colella R, Schiavulli L, *et al*. (2019) The INFREP Network: Present Situation and Recent Results. Open J Earthq Res **8**: 101–115

Bleier T, Dunson C, Alvarez C, *et al*. (2010) Correlation of pre-earthquake electromagnetic signals with laboratory and field rock experiments. Nat Hazards Earth Syst Sci **10**: 1965–1975

Boudjada MY, Schwingenschuh K, Döller R, *et al*. (2010) Decrease of VLF transmitter signal and Chorus-whistler waves before l'Aquila earthquake occurrence. Nat Hazards Earth Syst Sci **10**: 1487–1494

Boudjada MY, Biagi PF, Al-Haddad E, *et al*. (2017) Reception conditions of low frequency (LF) transmitter signals onboard DEMETER micro-satellite. Phys Chem Earth, Parts A/B/C **102**: 70–79

Contoyiannis, Y., Potirakis, S.M., Kopanas, J., Antonopoulos, G., Koulouras, G., Eftaxias, K., Nomicos, C. (2014) On the recent seismic activity at Kefalonia island (Greece): manifestations of an earth system in critical state. Geophysics, 1–12, arXiv:1401.7458.

Denisenko V V, Boudjada MY, Horn M, *et al*. (2008) Ionospheric conductivity effects on electrostatic field penetration into the ionosphere. Nat Hazards Earth Syst Sci **8**: 1009–1017

Dobrovolsky IP, Zubkov SI, Mjachkin VI (1979) Estimation of the size of earthquake preparation zones. Pure Appl Geophys **117**: 1025–1044

Dolea P, Cristea O, Dascal PV, *et al*. (2015) Aspects regarding the use of the INFREP network for identifying possible seismic precursors. Phys Chem Earth **85–86**: 34–43

Eftaxias K, Kapiris P, Dologlou E, *et al*. (2002) EM anomalies before the Kozani earthquake: A study of their behavior through laboratory experiments. Geophys Res Lett **29**: 64–69

Eftaxias K, Kapiris P, Polygiannakis J, *et al*. (2003) Experience of short-term earthquake precursors with VLF–VHF electromagnetic emissions. Nat Hazards Earth Syst Sci **3**: 217–228

Eftaxias K, Sgrigna V, Chelidze T (2007) Mechanical and electromagnetic phenomena accompanying preseismic deformation: from laboratory to geophysical scale

Eftaxias K, Panin VE, Deryugin YY (2007) Evolution-EM signals before earthquakes in terms of mesomechanics and complexity. Tectonophysics **431**: 273–300

Eftaxias K, Contoyiannis Y, Balasis G, *et al*. (2008) Evidence of fractional-Brownian-motion-type asperity model for earthquake generation in candidate pre-seismic electromagnetic emissions. Nat Hazards Earth Syst Sci **8**: 657–669

Eftaxias K, Balasis G, Contoyiannis Y, *et al*. (2010) Unfolding the procedure of characterizing recorded ultra low frequency, kHZ and MHz electromagnetic anomalies prior to the L'Aquila earthquake as pre-seismic ones - Part 2. Nat Hazards Earth Syst Sci **10**: 275–294

Eftaxias K, Potirakis SM, Chelidze T (2013) On the puzzling feature of the silence of precursory electromagnetic emissions. Nat Hazards Earth Syst Sci **13**: 2381–2397

Elshin O, Tronin AA (2020) Global earthquake prediction systems. Open J Earthq Res **9**: 170–180

Freund FT, Takeuchi A, Lau BWS (2006) Electric currents streaming out of stressed igneous rocks – A step towards understanding pre-earthquake low frequency EM emissions. Phys Chem Earth **31**: 389–396

Gershenzon, N., and G. Bambakidis (2001) Modeling of seismo-electromagnetic phenomena, Russ. J. Earth Sci. **3**(4): 247–275

Hadjicontis V, Mavromatou C, Antsygina TN, Chishko KA (2007) Mechanism of electromagnetic emission in plastically deformed ionic crystals. Phys Rev B **76**: 24106

Hayakawa M, Fujinawa Y (1994) Electromagnetic Phenomena Related to Earthquake Prediction. Terra Scientific Publishing

Hayakawa M, Fujinawa Y (1994) Electromagnetic Phenomena Related to Earthquake Prediction. Terra Scientific Publishing

Hayakawa M, Molchanov OA (2002) Seismo electromagnetics: lithosphere-atmosphere-ionosphere coupling. Terrapub Tokyo

Hayakawa M, Ohta K, Maekawa S, *et al*. (2006) Electromagnetic precursors to the 2004 Mid Niigata Prefecture earthquake. Phys Chem Earth, Parts A/B/C **31**: 356–364

Hayakawa M, Molchanov OA (2007) Seismo-electromagnetics as a new field of radiophysics: Electromagnetic phenomena associated with earthquakes. URSI Radio Sci Bull **2007**: 8–17

Hayakawa M, Kasahara Y, Nakamura T, *et al*. (2010) A statistical study on the correlation between lower ionospheric perturbations as seen by subionospheric VLF/LF propagation and earthquakes. J Geophys Res Sp Phys **115**

Ikeya M, Takaki S (1996) Electromagnetic fault for earthquake lightning. Japanese J Appl Physics, Part 2 Lett **35**

