Research Paper

Possible Precursors Linked to the 2021 Fin Doublet Earthquakes

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ABSTRACT

Precursors, as informer pioneers of near future occurrence of earthquakes, are very diverse in their natures. We examined three short term possible precursors contain foreshocks, b-value variations, and amplitude abnormalities in the Very Low Frequency (VLF) radio signals for the November 14, 2021, Fin double-earthquakes (M> 6). By searching-zoom method in earthquakes one degree on each side of the hypocenter location in the Iranian Seismological Center (IrSC), the International Earthquake Engineering and Seismology (IIEES) and the Building and Hosing Research Center (BHRC) catalogs, those data for the reviewing foreshocks were provided, then they analyzed by use of ZMAP for the b-value changes based on the Guttenberg-Richter empirical relation methodology. Whereas, in the BHRC accelerometer portal reported 8 events before the main shock times, none of them are not in the other catalogs. The temporal b-value variations from the normal, shown non-sharp fits to the rises or falls of the seismicity as an expected indicator. Some b-value, in accordance with the seismic up and down rate tracks, has high spatial uncertainties. We observed some amplitude anomalies in the VLF received signals from mean standard deviation in VLF signal measurements (2σ criterion in the statistical method) in about 4 days before and up to 5 days after the main shocks. Albeit, in follow the null hypothesis, for verifying (and not refused) these relations (before and after), are needed to be qualified data. As you will see, all three catalogs used in the coverage, quality, verification and appropriate data for logical and reliable review and processing are not less error than the expected standards. The main goal has been to investigate the possible precursors before the 2021 Fin doublet earthquakes by using available local ground base data and obtainable facilities in this field and considering their improvement. The possibility of some foreshocks associated with double earthquakes cannot be ruled out. Therefore, the reliability of the studied precursors completely dependent on the proper data, that sufficient-precise instruments for their observations and recording are vital requirement. It is possible to use that kind of reliable and high-quality data in the analysis of pre-earthquake signals or even reasonable forecasting, which, if possible, will bring a valuable achievement in the future. We came to the conclusion that with such researches, the necessity of data quality and improving the level of their acquisition/standard in the country's research centers, must be carefully defined for more scientific and practical effects.

Keywords:
Earthquake; Precursor; Foreshock; b-value; VLF radio signals

1. Introduction

The northern coastal areas of the Persian Gulf, as part of the tectonic structure of the Zagros in the zone of collision with the Arabian plate, are prone to moderate to large earthquakes. In the following of this background trend (Figure 1), two earthquakes occurred about one minute apart with epicenters around the small town of Fin, north of Bandar Abbas, on November 14, 2021 (1400/08/23 in the

