Accepted Manuscript

Review

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PII: S0031-9201(11)00087-2
DOI: [10.1016/j.pepi.2011.05.001](https://doi.org/10.1016/j.pepi.2011.05.001)
Reference: PEPI 5410

To appear in: *Physics of the Earth and Planetary Interiors*

Received Date: 23 November 2010
Revised Date: 1 May 2011
Accepted Date: 1 May 2011

Please cite this article as: Masci, F., On the seismogenic increase of the ratio of the ULF geomagnetic field components, *Physics of the Earth and Planetary Interiors* (2011), doi: [10.1016/j.pepi.2011.05.001](https://doi.org/10.1016/j.pepi.2011.05.001)

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On the seismogenic increase of the ratio of the ULF geomagnetic field components

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ABSTRACT

Following the paper by Fraser-Smith et al. (1990), many scientists have focused their research on the ULF geomagnetic field pulsations in the hope of finding possible anomalous signals caused by the seismic activity. Thereafter, many papers have reported ULF geomagnetic field polarization ratio increases which have been claimed to be related to the occurrence of moderate and strong earthquakes. Even if there is no firm evidence of correlation between the polarization ratio increase and seismic events, these publications maintain that these “anomalous” increases are without doubt precursors of pending earthquakes. Furthermore, several researchers suggest that these seismogenic signals may be considered a promising approach towards the possibility of developing short-term earthquake prediction capabilities based on electromagnetic precursory signatures. On the contrary, a part of the scientific community emphasizes the lack of validation of claimed seismogenic anomalies and doubt their association with the seismic activity. Since earthquake prediction is a very important topic of social importance, the authenticity of earthquake precursors needs to be carefully checked. The aim of this paper is to investigate the reliability of the ULF magnetic polarization ratio changes as an earthquakes' precursor. Several polarization ratio increases of the geomagnetic field, which previous researchers have claimed to have a seismogenic origin, are put into question by a qualitative investigation. The analysis takes into

account both the temporal evolution of the geomagnetic field polarization ratio reported in previous papers, and the global geomagnetic activity behaviour. Running averages of the geomagnetic index K_p are plotted onto the original figures from previous publications. Moreover, further quantitative analyses are also reported. Here, nine cases are investigated which include seventeen earthquakes. In seven cases it is shown that the suggested association between the geomagnetic field polarization ratio increases and the earthquake preparation process seems to be rather doubtful. More precisely, the claimed seismogenic polarization ratio increases are actually closely related to decreases in the geomagnetic activity level. Furthermore, the last two investigated cases seem to be doubtful as well, although a close correspondence between polarization ratio and geomagnetic activity cannot be unambiguously demonstrated.

Keywords: Earthquake precursors, Short-term earthquake prediction, Geomagnetic field, Seismology.

1. Introduction

The possibility of developing short-term earthquake prediction capabilities is one of the challenges of the Earth science but also one of the principal controversial main themes of discussion in the scientific community. Successful prediction could reduce both the number of victims and damages caused by earthquakes. Short-term earthquake predictions have been the topic of several scientific debates (Main, 1999) but at present their realization is rather remote. In order to be useful, short-term earthquake prediction requires reproducible earthquake precursors which provide real-time information regarding intensity, location and time of the predicted earthquake together with error estimates for each parameter. Therefore,

how to identify reliable earthquake precursors is a very important key in the hope of developing earthquake prediction capability.

Several researchers (e.g. Hayakawa et al., 2007; Uyeda et al., 2009; Hayakawa and Hobara, 2010) maintain that the preparation process of strong earthquakes could generate electromagnetic signals and suggest that the investigation of these precursors is one of the most promising approaches toward the realization of short-term earthquake prediction. While electromagnetic signals related to earthquake rupture strongly depend on earthquake magnitude, local geology, depth of hypocentre, distance between epicentre and point of observation, and azimuth to the rupture plane, it is not at all clear that precursive behaviour occurs. Several papers (e.g. Johnston, 1997; Mueller and Johnston, 1998; Johnston et al., 2006) report the observation of co-seismic electromagnetic phenomena within a few tens of kilometres of earthquake epicentres that are clearly related to earthquake rupture. However, no indication of precursive behaviour is apparent in the minutes or months before any of these events in electromagnetic or other seismic and geodetic data (Johnston et al., 2006). On the other hand, many other publications (e.g. Eftaxias et al., 2001; Pulinets and Boyarchuk, 2004; Varotsos, 2005; Molchanov and Hayakawa, 2008; Eftaxias et al., 2009) claim to observe electromagnetic earthquake precursors, sometimes many hundreds of kilometres from the earthquake, but with no clear co-seismic or post response effects. As a consequence, many in the scientific community doubt of the reality of claimed seismogenic electromagnetic signals and seriously question the claimed ability to develop short-term earthquake prediction capabilities using these precursory signatures. The principal criticisms of these researchers relate to: the absence of independent validation in other geophysical data; the lack of repeatability and reproducibility of the claimed precursory signals; failure to show that the claimed pre-seismic signals are not just chance events, random noise or global disturbances; and discussion as to why precursory signals should occur without the expected larger co-

78 seismic signals (see Geller, 1997; Geller et al., 1997; Kagan, 1997; Pham and Geller, 2002;
79 Johnston et al., 2006).

