Are there new findings in the search for ULF magnetic precursors to earthquakes?

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Abstract

Moore [1964] in a letter published in *Nature* reported disturbances in geomagnetic field data prior to the 27 March 1964 Alaska earthquake. After the publication of this report, many papers have shown magnetic changes preceding earthquakes. However, a causal relationship between preearthquake magnetic changes and impending earthquakes has never been demonstrated. As a consequence, after 50 years, magnetic disturbances in the geomagnetic field are still candidate precursory phenomena. Some researchers consider the investigation of

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Ultra-Low-Frequency (ULF: 0.001–10 Hz) magnetic data the correct approach for identifying precursory signatures of earthquakes [see, e.g., *Hayakawa et al.*, 2007; *Hattori et al.*, 2013 and references therein]. Other researchers, instead, have recently reviewed many published ULF magnetic changes that preceded earthquakes and have shown that these are not actual precursors [see, e.g., *Campbell*, 2009; *Masci*, 2010, 2011a; *Thomas et al.*, 2009a, 2009b]. The recent studies by *Currie and Waters* [2014] and *Han et al.* [2014] aim to provide relevant new findings in the search for ULF magnetic precursory signals. However, in order to contribute to science, alleged precursors must be shown to be valid and reproducible by objective testing. Here, we will briefly discuss the state-of-the-art in the search for ULF magnetic precursors, paying special attention to the recent findings of *Currie and Waters* [2014] and *Han et al.* [2014]. We do not see in these two reports significant evidence that may support the observation of precursory signatures of earthquakes in ULF magnetic records.

1. Introduction

Some researchers claim that anomalies do appear in ULF magnetic data prior to earthquakes. They hypothesize that these anomalies are induced by an alleged preparatory phase of the impending earthquake. If correct, reports of preearthquake anomalies claimed to be possible precursors could have important scientific and societal impacts because they might make it possible to make reliable and accurate short-term earthquake predictions. However, reports of false precursors give the illusion that earthquake prediction may be realized in the future. A prediction is a deterministic statement that an earthquake will occur in a particular geographic region, in given period of time, and magnitude range, with significance in excess of random chance. Unfortunately, given the current state of scientific knowledge, earthquake prediction is not yet possible. However, before we can answer the question *Will earthquakes someday be predictable?*, we must positively answer to the key question: *Are there reliable earthquake precursors?* Noise and other sources, both natural and artificial, must first be excluded before any anomaly can be considered a valid earthquake precursor, physical generation mechanisms must be identified, and the anomaly-earthquake relationship must be supported by experimental evidence.

Coseismic effects are observed to occur in geomagnetic field and ionospheric data at the time of rupture [see, e.g., *Astafyeva et al.*, 2013; *Calais and Minster*, 1995; *Johnston*, 1997; *Johnston et al.*, 2006a; *Utada et al.*, 2011]. In contrast, despite the great number of preearthquake ULF magnetic anomalous changes that continue to appear in scientific literature, strong evidence in support of an anomaly-earthquake relationship has never been provided, and other possible sources for the observed anomalies have not been seriously examined [see, e.g., *Masci* 2010, 2011a]. One of the main criticisms is the lack of corresponding coseismic changes when precursors are supposed to be generated in the earthquake focal region [*Park et al.*, 1993]. If precursors are generated in the earthquake focal region, larger coseismic signals are expected when the rupture occurs because the vast majority of energy is released at this time, and not before the earthquake. If a coseismic effect is not observed in the investigated data, it is unlikely that the identified preseismic changes have any physical relationship with the earthquake. The Parkfield Earthquake Prediction Experiment along the San Andres fault in California, in which multidisciplinary measurements were obtained close to the 28 September 2004 M_w6 Parkfield earthquake, has shown coseismic electric and magnetic effects but no electromagnetic precursory signals [*Johnston et al.*, 2006a]. The practice of retrospective identification of earthquake precursors is also heavily criticized [see, e.g., *Geller*, 1997]. Just because we have retrospectively found that an event precedes another, this does not imply that they are related. The spatial and temporal correspondence that sometimes occurs between two events may be just a coincidence, or may result from poor data analysis. Thus, some researchers do not agree that magnetic changes observed prior to earthquakes had seismogenic origin. They have demonstrated that many published preearthquake ULF magnetic changes [see *Campbell*, 2009; *Masci*, 2010, 2011a, 2011b, 2012a, 2012b, 2012c, 2013b; *Masci and De Luca*, 2013; *Masci and Thomas*, 2013a, 2013b, 2015b; *Moldovan et al.*, 2012; *Romanova et al.*, 2015; *Thomas et al*., 2009a, 2009b] and ionospheric disturbances [see *Foppiano et al.*, 2008; *Masci*, 2012d, 2013a; *Masci and Thomas,* 2014a, 2015a; *Masci et al.*, 2015; *Thomas et. al*, 2012a, 2012b] are reasonably related to instrumentation malfunction, to the analysis procedure, or to the normal geomagnetic activity in response to Sun-Earth interactions.

The idea that electromagnetic precursors are generated before earthquakes is based on the assumption that earthquake initiates in an alleged *preparation zone* where physical phenomena lead to the subsequent shock. According to some authors [e.g., *Dobrovolsky et al.*, 1979], precursory signals may appear in the preparation zone, which has a size that depends on the magnitude of the earthquake. However, there is no evidence that a preparatory stage of earthquakes exists. Prior to earthquakes, indeed, the observed stress does not have measurable changes over hundreds of kilometers around active faults that might indicate the start of the fault failure [*Johnston et al.*, 2006b]. The physical phenomena leading the fault in the critical state act in a very small volume whose dimension does not scale with final moment release [*Johnston*, 2015]. Earthquakes, indeed, appear to be chaotic, scale-invariant phenomena controlled by the local mechanical properties of the fault whose geometry and frictional characteristics determine the starting and stopping of the rupture [see, e.g., *Geller*, 1997; *Johnston*, 2015; *Kagan*, 1997]. Therefore, any small shock may grow into a stronger earthquake, and how big the quake will become is determined by how it is stopped, and not by how it starts. Consequently, the notion of a large earthquake preparation zone has no physical basis.

This paper is organized as follows. We briefly describe the way in which ULF precursors of earthquakes are identified in geomagnetic field data, which includes two examples of these claims. Afterward, we will comment on the recent studies by *Currie and Waters* [2014] and *Han et al.* [2014] and the implications of their findings in the search for ULF precursors for short-term prediction of earthquakes.

2. Many papers and many ULF precursors

One of the most frequently cited preearthquake ULF magnetic anomaly is that identified *by Fraser-Smith et al.* [1994] a few days before the 1989 Loma-Prieta earthquake. A detailed reanalysis of this anomaly can be found in *Campbell* [2009] and *Thomas et al.* [2009a]. *Fraser-Smith et al.* [2011] do not concur with the criticism of *Campbell* [2009] who argues that the magnetic changes preceding the Loma-Prieta earthquake were natural disturbances coincidental to the geomagnetic solar-terrestrial disturbance field. However, we agree with *Fraser-Smith et al.* [2011] when they affirm that further independent evidence is required before the magnetic field fluctuations prior to the Loma-Prieta earthquake may be considered as a real precursor.

Following *Fraser-Smith et al.* [1990], many in the scientific community have considered the investigation of ULF geomagnetic data as a promising way for identifying precursory signatures of earthquakes. ULF magnetic signals include those driven by the Sun-Earth interactions, artificial noise, and signals possibly generated in the Earth's interior. The frequency of ULF magnetic changes that have been reported as possible precursors completely overlap in the range of Pc1-Pc5 geomagnetic micropulsations that are induced by solar wind-magnetosphere and magnetosphere-ionosphere interactions. Thus, contributions coming from the ionosphere and magnetosphere may lead researchers to erroneously interpret their origin. *Balasis and Mandea* [2007] rightly stressed that the geomagnetic activity should be considered as a key parameter in interpreting observed preearthquake magnetic anomalies.

There are similarities in reports of anomalous changes in magnetic data, as well as in ionospheric parameters, that are observed prior to earthquakes. Usually preearthquake changes are retrospectively detected as follows: an earthquake occurs, are there changes in geophysical data in the preceding days?, if the answer is yes, the observed change is hypothesized to may be a precursor without checking other sources [*Rishbeth*, 2007]. What is very surprising is that some researchers [see, e.g., *Febriani et al.* 2014; *Hattori et al.*, 2013; *Ohta et al.*, 2013; *Schekotov and Hayakawa*, 2015; *Xu et al.*, 2013] seem to ignore the findings of recent reports which have shown that many published preearthquake ULF anomalies were, indeed, not precursors. There are papers [see, e.g., *Hayakawa*, 2011; *Surkov and Hayakawa*, 2014; *Varlamov et al.*, 2012] that cannot be considered as being part of a serious scientific debate, since the authors persist in showing alleged precursors whose seismogenic origin has been proved invalid in previous reviews [see, e. g., *Masci*, 2010, 2011b, 2011c].

In order for the electromagnetic signals possibly generated in the Earth's interiors to be identified in ULF geomagnetic data, they have to reach the Earth's surface and then be recorded by the instrumentation. The detection of these signals may depend on the characteristics of the instruments in operation in the magnetic station and on the distance of the station from the source. One of the first attempts to find a relationship between the earthquake magnitude and the epicentral distance where an alleged precursor was observed can be found in *Rikitake* [1987]. In a more recent report, in order to estimate the maximum detection distance for possible ULF magnetic precursors, *Hattori et al.* [2004] by using published preseismic anomalies believed to be seismogenic, obtain an empirical relationship between the earthquake magnitude and the distance from the earthquake epicenter of the ULF station where the anomaly was detected. After this report, many researchers [see, e.g., *Febriani et al.*, 2014; *Hayakawa et al.*, 2007; *Yumoto et al.*, 2009] have referred to this relationship in support of the seismogenic origin of the magnetic changes they observed. In Figure 1 we show this relationship as reported by *Febriani et al.* [2014] where we have highlighted with red dots the ULF magnetic changes that were proved to be invalid precursors (see Table S1 of the supporting information). Note that the relationship in Figure 1 is not supported by observational evidence since it has been derived using invalid precursors.