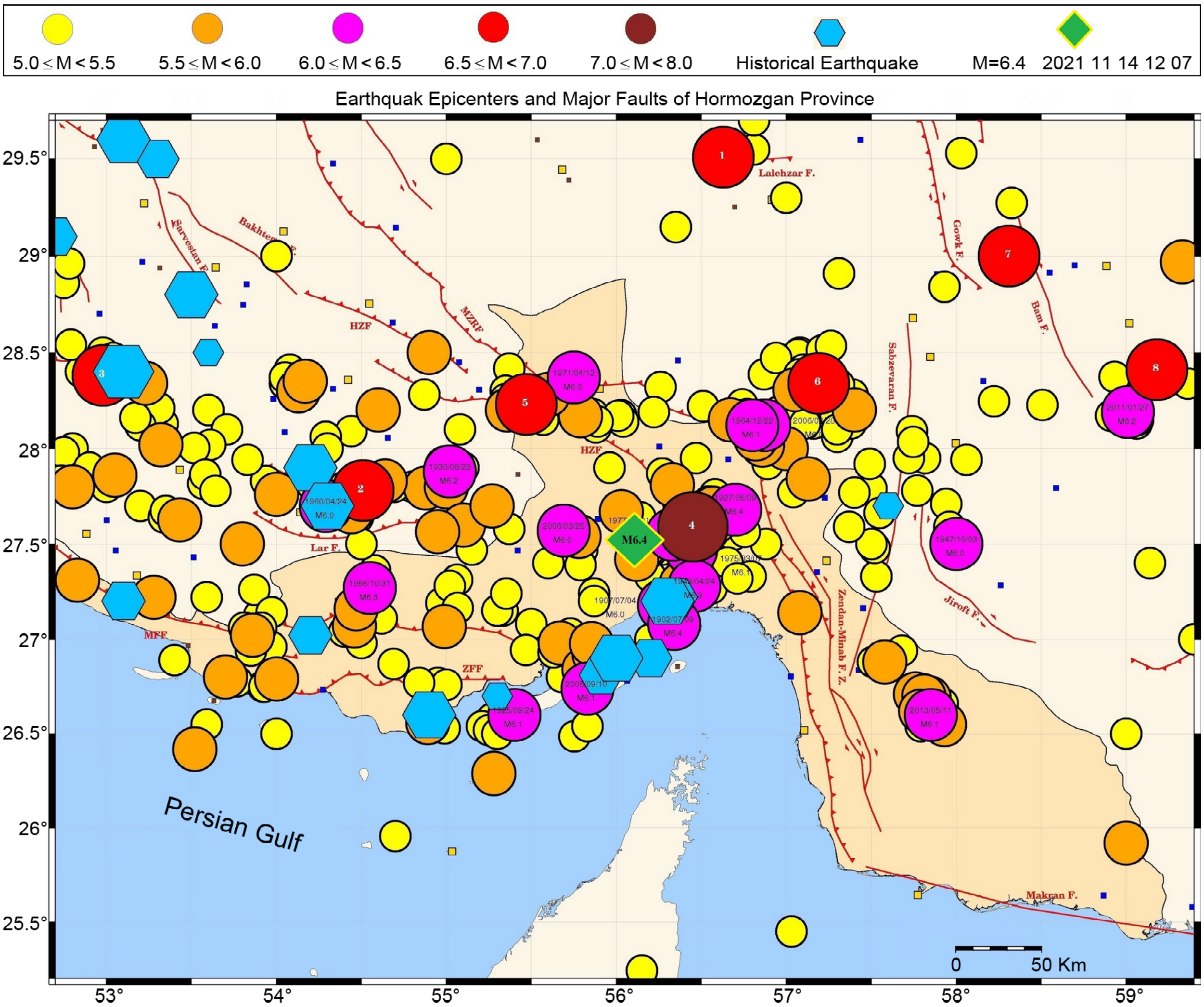

Figure 1. Historical and instrumental seismicity (M?5) of Hormozgan area, after IrSC published report. The numbered circles; (1) 1923/09/22, (2) 1961/06/11, (3) 1972/04/10, (4) 1977/03/21, (5) 1990/11/06, (6) 1999/03/04, (7) 2003/12/26 and (8) 2010/12/20, indicate locations and magnitudes of the large earthquakes. The Fin doublet earthquakes are shown by green rhombus.

Persian Calendar). The locations of two earthquakes (27.56°N, 56.13°E), the origin times (the first shock 12:07:04 and the second shock 12:08:38) and the magnitudes (the first 6.4 and the second 6.3, both in the MN magnitude scale) are reported preliminary by the Iranian Seismological Center (IrSC), then some parameters are modified later. The estimated characteristics of these earthquakes by Iranian seismological centers such as the International Institute of Seismology and Earthquake Engineering (IIEES), the accelerometer network of the Building and Housing Research Center (BHRC), and internationally (e.g., USGS, NEIC, Harvard Centroid Moment Tensor solution, CMT), have some differences that are not addressed here, because of less important role for the earthquake precursors reviewing.

Earthquake precursor assessments are multidisciplinary and interdisciplinary subjects. Foreshocks are considered one of the most promising indicators that a large earthquake is imminent (Jones & Molnar, 1979) and the most common precursory which inherently difficult to identify them as foreshocks when they occur (Bouchon et al., 2013). The earthquake precursors (EP) are very diverse in nature and wide variety of physical phenomena that reportedly before some earthquakes (Geller, 1997; Wyss & Booth, 1997; Wyss, 1997). Cicerone et al. (1996) mentioned that these phenomena include electric and magnetic fields, groundwater level changes, gas emissions, temperature changes, surface deformations, and anomalous seismicity patterns. The foreshock precursors are smaller earthquakes, well studied by ground-based seismic instruments, which are preceded within hours, days or weeks of a great earthquake as the premonitory seismic activities. Seismic observations exhibit the presence of abnormal b-values prior to numerous earthquakes. The temporal variation in b-value is one of significant precursors for volcano activities and earthquake occurrences, Wang et al., 2016 and some references therein.

The lithosphere-atmosphere-ionosphere coupling and interactions (LAI coupling) that following by effects of the seismic activities on the VLF (3-30 KHz) and LF (30-300 KHz) radio sky waves, are presented by several authors, that emphasized in Biagi et al. (2009). The work of Hayakawa et al. (1996), which eliminated the LF/VLF effected signals by the Kobe earthquake 1995, Japan, may be one of the first documentation of this precursory in the research field. At the Research Center for Earthquake Precursors (RCEP), after visual inspection of the graphs of changes in the normal amplitudes (anomalies) of the VLF signals received by the ELETTRONIKA receiver located in the center, we realized the possibility of anomalous connection with the Fin earthquake events and analyzed this issue with other data for more possible precursors. The twin earthquakes, both larger than 6 and very short (just over 1 minute) apart, also stimulated curiosity to investigate possible double changes (anomalies within the same short time intervals) in the amplitudes of the received radio waves. How radio signals are distributed in the ellipse containing the Fresnel Zone (see top panel in Figure 2), and the effect of the active seismic environment on the ionosphere layers and the change in phase and amplitude of the radio signals are well described by Hayakawa (2015). It should be noted that researchers mainly look for LF and VLF signals for earthquake precursors in earthquakes larger than 6 and are not very hopeful for the existence of these anomalies in smaller earthquakes. Studying earthquakes greater than 5 is considered due to its consequences in social vulnerability, building engineering and lifeline systems. It is also important and expected that with the increase in the magnitude of earthquake, they may cover a larger spatial extent, which strengthens the possibility of the occurrence of

Figure 2. The transmitter-receiver (T-R) map and assumed ellipsoid cross-section Fresnel zone plan for the VLF signals transmitted from RTX and received by ELETTRONIKA receiver in Tehran (top panel). The observed and analysed amplitude anomalies (compare to 2σ criterion) of the VLF signals before as foreshock possible precursors and aftershocks (middle and lower panels) associated with the Fin November 14, 2021, double-earthquakes.

