Article

Earthquakes Three-Stage Early Warning and Short-Term Prediction

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Abstract: Among the anomalous geophysical phenomena observed preceding earthquakes, specific attention has been given to VLF/LF, ULF (very low frequency/low frequency, ultra-low frequency) electromagnetic (EM) emissions, recorded before earthquakes, because of an interesting correlation between them and seismic activity. Numerous scientific papers have been published on this topic, providing convincing evidence of these processes observed using ground-based and satellite ground-based observations during the preparation for the earthquake. These phenomena are detectable both at laboratory and geological scales. The authors of this paper have used an avalanche-like unstable geological model of fault formation and a model of the generation of electromagnetic emissions detected before the earthquakes to prove the prediction capabilities of VLF/LF EM emissions. The first gives a clear imagination of earthquake preparation in all stages in the focal area from the beginning of the micro-cracks appearing to the final formation of fault. Another one, based on electrodynamics, explains the EM emissions origination process and offers a formula that analytically connects the observed frequency of EM radiation with the linear size of the emitted body (fault). It is worth emphasizing the synthesis and rather harmonious relation of the mentioned models. Based on the above models conducted studies clearly show that the description of a qualitative avalanche-unstable geological model of fault formation using VLF/LF EM radiation data made it possible to quantitatively characterize the full cycle of preparation and occurrence of earthquake process. Namely, in the case of VLF/LF emissions monitoring, the beginning of the "avalanche process" of ruptures is considered the first stage of early warning of an incoming earthquake. The so-called EM emissions "silence" period is assessed as the second stage of early warning. The third early warning or an alarm about an incoming earthquake may be announced immediately at the moment of the first anomaly appearance subsequently the "silence" period. This article offers the method of earthquake three-step early warning and short-term (hourly) prediction.

Keywords: earthquake; electromagnetic emissions; precursor

1. Introduction

Professor Emeritus of the University of Tokyo and a member of Japan Academy, Seiya Uyeda wrote in 2013: Japan's National Project for Earthquake Prediction has been conducted since 1965 without success. An earthquake prediction should be a short-term prediction based on observable physical phenomena or precursors. The main reason for no success is the failure to capture precursors.

Most of the financial resources and manpower of the National Project have been devoted to strengthening the seismographs networks, which are not generally effective for detecting precursors since many of precursors are non-seismic. The precursor research has never been supported appropriately because the project has always been run by a group of seismologists who, in the present author's view, are mainly interested in securing funds for seismology—on pretense of prediction. After the 1995 Kobe disaster, the project decided to give up short-term prediction and this decision has been further fortified by the 2011 M9 Tohoku Mega-quake. Thus, in Japan now, there is practically no support for short-term prediction research. Recently, however, substantial progress has been made in real short-term prediction by scientists of diverse disciplines" [1].

We are not going to discuss the reasons that make it impossible to describe the processes taking place in the focus of an earthquake from the point of view of seismology and explain the fact why despite efforts aimed at strengthening the seismometer network, it is impossible to detect a seismic precursor to the earthquake.

Since 2015 the Government of Japan has made significant investments to expand the study of the earthquake problem in addressing the country's disproportionate earthquake and tsunami risk, informed by past lessons [2]. Despite this, only in the past year, earthquakes occurred in various seismically active countries of the world, which caused not only material damage but also huge human casualties (Turkey and Syria, on 6 February 2023, M7.8 and M7.5, Morocco, on 8 September 2023, M6.9, Philippines on 17 November 2023, M6.7, China, on 18 December 2023, M 6.2, Japan, on 1 January 2024, M7.6, etc.).

Modern ground-based and satellite observations have revealed numerous anomalous geophysical phenomena, accompanied by various natural disasters directly related to the preparation processes of these phenomena. Of course, this also concerns earthquakes. The complexity of this issue, despite great scientific successes, gives reason to think that one country alone will not be able to completely solve the problems associated with any natural hazard.