With regard to the identification of generation mechanisms for ULF magnetic crustal signals, many models have been proposed (see the review of *Cicerone et al.*, 2009), but an actual physical mechanism has not yet been identified. Still, laboratory experiments on stressed rocks have been conducted to explain the generation of ULF signals. Even if experiments have shown that electric current is generated in dry rocks by stress loading [see, e.g., *Freund* et al., 2006] it is not clear how these small-scale experiments may be applied to the Earth's crust. Indeed, recent experiments on gabbro samples saturated with electrically conductive fluid similar to those observed in active earthquake fault zones have shown that neither transients nor stress-stimulated currents were observed during several cycles of stress loading [*Dahlgren et al.*, 2014]. Because the Earth's crust is fluid saturated, *Dahlgren et al*. [2014] conclude that significant electric currents are not expected to be generated during the slow stress accumulation prior to earthquakes or during any slow precursory stress release that may occur in the region of earthquake nucleation. As a consequence no electric and magnetic signals are expected to be observed on the Earth's surface.

In summary, reports of ULF magnetic precursors are flawed because they do not provide an adequate control of the seismogenic origin of the reported anomalies. The authors of these reports do not provide a rigorous qualitative definition of what constitutes an anomaly, nor do they show if the alleged anomalies appear only before quakes, or whether they appear frequently, more or less at random [*Pham and Geller*, 2002]. Theories on the physical mechanisms for generating electromagnetic precursors are controversial. Instead, many ULF magnetic changes identified prior to earthquake have been shown to be invalid precursors.

3. Are magnetic polarization ratio anomalies credible precursors of earthquakes?

The most commonly used methods to identify preearthquake ULF anomalies in geomagnetic field records are the so called spectral polarization ratio analysis [see, e.g., *Hayakawa et al.*, 1996] and fractal analysis [*Hayakawa et al.*, 1999]. Fractal anomalies preceding earthquakes have been extensively discussed and denied as precursors by *Masci*

[2010, 2013b] and *Masci and Thomas* [2013a, 2013b; 2015b]. Reports of precursory signatures in the spectral polarization ratio were proved invalid as well [see, e.g., *Masci*, 2011a, 2012a, 2012c; *Masci and Thomas*, 2015b; *Thomas et al.*, 2009b]. However, after the recent paper by *Currie and Waters* [2014], we are motivated to further examine if, as they suggest, the spectral polarization ratio may be considered as a promising parameter to identify earthquake precursors in ULF magnetic field data.

We completely agree with *Currie and Waters* [2014] that there is ambiguity in the definition of the magnetic polarization ratio. Some authors define the magnetic polarization ratio as the ratio between the integrated powers of the vertical and the horizontal components of the geomagnetic field. Other authors, instead, identify the polarization ratio as the ratio of the spectral powers of the geomagnetic field components. In any case, this method cannot be considered an actual polarization analysis but it is merely the calculation of the ratio of geomagnetic field components. In ground based magnetic observations, the vertical component of the geomagnetic field is considered the most sensitive component to magnetic disturbances that may be induced by crustal events. Thus, many researchers argue that before earthquakes the polarization ratio may increase as a consequence of an anomalous increase of the vertical component. Others researchers [see, e.g., *Takla et al.*, 2012; *Yumoto et al.*, 2009], instead, claim that a depression of the polarization ratio, caused by an increase of the horizontal component, may be found prior to an earthquake. It is evident that the description of preearthquake ULF changes in the magnetic polarization ratio can vary significantly from study-to-study, where anomalies have been reported to be either negative or positive departures with respect to a not well-defined “normal background”.

3.1 Magnetic polarization ratio, geomagnetic activity, and geomagnetic indices

Many examples of preearthquake changes identified in polarization ratio time series and an exhaustive discussion on their reliability as precursors can be found in *Masci* [2011a; 2011b; 2012a; 2012c] and *Thomas et al.* [2009b]. These authors have demonstrated that the majority of the polarization ratio changes claimed to be precursors of impending earthquakes are, indeed, normal disturbances induced by geomagnetic activity. More precisely, they have found an inverse correspondence between ULF polarization ratio changes preceding earthquakes and the global geomagnetic Kp index [see also *Masci and Di Persio*, 2012]. The 3h Kp index is obtained as the average value of the disturbance level in the horizontal field components of the geomagnetic field by combining data from 13 selected subauroral magnetometer stations located at mid and high latitudes. Kp is designed to be representative of magnetic activity on planetary scale [*Menvielle and Berthelier*, 1991]. The inverse correspondence between polarization ratio changes and Kp index is likely because of the different responses of the vertical and horizontal magnetic field components to changes in geomagnetic activity. Namely, an increase in geomagnetic activity (increase of Kp index) may increase the amplitude of the horizontal component more than that of the vertical component; as a consequence the polarization ratio decreases. On the contrary, when the geomagnetic activity decreases (decrease of Kp index), the reduction of the horizontal component may be more than that of the vertical component; therefore the polarization ratio increases [*Masci*, 2011a]. Nevertheless, due to the global averaging used to calculate Kp, the inverse correspondence between ULF polarization ratio variations and Kp index is not expected always and everywhere [*Masci*, 2012a].

In the next sections, we present two examples of how invalid precursors were (in the first example), and continue to be (in the second example) identified by means of polarization ratio analysis and published in leading scientific journals.

3.2 The ULF precursor of the Guam earthquake

On 8 August 1993 an M_w7.7 earthquake occurred offshore the island of Guam. In a paper published in *Geophysical Research Letters*, *Hayakawa et al.* [1996] claimed to have found precursory signatures of the Guam earthquake in polarization ratio time series of geomagnetic field data. After *Hayakawa et al.* [1996], many papers [see *Hayakawa et al.*, 1999; *Hobara et al.*, 2004; *Ida et al*., 2005; *Ida and Hayakawa*, 2006; *Smirnova et al.*, 2001] have documented ULF magnetic changes preceding the Guam earthquake using different methods of analysis. *Masci* [2010, 2011a, 2011b, 2013b] and *Thomas et al.* [2009b], however, have shown that the magnetic changes identified prior to the Guam earthquake are not precursors. Although Guam ULF precursors have been extensively discussed in these papers, given the importance of *Hayakawa et al.* [1996] that introduced the magnetic polarization ratio as a right approach in searching for precursors, and taking also into account the recent report of *Currie and Waters* [2014], we want to further discuss the possibility that precursors may be identified in magnetic field data at the time of the Guam earthquake. We are also motivated by recent publications in which, despite the many papers where the Guam precursor has been proven invalid, this earthquake is still considered as one of the seismic events that were accompanied by magnetic ULF disturbances that can be considered precursory signals [see *Surkov and Hayakawa*, 2014, page 374].

Hayakawa et al. [1996] analyze ULF magnetic data (frequency range 0.01-0.05Hz) from the Geomagnetic Observatory of Guam using the method that they defined as polarization ratio analysis. To minimize the day-side effects due to the Sun-Earth interactions, they investigate night time data (12:00–16:00 UT); to reduce spurious noise, they calculate the 5-day running mean of the geomagnetic field components, averaged once per day. We have reproduced the polarization ratio analysis of *Hayakawa et al.* [1996] using the same magnetic data. In Figure 2a we report the polarization ratio time series (Z/H) as 5-day running mean. *Hayakawa et al.* [1996] claim that Z/H shows an anomalous increase during the months preceding the Guam earthquake that they assume to be seismogenic. In Figure 2a the shadow area refers to the period in which, according to *Hayakawa et al.* [1996], precursory magnetic signals appeared, whereas the yellow solid line indicates the long-term Z/H increase claimed to have a seismogenic origin. We have compared Z/H with the global geomagnetic ΣKp index time series. ΣKp is the daily sum of the Kp index. The 5-day running mean of ΣKp has been calculated in order to compare data having the same temporal resolution. Figure 2 shows a close inverse correspondence between Z/H and ΣKp. Still, a 27-day modulation induced by the rotation of the Sun around its axis is also evident in the Z/H time series. This indicates that magnetospheric effects due to the Sun-Earth interactions have not been eliminated by using night time data. The close inverse correspondence between Z/H and ΣKp it is clearly evident during the months preceding the Guam earthquake as well. What is interesting is that the slow increase of the polarization ratio corresponds to a slow decrease of ΣKp (see section 3.1). In Figure 2b we report the correlation plot between the daily values of Z/H and ΣKp. We show the linear relationships throughout 1993 and in the period where, according to *Hayakawa et al.* [1996], precursory signals of the Guam earthquake are present (see the shadow area in

Figure 2a). Note that the two linear relationships are nearly identical and have similar correlation coefficients. This is further evidence that the slow increase of the ratio Z/H during the months before the Guam earthquake was not seismogenic, but, indeed, was part of global magnetic-field variation. We conclude that polarization ratio analysis of magnetic data has not identified any precursory signature of the Guam earthquake.

3.3 The long-term precursors of the 2007-2008 Peru earthquakes

Takla et al. [2012] document anomalous long-term preearthquake changes during 2007-2008 in the Pc3 band (22-100 mHz) of magnetic data from the Ancon station. This period includes two earthquakes off the coast of Peru: the 15 August 2007 M8 Pisco earthquake (180 km from Ancon) and the 29 March 2008 M5.3 earthquake occurred (50 km from Ancon). *Takla et al.* [2012] claim that long-term preearthquake changes were present in the amplitude of the geomagnetic field components, as well as in the spectral polarization ratio.

Figure 3 shows the amplitude (daily values and 10-day running mean) of the geomagnetic field components H_{Pc3} (North–South), D_{Pc3} (East–West), and Z_{Pc3} (vertical) as reported by *Takla et al.* [2012]. They hypothesize that the long-term increase between the end of 2007 and the beginning of 2008 of each component was related to the 29 March 2008 earthquake. In Figure 3, we have superposed the ΣKp index time series onto the original view. The figure shows a close correspondence between the amplitude of the geomagnetic field components and ΣKp. Thus, it is evident that the amplitude enhancements that occurred before the 29 March 2008 earthquake are associated to the long-term increase of the geomagnetic activity and not to seismicity.