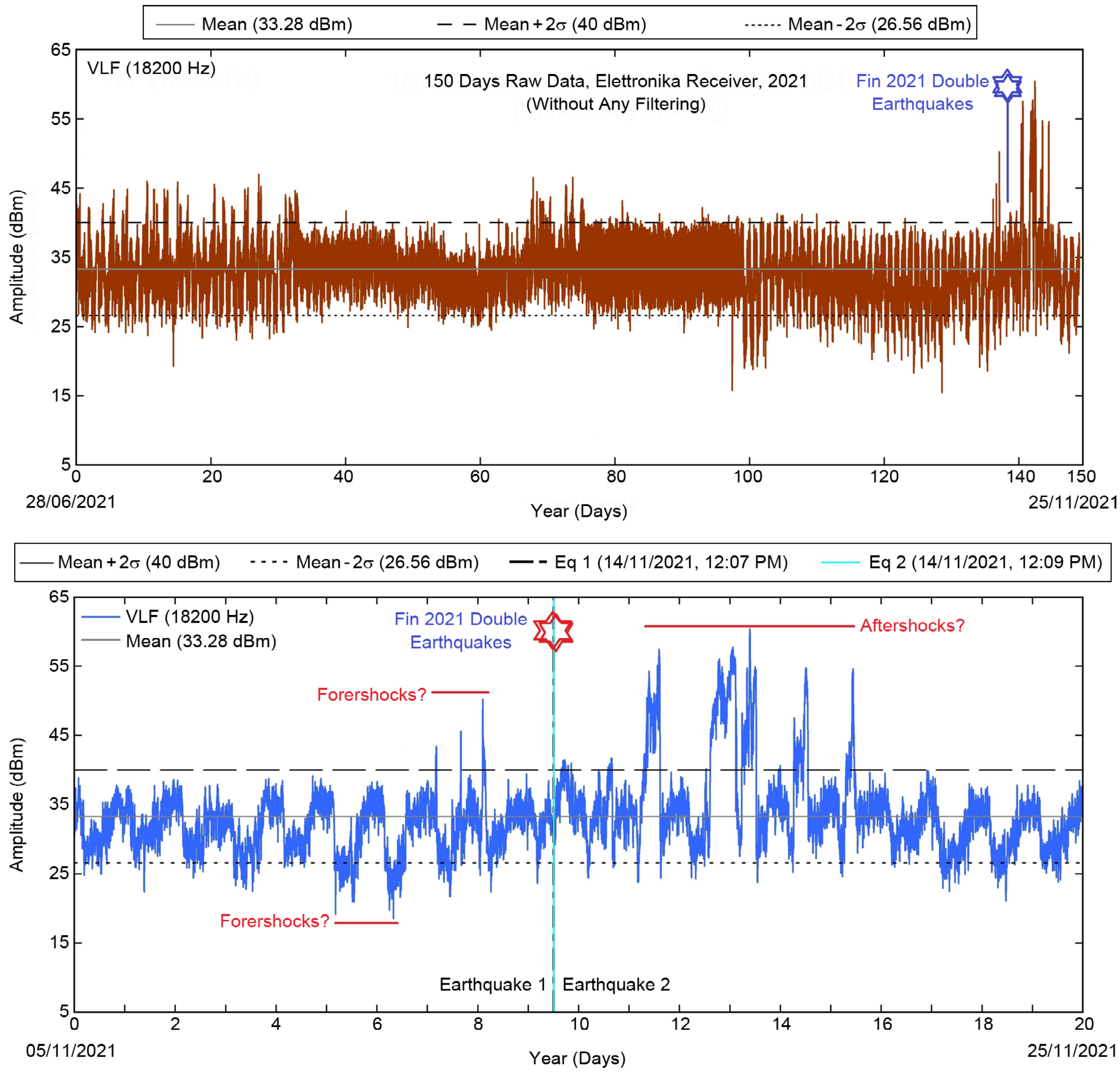

Figure 2. Continue

earthquake precursors on the larger scale. Another point is that the earthquakes that can be checked for radio signal anomalies should be in the location of the Fresnel zone covering the radio transmitter and receiver stations so that it is possible to receive the signals.

This condition was established for the frequency of 18200 Hz and the transmitting station of India and the receiving station of Tehran. The main objective has been to investigate the possible precursors before the 2021 Fin doublet earthquakes by using available local ground base data and obtainable facilities such as LF/VLF receiver in this field and considering their improvement. Therefore, we have examined three short term (hours up to days and weeks before an earthquake occurring) possible precursors (pre-indicators) contain foreshocks (searching-zoom method), b-value variations (the well-known statistical G-R empirical method), and amplitude abnormalities in the received 18,200 Hz VLF radio signals (statistical mean and standard deviation criteria of signal amplitude anomaly measurements method) for the November 14, 2021, Fin double-earthquakes in a concise and useful manner.

2. Methodology, Data and Processing

We selected three short-term pre-earthquake, and limited samples among several possible EP, contain probable related foreshocks of the earthquakes (i), b-value variations (ii) and an electromagnetic-limited frequency band, 18200 Hz of very low frequency (VLF) radio-signal amplitude anomalies (iii).

For the foreshocks reviewing, we use searching-zoom method for all seismic recorded events with magnitude smaller than the doublet desired earthquakes that occurred before them up to four months duration time span (2021/07 up to 2021/11) and one degree around the reported epicenters spatially (about 26.5° - 28.5°N, 55.1° - 57.2°E) and then we focused on the temporal and spatial intervals near the studied earthquakes. Hence, the available earthquake catalogs containing IrSC (http://irsc.ut.ac.ir/bulletin.php) and IIEES (http://www.iiees.ac.ir/en/eqcatalog/) are examined. Also, we searched in the BHRC accelerometer catalog for probable foreshocks (https://smd.bhrc.ac.ir/fa/search/) and found 8 events (1^{st} at 20:23 UT, November 13, 2021) before the first Fin main-shock as they shown in Table (1). In the BHRC website are not displayed any location of these probable seismic foreshock events at that searching time. So, for verifying of those events, we not found them in the IrSC and IIEES catalogs. In Figure (3) related events in the IrSC catalog for 50 kilometers around the Fin double-earthquakes are marked in map and magnitude diagram (middle and lower panels respectively). For these events before the Fin earthquakes, there are no specific locations reported in the table. Therefore, they remain as possible and doubted foreshocks.

Table 1. Probable foreshock events in accelerometer catalog of BHRC for the Fin earthquakes.

