Are pre-seismic ULF electromagnetic emissions considered as a reliable diagnostics for earthquake prediction?

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The ultra low frequency (ULF) electromagnetic (EM) emissions, a short-term or operative parameter under observation for diagnosing seismic regimes have been examined for their reliability with efforts aimed to consider them as a reliable diagnostics. It has now been realized that there exists serious problems regarding these seismogenic ULF emissions and so there is a need to develop different methods of analysis which not only detect the pre-seismic ULF-EM emissions but also associate it for predicting the location, magnitude and time of occurrence of imminent earthquakes.

Keywords: Earthquake, electromagnetic emissions, operative precursor, ultra low frequency.

ACCORDING to available statistics, earthquakes rate first among natural calamities with regard to the severity of damage and loss of human life. Even in early stages of its progress, seismology went beyond a mere study of earthquakes, and attempts were aimed at searching for reliable diagnostics to predict the location, magnitude and time of a looming earthquake[1]. Although earthquakes are known to be a complex phenomenon, there is growing evidence in the last five decades that earthquake precursory phenomena can be detected and utilized for earthquake prediction. For instance, the first well-documented earthquake prediction was made on the basis of temporal and spatial variation of t_s/t_p relation in Blue Mountain Lake, New York on 3 August 1973 (ref. 2). Seismologists also successfully predicted the Heicheng China earthquake of 4 February 1975 (ref. 3). With these successful prediction efforts, most researchers believe that much has already been done to solve the problem of predicting the maximum magnitude and location of approaching earthquakes. However, it is rather difficult to predict the time of seismic event accurately.

To address these problems, seismologists decided to narrow down their studies from long-term to short-term prediction. Many studies have been carried out in the past four decades and a broad conclusion has been arrive at based on the finding that the seismic process is preceded by a complex set of precursors. The current goal is to single out and study anomalies in any parameters related to the final stage prior to the shock.

The parameters under observation for the purpose of diagnosing seismic regimes include hydrochemical parameters, atmospheric electrical disturbances, electromagnetic (EM) emissions, anomalous disturbances in the ionosphere and the magnetosphere recorded by satellites, seismic noise and acoustic fluctuations. Despite the noticeable diversity of these parameters, many of them reflect a common physical origin for the precursor processes. Among the above-cited parameters, sesimo-electromagnetic parameter is considered as a promising candidate in the efforts made so far for the short-term or operative prediction of earthquakes.

Although, EM phenomena in ULF/ELF/VLF frequency ranges are also associated with volcanic activity, because source regions are known for their volcanic activity the observation becomes easier than in seismic cases. EM phenomena associated with volcanic activities have also been summarized by several workers[4,5]. In seismo-electromagnetic research evidence is based on studies of certain effects related to electric and magnetic fields, ionospheric perturbations, nightglow observations, EM emissions from DC to high frequency (HF) range and radiation belt electron precipitation in the topside ionosphere[6–8].

In the last three decades, evidence have accumulated on EM emissions in a wide frequency range associated with earthquakes. The first observed EM emissions in the frequency range of 17 MHz were attributed them to applying of stress to certain quartz-bearing rocks and other piezoelectric materials[9]. Yamada *et al.*[10] reported that stress induced rocks emitted EM emissions and acoustic emissions during micro-fracturing. In 1980 precursory EM emission was first detected at Sugadaira, Japan. After this, EM emissions associated with earthquakes have been reported[11–13]. The measured emissions were also found to be between ULF and HF range. However, scientists have focused on ULF range, because there have been convincing evidences on precursory occurrence of such emissions before large earthquakes due to primary advantage that, they can circulate just below the surface without any significant attenuation, if the depth of the earthquake is ~10 km (ref. 14).

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Unprecedented ULF electromagnetic anomalous emissions

The occurrence of strong ULF magnetic field disturbances has been reported[15] at Kodiak 1–2 h before the Great Alaska earthquake ($M = 9.2$) of 27 March 1964. This earthquake is the largest one that has occurred in the United States during modern times. Unusual ULF magnetic signals were recorded prior to the Loma Prieta $M_s = 7.1$ earthquake, on 17 October 1989 ($f = 0.01$–10 Hz, $d = 7$ km, $A = 1.5$ nT)[11,16]. Anomalous EM emissions were also observed before the great crustal $M_s = 6.9$ earthquake at Spitak, Armenia, on 7 December 1988 ($f = 0.005$–1 Hz, $d = 120$–200 km, $A = 0.03$–0.2 nT)[12,21], almost one month before the 8 August 1993 $M_s = 8.0$ Guam earthquake ($f = 0.02$–0.05 Hz, $d = 65$ km)[13–16]. Before the great $M_w = 8.2$ Biak earthquake in Indonesia, on 17 February 1996 ($f = 0.005$–0.03 Hz, $d = 80$ km, $A = 0.2$–0.3 nT)[17]. Possible seismic-related ULF ($f = 0.01$–0.015 Hz) anomalies occurred 2 weeks before the L'Aquila $M = 6.3$ earthquake with the distance up to 630 km (ref. 18). All these seismic-related ULF effects appeared several hours to several weeks prior to the main events with in a distance up to several kilometers from the epicentre.