In Figure 4 we show the polarization ratio Z_{Pc3}/H_{Pc3} as reported by *Takla et al.* [2012]. They claim that the long-term decrease in Z_{Pc3}/H_{Pc3} prior to the two earthquakes had a seismogenic origin. Also in this case, we have compared the ratio Z_{Pc3}/H_{Pc3} with the geomagnetic activity level by using the ΣKp index. We have found a close inverse correspondence between Z_{Pc3}/H_{Pc3} and ΣKp during 2007-2009. Note that the long-term Z_{Pc3}/H_{Pc3} depressions that can be seen before the two earthquakes show a close correspondence with the long-term rises of the geomagnetic activity. Afterward, slow decreases of the geomagnetic activity causes the increases of the ratio Z_{Pc3}/H_{Pc3} that reaches the pre depression level in a few months. In any case, taking into account the global averaging of ΣKp, we cannot expect that there is a strict correspondence between Z_{Pc3}/H_{Pc3} and ΣKp on short time scale (see section 3.1). In Figures S1-S2 of the supporting information, the amplitude of the geomagnetic field component and the Z_{Pc3}/H_{Pc3} ratio are compared with the geomagnetic Dst index and the solar wind speed, respectively. We conclude that, contrary to the claims of *Takla et al.* [2012], the long-term changes of the spectral polarization ratio, as well as the changes of the amplitude of the geomagnetic field components, that preceded the two Peru earthquakes vary much too closely with ΣKp index, Dst index, and solar wind speed to be considered of seismogenic origin.

Next we discuss the recent papers by *Currie and Waters* [2014] and *Han et al.* [2014] where the authors claim to report new findings regarding ULF magnetic precursors of earthquakes.

4. The study by Currie and Waters [2014]

The recent report of *Currie and Waters* [2014] would like to provide relevant news in the search for magnetic ULF precursors by means of polarization ratio analysis. Here we will discuss their results starting from the scientific literature that motivated their study.

4.1 Opposite views on ULF earthquake precursors

According to *Currie and Waters* [2014], some researchers have a contradictory view with respect to authors that have proposed the occurrence of possible ULF seismogenic signatures in geomagnetic data prior to earthquakes. *Currie and Waters* [2014] have not correctly summarized the state-of-the-art in the search for ULF magnetic precursors. To be more precise, we concur that there are many reports of changes in ULF geomagnetic field data prior to earthquakes. However, we want to stress once again that evidence of the proposed relationship between magnetic anomalies and incoming earthquakes has never been provided. Conversely, in recent papers [see, e.g., *Masci*, 2010, 2011a, 2011b2012a, 2012b, 2013b; *Thomas et al.*, 2009a, 2009b] the authors have demonstrated that many of the reported preearthquake ULF magnetic changes are invalid precursors of earthquakes.

As examples of the contradictory views about ULF precursors, in Figure 1 of their report *Currie and Waters* [2014] show two lists of papers. *Fraser-Smith et al.*[1990], *Bernardi et al.* [1991], *Molchanov et al.* [1992], *Hayakawa et al.* [1996], *Yumoto et al.* [2009], and *Hasbi et al.* [2011] are taken as examples of reports proposing possible ULF magnetic precursors of earthquakes. *Campbell* [2009], *Masci* [2011a], and a not well identified *Masci* [2012] (that is missing in the References section of *Currie and Waters*

[2014]), are taken as examples of papers whose authors have a negative view on the seismogenic origin of reported preearthquake ULF anomalies. Note that the papers cited by *Currie and Waters* [2014] cannot be taken as examples showing actual magnetic precursors. More precisely, *Hasbi et al.* [2011] cannot be considered as a paper proposing magnetic ULF precursors just because they have reported preearthquake ionospheric changes in Total Electron Content (TEC) over Sumatra during 2004-2007 and not in magnetic records. *Thomas et al.* [2009a] have shown that the ULF enhancement reported by *Fraser-Smith et al.* [1990], as well as *Bernardi et al.* [1991], was not a convincing precursor of the Loma Prieta earthquake but, indeed, was an artifact due to sensor-system malfunction. The Guam precursor reported by *Hayakawa et al.* [1996] has been widely denied by *Thomas et al.* [2009b] and *Masci* [2011], as well as in section 3.2 of this paper. Note that *Currie and Waters* [2014] also cite other reports of alleged ULF precursors, e.g., *Hattori* [2004] and *Hayakawa et al.* [1999], the results of which have been demonstrated to be invalid [see *Masci*, 2010, 2011a]. In summary, papers that motivated the study of *Currie and Waters* [2014] cannot be considered reliable, nor possible, examples of observation of precursory signatures of earthquakes in ULF magnetic data.

4.2 Geomagnetic indices and ULF waves

Currie and Waters [2014] analyze data from CARISMA (Canadian Array for Realtime Investigations of Magnetic Activity) and McMAC (Mid-continent Magnetoseismic Chain) magnetometer arrays [see *Currie and Waters*, 2014, Table 1]. One year (2009) of magnetic data from 14 stations located in the latitude range 24.80 - 69.54N and longitude range 260.40 - 267.89E are examined in the Pc3 (22-100 mHz), Pc4 (7-22 mHz), and Pc5 (2-7 mHz) bands of frequency. *Currie and Waters* [2014] report only the Pc3 analysis claiming similar results in Pc4 and Pc5 bands. They examined the correlation between the integrated power of the geomagnetic field trace component, the spectral polarization ratio, and geomagnetic indices, as well as the Kp index. The correlation coefficients between the spectral polarization ratio and solar wind parameters were calculated as well. In brief, they have found a poor correlation between geomagnetic indices and ULF waves; small correlation coefficients were also found between polarization ratio and solar wind parameters. What is interesting for us is that they have found a poor correlation between the polarization ratio and the geomagnetic Kp index at all magnetic latitudes and magnetic local times they investigated [see *Currie and Waters*, 2014, Figure 6]. Based on these results they conclude that the ULF spectral polarization ratio is independent of geomagnetic indices and may be considered a promising parameter for detecting precursors of earthquakes.

We appreciate the detailed analyses reported by *Currie and Waters* [2014] and we agree with their results, that, indeed, confirm our thinking and the findings of previous studies that suggested a possible, but not steady, correspondence between the Kp index and ULF waves [see, e.g., *Campbell*, 1959; *Jacobs*, 1970; *Nagata and Fukunishi*, 1968; *Saito*, 1969]. More precisely, the poor correlation between local geomagnetic field changes and global geomagnetic Kp index variations shown by *Currie and Waters* [2014] is what we usually expect to occur at anytime and anywhere. Kp is designed to be an indicator of geomagnetic field variations averaged over planetary scale, and therefore it does not always necessarily represent local magnetic field changes. Thus, we may find just a close correspondence, and not a strict correlation, between the variations of Kp and fluctuations of the local geomagnetic field. What is more important, this correspondence is not expected always and everywhere.

Conversely, if it is shown that there is close correspondence between alleged ULF magnetic precursors and geomagnetic indices (e.g. Kp) [see *Masci*, 2010, 2011a, 2011b, 2012a, 2012c, 2013c; *Masci and Thomas*, 2013a, 2013b], this indicates that the magnetic changes are part of global geomagnetic field changes and cannot be described as earthquake-related signals. Therefore, the real issue is not the poor correlation that *Currie and Waters* [2014] have found between local ULF magnetic changes and geomagnetic indices, but the correspondence that many papers have shown between ULF magnetic changes claimed to be precursors of earthquakes and global geomagnetic activity changes. We do not agree with *Currie and Waters* [2014] when they claim to have shown that polarization ratio is a promising parameter in the search for earthquake precursory signals in ULF magnetic records. Just because they have found that during 2009 the polarization ratio in magnetic data from CARISMA and McMAC magnetometer arrays are insensitive to global trends in geomagnetic activity, this does not mean that the polarization ratio may be taken as reliable indicator of possible ULF precursory signatures of impending earthquakes. Such a statement should be supported by actual observations of precursory signatures in polarization ratio time series. Unfortunately, the scientific literature of the last two decades demonstrates the opposite. Changes in polarization ratio and fractal properties of the geomagnetic field identified as possible precursors of earthquakes have been recently reviewed in many papers [see, e. g., *Masci*, 2010, 2011a, 2012a, 2012c, 2013b; *Masci and Thomas*, 2013a, 2013b] in which the authors have found a close correspondence between the reported preearthquake ULF magnetic changes and Kp (see section 3). This shows that the reported ULF changes do not have a local geological origin, but a global origin in response to Sun-Earth interactions. Thus, preearthquake changes in polarization ratio, as well as in the fractal characteristics of the geomagnetic field, cannot be considered to be independent of geomagnetic indices, as asserted by *Currie and Waters* [2014]. We agree with *Currie and Waters* [2014] when they say that the methodology adopted in these reviews identifies just qualitative similarities between polarization ratio and geomagnetic indices, but, this is what we really expect due to the global averaging of the geomagnetic indices. However, we would like to point out that all the ULF anomalies that were claimed to be earthquake precursors were recognized just by a visual inspection of magnetic time series, as well as the spectral polarization ratio, and, what is more important, their seismic origin have never been demonstrated.

We conclude that real and reproducible earthquake-related disturbances in magnetic polarization ratio time series must be identified in order to say that it is a promising parameter for detecting earthquake precursory signals. Currently we do not see any actual precursor in polarization ratio time series reported in scientific literature, as well as in *Currie and Waters* [2014]. Note that *Currie and Waters* [2014] do not show any comparison between ULF magnetic data and earthquakes.

4.3 Data Averaging

Currie and Waters [2014] pay attention to the practice of data averaging used in many reports [see, e.g., *Masci*, 2011, 2012a], as well as in section 3 of this paper. We agree with *Currie and Waters* when they assert that over-smoothing makes correlation coefficients meaningless. However, ULF magnetic data in which alleged precursors were identified are usually smoothed to remove high frequencies [see, e.g., *Hayakawa et al.*, 1996; *Takla et al.*, 2012]. Thus, in reanalyzing these precursors and to compare data having the same temporal resolution, geomagnetic indices were low-pass filtered using the same smoothing procedure adopted for the original magnetic records [see, e.g., *Masci*, 2010, 2011a, and here section 3]. In any case, according to *Currie and Waters* [2014, Figure 9], a running average having a relatively small window size does not significantly affect the linear Pearson correlation coefficient between ΣKp and the Pc3 spectral power. In Figure 9 of their paper, the correlation coefficient is seen to increase if the window is greater than 100 days and approaches unity if the window is about 200 days. Note that a window of a few days is typically used in papers where alleged ULF magnetic precursors are reviewed [see, e.g., Masci 2010, 2011a]. Therefore, the findings of these reviews were not significantly influenced by data smoothing.