80 During the last twenty years several authors (e.g. Hayakawa et al., 2007; Fraser-Smith,
81 2008, and reference therein) have suggested investigating ULF (Ultra-Low- Frequencies:
82 0.001-10Hz) magnetic emissions as a promising approach to highlight seismogenic signals.
83 ULF magnetic waves result from superposition of different signals. These include natural
84 signals from solar-terrestrial interaction, man-made noise, and signals possibly generated in
85 the Earth's interior. However, the majority of ULF emissions have a magnetospheric origin,
86 whereas any seismogenic signals should be very weak. Different methods of analysis have
87 been considered to discriminate the low ULF crustal signals from other signals (see Hattori et
88 al., 2004 and Hayakawa et al., 2007 and references therein). Moreover, several physical
89 mechanisms have been proposed to account for the generation of ULF magnetic seismogenic
90 emissions (e.g. Fenoglio et al., 1995; Molchanov and Hayakawa, 1995; Draganov et al., 1991;
91 Merzer and Klemperer, 1997; Molchanov et al., 2004b; Simpson and Taflöve, 2005), but none
92 of them can be considered completely satisfactory (Thomas et al., 2009a).

93 One of the most well-known seismogenic ULF magnetic field anomaly claims has been
94 reported by Fraser-Smith et al. (1990) as a precursor of the 18 October 1989 $M_s=7.1$ Loma-
95 Prieta, California, earthquake. After this paper, ULF magnetic anomalies were claimed to be
96 related to strong earthquakes by several authors (e.g. Molchanov et al., 1992; Kopytenko et
97 al., 1993; Hayakawa et al., 1996). In retrospect, some researchers seriously doubt the
98 authenticity of the Loma-Prieta precursor. They maintain that the ULF magnetic field
99 anomaly reported by Fraser-Smith et al. (1990) could actually be caused by instrumentation
100 malfunction (Thomas et al., 2009a) or that it is generated by normal geomagnetic activity
101 (Campbell, 2009). Furthermore, Masci (2010) put in doubt the reliability of fractal magnetic
102 ULF signatures in the geomagnetic field that previous publications have claimed to be related

without doubt to the preparation process of strong earthquakes by showing that these fractal “anomalies” are likely caused by normal geomagnetic activity. In light of this, in attempting to resolve the problem of clearly identifying reliable earthquake precursory signals, a closer inspection concerning the presence of seismogenic signals in geophysical data sets is required.

In the next section, the reliability of ULF geomagnetic field polarization ratio increases which previous papers related to the seismic activity is investigated.

2. Polarization ratio analysis

Many researchers (e.g. Hattori, 2004; Hattori et al., 2004; Hayakawa et al., 2007) consider the investigation of ULF geomagnetic field polarization ratio to be a key parameter which allows us to detect possible magnetic seismogenic signals.

If H , D , and Z represent the variations (nT) of the geomagnetic field components around the NS, EW, and vertical direction respectively, then $G = \sqrt{H^2 + D^2}$ is the total horizontal variation of the geomagnetic field (Kopytenko et al., 1991). In a fixed range of frequency, the magnetic polarization ratio is defined as the ratio between the integrated power P (nT²) of the vertical component and the one of the horizontal component, that is: P_Z/P_H , P_Z/P_D , and P_Z/P_G . In any case, hereafter we refer to the polarization ratio as Z/H , Z/D , and Z/G . Sometimes polarization ratio is defined as the ratio of the amplitudes (nT), that is the square root of the integrate powers, or other authors (e.g. Hattori et al., 2002) report the ratio of the spectral intensities (nT/ $\sqrt{\text{Hz}}$). As a matter of fact, this method is not really a "polarisation analysis" (where polarisation azimuth and ellipticity are available), but merely the calculation of the ratio between the vertical and the horizontal components of the geomagnetic field. However, here we refer to this ratio as “polarization ratio” as has been

used in previous papers. The fundamental assumption of this methodology is that presumed ULF magnetic seismogenic emissions prevail in the vertical direction, contrary to ULF signals of magnetospheric origin which typically have horizontal components larger than the vertical one. Therefore, the ULF magnetic polarization ratio should increase in correspondence with seismogenic magnetic emissions, whereas it is relatively small for geomagnetic pulsations.

Usually the possible seismogenic electromagnetic radiation, which could affect the ULF signals amplitude on the ground surface, may be distinguished between the direct radiation from the earthquake hypocentre region (see Fenoglio et al., 1995; Molchanov and Hayakawa, 1995) and the indirect effect on the ULF signals of external origin due to the variation of the electric Earth's crust conductivity caused by seismic activity (see Merzer and Klemperer, 1997). In addition, several authors maintain that a further contribution to observed polarization ratio increases could be related to the depression of the geomagnetic field horizontal components caused by indirect mechanisms of lithosphere-atmosphere-ionosphere coupling which take place during seismic activity (see Molchanov et al., 2004b).