Our group has been studying anomalous changes in various geophysical fields before an earthquake for a long time and concluded that for further research in the right direction, it is necessary to classify geophysical fields into triggers, indicators, and precursors according to their generation mechanisms and role in the earthquake preparation process [3]. This classification will simplify the vague picture created by the set of anomalous geophysical fields existent during the period of earthquake preparation that makes it difficult to detect the true precursor necessary for high-precision earthquake prediction. Although earthquake problems scientific study is widespread in the world, there are still many anomalous fields that existed before an earthquake, the research of which requires the implementation of various joint scientific projects involving researchers from different scientific areas of activity.

Let us briefly introduce readers to the novelties achieved in the field of earthquake research over the past decades, which short-term earthquake forecasting has led us.

An earthquake is a geological phenomenon. A well-known avalanche-unstable geological model of fault formation describes [4] the origination of different size cracks and finally, the main fault length formation process in the focal area of an incoming earthquake. If any geophysical field is a true precursor, it must not only qualitatively, but also quantitatively accurately describe the above-mentioned geological model and in this regard, the fault formation complex process from the beginning of the micro-cracks appearance to the final formation of the main fault and the restoration of equilibrium in the medium analytically have to explain.

This opportunity to improve studies on the earthquake problem has been given to us by the research results conducted by world-famous scientists, whose works have been going on since the end of the last century up to today. On the one hand, according to these works:
(1) EM emissions appear approximately several weeks before the earthquake;
(2) The spectrum of electromagnetic radiation is characterized by the following sequence: MHz, kHz;
(3) These emissions are accompanied by ULF radiation;
(4) VLF/LF electromagnetic emissions before the earthquake become very weak or completely disappear (so-called "silence" appears);
(5) The "silence" of VLF/LF EM radiation is followed by an earthquake [5–15].

On the other hand, for detecting EM radiation that existed before the earthquake, the relevant radio networks were established in the 2000s (Japanese-Pacific VLF/LF Network and the European Network of Electromagnetic Radiation, INFREP). INFREP in European territory consists of VLF (20–60 kHz) and LF (150–

300 kHz) radio receivers to measure the intensity and phase of VLF radio signals from different transmitters [7,16].

It is worth emphasizing that there is a case of strong earthquakes when no radiation has been detected by INFREP but this defect is improvable [17].

An article was published in 2010 where the evolution of EM emissions was shown in the case of the L'Aquila earthquake [13]. This work combines the studies pointed out above during the current process in the pre-earthquake period (27 March 2009–6 April 2009). It confirms the existence of EM radiation before an earthquake and its frequency changing with the above-mentioned regularity (MHz → kHz → EM "silence") [5–15].

However, the possibility of predicting an earthquake was not seen. After studying so many rich experimental works searching for the following tasks became our primary goal:
- To determine the immediate cause of the generation of EM emissions detected before earthquakes;
- To study the relationships between the EM emissions frequency change character and a fault formative process of the incoming earthquake.

As a result of these issues' successful research, it was possible to simultaneously predict the magnitude, location, and time of the incoming earthquake approximately 19 days in advance [18–20]. After, the issue of studying earthquake short-term (hourly) prediction arose before us. The presented article offers a way of solving this problem.

2. Discussion

2.1. Some Information on Anomalous EM Radiation Before an Earthquake

According to Professor Emeritus Seiya Uyeda: "Earthquake prediction must specify the time, epicenter, and size of impending EQ with useful accuracy. Among the long-, intermediate- and short-term predictions, only the short-term prediction is meaningful for directly protecting human lives and social infrastructures. The other two are mainly mere statistic forecasts based on past experiences and should not even be called prediction, although the intermediate-term forecast has entered into a new stage thanks to the GPS measurements" [1].

Our study found that VLF/LF EM emissions are responsible for earthquake short-term prediction [18–20]. We will return to this issue in detail below. We now want to re-emphasize the pre-earthquake properties of VLF/LF EM radiation that give it short-term predictive capabilities.