The importance of *Currie and Waters* [2014] is that this paper continues to motivate researchers searching for precursory signals in ULF polarization ratio time series although to date no actual precursor has been reported in the scientific literature. Unfortunately, papers where a misinterpretation of the obtained results leads the authors to unfounded conclusions continue to be published. For example, *Schekotov and Hayakawa* [2015], despite the recent literature [see, e.g., *Masci*, 2010, 2011a], did not consider the geomagnetic activity as possible source of the observed preearthquake magnetic changes that they claim to be of seismogenic origin. In the supporting information (see Text S1 and Figure S3) we report a brief comment on *Schekotov and Hayakawa* [2015].

5. The statistical analysis by Han et al. [2014]

Han et al. [2014] report a statistical analysis of ULF geomagnetic field data from the Kakioka Observatory in Japan. By means of Superposed Epoch Analysis they claim that during 2001-2010 there is a statistical significance in magnetic anomalies that appear 6-15 days before 50 earthquakes. They conclude that ULF seismo-magnetic phenomena may be useful in the context of short-term earthquake prediction. Note that *Han et al.* [2014] is another example of a paper that failed to cite the recent literature on the reliability of ULF magnetic precursors. Instead, in support of their study, they referred to many papers not reporting any actual magnetic ULF precursors. In Table S2 of the supporting information there are some of these papers and the corresponding rebuttal reviews. For instance, in support of their findings, *Han et al.* [2014] cite the study by *Kon et al.* [2011] where the authors use SEA in the search for ionospheric precursors. Note that, as reported by *Masci* [2012d], the statistical analysis of Kon *et al.* [2011] is not reliable since it may be seriously influenced by global geomagnetic events.

In our opinion, *Han et al.* [2014] present some weak points that cast serious doubts on the reliability of their results. Here we report our remarks starting with the seismic data they used.

5.1 Seismic data

Based on the idea that the detection of possible ULF seismogenic signals may depend on the distance between the magnetic station and the earthquake hypocenter, *Han et al.* [2014]

introduce the daily index $E_s = \sum_{1day} \frac{10^{4.8+1.5M_i}}{r_i^2}$ where M_i is the magnitude of the *ith* earthquake occurred in a day, and r_i is the distance between its hypocenter and the observation site. They argue that E_s is the seismic energy received at the magnetic station per day. More specifically, for earthquakes that occurred in the same day they consider just a single event, defined *earthquake event*, whose energy received at the magnetic station is the sum of the energies of each earthquake that occurred that day. According to *Han et al.* [2014], preseismic ULF disturbances generated by an *earthquake event* may be observed in a magnetic station when E_s exceeds 10^8. With this in mind, during 2001-2010 they identify 50 $E_s>10^8$ *earthquake events* associated with earthquakes (magnitude from 4.4 to 6.3) that occurred within 100 km from the observatory of Kakioka (Region A). An additional 50 $E_s>10^8$ events associated with earthquakes (magnitude from 4.9 to 7.0) that occurred in the area from 100 to 216 km from Kakioka (Region B) are selected in order to investigate the dependence of the ULF anomalies with the distance from the epicenter. The magnitude is expressed in term of Japan Meteorological Agency (JMA) scale. Refer by *Han et al.* [2014, Figure 2, Tables 2 and 3] for the spatial distribution and details of the Japanese earthquakes.

Our first remark concerns the $E_s>10^8$ earthquakes selected in Region A and B. In our opinion, the two dataset do not include earthquakes having similar characteristics that make appropriate their comparison. *Salah and Zhao* [2004] report a case study of Moho (the boundary between Earth's crust and mantle) mapping in South-West Japan, in the region between latitude 33°-37° N and longitude 133°-137°E. They found crustal thickness ranging between 29 and 32 km. Previous studies [*Ashiya et al.*, 1987; *Zhao et al.*, 1992] revealed comparable values of Moho depth in Central Japan, whereas values exceeding 40 km are found only in limited areas (e.g., Chubu District). We note that the majority of the earthquakes in Region A [see *Han et al.*, 2014, Table 2] were generated in the upper mantle, while earthquakes in Region B [see *Han et al.*, 2014, Table 3] are mostly divided between the crust and the upper mantle. The two earthquakes dataset they reported, while including only shallow earthquakes, that is, earthquakes having hypocenter depth <70 km [*Lay and Wallace*, 1995], do not distinguish between earthquakes that occur in the crust and earthquakes in the upper mantle. The different chemical, physical, and rheological properties of these two layers of the Earth's lithosphere suggest us that the generation mechanisms of possible electromagnetic signals may be different for crustal earthquakes and earthquakes in the mantle. Thus, it is reasonable that, if ULF magnetic signals are generated in the crust and in the mantle before earthquakes, these signals may have different properties, e.g., they may differ in frequency. According to *Han et al.* [2014] all the possible precursors should appear in an unspecified narrow frequency band around 10 mHz, irrespective of the tectonic and geodynamic context of their source.

Now we are going to discuss the E_s index. In our opinion the definition of *earthquake event* is highly questionable. *Han et al.* [2014], as well as *Hattori et al.* [2006, 2013] to which they refer, do not explain how this index may have a physical relationship with possible magnetic ULF precursory signals. E_s is designed to represent the daily sum of the mechanical energy released by each earthquake that occurred in a day weighed by the square of the hypocenter distance. In E_s the mechanical energy of the earthquake is estimated by means of the Gutenberg Richter magnitude-energy relation [*Gutenberg and Richter*, 1956] expressed in joules, where the Richter magnitude is replaced by the JMA magnitude. Although *Han et al.* [2014] do not consider any generation mechanism for the ULF preearthquake changes they observed, the use of E_s index implies a relationship between the mechanical energy released during the earthquake and the electromagnetic energy of possible ULF magnetic precursory disturbances. If we accept this hypothesis, ULF preseismic disturbances should be generated in the focal region of the earthquake, then larger coseismic signals (that we do not see in *Han et al.*, 2014) should appear during the earthquake when the primary mechanical energy is released. See also in section 1 the discussion on *preparation zone* of earthquakes.

As a last remark, we would like to point out that it is also highly questionable that earthquakes occurred in the same day can be considered as a single event. This assumption, indeed, implies that: i) the sum of the observed electromagnetic energy of possible precursory disturbances of many small earthquakes that occur in one day should be comparable with the observed electromagnetic energy of possible disturbances generated by one, or a few strong earthquakes that occurred in another day; ii) possible precursory effects of earthquakes that occurred in one day should be detected during the same day. We think that this scenario is not realistic.

5.2 Magnetic data and anomalies

Han et al. [2014] investigate the possible occurrence of ULF anomalies preceding earthquakes in magnetic field data from Kakioka (KAK) observatory. Data from Kanoya (KNY) observatory are taken as reference model to remove global geomagnetic disturbances since, as the authors claim, KNY station is located in an aseismic area. Even if a quick look at the Japan Seismicity Map (http://www.japanquakemap.com/) shows that Southern Japan is affected by a seismicity lower than that in the central and northern sectors, recently published papers [see, e. g., *Matsubara et al.*, 2008] show a significant concentration of seismicity in this region that, indeed, in the last 3 years was struck by more than 15 M>5 crustal earthquakes. Therefore, the statement that the KNY observatory is located in an aseismic area is not exactly correct. Still, the station of KNY (31.42° N, 130.88° E) is about 1000 km from Kakioka (36.23° N, 140.12° E). Due to the large distance between the two sites, we do not agree that KNY may be considered as a reference station in order to remove the effect of global geomagnetic activity, since global ULF disturbances may have different amplitudes in distant stations [*Campbell*, 1997]. The majority of ULF signals come from the interplanetary space and magnetosphere; some of these signals have a worldwide extension, whereas others could have latitude dependence [*Samson et al.*, 1971]. Note the different latitude of KAK and KNY observatories.

Han et al. [2014] analyze 1Hz geomagnetic data measured during nighttime (LT 2:30-4:00). They calculate the daily averaged energy of the geomagnetic field vertical component Z around the frequency of 0.01 Hz. Based on the idea that KNY is located in aseismic area, they assume that the variation of the energy Z_{KNY} at KNY is mostly related to global geomagnetic activity contrary to the energy Z_{KAK} at KAK that may be influenced by seismogenic disturbances. In order to identify magnetic anomalies, they consider the predicted energy Z^*_{KAK} at KAK modeled by calculating the linear relationship between the energy of the Z component at KAK and KNY during 2001-2010. According to them, the comparison between Z_{KAK} and its linearly modeled Z^*_{KAK} by means of the ratio $P = \frac{Z_{KAK}}{Z^*_{KAK}}$ may isolate seismogenic regional magnetic anomalies. In their Figure 7, *Han et al.* [2014] report the distribution of P during 2001-2010. The figure shows that the majority of the P values are around 1. This means that modeled and observed energies at KAK are usually similar. *Han et* *al.* [2014] define a magnetic anomaly when $P > m + 1.5\mathrm{IQR}$, where m is the median, and IQR is the interquartile range of the P distribution [see *Han et al.*, 2014, section 4 for details]. By means of this method they isolated 324 days during 2001-2010 in which there was an anomalous increase of the P ratio.

5.3 Superposed Epoch Analysis

To investigate the possible seismogenic origin of the P anomalies they identified, *Han et al.* [2014] use Superposed Epoch Analysis (SEA), a statistical method that highlights weak periodic signals. More specifically, for each of the 50 earthquakes selected for Region A, they consider P anomalies during the period from 45 days before to 45 days after each earthquake, and then they apply SEA. To verify the statistical significance of their analysis, SEA is repeated for 50 randomly chosen days. Still, the random test is repeated 100,000 times for calculating the mean value μ_{random} of the P anomalies and the corresponding standard deviation σ. In Figure 5 we show SEA for the Region A as reported by *Han et al.* [2014, Figure 8]. According to them there is statistical evidence that P anomalies occurred in Region A during the two periods 6-10 and 11-15 days before the earthquakes date.