Even though many papers report examples of ULF polarization ratio increases before the earthquake occurrence, several problems remain concerning the reliability of these “anomalous” signals. An issue of the fundamental importance is how to separate the possible ULF seismogenic signals from other signals such as natural signals (geomagnetic pulsations caused by solar-terrestrial interaction, thunderstorms, etc.) and the artificial noise caused by human activities (DC electric trains, power lines, etc.). The man-made noise can be reduced by focusing the analysis only on night-time data. On the contrary natural signals might not be eliminated using this method. Since the majority of ULF emissions result from magnetospheric disturbances, caused by the interaction of the solar wind with the Earth's magnetosphere, the simplest way to check the real presence of non-space signatures in the

geomagnetic field is comparing the ULF signals with the global geomagnetic activity behaviour (Masci, 2010). More precisely, several publications (see Saito, 1969 and references therein) show that the amplitude of ULF geomagnetic field continuous micropulsations (PCs) have a clear positive relation with K_p index, which is representative of average disturbances of the planetary geomagnetic field. This positive relation is evident mainly in PC₂, PC₃ and PC₄ bands. Note that the ULF seismogenic signals here put into question are observed in these bands of frequency. Therefore, if we demonstrate a close correspondence between the time-series of a ULF geomagnetic field parameter and the K_p index we can affirm that the changes of the geomagnetic field parameter is mainly caused by the variation of the geomagnetic activity or, more precisely, it is due to non-earthquake sources.

In the following sections several cases of the ULF geomagnetic field polarization ratio increases, which previous researchers have claimed to be related without doubt to earthquake occurrences, are put into question by comparing their temporal evolution with the geomagnetic behaviour of K_p index. Furthermore, for the first two cases the linear residual time-series and the correlation coefficient between polarization ratio and K_p index have been calculated by digitalizing the published figures.

2.1 Guam earthquake 1993

On 8 August 1993, a strong earthquake ($M_w=7.7$, depth=60km) occurred offshore the island of Guam. In the hope of finding possible magnetic earthquake precursors, Hayakawa et al. (1996) performed polarization ratio analysis in the frequency band [0.01-0.05]Hz. They analysed the ULF (1Hz sampling rate) geomagnetic field data of Guam observatory, which is located about 65 km away from the earthquake epicentre. To reduce man-made noise, the authors focused their investigation on the night period [22:00-02:00]LT. The principal claim of Hayakawa et al. (1996) is an “anomalous” increase in the polarization ratio Z/H which

occurs during the period before the earthquake date. Hayakawa et al. (1996) also maintain the presence of an enhanced maximum in the polarization ratio two months before the seismic event (see Fig. 1, panel (a)). According to these authors, this maximum may be strong evidence of magnetic precursory signals caused by the earthquake preparation process. As a matter of fact, Thomas et al. (2009b) seriously put into question the reliability of Hayakawa et al. (1996) conclusions by performing new analysis and comparing Guam data with data coming from the geomagnetic observatory of Kakioka, Japan. The results of Thomas et al. (2009b) are shown in Fig. 1 and can be summarized in the following three points: 1) problems of analysis have been found in Hayakawa et al. (1996) since the new analysis does not match the previous one (compare panel (a) and panel (b) of Fig. 1); 2) Guam and Kakioka data show a significant correlation with the geomagnetic activity. More precisely, both Guam and Kakioka geomagnetic field horizontal components show a similar temporal behaviour of the K_p index (see Thomas et al., 2009b, Fig. 1); 3) no clear seismogenic signatures have been highlighted in the Guam data. The authors conclude that the Z/H ratio increase, which occurred before the Guam earthquake is caused by the normal global geomagnetic activity, therefore it is not related to the earthquake occurrence.

To verify Thomas et al. conclusions, the temporal evolution of the geomagnetic index K_p daily sum (ΣK_p) is superimposed onto the panel (b) of Fig. 1. Both the 5-day running average and the 6th order polynomial fitting of ΣK_p are reported in the figure. Consider that ΣK_p vertical axis is descending. As a matter of fact, the 5-day running average confirms the close inverse correspondence between the Guam polarization ratio and the geomagnetic activity level: on average Z/H increases (decreases) when ΣK_p decreases (increases). Moreover, all the principal maxima of the Guam polarization ratio can be undoubtedly associated with the geomagnetic activity. Furthermore, the 6th order polynomial fitting highlights that also the slow increase, which the polarization ratio shows the period before the

Guam earthquake, mainly depends on the geomagnetic activity. Thus, as previously pointed out by Thomas et al., its association with the seismicity seems to be rather inappropriate.

As further confirmation of previous mentioned conclusions, Guam polarization ratio data are drawn out by digitalizing the figure of Thomas et al. (here panel (b) of Fig.1). The correlation coefficient (-0.7) shows that Guam Z/H ratio and ΣK_p time-series are generally well correlated with each other during the period before the earthquake data; its negative value demonstrates the inverse correspondence. This shows that, the period before the earthquake occurrence, Guam ULF Z/H variations are mainly caused by changes of the global geomagnetic activity. On the other hand, the correlation coefficient between Guam Z/H ratio and ΣK_p time-series is lower (- 0.4) in the period after the earthquake date. Thomas et al. show similar results by calculating the correlation coefficient between Guam H component and K_p index. As previously shown by the qualitative investigation, Z/H and ΣK_p time-series have similar trends. This can be demonstrated calculating their linear relationship (Thomas et al., 2009b). This relationship is: $Z/H = - 0.083 \times \Sigma K_p + 0.57$. In Fig. 1, panel (e), the linear residual time-series is reported. Here we see that on average the residual time-series is mainly flat and does not show any anomalous signature which could be related to the seismic activity of the Guam area. Moreover, the root mean square (0.06) of the residual is much lower, as Thomas et al. pointed out, than the year-long trend (≈ 0.2) of the Guam Z/H time-series.