A seismogenic zone can be considered a distributed system since the time of transfer of perturbation along the system is not less than its oscillation period. In distributed systems, parameters are distributed continuously throughout the entire volume of the system. Every as small as is wished element of a distributed system has both mass and elasticity. In the case of an electrical distributed system, each element has an inherent capacitance and inductance [21]. Electromagnetic oscillations in the system are practically conditioned by constant and continuous changes in inductance and capacitance, which are also caused by constant changes in tectonic stress in the area of the earthquake focus. Any change in capacitance (or inductance) in a virtual oscillatory circuit means that the circuit's natural frequency ω also changes instantly.

For its part, even the smallest change in the fault length is immediately reflected exactly on the change of capacitance (or inductance), i.e. in the change of the natural frequency ω of the circuit [18–20], which, during real observations in the earthquake preparation period, makes it possible to determine the change in the fault length (magnitude) in the focus with extremely high accuracy Equations (1) and (2):

$$\omega = \beta \frac{c}{l} \tag{1}$$

where ω is the frequency of electromagnetic radiation, l is the linear size of the fault in earthquake focus, and β is the characteristic coefficient of geological medium (it approximately equals 1).

$$\lg l = 0.6 Ms - 2.5 \tag{2}$$

where Ms is earthquake magnitude [22].

It should be emphasized that the very high accuracy of measuring VLF/LF EM radiation also leads to a highly accurate determination of the rupture length. For example, before the L'Aquila catastrophic earthquake that occurred on 6 April 2009 besides Ultra-low frequency and kHz electromagnetic anomalies, 41 MHz (ω_1) and

54 MHz (ω_2) radiation were also recorded [9]. According to Equation (1), the corresponding length of the first emitting body (which radiates ω_1 frequency) would be $l_1 = 0.007$ km, and the corresponding length of the second body (which emits ω_2 frequency) would be $l_2 = 0.006$ *km*. This means that even the slightest changes in the length of microcracks are possible to detect by electromagnetic radiation. However, there are restrictions in terms of reaching high-frequency electromagnetic radiation to the earth's surface.

Our research has proven that for predicting earthquakes at the final stage of the process monitoring, determining the length of the fault with an accuracy of not a kilometer, but a higher order, as we mentioned above, is provided by EM radiation records. Since for earthquakes with a magnitude of $1 \leq M \leq 9$ significant is electromagnetic radiation of the order of kHz (23,830 kHz ≥ f ≥ 0.378 kHz), which is not absorbed by the earth and if we consider the speed of electromagnetic waves, then we can assume, that all processes occurring in the source, from the initiation of micro-cracks to the final formation of a fault, can be observed on the earth's surface in an almost parallel regime.

2.2. Earthquake's Early Warnings and Prediction

It is clear that the expression "VLF/LF EM radiation is responsible for earthquake short-term prediction" means, that in the case of VLF/LF EM emissions data monitoring, it should be possible to describe quantitatively the full cycle of earthquake preparation and occurrence, based on the avalanche-like unstable geological model of fault formation [4] and a model of the generation of electromagnetic emissions detected before earthquakes. [20].

A study was conducted for the Crete Earthquake (M5.6, 25 May 2016, 08:36:13 UTC) according to 73-day records of INFREP. Since the INFREP network records the occurring every-minute amplitudes of electromagnetic radiation of 10 different frequencies, a once-a-minute frequency value transformed by a Gaussian normal distribution was calculated and used [23]. It turned out that of these 10 frequency channels, only one (37,500 kHz) was "active", on which the process of earthquake preparation was observed [19].

At this stage, the cases of aftershocks and foreshocks are not considered.