	Fin Eq. Alarms?!	
	Day/H:M	**Acceleration (cm/s^2)**
Probable foreshocks?! (Before the Eq. 1)	13/ 20:23	12 (1)
	13/ 20:30	12 (2)
	13/ 20:39	14 (3)
	13/ 20:40	36 (4)
	13/ 21:28	15 (5)
	13/ 22:02	74 (6)
	13/ 23:11	39 (7)
	14/ 00:11	16 (8)
Double Main-Shocks	14/ 12:07	369 (Eq. 1)
	14/ 12:08	565 (Eq. 2)
Aftershocks (After the Eq. 2)	14/ 12:18	27
	15/ 09:45	23
	15/ 13:36	3
	15/ 13:36	3
	15/ 20:19	117

For the b-value variation calculations, we used the searched earthquakes in the IrSC and IIEES catalogs, which reselect and rearrange by applying the criteria for more data reliability and confidence, then by applying ZMAP software (Wiemer & Malone, 2001), we examined and processed the dataset selections on the IrSC catalog due to more duration catalog data (2006 up to present). The estimations of b-value in this analysis is based on the well-known Gutenberg-Richter empirical relationship (1).

$$\log N\left(m\right) = a - bm \quad (1)$$

where N is the cumulative number of earthquakes with magnitude equal or greater than m, a, is one constant related to the seismic activity and b, is the other constant linked to the earthquake size (Gutenberg & Richter, 1944). The defined b-value (b coefficient) is calculated as the slope of the fitted line based on the magnitude data and the number of earthquakes in the estimated ranges. It is obviously that this relation completely depends on spatial (extent of the study area) and temporal (time span) distribution of earthquakes and the b related values have variations by selected area and time domain of the available data. The b-value variations before some moderate to large earthquakes are reported by many researchers before, during and after earthquakes. A decrease of the normal b-value variations before earthquakes as abnormal anomaly, sometimes it can be used as an earthquake indicator, a premonition of the occurrence of the future earthquakes, which mentioned as an earthquake precursory.

The overall seismicity surrounded the doublet earthquakes and azimuthally gaps less and equal than 90 degrees which tested by IrSC catalog and some figure captions such as completeness magnitude, b-value - depth and b-value - magnitude, are presented in Figure (4) panels.

We tested and compared the IrSC and IIEES data catalog separately many times by temporal and spatial analyzing, clustering and de-clustering them. Herein, seismic events with $M \geq 3.5$ in 2020 up to 2022 of the both catalogues and their b-value fluctuations from 2006 up to 2022 time span are compared. One of the temporal b-value variations analyzing results is shown in Figure (5).

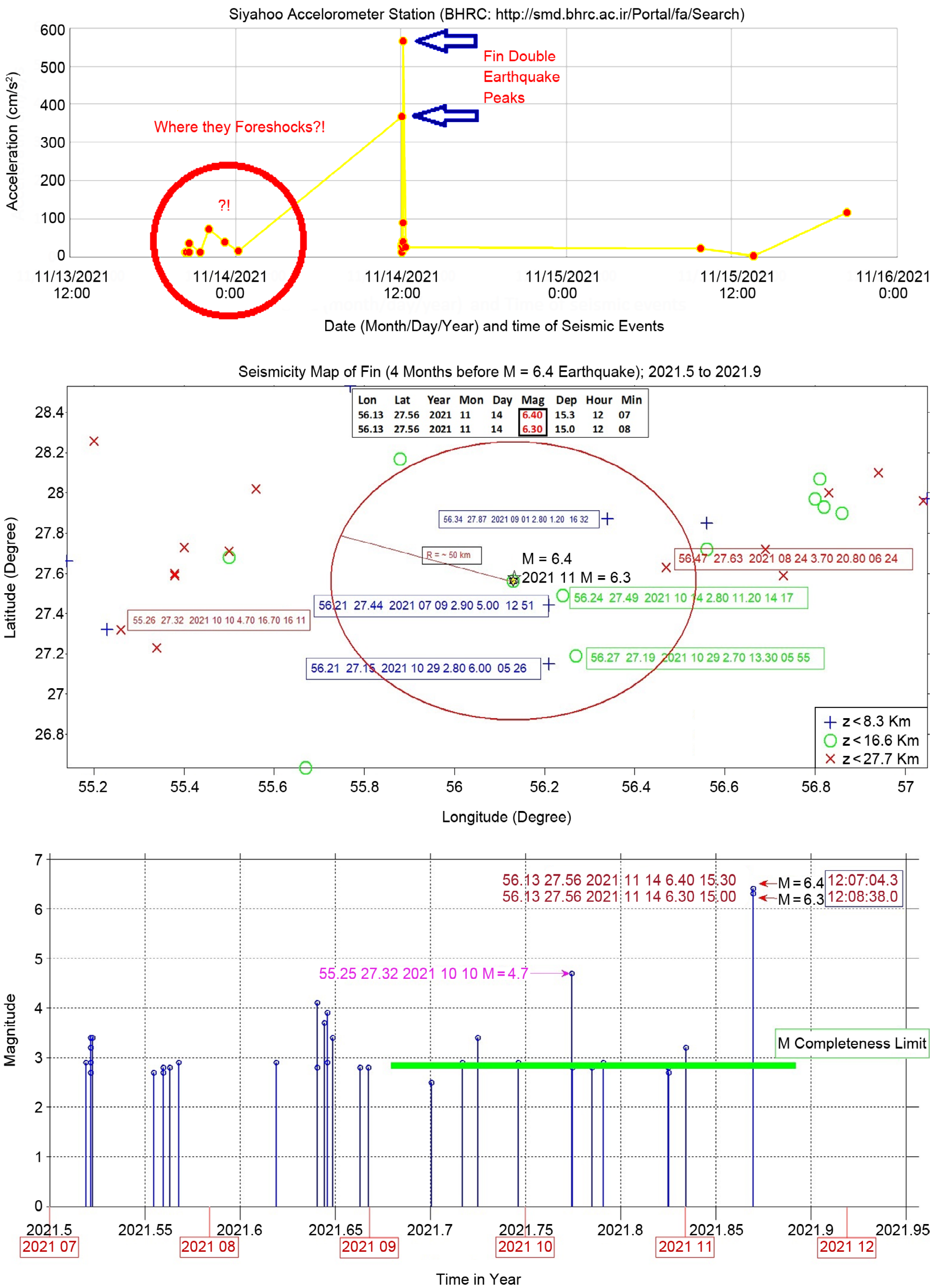

Figure 3. The searched-zoom foreshock events for the Fin double earthquakes. The probable and doubted foreshocks in accelerometer catalog of BHRC (top panel). Map of related events in the IrSC catalog for 50 km around and four months before the desired earthquakes (middle panel) and the magnitude diagram for the doubted foreshocks (lower panel).