2.2 Biak earthquake 1996

On 17 February 1996, a strong earthquake ($M_w=8.2$, depth=20km) struck Biak island, Indonesia. Hayakawa et al. (2000) investigated the ULF geomagnetic field polarization ratio behaviour at two observatories: Biak and Darwin, Australia, located respectively about 100 km and 1200 km away from the earthquake epicentre. The authors analysed the ULF geomagnetic signals, in the frequency band [5-30]mHz and during the night period [22:00-

04:00JLT, maintaining that the Biak polarization ratio Z/H shows two anomalous increases about 1.5 months and 2 weeks before the earthquake occurrence. On the contrary Darwin Z/H ratio does not show corresponding increases. Hayakawa et al. (2000) concluded that the enhancements of the Biak polarization ratio are seismogenic precursory signatures of the forthcoming earthquake. Figure 2a shows the ± 5 -day running average of the polarization ratios as reported by Hayakawa et al. (2000). Dashed green circles on the original view highlight the two polarization ratio increases. To investigate the reliability of these results, the ± 5 -day running average of ΣK_p has been superimposed onto the Biak panel. Figure 2a shows that the two increases of the polarization ratio actually correspond to decreases of ΣK_p . Thus, the claimed precursory signals seem to be once again mainly related to the geomagnetic activity level. As a matter of fact, a close inverse correspondence between polarization ratio and geomagnetic activity cannot be unambiguously demonstrated during the whole period. In any case, since K_p index is representative of the geomagnetic field activity over global scales, a strict correspondence between polarization ratio and ΣK_p cannot always exist, otherwise the geomagnetic field polarization ratio pattern should be the same in all the observation sites (refer also to the comments reported in section 3).

As for the Guam case, Biak polarization ratio values are drawn out by digitalizing the figure of Hayakawa et al. (2000) (here upper panel of Fig. 2a). However, looking at Fig. 2 it is evident that there is a good inverse correspondence between Biak Z/H ratio and ΣK_p time-series the period after the middle of December 1995, but on the contrary the correlation fails before this period. This is confirmed by the calculation of the correlation coefficient between Z/H and ΣK_p : (0.22) before the middle of December 1995 and (-0.64) after this period. In any case, the correlation coefficient shows that a good inverse correspondence between Z/H and ΣK_p really exists during the period of the claimed seismogenic “anomalies” occurrence. In light of this, we have calculated the linear relationship between Z/H ratio and ΣK_p time-series

after the middle of December 1995. This relationship is: $Z/H = -0.0019 \times \Sigma K_p + 0.56$ (root mean square = 0.05). The little panel at the top of Fig. 2a reports the residual time-series. Also in this case no seismogenic anomaly may be stated.

Furthermore, Hayakawa et al. (2000) seem to show inconsistencies in their results as well. Figure 2b reports the geomagnetic field components H and Z observed at Biak and Darwin as shown by Hayakawa et al. (2000). The authors report, in unspecified units, the ULF wave activity (see Hayakawa et al., 2000 for details) of the geomagnetic field components integrated in the frequency band [5-30]mHz. We note that Z and H values reported in Fig. 2b do not correspond with Z/H values of Fig. 2a. More precisely, In Fig. 2b the differences between Z and H are very small during the whole period, thus the ratio Z/H should have small fluctuations with a mean value near 1 and not the values reported in Fig. 2a. Finally, it is important to note that Hobara et al. (2004) report further analysis of Biak data and conclude that there are no significant increases in the geomagnetic field polarization ratio before the 17 February 1996 earthquake.

2.3 Iwateken Nairiku Hokubu earthquake 1998

Hattori et al. (2004), and later Hattori (2004), report ULF ([10±3]mHz) geomagnetic field polarization ratio analysis during the period of the Iwateken Nairiku Hokubu earthquake (M=6.1, depth=10km) which occurred on 3 September 1998 at Honshu island, Japan. The authors analysed geomagnetic data measured during night-time [00:00-04:00]LT at three different stations: Matsukawa, Memambetsu and Kanoya which are located respectively about 15km, 500km and 1300km away from the epicentre. To reduce spurious noise the authors perform a 5-day backward running average on the polarization ratio daily values. They conclude that the polarization ratio S_z/S_D of Matsukawa shows an increase about two weeks before the earthquake when it reaches a value (≈ 1.5) which is twice the normal level.

According to the authors, this increase is a local phenomenon restricted to Matsukawa, the closest station to the epicentre area, since the polarization ratio of the stations further from the earthquake epicentre do not show a similar behaviour.

Figure 3 shows the polarization ratios as reported by Hattori (2004) and Hattori et al. (2004). Checking their conclusions, the 5-day backward running average of ΣK_p is superimposed on the upper panel of the figure. As a matter of fact, we can note that the Matsukawa polarization ratio increase corresponds to a decrease of the geomagnetic activity. Unfortunately, due to a gap in data we cannot check the polarization ratio behaviour of Matsukawa during the period just following the anomaly occurrence. To better investigate the reliability of the claimed “anomaly” an enlarged view is added onto the original figure. Actually, the enlarged view shows that, during the period of the anomaly occurrence, the polarization ratio has a similar increase in all the stations. The only difference is that the three increases of the polarization ratio have different amplitudes as would be expected for data coming from stations located at different magnetic latitudes. Furthermore, the polarization ratio analysis seems to also show inconsistency in the results because S_Z and S_D (see Hattori et al., 2004 Fig. 11) do not agree with their ratio S_Z/S_D reported in Fig. 3.