According to the average hourly data of the 73-day frequency records of INFREP, by the Equation (1) the lengths of the corresponding ruptures were calculated, and a graph (Figure 1) was constructed, on which the initial moment of the avalanche-like unstable process of fault formation was clearly expressed. The X-axis indicates the time in hours, and the Y- the rupture lengths.
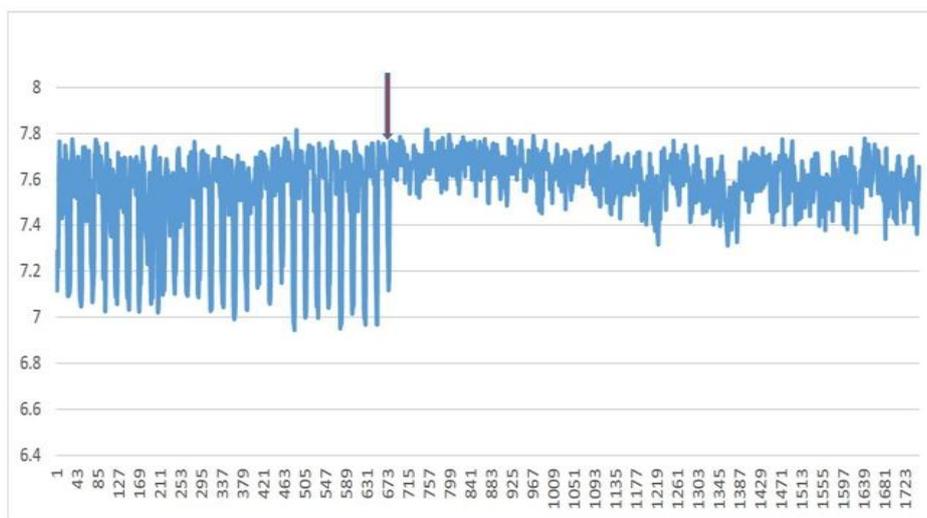

Figure 1. A graph of rupture lengths by 73-day average hourly data. An arrow indicates the initial moment of the fault formation avalanche-like unstable process. The red triangle marks the moment of the earthquake's occurrence.

To analyze of average hourly values data of the fault length, the average square deviation method was used and calculated x ± σ significancies (Figure 2).

In real rocks, there always are randomly distributed defects (cracks of various sizes). Under the influence of tectonic stresses, there is a slow increase in the number and size of favorably oriented defects and the formation of new ones. In a statistically homogeneous medium, under the effect of a uniformly distributed load, crack formation occurs throughout the entire volume. This quasi-homogeneous cracking corresponds to the subcritical stage of failure. One of the reasons for the uniformity of cracking may be the formation of stable detachment cracks, as well as the stopping (delay) of cracks on the heterogeneities of the medium. The properties of the medium should change already at this stage, for example, effective elastic moduli and quasi-anisotropy.

The total cycle of earthquake preparation and occurrence, which is depicted in Figure 2, is divided into stages:

Stage I. In the first stage, uniform cracking occurs in the earthquake preparation zone. During this period, only probabilistic conditions for the occurrence of an earthquake are created [4].

Our research has found an important fact that even this early stage of earthquake preparation is accurately described by VLF/LF EM emissions data. This was expected since even the slightest change in inductance and capacitance caused by crack formation is exactly reflected in the VLF/LF EM frequency data, which makes it possible to determine the length of the crack propagation zone formed under the influence of a uniformly distributed load. In this zone of crack propagation, only probabilistic conditions for the occurrence of an earthquake will be created in the future (Figure 2). The X-axis indicates the time in hours, and the Y- $(x \pm \sigma)$ significances of the hourly values of the rupture lengths.
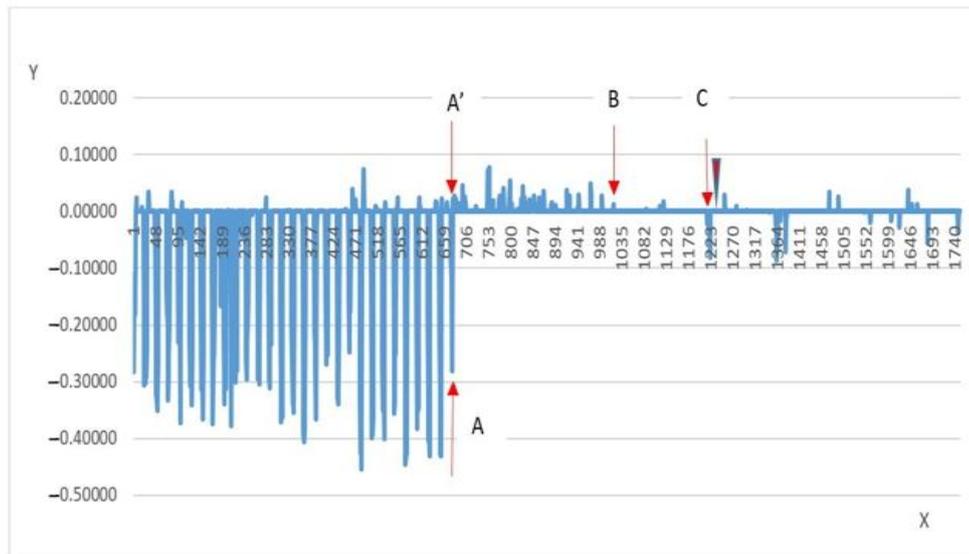