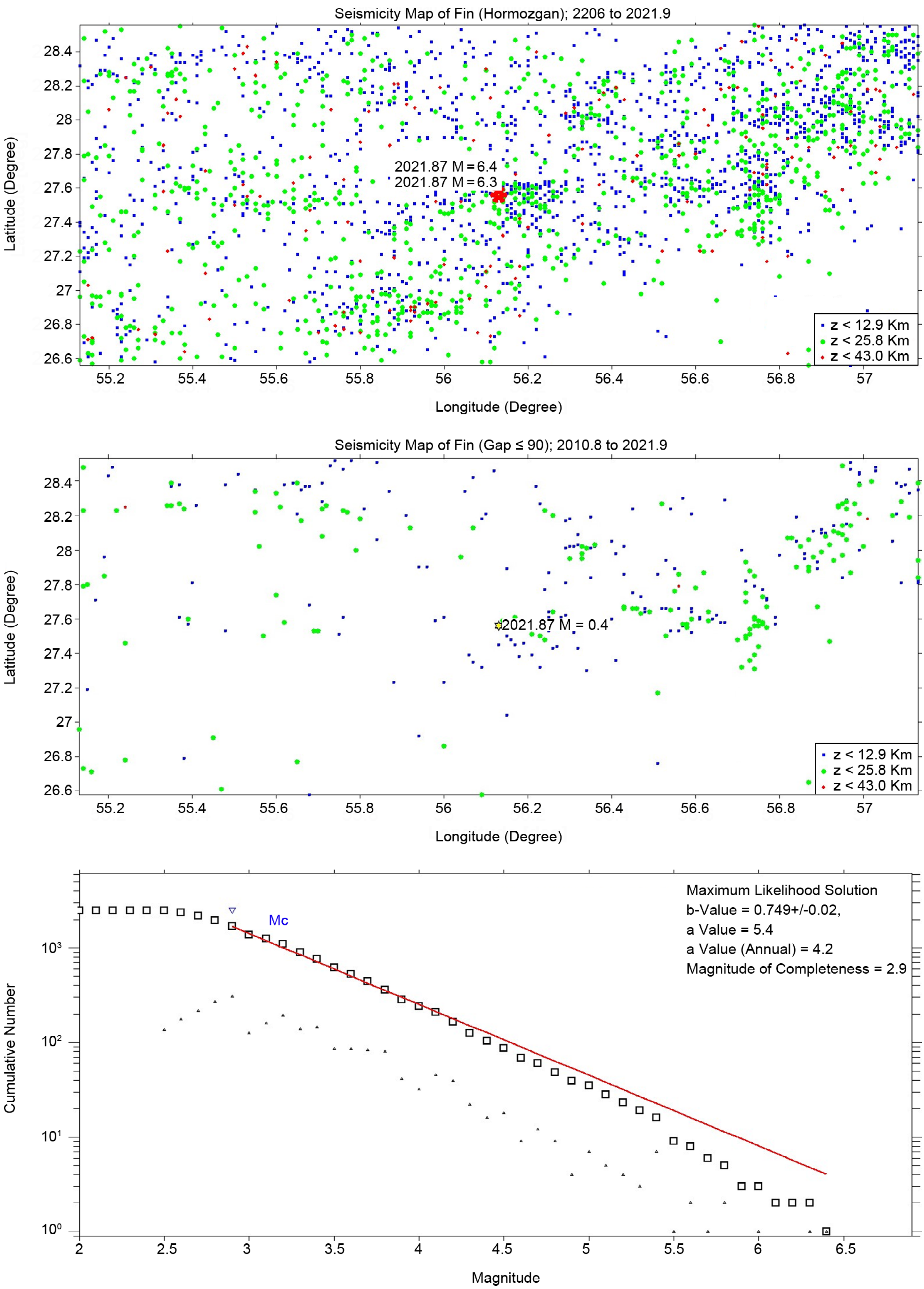

Figure 4. The overall seismicity surrounded the Fin doublet earthquake and the azimuthal gap less and equal than 90 degrees by the IrSC catalog data set selected and examined. The completeness magnitude (Mc), b-value - magnitude, b-value - depth. Note that quality increasing criteria for selected events (by decreasing the azimuthal gap to 90 degrees), the seismicity map has been changed drastically. The b-value - magnitude, b-value - depth diagrams are changed by magnitude and depth variations respectively. Increasing the value of b in terms of magnitude, changes in depth and the default depth of 10 km are also problems.