Proposed physical generation mechanism models

The seismogenic ULF range EM emissions believed to be coming from within focal zones, have emerged as a potential precursor candidate for short-term earthquake prediction[13,17,19–23]. This is further reinforced by the suggestions that mechanical deformation or microfacturing in the looming focal zones may give rise to pre- or co-seismic ULF-range EM emissions due to the following generation mechanisms: (1) inductive effect resulting from the movement of conductive medium in the Earth's geomagnetic field[24,25]; (2) displacement of boundaries between high and low conductive crustal blocks[26]; (3) electrokinetic effects[27–30]; (4) piezoelectric or piezomagnetic effects[31–34] and (5) microfacture electrification[21].

However, seismo-ULF EM study is mainly empirical, indicating an experience-based approach with well-accepted consideration that no matter what the physics underlying of the observed phenomenon is, one tends to make a prediction based on the past experience learned from the phenomena. Further, such experience is not sufficient to ensure that a prediction is right on the basis of location, magnitude and time, because the earthquake related EM phenomena have not been fully understood despite the above-mentioned proposed physical generation processes, due to the complexity of the seismogenic process.

Potential interpretations of the seismogenic ULF EM emissions

Modern high-sensitivity magnetometers can detect these weak signals from the lithospheric sources, although there is a problem with strong artificial EM noise, especially in the industrial areas. Additionally, there are ULF geomagnetic pulses of ionospheric origin that can have high amplitudes during disturbed geomagnetic periods. Therefore, before an earthquake, we can usually observe a superposition of ULF emissions from different sources on the Earth's surface.

It is usually believed that seismo-associated ULF variations could be either due to direct radiation from earthquake origin zone[21,35] or due to a change in geoelectric conductivity inside and near the earthquake zone, which leads to a change in ULF waves generated by magnetospheric sources[36]. The underground ULF EM field attenuates only little in crustal material and hence on theoretical consideration the associated magnetic field can be detected to large distances up to 100–150 km (ref. 20).

Theoretical analysis of recorded preseimic ULF signals

With the availability of very sensitive instruments with high suppression of man-made interference, the recording of high-quality signals in ULF range has greatly improved[20]. However, the practical detection and application of precursory ULF EM signals in real-time earthquake prediction consist of several problems: (i) intensity of anticipated ULF signal is low; (ii) discrimination of weak seismo-electromagnetic signals from the natural EM fields is difficult; (iii) limitation in the localization of precursor source or at least, determination of azimuth direction to the source zone. For the discrimination polarization analysis is found effective, at least partially, in distinguishing seismoelectromagnetic signals from natural signals in the ULF range[13,37,38]. Principal component analysis and fractal analysis have been used in isolating components of extra-terrestrial and seismotectonic origin in magnetic field records[14,20,39]. For the identification of source or its direction gradiometric method has been developed[40–42], but the techniques lack reliability as the ULF EM waves undergo dissipation and dispersion, making identification of the desired signal ambiguous[43]. Further, use of amplitude difference, employing synchronous observation in two or multiple sites was also advocated[43], but as space derivative of magnetic field perturbation tends to be unstable at low signal-to-noise ratio, it gives error in estimation of source direction.

The application of polarization ellipse in direction-finding problem, i.e. goniometric method was also studied[44–46]. This technique allows determination of trends in azimuth angle of anomalous ULF signal area of the earthquake epicentre.

All the above-mentioned methods are applied to improve the detection of the seismogenic ULF range emissions and also for an understanding of their association with earthquake activity, but no single method can solve all the above-mentioned problems.

Fraser-Smith[47] summarized the evidence for ULF electromagnetic field fluctuations preceding large earthquakes. He clearly pointed out that the presence of many natural and man made ULF-range fluctuations acted as an obstacle in the detection process of any earthquake-related fluctuations and ultimately questioned their association with the considered event[47]. This uncertainty on reliability made the earthquake preparation process a subject for recent discussions specially based on two important points: (1) How to detect weak ULF EM signals as an earthquake precursor? (2) How can we associate these detected ULF EM emissions to earthquake preparation process?