Figure 2. A graph portrayal of the total cycle of earthquake preparation and occurrence, constructed by the $x \pm \sigma$ significances of the hourly values of the rupture lengths. The avalanche period of fault origin is marked between A, A' and B. The so-called period of "silence" is marked between B and C. The red triangle marks the moment of the earthquake's occurrence.

For example, the average length of fracture formations from the beginning of data records to point A equals 7.118 km (here and everywhere below INFREP minute records are used for the values estimation of the rupture lengths and the time moments). It was also revealed that it is possible to "mark" the approximate length of the rupture of the impending earthquake (for example, at point A' in Figure 2), long before the earthquake, at the very beginning of the avalanche process of fault formation, that is, a preliminary determination of the magnitude. In our considered case, the "marked-probable" length of the rupture of the impending earthquake was approximately 7.73 km, and it was already possible to determine it 50 days before the earthquake.

However, it should be noted here that during the total cycle of earthquake preparation, even according to the geological model, the length of this probable main fault of the impending earthquake adjusts.

Stage II. The transition to the second stage occurs when the average density of ruptures reaches a certain critical value in the entire volume or a significant part of it. As a result of the interaction of cracks, an avalanche stage of a given earthquake preparation sets in. The involvement of an increasing number of inhibited cracks in

this process is associated with a rapid and sharp redistribution of the local stress field due to the cracks combining a higher rank (larger size). An avalanche increase in the number and sizes of cracks leads to a sharp increase in the rate of general deformation and a change in the integral physical characteristics of the medium. If this process leads to an earthquake, then it must be unstable [4].

Since one of the important stages of earthquake preparation begins with the onset of an avalanche-like unstable process, we will use an excerpt from Figure 2 (Figure 3) to describe it. Our studies also confirmed that this stage is indeed an active stage of fault formation (section AA'B in Figure 3). Consider this process in more detail:
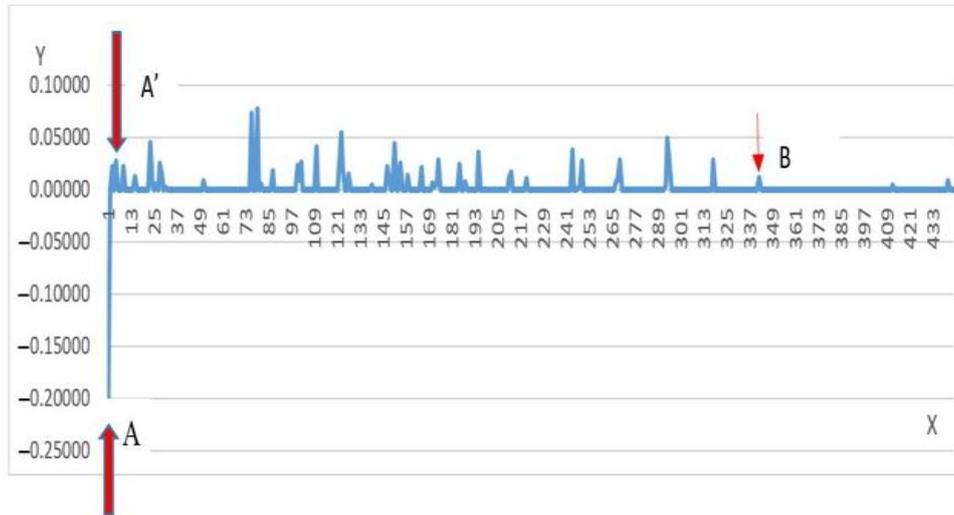

Figure 3. (Excerpt from Figure 2). The active stage of the avalanche-unstable process of fault formation.