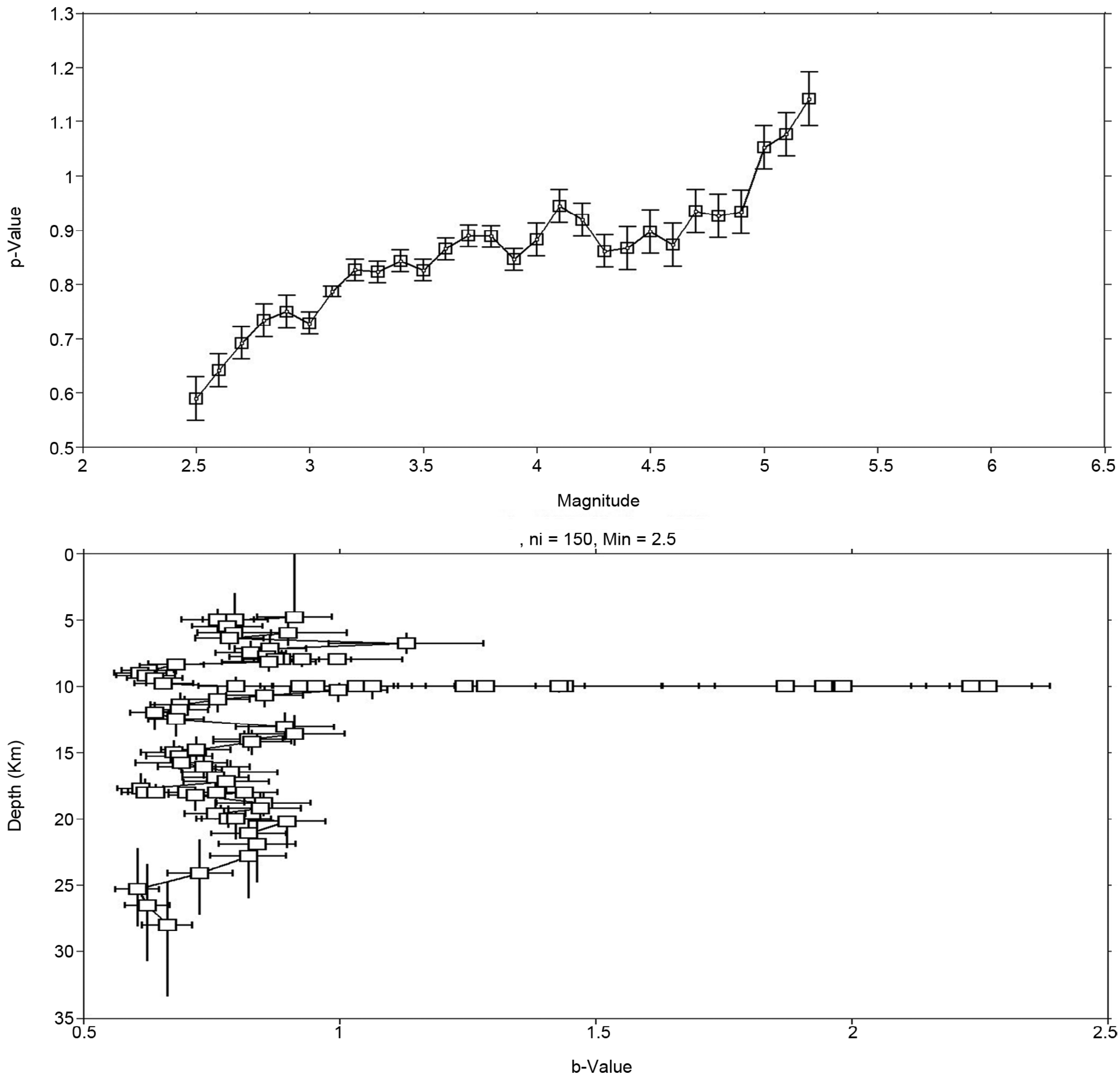

Figure 4. Continue

Abnormalities from the normal, shown non-sharp fits to the rises or falls of the seismicity as an expected indicator (top panel). Some b-value, in accordance with the seismic up and down rate tracks, have high spatial uncertainties. Fortunately, both catalogs are consistent in reducing the b-value trend before the Fin earthquakes. Some inconsistencies in the catalogs are apparent in estimating the magnitudes or number of events.

For the *VLF* precursory, the applied methodology is based on anomaly fluctuations of the received *LF* and *VLF* signal amplitudes in the statistical manner that many times used by authoritative researchers in this field (such as Hayakawa and Biagi). In this method increasing of in the LF/VLF signal amplitude, $A(t)$ from the normal background (Trend in Equation 2) can be related to the seismic activities that influenced the sky waves in especially the *LF*/ *VLF* and prepare some anomalies, $dA(t)$ in Equation (3), which can create useful signals for analyzing as the radio signal earthquake precursors. An important statistical criterion is the standard deviations of signal amplitude ($\pm\sigma$) by averaging (mean amplitude samples, $< dA(t) >$ in a desired time window, which usually means several days before and after the local anomalies) in long time duration in such a way that increasing the range beyond that can be considered anomalous. The upper and lower ranges ($\pm 2\sigma$) experimentally are