Let us now to discuss the results of *Han et al.* [2014]. Here, we pay attention on the P anomalies counted in 5-day intervals that, as the authors pointed out, show more stable values. In Figure 5, gray bars and the green line refer to 5-day counted P anomalies and the corresponding $\mu_{random}+2\sigma$, respectively. The authors noted that during 6-15 days before the earthquake the 5-day P anomalies exceed $\mu_{random}+2\sigma$. As a consequence, according to them, there is statistical significance that the magnetic anomalies identified during this period were of seismogenic origin. Let us say that there is no physical reason that in Figure 5 the green line represents the "normal background" for magnetic anomalies, whatever might be their origin, above which seismogenic signals may be isolated. Still, we note that $\mu_{random}+2\sigma$ is about 33 counts and the counted anomalies during the two periods 11-15 and 6-10 days before the earthquake are 39 and 36, respectively. In our opinion, these small differences of 6 and 3 counts (a deviation of 18% and 9%) from the assumed background $\mu_{random}+2\sigma$ cannot support that the *P* anomalies identified 6-15 days before the earthquakes had seismogenic origin.

If we assume that ULF magnetic seismogenic signals actually appear before earthquakes, there is no physical reason that the *P* anomalies must show periodicity in a restricted time range (e.g., 11-15 days) before the main shock. This hypothesis is highly questionable since earthquakes occurred in an area having a radius of 100 km were generated by different fault zones, and thus it is unlikely that they might share similar precursory phases [see *Masci et al.*, 2015]. Still, what is the physical mechanism that would generate electromagnetic signals just a few days before the earthquake? *Han et al.* [2014] conclude that generation mechanisms for the anomalies they reported are being studied. We note that this conclusion is common to many papers published in the last 50 years. At the hypocentral depth, the level of the local stress does not significantly change even during the period prior to the shock [*Lay and Wallace*, 1995]. High-resolution borehole strain and pore pressure measurements in active fault areas do not indicate a significant precursory stress increase during the days before the earthquake [*Johnston et al.*, 2006b]. In addition to that, as previously reported, recent laboratory experiments on fluid-saturated rock samples do not support the hypothesis that electromagnetic signals are generated prior to earthquakes [see *Dahlgren et al.*, 2014]. Conversely, coseismic electromagnetic effects are observed during earthquakes [*Johnston et al.*, 2006a]. What is very surprising in the study of *Han et al.* [2014], indeed, is the lack of coseismic signals. As previously reported in section 5.1, since the E_s index implies a relationship between the mechanical energy released during earthquakes and possible ULF magnetic precursors, the magnetic signals that *Han et al.* [2014] hypothesize to occur before the Japanese earthquakes should be generated in the earthquake focal region. In our opinion, this should result in the appearance of larger coseismic signals identified by SEA.

According to *Han et al.* [2014] there is no statistical evidence that ULF precursors possibly generated by the 50 selected earthquakes in Region B were observed at KAK. This should demonstrate that the detection of seismogenic anomalies depends on the distance of the magnetic station from the earthquake epicenter. In our opinion, this conclusion is unsupported, since, as we have previously emphasized in section 5.1, the two sets of earthquakes do not have comparable characteristics.

Our last remark concerns the threshold value of E_s=10^8 above which the ULF anomalies have a statistical significance. According to *Han et al.* [2014], using thresholds < 10^8 the statistical significance decreases as the threshold decreases. Note that by decreasing the E_s threshold from 10^8 to 10^5, the number of earthquakes that they used in SEA increases from 50 to 1440. Thus, since the number of magnetic anomalies identified during 2001-2010 remains constant (324), by increasing the number of earthquakes, SEA necessarily provides results that are increasingly flat as can be seen in Figure 11 of *Han et al.* [2014].

6. Conclusions

We have reviewed the reports of *Currie and Waters* [2014] and *Han et al.* [2014] on ULF magnetic precursory signals. The report by *Currie and Waters* [2014] seems to promise new findings in the search of precursors in spectral polarization ratio time series. In our opinion, *Currie and Waters* [2014] have not provided any evidence that supports the idea that the magnetic polarization ratio may be considered a valid method for identifying earthquake precursors, since they have not shown any valid earthquake precursors in magnetic polarization ratio time series. We agree with *Currie and Waters* [2014] that geomagnetic indices may not be satisfactory predictors of ULF activity, but, at the same time, the polarization ratio cannot be considered a useful parameter to detect possible seismogenic signals independently of geomagnetic activity. We are motivated to reiterate our findings and overall position on precursors. A necessary, but at the same time not sufficient, requisite in the search for magnetic ULF precursors is to take into account the variation of the global geomagnetic activity, which may induce change in local magnetic parameters. Therefore, global geomagnetic indices help us to avoid erroneous interpretations of normal geomagnetic signals. In any case, in order to be useful for earthquake prediction, the seismogenic origin of magnetic anomalies that are unrelated to geomagnetic indices must always be demonstrated, not just conjectured.

We have also discussed the statistical study by *Han et al.* [2014]. We think that the *Es* index they proposed is not useful to identify earthquakes that may have been preceded by magnetic anomalies. We do not see, indeed, any evidence that may support a possible relationship between the mechanical energy released during the earthquake and the electromagnetic energy of possible precursory signals. In our opinion, the Superposed Epoch

Analysis reported by *Han et al.* [2014] does not show any actual (nor possible) preseismic, as well as coseismic, ULF magnetic phenomenon for Japanese earthquakes that occurred during 2001-2010. Thus, we find no evidence to support their conclusion that this method could be used in the future to predict earthquakes.

Contrary to the opinion of *Currie and Waters* [2014] and *Han et al.* [2014], we conclude that at present the investigation of ULF geomagnetic field data cannot be considered a promising way in the search for magnetic precursors of earthquakes. Of the preearthquake ULF changes reported to date, none of these have been proven to be successful observations of magnetic earthquake precursors. Instead, many of these preearthquake changes have been shown to be invalid precursors. Claims of earthquake precursors should be seriously examined for their reliability, and precursors that are shown to be invalid should not be referred to as good candidates for earthquake prediction [*Masci*, 2011b]. More than fifty years since the publication of *Moore* [1964], in which, however, many public funds have been used to search for magnetic precursors of earthquakes [*Campbell*, 1998], we do not see significant progress in this field.

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References

Ashiya, K., S. Asano, T. Yoshii, M. Ishida, and T. Nishiki (1987), Simultaneous determination of the three-dimensional crustal structure and hypocenters beneath the Kanto-Tokai District, Japan, Tectonophysics, 140, 13-27, doi:10.1016/0040-1951(87)90137-5.

Astafyeva, E., S. Shalimov, E. Olshanskaya, and P. Lognonné (2013), Ionospheric response to earthquakes of different magnitudes: Larger quakes perturb the ionosphere stronger and longer, *Geophys. Res. Lett.*, 40, 1675–1681. doi:10.1002/grl.50398.

Balasis, G., and M. Mandea (2007), Can electromagnetic disturbances related to the recent great earthquakes be detected by satellite magnetometers?, *Tectonophysics*, 431,173–195, doi:10.1016/j.tecto.2006.05.038.

Bernardi, A., A. C. Fraser-Smith, P. R. McGill, and O. G. Villard (1991), ULF magnetic field measurements near the epicenter of the M*s* 7.1 Loma Prieta earthquake, *Phys. Earth Planet. Int.*, 68, 45–63, doi:10.1016/0031-9201(91)90006-4.

Calais, E., and J. B. Minster (1995), GPS detection of ionospheric perturbations following the January 17, 1994, Northridge earthquake, *Geophys. Res. Lett., 22*, 1045–1048, doi: 10.1029/96GL01256.

Campbell, W. H. (1959), Studies of magnetic field micropulsations with periods of 5 to 30 seconds, *J. Geophys. Res.*, 64(11), 1819–1826, doi:10.1029/JZ064i011p01819.

Campbell, W. H. (1997), Introduction to Geomagnetic Fields, Cambridge University Press, New York, 304 pp.

Campbell, W. H. (1998), A misuse of public funds: U.N. support for geomagnetic forecasting of earthquakes and meteorological disasters, *Eos Trans. AGU*, 79, 463, doi:10.1029/98EO00354.

Campbell, W. H. (2009), Natural magnetic disturbance fields, not precursors, preceding the Loma Prieta earthquake, *J. Geophys. Res.*, 114, A05307, doi:10.1029/2008JA013932.

Cicerone, R. D., Ebel, J. E., Britton, J. (2009), A systematic compilation of earthquake precursors, *Tectonophysics*, 476, 371–396, doi: 10.1016/j.tecto.2009.06.008, 2009.

Currie, J. L., and C. L. Waters (2014), On the use of geomagnetic indices and ULF waves for earthquake precursor signatures, *Geophys. Res. Space Physics*, 119, 992–1003, doi: 10.1002/2013JA01953.

Dahlgren, R.P., M. J. S. Johnston, V. C. Vanderbilt, and R. N. Nakaba (2014), Comparison of the Stress-Stimulated Current of Dry and Fluid-Saturated Gabbro Samples, *Bull. Seismol. Soc. Am.*, 104(6), 2662–2672, doi: 10.1785/0120140144.

Dobrovolsky, I. P., S. I. Zubkov, and V. I. Miachkin (1979), Estimation of the size of earthquake preparation zones, *Pure Appl. Geophys.*, 117, 1025–1044, doi:10.1007/BF00876083.

Febriani, F., P. Han, C. Yoshino, K. Hattori, B. Nurdiyanto, N. Effendi, I. Maulana, Suhardjono, and E. Gaffar.: Ultra low frequency (ULF) electromagnetic anomalies associated with large earthquakes in Java Island, Indonesia by using wavelet transform and detrended fluctuation analysis, *Nat. Hazards Earth Syst. Sci.*, 14, 789–798, doi:10.5194/nhess-14-789-2014, 2014.