Kachakhidze, M.K., Kachakhidze, N.K., Kaladze, T.D (2015) A model of the generation of electromagnetic emissions detected prior to earthquakes. Physics and Chemistry of the Earth **85–86**: 78–81

Kachakhidze M, Kachakhidze-Murphy N, Khvitia B, Ramishvili G (2019) Large Earthquake Prediction Methods. Open J Earthq Res **8**: 239–254

Khamidov KL (2017) Assessment of strain effect of strong-motion (focus) zones of earthquakes on earth's surface displacement. Geod Geodyn **8**: 34–40

Khazaradze G, Pena-Castellnou S, Santamaría-Gómez A, Vernant P (2019) 3D GPS velocity field of the Iberian Peninsula. Geophys Res Abstr **21**: 66263

Maggipinto T, Biagi PF, Colella R, *et al*. (2015) The LF radio anomaly observed before the Mw = 6.5 earthquake in Crete on

October 12, 2013. Phys Chem Earth, Parts A/B/C **85–86**: 98–105

Mjachkin VI (1978) Processes of earthquake preparation (Процессы подготовки землетрясений). Nauka Publisher, Moscow

Mognaschi ER (2002) On the possible origin propagation and detectability of electromagnetic precursors of earthquakes. Atti Ticin di Scinese Della Terra **43**: 111

Molchanov OA, Hayakawa M (1998) Subionospheric VLF signal perturbations possibly related to earthquakes. J Geophys Res Sp Phys **103**: 17489–17504

Moldovan I, Constantin A, Biagi P, et al. (2015) The development of the Romanian VLF/LF monitoring system as part of the international network for frontier research on earthquake precursors (INFREP). Rom J Phys **60**: 1203–1217

Onishi T, Parrot M, Berthelier J-J (2011) The DEMETER mission, recent investigations on ionospheric effects associated with man-made activities and seismic phenomena. Comptes Rendus Phys **12**: 160–170

Papadopoulos GA, Charalampakis M, Fokaefs A, Minadakis G (2010) Strong foreshock signal preceding the L'Aquila (Italy) earthquake (Mw 6.3) of 6 April 2009. Nat Hazards Earth Syst Sci **10**: 19–24

Politis D, Potirakis SM, Hayakawa M (2020) Criticality analysis of 3-year-long VLF subionospheric propagation data possibly related to significant earthquake events in Japan. Nat Hazards **102**: 47–66

Potirakis SM, Karadimitrakis A, Eftaxias K (2013) Natural time analysis of critical phenomena: The case of pre-fracture electromagnetic emissions. Chaos An Interdiscip J Nonlinear Sci **23**: 23117

Potirakis SM, Contoyiannis Y, Eftaxias K, et al. (2015) Recent Field Observations Indicating an Earth System in Critical Condition Before the Occurrence of a Significant Earthquake. IEEE Geosci Remote Sens Lett **12**: 631–635

Rabinovitch A, Frid V, Bahat D (2007) Surface oscillations - A possible source of fracture induced electromagnetic radiation. Tectonophysics **431**: 15–21

Reilinger R, McClusky S, Vernant P, et al. (2006) GPS constraints on continental deformation in the Africa-Arabia-Eurasia continental collision zone and implications for the dynamics of plate interactions. J Geophys Res **111**: 26

Rozhnoi A, Solovieva M, Molchanov O, et al. (2009) Anomalies in VLF radio signals prior the Abruzzo earthquake (M=6.3) on 6 April 2009. Nat Hazards Earth Syst Sci **9**: 1727–1732

Schwingenschuh K, Prattes G, Besser BP, et al. (2011) The Graz seismo-electromagnetic VLF facility. Nat Hazards Earth Syst Sci **11**: 1121–1127

Sokhadze G, Floyd M, Godoladze T, et al. (2018) Active convergence between the Lesser and Greater Caucasus in Georgia: Constraints on the tectonic evolution of the Lesser–Greater Caucasus continental collision. Earth Planet Sci Lett **481**: 154–161

Sokhadze G, Hahubia G, Kachakhidze M, Khazaradze G (2020) Present-day crustal deformation of Georgia (Caucasus). Geophys Res Abstr **22**: 8100

Triep EG, Abers GA, Lerner-Lam AL, et al. (1995) Active thrust front of the Greater Caucasus: The April 29, 1991, Racha earthquake sequence and its tectonic implications. J Geophys Res **100**: 4011

Uyeda S, Nagao T, Kamogawa M (2009) Short-term earthquake prediction: Current status of seismo-electromagnetics. Tectonophysics **470**: 205–213

Yoshida S, Uyeshima M, Nakatani M (1997) Electric potential changes associated with slip failure of granite: Preseismic and coseismic signals. J Geophys Res Solid Earth **102**: 14883–14897

Yoshino T (1991) Low frequency seismogenic electromagnetic emissions as precursors to earthquakes and volcanic eruptions in Japan. J Sci Explor **5**: 121–144

Zhang X, Shen X, Parrot M, et al. (2012) Phenomena of electrostatic perturbations before strong earthquakes (2005–2010) observed on DEMETER. Nat Hazards Earth Syst Sci **12**: 75–83