It was found that the beginning of the avalanche-unstable process is distinctly manifested in a sharp change in the length of the cracks already formed by this time. In the case we considered, this sharp change in the length of the cracks started at 3:00 on 2 May and continued until 6:00 on the same day. During these approximately three hours, as expected from the geological model, it appears that a rapid coalescence of cracks did indeed occur. The length of united cracks changed from 7.118 km to 7.73 km (section AA' in Figure 3).

The main fault of the future earthquake is intensively growing during this active stage of the avalanche-unstable process, and by the end of this stage, the length of the fault is almost completely formed. This fact is pictorially reflected in Figure 3, expressed by positive anomalies in the AA'B section. Since there are small periods of "silence" between anomalies (time intervals during which the length of the fault remains almost unchanged), it is obvious that this process is not continuous. The average duration of these small "silences", calculated in hours, in this consideration case, is 8.4, and the maximum duration is 24. This process continues until the beginning of a much longer main "silence" (Figure 3, point B), after which the process moves to the third stage of the formation of the main fault. It happened on 15 May at 9:00. At this moment the fault length was 7.828 km. These studies allow us to declare as the early warning first stage of an impending earthquake the moment of such a sharp change onset in the length of cracks in a relatively short time, which in our case begins at 6 o'clock on 2 May (Figure 3, Point A'). In our particular case, this active stage of the formation of fault lasted for 13 days and 3 hours. During this period, the length of the fault increased to 7.828 km. It should be noted that this first stage of warning only indicates that an earthquake of a given magnitude is expected at that particular location. However, before the earthquake, we have some time until the main fault of the future earthquake is finally formed (at least 10–14 days). The duration of this time will depend on the geological features of the environment. After the first notification, there are still stages to go through described by the classical, qualitative geological model, which, during the monitoring period, should be accurately reflected in VLF/LF EM radiation records.

Stage III. In the third stage, the increase in deformation is already accompanied by a drop in stress. Due to the heterogeneity of the properties of the medium, the unstable deformation is drawn up into a narrow zone in which several relatively large cracks form. At the same time, due to the general drop in average macro stresses in

most of the volume, the cracks stop developing and partially close up. As a result, the integral deformation rate of the total zone decreases at this third stage (stage of instability). Take place the restoration of many integral characteristics of the zone. A narrow zone of unstable deformation is characterized by an increased concentration of cracks and represents itself as the surface of the future main fault [4]. This process, in fact, is the so-called main "silence" period, which begins immediately after the end of the active stage of the avalanche process and graphically is represented by the BC area in Figure 4. It is clear, that minor changes in the main fault length of the impending earthquake are expected even during the main "silence" period.