Foppiano, A.J., E.M. Ovalle, K. Bataille, and M. Stepanova (2008), Ionospheric evidence of the May 1960 earthquake over Concepcion? *Geofis. Int.*, 2008, 47, 3, 179–183.

Fraser-Smith, A.C., A. Bernardi, P.R. McGill, M.E. Ladd, R.A. Helliwell, O.G. Villard Jr. (1990), Low frequency magnetic field measurements near the epicenter of the Loma-Prieta earthquake, *Geophys. Res. Lett.*, 17, 9, 1465–1468, doi: 10.1029/GL017i009p01465.

Fraser-Smith, A., P. McGill, R. Helliwell, and O. Villard Jr. (1994), Ultra-low frequency magnetic field measurements in southern California during the Northridge earthquake of 17 January 1994, *Geophys Res. Lett.*, 21(20), 2195–2198, doi: 10.1029/94GL01984.

Fraser-Smith, A. C., P. R. McGill, and A. Bernardi (2011), Comment on “Natural magnetic disturbance fields, not precursors, preceding the Loma Prieta earthquake” by Wallace H. Campbell, *J. Geophys. Res.*, 116, A08228, doi:10.1029/2010JA016379.

Freund, F., A. Takeuchi, and B. Lau (2006), Electric currents streaming out of stressed igneous rocks – a step towards understanding preearthquake low frequency EM emissions, *Phys. Chem. Earth*, 31, 389–396, doi:10.1016/j.pce.2006.02.027, 2006.

Geller, R. J. (1997), Earthquake prediction: A critical review, *Geophys. J. Int.*, 131, 425–450, doi:10.1111/j.1365-246X.1997.tb06588.x.

Gutenberg, B. and C. F. Richter (1956). Magnitude and energy of earthquakes, *Ann. Geofis.* 9, 1-15.

Han, P. , K. Hattori, M. Hirokawa, J. Zhuang, C. H. Chen, F. Febriani, H. Y., C. Yoshino, J. Y. Liu, and S. Yoshida (2014), Statistical analysis of ULF seismo-magnetic phenomena at Kakioka, Japan, during 2001-2010, *J. Geophys. Res. Space Physics*, 119, doi: 10.1002/2014JA019789.

Hasbi, A. M., M. A. Mohd, and N. Misran (2011), Ionospheric variations before some large earthquakes over Sumatra, *Nat. Hazard. Earth Syst. Sci.*, *11*(2), 597–611, doi:10.5194/nhess-11-597-2011.

Hattori, K. (2004), ULF geomagnetic changes associated with large earthquakes, *Terr. Atmos. Ocean Sci.*, *15*(3), 329–360.

Hattori, K., Takahashi, I., Yoshino C., Isezaki N., Iwasaki H., Harada M., Kawabata K., Kopytenko E., Kopytenko Y., Maltsev P., Korepanov V., Molchanov O., Hayakawa M., Noda Y., Nagao T., and S. Uyeda (2004), ULF geomagnetic field measurements in Japan and somerecent results associated with Iwateken Nairiku Hokubu earthquake in 1998, *Phys. Chem. Earth*, 29, 481–494, doi:10.1016/j.pce.2003.09.019.

Hattori, K., A. Serita, C. Yoshino, M. Hayakawa, and N. Isezaki (2006), Singular spectral analysis and principal component analysis for signal discrimination of ULF geomagnetic data associated with 2000 Izu Island Earthquake Swarm, *Phys. Chem. Earth*, *31*, 281–291, doi:10.1016/j.pce.2006.02.034.

Hattori, K., P. Han, C. Yoshino, F. Febriani, H. Yamaguchi, and C-H Chen (2013) , Investigation of ULF Seismo-Magnetic Phenomena in Kanto, Japan During 2000–2010: Case Studies and Statistical Studies, *Surv. Geophys.*, 34, 293–316, doi: 10.1007/s10712-012-9215-x.

Hayakawa, M. (2011), On the fluctuation spectra of seismoelectromagnetic phenomena, *Nat. Hazards Earth Syst. Sci.*, 11, 301–308, doi:10.5194/nhess-11-301-2011.

Hayakawa, M., R. Kawate, O. A. Molchanov, and K. Yumoto (1996), Results of ultra-low-frequency magnetic field measurements during the Guam earthquake of 8 August 1993, *Geophys. Res. Lett.*, 23, 241– 244, doi:10.1029/95GL02863.

Hayakawa, M., T. Ito, and N. Smirnova (1999), Fractal analysis of ULF geomagnetic data associated with the Guam earthquake on August 8, 1993, *Geophys. Res. Lett.*, *26*, 2797-2800, doi: 10.1029/1999GL005367.

Hayakawa, M., K. Hattori, and K. Ohta (2007), Monitoring of ULF (ultra-low-frequency) geomagnetic variations associated with earthquakes, *Sensors*, 7, 1108–1122. doi:10.3390/s7071108.

Hobara, Y., H. C. Koons, J. L. Roeder, K. Yumoto, and M. Hayakawa (2004), Characteristics of ULF magnetic anomaly before earthquakes. Phys. Chem. Earth, 29, 437-444, doi:10.1016/j.pce.2003.12.005.

Ida, Y., and M. Hayakawa (2006), Fractal analysis for the ULF data during the 1993 Guam earthquake to study prefecture criticality, *Nonlin. Process. Geophys.*, *13*, 409-412, doi:10.5194/npg-13-409-2006.

Ida, Y., M. Hayakawa, A. Adalev, and K. Gotoh (2005), Multifractal analysis for the ULF Geomagnetic data during the 1993 Guam earthquake, *Nonlin. Process Geophys.*, *12*, 157-162, doi:10.5194/npg-12-157-2005.

Jacobs J. A. (1970), Geomagnetic Micropulsations, Springer-Verlag, Berlin Heidelberg New York, ISBN: 978-3-642-86830-6.

Johnston, M. J. S. (1997), Review of electrical and magnetic fields accompanying seismic and volcanic activity, *Surv. Geophys.*, 18(5), 441–475, doi:0.1023/A:1006500408086.

Johnston, M. J. S. (2015), On earthquake fault failure, 26th IUGG General Assembly, P121, IUGG-100, Prague, Czech Republic, June 22-July 2, 2015.

Johnston, M. J. S., Y. Sasai, G. D. Egbert, and R. J. Muller (2006a), Seismomagnetic effects from the long-awaited 28 September 2004 M 6.0 Parkfield earthquake, Bull. Seismol. Soc. Am., 96(4B), S206–S220, doi:10.1785/0120050810.

Johnston, M. J. S., D. Borcherdt, A. T. Linde, and M. T. (2006b), Continuous Borehole strain and pore pressure in the near field of the 28 September M 6.0 Parkfield, California Earthquake: Implications for nucleation, fault response, earthquake prediction, and tremor, *Bull. Seismol. Soc. Am.*, 96, S56–S72, doi:10.1785/0120050822.

Kagan, Y. Y. (1997), Are erathquake predictable?, *Geophys. J. Int.*, 131, 505-525, doi: 10.1111/j.1365-246X.1997.tb06595.x.

Kon, S., M. Nishihashi, and K. Hattori (2011), Ionospheric anomalies possibly associated with M≥ 6.0 earthquakes in the Japan area during 1998–2010: Case studies and statistical study, *J. Asian Earth Sci.*, 41, 410–420, doi:10.1016/j.jseaes.2010.10.005.

Lay, T., and T. C Wallace, Modern global seismology, Accademic Press, San Diego, pp. 521, 1995.

Mann, I. R. (2008), The upgraded CARISMA magnetometer array in the THEMIS era, *Space Sci. Rev., 141*, 413–451, doi:10.1007/s11214-008-9457-6.

Masci, F (2010), On claimed ULF seismogenic fractal signatures in the geomagnetic field, *J. Geophys. Res. Space Physics.*, A10236,115, doi:10.1029/2010JA015311.

Masci, F. (2011a), On the seismogenic increase of the ratio of the ULF geomagnetic field components. *Phys. Earth Planet. Int.*, 187, 19-32, doi:10.1016/j.pepi.2011.05.001.

Masci, F. (2011b), Brief communication "On the recent reaffirmation of ULF magnetic earthquakes precursors", *Nat. Hazards Earth Syst. Sci.*, 11, 2193–2198, doi:10.5194/nhess-11-2193-2011.

Masci, F., (2012a), Comment on ''Ultra low frequency (ULF) European multi station magnetic field analysis before and during the 2009 earthquake at L'Aquila regarding regional geotechnical information'' by Prattes et al. (2011), *Nat. Hazards Earth Syst. Sci*,. 12, 1717–1719, doi:10.5194/nhess-12-1717-2012.

Masci, F. (2012b), Comment on ''Possible association between anomalous geomagnetic variations and the Molise earthquakes at central Italy during 2002" by Takla et al. (2011), *Phys. Earth Planet. Int.*, 202–203, 92–94, doi:10.1016/j.pepi.2012.02.006.

Masci, F. (2012c), On the ULF magnetic ratio increase before the 2008 Iwate–Miyagi Nairiku earthquake by Hirano and Hattori (2011), *J. Asian Earth Sci.*, 56, 258–262, doi:10.1016/j.jseaes.2012.06.009.

Masci, F. (2012d), The study of ionospheric anomalies in Japan area during 1998–2010 by Kon et al.: An inaccurate claim of earthquake-related signatures?, *J. Asian Earth Sci.*, 57, 1–5, doi:10.1016/j.jseaes.2012.06.009.

Masci, F. (2013a), Further comments on the ionospheric precursor of the 1999 Hector Mine earthquake, *Nat. Hazards Earth Syst. Sci.*, 13, 193–196, doi:10.5194/nhess-13-193-2013.

Masci, F. (2013b), On the multi-fractal characteristics of the ULF geomagnetic field before the 1993 Guam earthquake, *Nat. Hazards Earth Syst. Sci.*, 13, 187–191, doi:10.5194/nhess-13-187-2013.

Masci, F., and G. De Luca (2013), Some comments on the potential seismogenic origin of magnetic disturbances observed by Di Lorenzo et al. (2011) close to the time of the 6 April 2009 L'Aquila earthquake, *Nat. Hazards Earth Syst. Sci.*, 13, 1313–1319, doi:10.5194/nhess-13-1313-2013.