2.4 Izu swarm 1998

Kopytenko et al. (2001) report the temporal evolution of the ULF geomagnetic field polarization ratio at Kamo station during two earthquakes swarms which occurred in the period April-May 1998 near the Japanese Izu peninsula. The distance between the station and the epicentres is about 30-40 km. The main shocks occurred respectively on 26 April ($M_s=4.7$) and on 3 May ($M_s=5.7$). Fig. 4 (lower) shows the 5-day running average of the polarization ratio Z/G as reported by Kopytenko et al. (2001). The polarization ratio has been calculated in three bands of frequencies during the night period [00:00-04:00]LT. The

temporal evolutions of the seismic activity and the geomagnetic index ΣK_p are reported as well. Note that, in the original figure the time scale of the upper panel does not match with the time scale of the other two panels. The inconsistency of the time scales has been checked by plotting ΣK_p data on the original view of the upper panel using the time scale of the two lower panels. Therefore, in Fig. 4 the upper panel has been horizontally shifted in order to match the time scales. Kopytenko et al. note that: 1) in correspondence with the two main shocks, sharp increases of the geomagnetic activity occur; 2) there is an evident increase of the polarization ratio which starts about twenty days before the first swarm; this increase reaches its maximum two days before the beginning of the swarm; then the polarization ratio decreases and reaches a minimum in correspondence of the $M_s=5.7$ seismic event; 3) the changes in polarization ratio depend on the frequency range and they are more pronounced in the lower frequency bands. Finally, the authors conclude that the behaviour of the polarization ratio is caused by a combination of the geomagnetic activity and the seismogenic ULF emissions.

In order to check the conclusions of Kopytenko et al. (2001), the 5-day running average of ΣK_p is plotted onto the lower panel of Fig. 4. Actually, Fig. 4 shows a close inverse correspondence between the geomagnetic activity and the polarization ratio during the whole period. In light of this, the increase before the first swarm, the decrease before the $M_s=5.7$ shock and the following recovery of the polarization ratio to ordinary values seems to depend mainly on the geomagnetic activity level. Thus, the possible presence of seismogenic signatures in the geomagnetic field polarization ratio is rather doubtful.

2.5 Izu swarm 2000

Between June and August 2000, a seismic swarm occurred near the Izu peninsula. Five strong $M > 6$ earthquakes occurred on 1, 8, 15 and 30 July and 18 August. Ismaguilov et al. (2001) report the ULF geomagnetic field polarization ratios at the stations of Molchikoshi,

Seikoshi and Kamo about 80km away from the epicentre area. The polarization ratio has been calculated in the frequency range $[5\pm 3]$ mHz during the night period [00:00-06:00]LT. Figure 5a shows the 20-day running average of the polarization ratio Z/G as reported by Ismaguilov et al. (2001). The amplitude variations of the geomagnetic field components Z and G are shown as well. The authors maintain that the polarization ratio increases before the seismically active period at all the stations. They also note an increase in the amplitude of the geomagnetic field components Z and G . Since the amplitude enhancement is more pronounced in the vertical component Z they concluded that the Z/G ratio increase is caused by seismic activity. As in previous cases, the running mean of ΣK_p is superimposed onto the original view of the polarization ratios. In this case the time window of the running average is ± 10 -day. Figure 5a once again shows a close inverse correspondence between ΣK_p and polarization ratios. Both the increase before the seismic active period and the following decrease seem mainly to depend on the geomagnetic activity level. Therefore, their association with the seismic events is rather inappropriate.

Ismaguilov et al. (2003) compare the ratios Z/G of Kamo station and Kakioka observatory located more than 200 km from Izu. The 3-day running averages of the polarization ratio are calculated at 0.042Hz during night-time [00:00-07:00]LT. Figure 5b shows the polarization ratios Z/G as reported by Ismaguilov et al. (2003). The authors maintain that at Kamo station Z/G shows features which could be related to the seismic activity even if the sharp decrease of 15 July is probably caused by a geomagnetic storm. Checking a possible correspondence between the ratio Z/G and the geomagnetic activity, the 3-day running average of ΣK_p is superimposed on the polarization ratio of Kamo station. As a matter of fact, Fig. 5b shows that the behaviour of Z/G is closely related to the geomagnetic activity level before and during the seismic swarm. Therefore, the possible association with the seismic activity seems to be once again rather doubtful.