The third, i.e., the stage of the main "silence" can be considered starting from point B (Figures 3 and 4). The time of duration of this "silence" should already be approximately three times greater than the average "silence" value of the previous stage (no doubt, this value will depend on the characteristics of the region). In the case of the mentioned earthquake, the main period of "silence" began on 15 May at 09:00 and ended on 24 May at 16:00, i.e., it extended for 9 days and 7 hours. At the moment of the onset of the main "silence", the second stage of early warning about the upcoming earthquake can already be announced, which will only adjust the time of the earthquake occurrence. In particular, it is indicated that before the earthquake less and less time left. It means that we are waiting for an alarm about an incoming earthquake. The phase of the main "silence" phase ends when the very first pre-earthquake anomaly appears (Figure 4, point C'). In our case, during the main "silence" the length of the fault decreases from 7.828 km to 7.5 km.
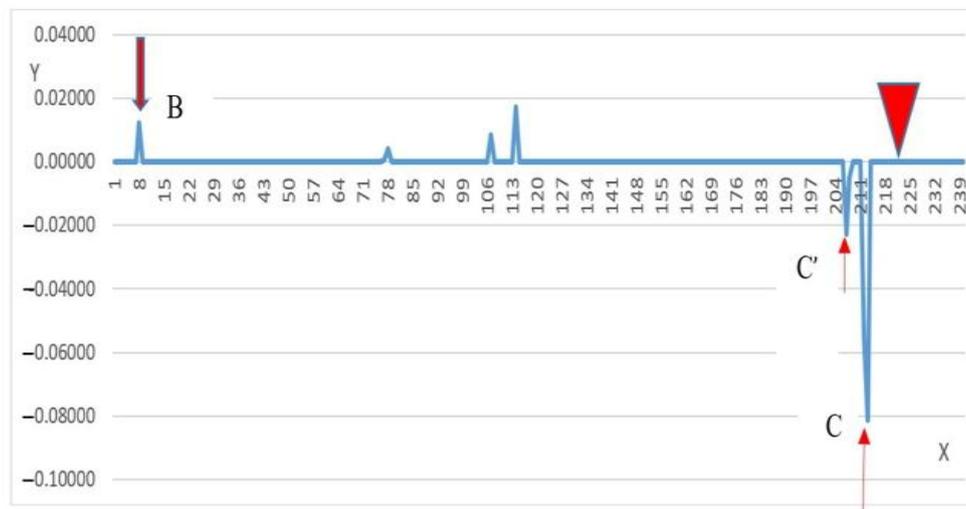

Figure 4. (Excerpt from Figure 2). The main silence period with the two post-silence anomalies (C' and C) preceding the earthquake. An earthquake is marked with a red triangle.

As known, the fault—an earthquake is formed by ripping apart bridges between large cracks. The apart bridges ripping process is qualitatively similar to the general process and therefore, it must be preceded by short-term and smaller changes in the amplitude of the strain rate. Since the destruction of one of the bridges may not be sufficient to rip apart the entire main fault, there may be several such short-term changes in the deformation rate. In this case, at least part of these oscillations must precede large foreshocks, and the final one must be a direct foreshock or the main shock itself [4].

The real earthquake records accurately describe the qualitative geological model described above. In particular, immediately after the end of the main "silence", two negative anomalies were revealed, which indicate the closing of microcracks and the reduction of the rupture length (Figures 4 and 5). Let's consider the period after the end of the main "silence" in detail (Figure 5):
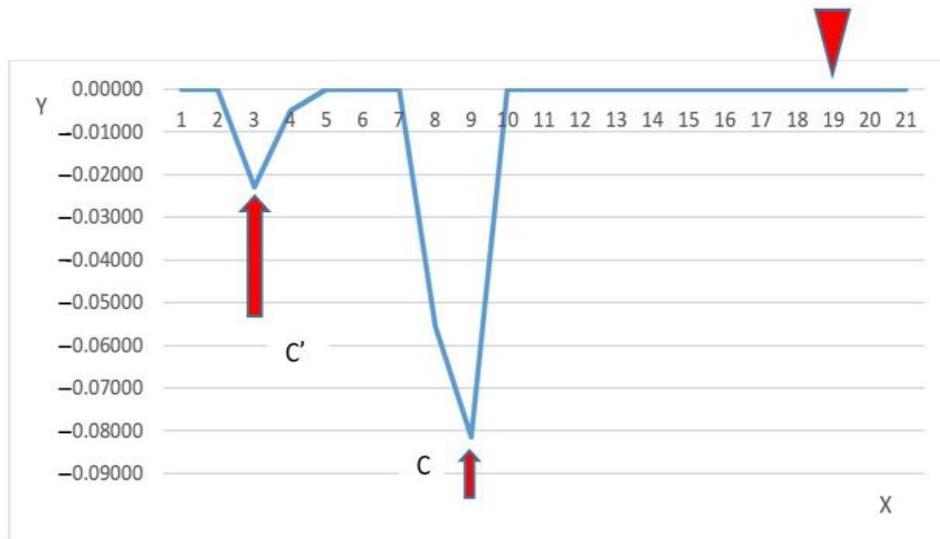
Figure 5. (Excerpt from Figure 2). Post-silence anomalies (C' and C) and the moment of the earthquake occurrence (red triangle).