Prevailing arguments related to pre-seismic ULF EM emissions

Fraser-Smith *et al.*[48] claimed that they did not record any ULF emissions associated with some significant earthquakes like Landers earthquake, 1992 and Northridge earthquake, 1994. EM emission is of the nature of selectivity or directivity and could be possibly detected before part of strong earthquakes ($M_s > 6$) or at some stations in the observation networks. Selectivity is an important property of seismic electric signals which are related to earthquakes[49]. Analytical solutions of Maxwell equations, as well as numerical ones, show that selectivity results from the fact that earthquakes occur by slip on faults, which are appreciably more conductive than the surrounding medium[50–52].

In recent years, several studies[53–62] have shown strong evidence that the detected ULF-range geomagnetic anomalies claimed to be earthquake precursors after examination attributed to normal magnetic disturbances driven by solar–terrestrial interaction.

Controversial reports of earthquake-related ULF-range signals

The above-mentioned studies have examined many controversial reports of earthquake-related signals demonstrating that several methodologies used in previous studies are not appropriate to detect the presence of earthquake precursors[62]. Few researchers[63] have criticized the findings in some of the studies[53,60,64], but they have failed to provide solid facts in support of their criticism. Some studies[54,65] demonstrated that the fractal analysis of the geomagnetic field in the ULF band is not a good indicator of an imminent earthquake. On the contrary, few workers[63] emphasized the importance of fractal analysis of the ULF band of the geomagnetic field components to identify precursors of earthquakes. But they failed to address studies[54] which demonstrated that the fractal precursors documented in these claimed evidences are signals that are part of normal geomagnetic activity, which therefore cannot be described as earthquake-related anomalies. The observed results have shown only variation of parameters (fractal dimension and polarization ratio) of the geomagnetic field that were part of normal geomagnetic activity driven by solar–terrestrial interactions. Consequently, short-term earthquake prediction based on these precursors, which we have shown to be unreliable, would be highly vulnerable to false alarms, and the possible development of prediction capabilities would be adversely affected[65].

Research of short-term and operative earthquake prediction[66] is less favoured. Arguments also extend to the extreme claim that any ULF precursory activity is impossible[67]. Considering the difficulties associated with factors such as the highly complex nature, rarity of large earthquakes and subtleties of possible pre-seismic signatures, the present negative views are not baseless. It is difficult to prove associations between any two events (possible ULF precursor and earthquake) separated in time and there may be legitimate reasons for the critical views. The degree to which we can predict a phenomenon is often measured by how well we understand it.

The views mentioned above do not appear to be unjustified as many issues related to earthquake generation are not fully clear as yet. It is reasonably expected that the preparatory process of earthquakes has various aspects which may be observed before the final catastrophe through seismic, geochemical, hydrological and EM changes[66]. Therefore, the study of multidisciplinary character of the science of ULF earthquake prediction is indubitable for consideration as a reliable diagnostic.

Pre-seismic ULF EM emissions as a reliable diagnostic precursor

Two criteria have been recently proposed for the acceptance of an observed signal as an earthquake precursor[68]. (1) The reported existence of believable scientific testimony for anomalies in the observables prior to at least some earthquakes. (2) The existence of satisfactory physical models to describe the existence of the precursor. The given criteria could prove the association between the earthquake and observed ULF EM emissions, but they are not sufficient to consider ULF EM pre-seismic emissions as a reliable precursor, as the efforts are aimed at searching for a reliable diagnostics to predict the location, magnitude and time of an imminent earthquake, so that early warning of the event could make it possible to evacuate the population.

So far much has been done to solve the problem of measuring the seismic associated ULF EM emissions and on finding the detected ULF EM, which could be helpful in only predicting the possibility of occurrence of an earthquake in the nearby region. We cannot measure the hypocentre location, maximum magnitude of the impending earthquake and also its precise time of occurrence, as in most of the cases measurement of ULF is based on multi-station approach and the distance (at which the signals are detected) from the hypocentre with direction cannot be predicted with this approach. Also the time of detection of the ULF EM precursor cannot be associated with the time of the occurrence of the approaching earthquake.

We have discussed the problems regarding the seismogenic ULF emissions and now we believe that there is need to develop different kinds of analytical methods which not only detect the pre-seismic ULF EM emissions, but also associate them with predicting the location, magnitude and time of occurrence of an imminent earthquake[69].

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