2.6 Kamchatka earthquakes 2000-2001

Several papers report the analysis of geomagnetic field data measured at the observatory of Karimshino, Kamchatka, Russia (e.g. Gladyshev et al., 2001; Molchanov et al., 2003; Molchanov et al., 2004a). According to the authors Kamchatka peninsula is an ideal place to observe low ULF seismogenic signals because it is characterized by low man-made noise and by a significant seismicity as well. Furthermore, they claim several increases of the ULF geomagnetic field polarization ratio related to the Kamchatka seismic activity. Figure 6a shows the square root of the amplitude polarization ratio Z/G in the period 2000-2001 as reported by Molchanov et al. (2003). The authors calculated $\sqrt{Z/G}$ in the frequency band [10-30]mHz and averaged it over a 2-hour window. The temporal evolution of the geomagnetic K_p index and K_s index (yellow stars in Fig. 6a) are reported as well. K_s is an index which depends both on the earthquake magnitude and on the distance between the observation point and the earthquake epicentre (see for details Molchanov et al., 2003). The authors maintain that, during night-time, $\sqrt{Z/G}$ increases from 2 to 7 days before the occurrence of five strong earthquakes (yellow stars with a red dot in Fig. 6a). Green circles are added on the original view to highlight the claimed seismogenic polarization ratio increases. To investigate the behaviour of $\sqrt{Z/G}$, the corresponding K_p index temporal evolution is superimposed onto the polarization ratio panels. As a matter of fact, Fig. 6a shows that on average high polarization ratio values correspond to low K_p values. More precisely, the polarization ratio increases, which are claimed to have a seismogenic origin, actually correspond to low geomagnetic activity levels; on the contrary low polarization ratio values correspond to high geomagnetic activity levels. This relation is evident over the whole period reported in the figure. Furthermore, Fig. 6a also shows further polarization ratio increases which are not related to

any strong earthquake; refer to the increases of 13 July and 26 August. In light of this, once again a close inverse correspondence between polarization ratio and geomagnetic activity is shown. Thus, the previous claims to a seismogenic origin are rather dubious.

To better investigate the origin of the Z/G increases the authors compare the ratios Z/G and $1/G$. Figure 6b shows the daily values of Z/G and $1/G$ ratios as reported by Molchanov et al. (2003) in the same periods of Fig. 6a. Since the two ratios show the same behaviour over the whole period the authors conclude that the Z/G increases are caused by the suppression of the horizontal magnetic field component G and not by the increase of the vertical component Z . They suggest that the suppression of the ULF horizontal component is not related to electromagnetic emissions generated by a source located inside the Earth, but it is caused by the perturbation of the lower ionosphere due to a lithosphere-atmosphere-ionosphere coupling mechanism. According to them the conductivity of the ionosphere could be modified by the intensification of the atmospheric gravity waves related to changes of atmospheric temperature and pressure near the Earth's surface caused by the seismicity (see Molchanov et al., 2004b). In Fig. 6b, the temporal evolution of the geomagnetic index K_p daily sum (ΣK_p) is superimposed onto the polarization ratio daily values. The figure shows an evident inverse correspondence between the polarization ratio and the geomagnetic index ΣK_p over the whole period. Therefore, once again Fig. 6b confirms that the polarization ratio increases are closely related to low geomagnetic activity levels.

2.7 Bovec earthquake 2004

Prattes et al. (2008) report the ULF polarization ratio analysis of magnetic data coming from the South European Geomagnetic Array (SEGMA) during the period of Bovec, Slovenia, earthquake ($M=5.5$, depth 6Km) which occurred on 12 July 2004. According to the authors the ULF geomagnetic field polarization ratio of Castello Tesino, the closest station to

the earthquake epicentre, shows significant increases before the earthquake occurrence. Fig. 7 shows the geomagnetic field components, Z and H, and the polarization ratio $R=Z/H$ as reported by Prattes et al. (2008) in the frequency band [0.01-0.05]Hz. Taking into account the geomagnetic field components behaviour, the authors maintain that the polarization ratio increases could be caused by decreases of the horizontal component amplitude. They also claim an increase of the polarization ratio occurred on 12 July caused by the high amplitude of the geomagnetic field vertical component. To check the possible relation between the polarization ratio enhancements and the Bovec earthquake, the temporal evolution of the K_p index is plotted on the polarization ratio panel. Taking into account the K_p behaviour, it is clearly evident that, before the Bovec earthquake, there is a close inverse correspondence between the polarization ratio increases and the geomagnetic activity. This correspondence can also be found in the period following the earthquake data but it is not the case during week 7. However, since week 7 is a period characterized by a very high geomagnetic activity level, as expected, the polarization ratio shows on average low values because the horizontal component amplitude increases dominate the lower vertical component increases (see Prattes et al., 2008).

In another figure, not reported here, the authors compare the polarization ratios daily averages of three SEGMA stations: Castello Tesino, Nagycenk and Ranchio (see Fig. 5 of Prattes et al., 2008). The distance of the stations from the epicentre area is respectively 153, 275, and 291 km. The authors conclude that the highest polarization ratio amplitude is observed at Castello Tesino, the closest station to the epicentre. Actually, Fig. 5 of Prattes et al. (2008) shows that the three polarization ratios display a similar behaviour. The only difference is in their amplitudes as expected for different stations. Concerning the polarization ratio increase of 12 July, it disappears in the daily values. This suggests that the increase

could be caused by environmental noise or, at least, this could suggest that the possible seismogenic emission has a short duration.

In the last two cases reported in the following sections, the correlation between the polarization ratio and the geomagnetic activity cannot be unambiguously demonstrated. However, the claimed polarization ratio enhancements can be considered doubtful as well.