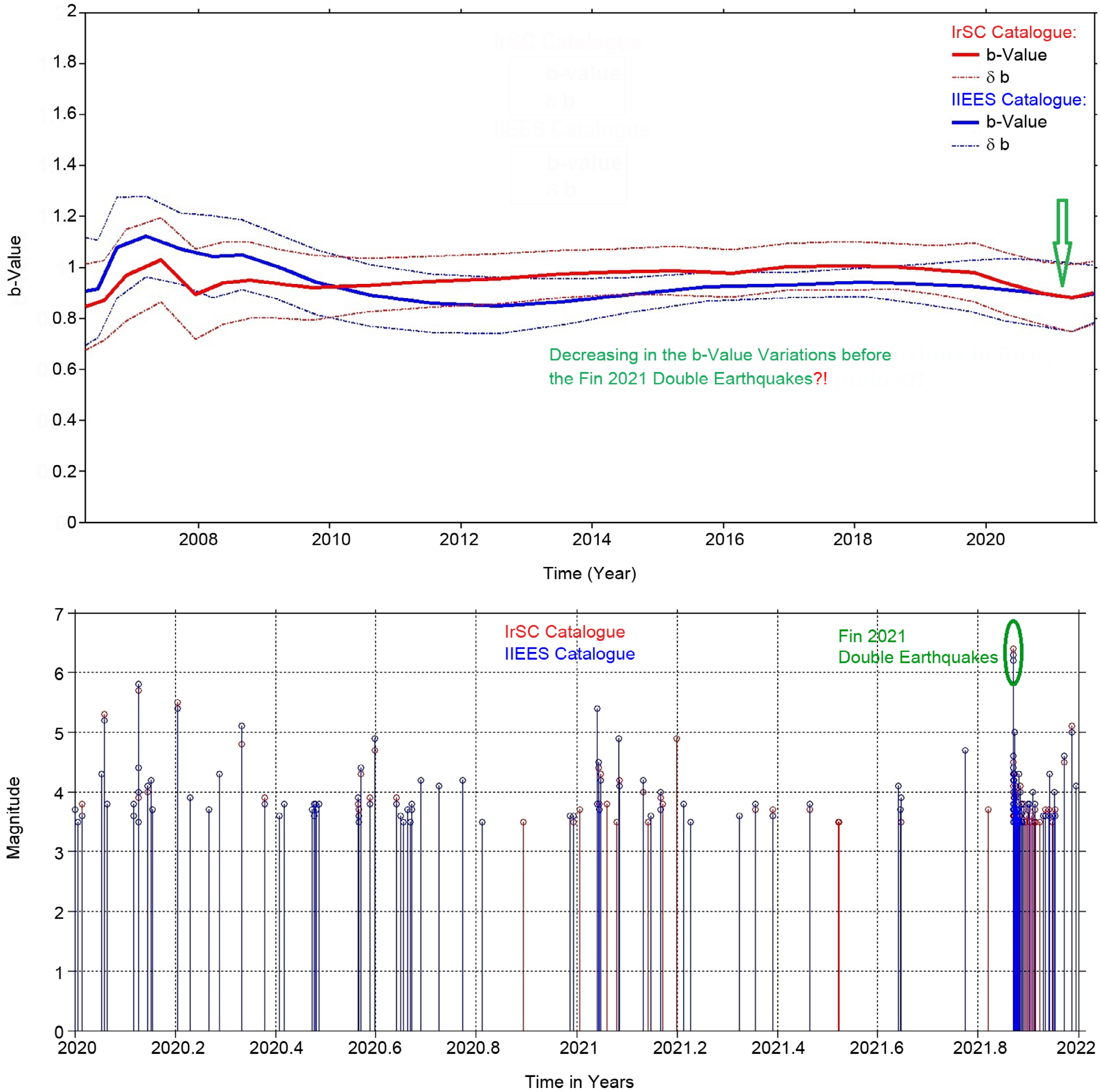

Figure 5. Temporal analysing of b-value variations of IrSC and IIEES catalogues for the Fin earthquakes. Seismic events, M ≥ 3.5 in 2020 up to 2022 of the both catalogues (top), and their b-value fluctuations from 2006 up to 2022 time span (lower). Both catalogues are consistent in reducing the b-value trend before the Fin earthquakes. Pay attention to some inconsistencies in the catalogues in estimating the magnitudes or the number of events. Note that the catalog some b-value differences is more than the b-value variation estimations by each catalog individually.

assumed to be more reliable abnormalities can be related to the studied seismic activities.

$$Trend = \frac{\int_{Ns}^{Ne} dA(t)dt}{Ne - Ns} \quad (2)$$

where, Ns and Ne are the start and the end time of the sampling, respectively.

$$dA(t) = A(t) - \langle dA(t) \rangle \quad (3)$$

We used the *VLF* 18200 Hz band frequency data which have transmitted from the radio transmitter at India (VTX location, T) and after probable affected by the Fin seismic environment, then received by ELETTRONIKA receiver in the building No. 2 of IGUT/IrSC (Tehran-R) as indicted in Figure (2) (top panel). The transmitter (T) and the receiver (R) are assumed to be at the focuses of an ellipsoid plane cross section of the Fresnel zone on the map. With these assumptions, we use of 150 days continuous the raw VLF data in RCEP for analyzing a probable anomaly in the VLF signal amplitudes (right top panel in Figure 2). The twice standard deviation criterion (2σ) for the average signal amplitudes (33.28 dBm) is calculated 6.72 dBm (40 for +2σ and 26.56 for -2σ), when we observed some anomalies much greater than the criterion about 19 (down) up to 50 (up) dBm in amplitudes, respectively, from about 4 days before and 5 days after the main shocks abstracted in the middle and lower panels of Figure (2). Although, the increase in the amplitude of the *VLF* signals from the two-sigma criterion is seen a few days before the time of earthquakes.

3. Discussions and Conclusions

After the double Fin earthquake and the visual observation of abnormal radio signals by the installed receiver at RCEP, we doubted the possibility of its connection with the earthquakes due to the insufficient number of radio receivers (at least three stations are required). Therefore, with having one station and one receiver, it is very difficult to attribute anomaly to a seismic activity and a definite earthquake precursor. In order to prove or disprove the possible connection of the earthquake with the space-based radio waves, we checked two other ground-based precursors with the available local and easy access data.

The BHRC accelerometer stations are relatively proper numbers and distribution, the probable nearing one of them to an earthquake epicenter more than the seismological stations (IrSC and IIEES seismic networks), hence, the proceeded events by the main-shocks (see Table 1) must be re-examined. They should be verified and evaluated for man-made activities such as explosions, industrials/rural and urban development's activities, construction and/or the technical issues as well as their locations. Therefore, these doubted foreshocks need to be reexamined locally and by the ground-based data. So far, we did not have enough facilities to resolve this problem.

The seismicity map has been changed drastically due to lack of the proper coverage of the seismic stations, which are either few or their distribution is inappropriate. The b-value-magnitude, b-value-depth plots show the unstable estimates in the selection of datasets and variable applied criteria that are improper messages. These may be due to inaccuracy and uncertainty in magnitude or depth measurements. Increasing the b-value by magnitude, variations by depth, are not proper messages. The default determined depths of 10 km that executive location programs create, which are no small numbers, have biased the calculations and remains unresolved. These are examples of data inaccuracies and effective uncertainties that are necessarily associated with calculations.