Masci, F., M. Di Persio (2012), Retrospective investigation of geomagnetic field time-series during the 2009 L'Aquila seismic sequence, *Tectonophysics*, 530-531, 310–317, doi:10.1016/j.tecto.2012.01.008.

Masci, F., and J.N. Thomas (2013a), Comment on "Fractal analysis of ULF electromagnetic emissions in possible association with earthquakes in China" by Ida et al. (2012), *Nonlin. Processes Geophys.*, 20, 417–421, 2013, doi:10.5194/npg-20-417-2013.

Masci, F., and J.N. Thomas (2013b), On the relation between the seismic activity and the Hurst exponent of the geomagnetic field at the time of the 2000 Izu swarm, *Nat. Hazards Earth Syst. Sci.*, 13, 2189-2194, doi:10.5194/nhess-13-2189-2013.

Masci, F., and J. N. Thomas (2014a), Comment on "Temporal and spatial precursors in ionospheric total electron content of the 16 October 1999 M_w7.1 Hector Mine earthquake", by Su et al. (2013), *J. Geophys. Res. Space Physics*, 119, 6994–6997, doi: 10.1002/2014JA019896.

Masci, F., and J. N. Thomas (2015a), On the reliability of the Spatial Scintillation Index to identify ionospheric precursors of earthquakes, *Radio Science*, 50, 745-753, doi:10.1002/2015RS005734.

Masci, F., and J. N. Thomas (2015b), Comment on "Ultra low frequency (ULF) electromagnetic anomalies associated with large earthquakes in Java Island, Indonesia by using wavelet transform and detrended fluctuation analysis", by Febriani et al. (2014), under review, *Nat. Hazards Earth Syst. Sci.*.

Masci, F, J. N. Thomas, F. Villani, J. A. Secan, and N. Rivera (2015), On the onset of ionospheric precursors 40 minutes before strong earthquakes, *J. Geophys. Res. Space Physics.*, 120, 1383-1393, doi:10.1002/2014JA020822.

Matsubara, M., K. Obara, and K. Kasahara (2008), Three-dimensional P- and S-wave velocity structures beneath the Japan Islands obtained by high-density seismic stations by seismic tomography, *Tectonophysics*, 454, 86-103, doi: 10.1016/j.tecto.2008.04.016.

Menvielle, M., and A. Bertelier (1991), The K-derived planetary indices: description and availability, *Rev. Geophys.*, 29 (3), 415-432, doi: 10.1029/91RG00994.

Molchanov, O. A., Y. A. Kopytenko, P. M. Voronov, E. A. Kopytenko, T. G. Matiashvili, A. C. Fraser-Smith, and A. Bernardi (1992), Results of ULF magnetic field measurements near the epicenters of the Spitak (ms = 6.9) and Loma Prieta (ms = 7.1) earthquakes: Comparative analysis, *Geophys. Res. Lett.*, *19*(14), 1495–1498, doi:10.1029/92GL01152.

Moldovan, I. A., A. O. Placinta, A. P. Constantin, A. S. Moldovan, and C. Ionescu (2012), Correlation of geomagnetic anomalies recorded at Muntele Rosu Seismic Observatory (Romania) with earthquake occurrence and solar magnetic storms, *Ann. Geoph.*, 55, 1, 125-137, doi: 10.4401/ag-5367.

Moore, G. W. (1964), Magnetic disturbances preceding the 1964 Alaska earthquake, *Nature,* 203, 508–509, doi:10.1038/2031106a0.

Nagata, T., and H. Fukunishi (1968), Dependence on Geomagnetic Activity of Magnetic Pulsation Frequency of pc-3 and pc-4 Ranges, *Geopliys. J. R. astr. Soc.*, 15, 69-78.

Ohta, K., J. Izutsu, A. Schekotov, and M. Hayakawa (2013), The ULF/ELF electromagnetic radiation before the 11 March 2011 Japanese earthquake, *Radio Sci.*, 48, 589–596, doi:10.1002/rds.20064.

Park, S.K., M.J.S. Johnston, T.R. Madden, F.D. Morgan, and H.F. Morrison (1993), Electromagnetic precursors to earthquakes in the ULF bands: a review of observations and mechanisms, *Rev. Geophys.*, 31, 117–132, doi: 10.1029/93RG00820.

Pham, V. N., and R. J. Geller (2002), Comment on ‘‘Signature of pending earthquake from electromagnetic anomalies’’ by K. Eftaxias et al., *Geophys. Res. Lett.*, 29, 18, 1871, doi:10.1029/2002GL015328.

Rishbeth, H. (2007), Do earthquake precursors really exist?. *Eos Trans. AGU*, 88(29), 296. doi:10.1029/2007EO290008.

Rikitake, T. (1987), Earthquake Precursors in Japan: precursor time and detectability. *Tectonophys*, 136, 265-282. doi:10.1016/0040-1951(87)90029-1

Romanova, N.V., V.A. Pilipenko, and M.V. Stepanova (2015), On the Magnetic Precursor of the Chilean Earthquake of February 27, 2010, *Geomagn. Aeronomy*, 55, 2, 219–222, doi: 10.1134/S0016793215010107.

Saito, T. (1969), Geomagnetic pulsations, *Space Sci. Rev.*, 10, 319–342, doi:10.1007/BF00203620.

Salah, K. M., and D. Zhao (2004), Mapping the crustal thickness in southwest Japan using Moho-reflected waves, *Phys. Earth Planet. Int.*, 141, 79-94, doi: 10.1016/j.pepi.2003.10.002.

Samson, J. C., J. A. Jacobs, and G. Rostoker (1971), Latitude-dependent characteristics of long-period geomagnetic micropulsations, *J. Geophys. Res.*, 76, 3675–3683, doi:10.1029/JA076i016p03675.

Smirnova, N., M. Hayakawa, K. Gotoh, and D. Volobuev (2001), Scaling characteristics of the ULF geomagnetic fields at the Guam seismoactive area and their dynamics in relation to the earthquake, *Nat. Hazards Earth Syst. Sci.*, *1*, 119-126, doi:10.5194/nhess-1-119-2001.

Schekotov, A., and M. Hayakawa (2015), Seismo-meteo-electromagnetic phenomena observed during a 5-year interval around the 2011 Tohoku earthquake, *J. Phys. Chem. Earth*, in press, http://dx.doi.org/10.1016/j.pce.2015.01.010.

Surkov, V., and M. Hayakawa (2014), Ultra and Extremely Low Frequency Electromagnetic Fields, Springer Geophysics, Springer Tokyo Heidelberg New York Dordrecht London, 486 p., ISBN: 978-4-431-54366-4, doi: 10.1007/978-4-431-54367-1.

Takla, E.M., K. Yumoto, J. Ishitsuka, D. Rosales, S. Dutra, T. Uozumi, and T. Abe (2012), Geomagnetic variations possibly associated with the Pisco earthquake on 15 August 2007, Peru, *Tectonophysics*, 524–525, 29–36. doi:10.1016/j.tecto.2011.12.008.

Thomas, J. N., J. J Love, and M. J. S. Johnston (2009a), On the reported magnetic precursor of the 1989 Loma Prieta earthquakes, *Phys. Earth Planet. Int.*, 173, 207-215, doi:10.1016/j.pepi.2008.11.014.

Thomas, J. N., Love, J. J, Johnston, M. J. S., Yumoto, K. (2009b), On the reported magnetic precursor of the 1993 Guam earthquake, *Geophys. Res. Lett.*, 36, L16301, doi:10.1029/2009GL039020.

Thomas, J. N., J. J. Love, A. Komjathy, O. P. Verkhoglyadova M. Butala, and N. Rivera (2012a), On the reported ionospheric precursor of the 1999 Hector Mine, California earthquake, *Geophys. Res. Lett.*, *39*, L06302, doi:10.1029/2012GL051022.

Thomas, J. N., F. Masci, J. J. Love, and M. J. S. Johnston (2012b), Reported geomagnetic and ionospheric precursors to earthquakes: Summary, reanalysis, and implication for short-term prediction, *AGU Fall Meeting*, San Francisco, USA, 3–7 December 2012.

Utada, H., H. Shimizu, T. Ogawa, T. Maeda, T. Furumura, T. Yamamoto, N. Yamazaki, Y. Yoshitake, and S. Nagamachi (2011), Geomagnetic field changes in response to the 2011 off the Pacific Coast of Tohoku earthquake and tsunami, *Earth Planet. Sci. Lett.*, 311, 11–27, doi:10.1016/j.epsl.2011.09.036.

Varlamov, A., N. Smirnova, M. Hayakawa, and K. Yumoto (2012), Fractal Characteristics of the ULF Emissions Along a Meridian Profile, Based on the 210 MM Stations Data, *Acta Geophysica*, 60, 3, 928-941, doi: 10.2478/s11600-012-0035-7.

Xu, G., P. Han, Q. Huang, K. Hattori, F. Febriani, and H. Yamaguchi (2013), Anomalous behaviors of geomagnetic diurnal variations prior to the 2011 off the Pacific coast of Tohoku earthquake (Mw9.0), *J. Asian. Earth Sci.*, 77, 59–65, doi: 10.1016/j.jseaes.2013.08.011.

Yumoto, K., S. Ikemoto , M.G. Cardinal, M. Hayakawa, K. Hattori, J.Y. Liu, S. Saroso, M. Ruhimat, M. Husni, D. Widarto, E. Ramos, D. McNamara, R.E. Otadoy, G. Yumul, R. Ebora, N. Servando (2009), A new ULF wave analysis for seismo-electromagnetics using CPMN/MAGDAS data, *Phys. Chem. Earth*, *34*,360–366.

Zhao, D., S. Horiuchi, and A. Hasegawa (1992), Seismic velocity structure of the crust beneath the Japan Islands, *Tectonophysics*, 212, 289-301, doi: 10.1016/0040-1951(92)90296-I

Figure 1. The empirical relationship proposed by *Hattori et al.* [2004] (see Febriani et al., 2014, Figure 10) between the earthquake magnitude and the distance from the epicenter of the ULF station where the preseismic anomaly was observed. The Biak earthquake has been included as reported in the original view of *Hattori et al.* [2004]. Note that the relationship was derived mainly using invalid ULF precursors (see Table S1).