The analysis showed that the first destruction of one of the bridges occurred on 24 May at about 16:00 and at that time the length of the rupture was 7.5 km (the corresponding anomaly is marked with C' in Figures 4 and 5). As was expected according to the geological qualitative model, this destruction turned out to be insufficient to rip up the total main fault.

The second destruction of another bridge occurred when the length of the rupture became 7.496 km. It happened on 24 May at 22:00.

The final short-term change in the rate of deformation that caused the earthquake occurred on 25 May at 08:36, 16 hours and 36 minutes after the appearance of the first anomaly and 10 hours and 36 minutes after the appearance of the second anomaly. At the moment of the earthquake, the length of the main fault has been reached 7.475 km.

Thus, based on the above, we can conclude that at the moment of detection of anomaly (or anomalies), arising immediately after the end of the main "silence", it is already possible to declare a third alarm about an incoming earthquake, because at present, in addition to the magnitude and location of the impending earthquake [20], we already know that there are only a few hours left before the earthquake.

2.3. The Additional Practical Use of the Research

It is noteworthy that with the continuous extension of coal mining deeper underground, ground stress and gas pressure in coal seams gradually increase, and coal and gas outbursts, rock bursts, and other coal rock dynamic disasters become more serious and complex [24]. It is known that in the processing of rocks in the mines electromagnetic radiation occurs. In this direction, relevant studies have been going on for a long time [25–28].

Landslides also are one of the catastrophic events that result in massive destruction and loss of lives. Hence, an appropriate technique is essential to predict potential weak slip planes which may eventually lead to landslides. Recently, a study appeared, where to identify such districts of potential "activity" Fracture-Induced Electromagnetic Radiation (FEMR) technique was used [28,29].

Research, similar to the above proposed can make a significant contribution to the study of the stress-deformed state of rock mass around tunnels and underground structures [30] in terms of perfecting assessment methods, as well as identifying landslide-prone areas by detecting the adjoining weak slip planes.

3. Conclusions

Based on the conducted studies, it was found that the description of the qualitative avalanche-unstable geological model of fault formation by data of VLF/LF EM radiation, existing before the earthquake, made it possible to quantitatively characterize the complete cycle of earthquake preparation and occurrence:

(1) The length (i.e., magnitude) of the main rupture of an upcoming earthquake can be approximately determined several tens of days before the earthquake;

(2) In the case of monitoring, the beginning of the "avalanche process" of ruptures is observed, during which there is a sharp, rapid increase in the length of the cracks. The beginning of the "avalanche process" can already be considered as the first stage of early warning of an incoming earthquake can already be considered. Immediately after the end of the active avalanche process, the so-called "silence" period begins, during which can be announced a second stage of early warning of an incoming earthquake. "Silence" can be considered finished at the moment when the first anomaly, indicating a radical change in the length of the main fault, appears. At this time, it already is possible to announce an alarm about an incoming earthquake;

The time interval between the first and second stages of early warning of an incoming earthquake allows us to minimize human and material damage caused by an earthquake;

(3) The possibilities of the quantitative description of earthquake preparation and occurrence process have been created on the base classical geological qualitative model of fault formation;

(4) The offered article presents pioneering work because in the case of monitoring, based on the frequency data of VLF/LF electromagnetic radiation before the earthquake, the methods of earthquake three-stage early warning (including alarm at the last stage) and earthquake short-term prediction have been created.

Author Contributions

G.R., prepared INFREP network VLF/LF electromagnetic radiation data for processing, ensured construction of drawings 1-5; B.K., converted every minute amplitudes of electromagnetic radiation data recorded by the INFREP network into frequency numerical values using the normal distribution of Gauss; M.K., and N.K.-M., set the task, equally took part in the mathematical elaboration of data, created a quantitative model of earthquake short-term prediction, analyzed results, wrote and revised the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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