It is possible to look optimistically at the agreement of both catalogs in the reduction of the b-value before the Fin earthquakes. The spatial b-value variations due to much earthquake location errors (sometimes up to 10 km and more) is associated with high uncertainties (see b-value-depth panel). An important note is the catalog's b-value fluctuations individually are more than the lower and upper limit different estimations by them. Hence, despite the relative consistency of the changes in b in both catalogs, sometimes the difference in the values of the catalogs is greater than the expected fluctuation of *b* as the forecasting earthquake precursory. It is obvious that there is no proper coverage of seismic stations, which are either few or their distribution is inappropriate.

Some random temporal b-value variation fits to the seismic up-down tracks, do not have high certainties for reliable evaluating relation to the earthquakes, see Wang et al. (2016) as an important reference for the precursor time (TP) and the fluctuations of the b-value and magnitude variations in the montaged diagrams in duration time from 2006 to 2022 available data in Figure (6).

The foreshocks searching and b-value analyzing are sensitive to the precise locations and the completeness of the used catalogs, whereas much location errors and obvious incompleteness, are in high uncertainty and risk. These deficiencies are affected by temporal b-value estimations, too.

Certain observed amplitude anomalies in the VLF signals from 2σ criterion in only using one receiver station is not enough to attribute the anomaly to the earthquakes. In follow the null hypothesis, despite decisive uncertainties in the b-value variations, the questionable locations of the foreshocks in BHRC catalog and the lack of *VLF* receiving stations, it cannot be ruled out that there are no precursors for these earthquakes. Especially if these events (Table 1), for which a specific location and magnitude are not reported,

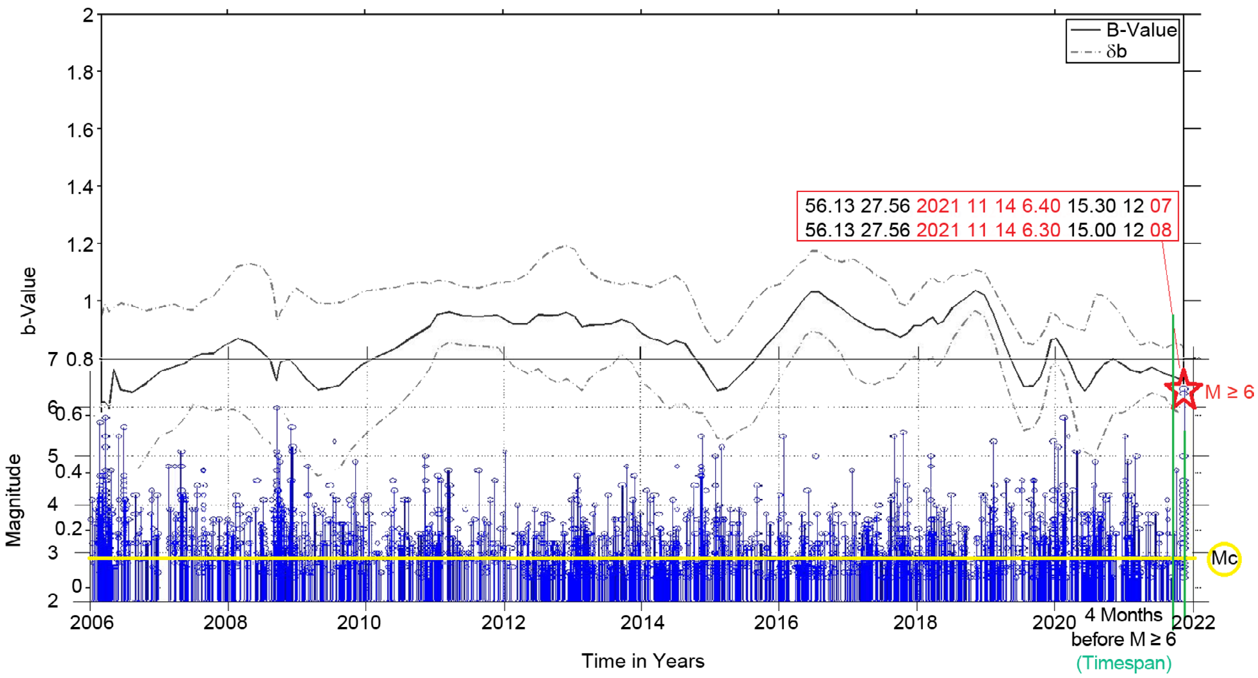

Figure 6. The b-value - magnitude variations in the montaged diagrams in the data time span 2006-2022.

are in the range below the completeness magnitude (MC) of other catalogs.

The studied EP completely depend on the appropriate data in several types and multidisciplinary, which can be obtained by sufficient-proper instruments. It seems, not every earthquake alone creates all types of *EP*, or it is less possible to record, monitor and detect all of them. There are some facilitates and many restrictions simultaneously for the distributions of the receiver instruments on the ground and in space. Many prominent researchers (see Hayakawa & Biagi in the text and the main references used by them) pointed out that space-based data were needed to validate and approval of the use of ground-based data for *EP* analysis. Therefore, the quality and standardization of seismic data acquisitions by IrSC, IIEES and BHRC are of vital important in these fields.

We came to the conclusion that with such reviews and researches, the necessity and im-portance of data quality and improving the level of their acquisition/standard in the country's research centers, should be carefully defined and confirmed for the more scientific effects. For the first step, it is possible to provide and use such kind of reliable and high-quality data in the analysis of pre-earthquake signals or even high-reliability and or logicalscientific predictions. If possible, it will be a valuable achievement in the future. Secondly, important and certain note is that if many pre-earthquake signals with considerable care and confidence being examined, yet an early warning sub-system in private and or public awareness disciplines must be design and implement that can be use them in engineering lifelines and social systems.

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