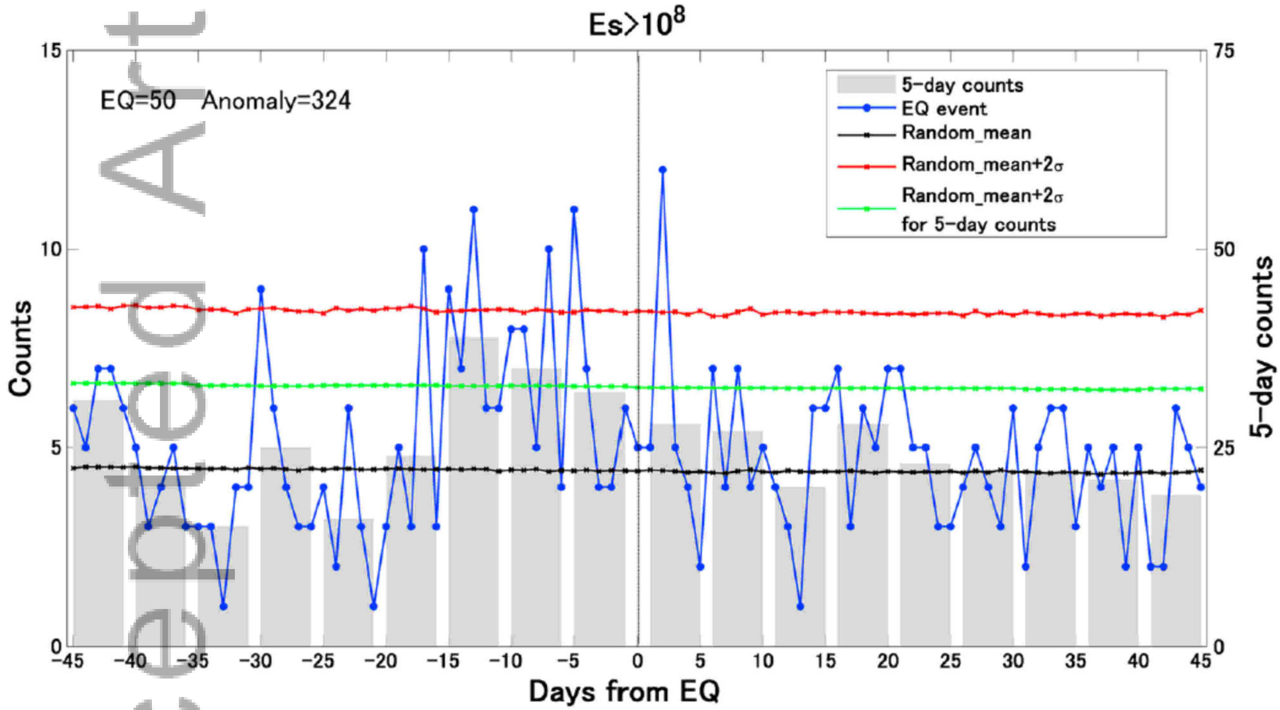
Figure 2. Polarization ratio analysis at the time of the 8 August 1993 Guam earthquake. a) 5-day running means of the polarization ratio Z/H and the geomagnetic index ΣKp for 1993. The shadow area refers to period of the occurrence of alleged precursory signals. The yellow solid line indicates the long-term increase in the Z/H ratio claimed to have a seismogenic origin by *Hayakawa et al.* [1996]. b) correlation plot between the daily values of Z/H and ΣKp. See text for details.

Figure 3. Daily values (blue line) and 10-day running mean (red line) of the amplitude of the geomagnetic field components H, D, and Z in the Pc3 band of frequency as reported by *Takla et al.*[2012, Figure 9] at the time of the 2007-2008 Peru earthquakes. The ΣKp index ±5-day running mean is superposed onto each panel of the original view. See text for details.

Figure 4. Polarization ratio analysis as reported by *Takla et al.* [2012, Figure 10] at the time of the 2007-2008 Peru earthquakes. The ΣKp index ±5-day running mean is superposed onto the original view. See text for details.

Figure 5. Superposed epoch analysis of *P* anomalies as reported by *Han et al.* [2014, Figure 8] for Region A. The blue, the black, and the red lines refer to the counted *P* anomalies, μ_{random}, and $\mu_{random} + 2\sigma$, respectively. The gray bars and the green line refer to *P* anomalies

counted in 5-day intervals and the corresponding $\mu_{random} + 2\sigma$, respectively. The vertical black line indicates Es>10^8earthquake at the Observatory of Kakioka.



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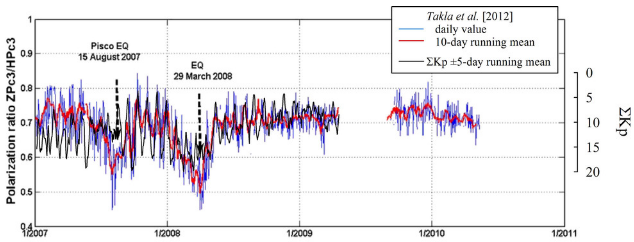

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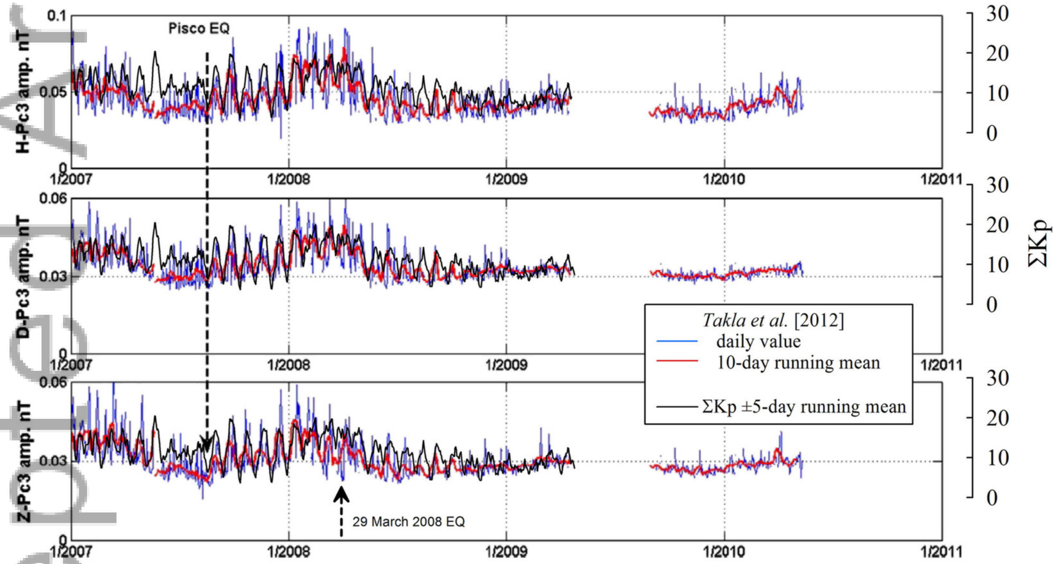

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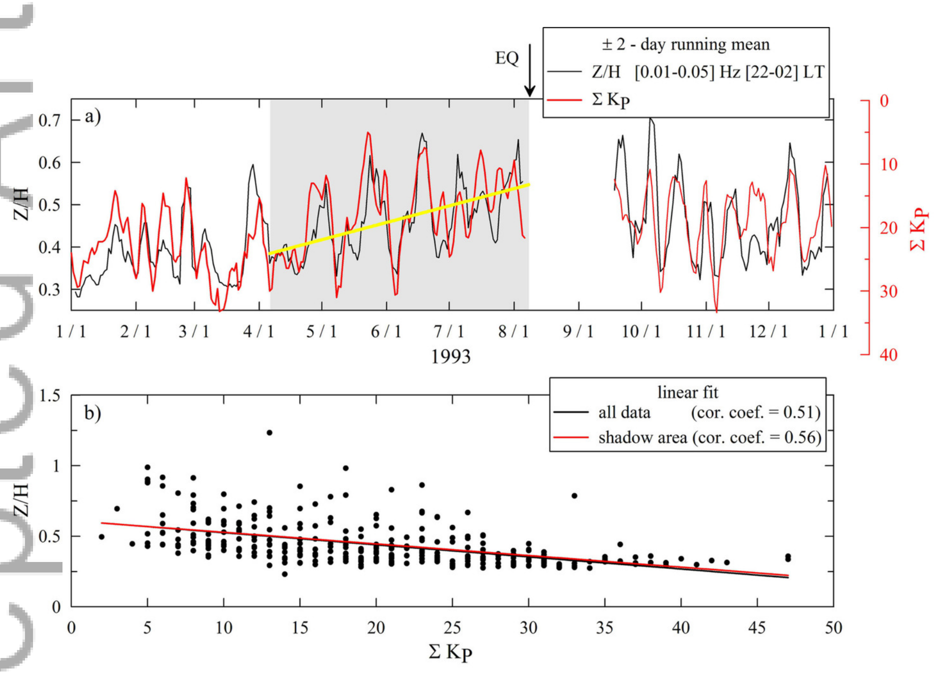

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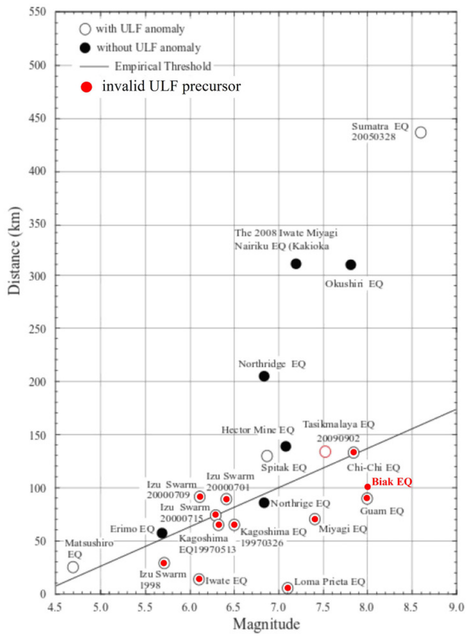

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