2.8 Kagoshimaken-Hokuseibu earthquakes 1997

Hattori (2004) report the ULF polarization ratio S_Z/S_G at Tarumizu station, Japan, located 60km away from the epicentre area of the $M=6.5$, 26 March 1997, and $M=6.3$, 13 May 1997, Kagoshimaken-Hokuseibu earthquakes. The polarization ratio has been calculated in the frequency band $[0.010 \pm 0.003]$ Hz during night-time $[00:00-04:00]$ LT. Figure 8a shows the 10-day backward running average of the ratios S_Z/S_G at Tarumizu and two reference stations which are located very far from the epicentre area: Chichijima, Bonin Islands, and Darwin, Australia. The regional seismicity and the geomagnetic index ΣK_p are reported as well. The author claims a significant increase of the S_Z/S_G ratio occurred at Tarumizu about one month before the 26 March earthquake. Since the polarization ratios of the two reference stations do not show similar increases the author maintains that the Tarumizu polarization ratio increase is without doubt a precursory signature of Kagoshimaken-Hokuseibu earthquakes. Checking the conclusions of the author, the 10-day backward running average of ΣK_p is also superimposed in the polarization ratio panel. Even if both Tarumizu polarization ratio and ΣK_p show a similar behaviour in the period before the claimed anomaly occurrence, their temporal evolutions are rather different in the following period.

As a matter of fact, the results of Hattori (2004) were previously reported by Hattori et al. (2002). This paper also shows the temporal evolution of S_Z and S_G which are reported here

in Fig. 8b. Actually, comparing S_Z and S_G with their ratio S_Z/S_G we can note inconsistency in the results of the previous research. More precisely, the ratio between S_Z and S_G provides values lower than the ratio S_Z/S_G reported in Fig. 8a. For example, referring to Tarumizu data, on 5 March 1997 S_Z is about 0.0040 and S_G is about 0.0035, so S_Z/S_G should be about 1.15, but the value reported in the previous papers is about 2.2. Furthermore, we can also note that before the first earthquake the polarization ratio of Chichijima station shows a slight increase similar to that of Tarumizu station. This suggests that the behaviour of the polarization ratio of Tarumizu station could have a global origin. Unfortunately a gap in data, which occurred at the Darwin station (the conjugate point of Tarumizu) during the period of the claimed anomaly, precludes further investigation. In conclusion, the Tarumizu precursor also seems to be not totally reliable.

2.9 Chi-Chi earthquake 1999

Akinaga et al. (2001) report the ULF polarization ratio Z/G at Lunping station, 120 km from the epicentre of Chi-Chi, Taiwan, earthquake ($M_w=7.7$, depth 11km) occurred on 21 September 1999. Figure 9 shows the temporal evolution of the polarization ratio as reported by Akinaga et al. (2001) in the frequency band $[0.010 \pm 0.003]$ Hz during the night period $[00:00-04:00]$ LT. The authors claim an increase in the geomagnetic field polarization ratio before the earthquake occurrence. To investigate the polarization ratio behaviour, the ± 5 -day running average of ΣK_p is reported in the figure both with a descending vertical axis and, for the last period, with an increasing vertical axis. Figure 9 emphasizes a rather strange behaviour of Z/G . To be more precise, Z/G shows a close inverse correspondence with ΣK_p up to April 1999 just before a gap in the data. On the contrary, it seems to show a positive correlation with ΣK_p in the period following this gap in data. Unfortunately, lack of data does not permit investigation of the behaviour of Z/G in the period following the earthquake date.

In light of this, I think that there are two possibilities: 1) the close positive correlation after April 1999 is just a chance event, therefore the polarization increase is real; 2) there are analysis problems just after the gap in data which occurred on April 1999. In my opinion, this is enough to cast doubt on the reliability of the results until further analysis confirms the seismogenic origin of the claimed anomaly. As a final consideration I would like to point out that Liu et al. (2006) analysis of data from the Taiwan geomagnetic network in the period of Chi-Chi earthquake uses Lunping as reference station. Taiwan geomagnetic network consists of eight stations in which the total geomagnetic field intensity is measured. According to the authors Lunping is located in a seismic quiet area, so its magnetic measurements are not affected by the seismic activity. Using Lunping as reference station, Liu et al. (2006) claim seismogenic magnetic anomalies at the two stations of the Taiwan network closest to the epicentre area. In conclusion, it is very strange that Lunping station, in which an anomaly on the geomagnetic field polarization ratio has been claimed to be related to the Chi-Chi earthquake by Akinaga et al. (2001), is used as reference station in a similar research performed during the same period.

3. Comments and conclusions

In this paper, nine cases of ULF geomagnetic field polarization ratio increases which previous publications have related, without doubt, to the occurrence of strong earthquakes have been investigated by a qualitative inspection. The analysis compares the polarization ratio behaviour reported in previous papers with the geomagnetic activity level. Running averages of the ΣK_p geomagnetic index are plotted onto the original figures from previous publications. Furthermore, several problems are identified in the previous research. First of all, in the majority of the cases are reported data sets which are too short; they sometimes represent just a few months. This does not permit a complete view of the behaviour of the

parameters under investigation. Moreover, usually in order to exclude the presence of magnetospheric signals, the authors point out that the claimed seismogenic anomalies took place during periods characterized by a low geomagnetic activity. In my opinion this is an oversimplified assumption because the variation of the geomagnetic activity, which induces changes in several geomagnetic parameters, must be taken into account. For example, when the geomagnetic activity decreases, both polarization ratio and fractal dimension (see Masci, 2010) of the geomagnetic field increase. Thus, this paper shows that the claims of previous publications concerning the correlation between the ULF polarization ratio increases and the seismic activity are not meaningful without properly taking into account the behaviour of other ULF sources evident in the global geomagnetic activity. Furthermore, the comparison between the analysed parameters and the geomagnetic indices must be performed using the same temporal resolution. More precisely, the correlation between the temporal behaviour of the polarization ratio and the geomagnetic index must be investigated by averaging procedures using the same time window.

This paper shows that in seven of the investigated cases, for a total of fourteen earthquakes, the increases of the geomagnetic field polarization ratio, which previous authors have claimed without doubt to be related to strong earthquakes, apparently result from a decrease of the geomagnetic activity level. On average, when the geomagnetic activity decreases, the reduction of the geomagnetic field horizontal components are larger than the reduction of the vertical component, therefore the polarization ratio increases. On the contrary, an increase of the geomagnetic activity causes an increase in the geomagnetic field horizontal components larger than the increase of the vertical component, therefore the polarization ratio decreases. In light of this, if we may exclude that all the correspondences reported in this paper are just chance events, the simple association between the polarization ratio increases and the seismic events are doubtful in all seven cases. Regarding the last two

investigated cases, they seem to be doubtful as well: the first case shows inconsistency in the results so that the claimed polarization precursor could not be totally reliable; in the second case, the apparent correspondence between the polarization ratio and the geomagnetic index seems to behave oddly during the analysed period. Moreover I want point out that Masci (2010) seriously put in doubt ULF magnetic fractal precursors which previous papers have related to the occurrence of the three seismic events (Guam 1993, Biak 1996 and Izu 2000) also questioned in this paper.

I want to point out again that the methodology adopted in this paper, and previously in Masci (2010), is just a qualitative or, more precisely, a visual investigation, even if the quantitative analyses here reported for the first two cases confirm the qualitative claims. Furthermore, I would like to emphasize that all the polarization ratio increases, put into question here, were claimed to be seismogenic signatures just by visual inspection. In my opinion, an anomaly cannot be recognized as seismogenic just by visual investigation on the contrary, the seismogenic origin of a by-eye anomaly can be put into question by a visual investigation. Obviously, it's likely that an "anomalous variation" of a geomagnetic field parameter (e.g. polarization ratio or fractal dimension) can happen before the occurrence of an earthquake, but relating these variations to the seismic events without further validations is just an oversimplified conclusion. However, the geomagnetic activity behaviour must be taken properly into account in order to quantify how much variability in the data can be attributed to the geomagnetic global activity and how much to the possible ULF precursors.

Concerning the correspondence between polarization ratio changes and geomagnetic activity, since Kp index is representative of the geomagnetic field average disturbances over global scales, it is impossible that the polarization ratio must always show the same features of ΣKp , otherwise the geomagnetic field polarization ratio pattern should be the same in all the observation sites. To be more precise, the majority of ULF signals are external signals

which come from the interplanetary space and magnetosphere. These signals include upstream waves, resonances processes, ion-cyclotron waves, and others, and are generated by well-known and different sources (McPherron, 2005). Each external source gives its contribution, at different frequencies inside the ULF band, to the signals observed on the ground. Some of these signals have a worldwide extension, whereas others could have latitude dependence (Saito, 1969). Thus, even if the amplitude of ULF geomagnetic field signal has a clear positive relation with Kp index, we should not expect that a strict correspondence between polarization ratio and ΣKp will always exist. On the other hand, if we demonstrate a close correspondence between the ULF geomagnetic field ratio Z/H changes and the geomagnetic index variations, we can affirm that the Z/H changes are caused by the variation of the geomagnetic activity, or more precisely we can point out that they are related to signals having external origin, and not to signals generated by sources located inside the Earth. Therefore, appeals to a seismogenic origin are rather dubious.

In conclusion, it is evident that some problems of fundamental importance in the investigation of seismo-magnetic signals are still remaining unresolved and a huge amount of research and a constructive criticism of the results are needed. Finally, I would like to emphasize that, as Eftaxias et al. (2009) point out, a single analysis by itself cannot establish if an anomaly is a precursor or just a chance event. Therefore, as Uyeda et al. (2009) suggest, a really multidisciplinary approach, which involves the investigation of physical, geochemical, hydrological and other parameters, could be useful to recognize an anomaly as a real seismogenic signature.

571 **Acknowledgements**

572 A special thanks to Dr. Roberta Giangiuliani for her invaluable help. I am also grateful
573 to the Editor and two anonymous reviewers for the constructive comments that were useful to
574 improve the manuscript. The author also thanks Dr. Paolo Palangio, for the constructive
575 discussions. The geomagnetic Kp index has been downloaded from Kyoto World Data Center
576 for Geomagnetism (<http://swdcwww.kugi.kyoto-u.ac.jp/>).

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Figure captions

Fig. 1. ULF polarization ratio analysis during the period of Guam earthquake as reported by Thomas et al. (2009b) (a reproduction of Thomas et al., 2009b, Fig. 2). EQ refers to the earthquake date. The panel (a) shows the 5-day running average of the ratio Z/H at Guam observatory as reported by Hayakawa et al. (1996). Panels (b), (c) and (d) show respectively the 5-day running average of the ratio Z/H at Guam observatory, the 5-day running average of the ratio Z/H at Kakioka observatory, and the residual of the linear relationship between Guam and Kakioka polarization ratios. The 5-day running average and the 6th order polynomial fitting of ΣK_p are superimposed onto panel (b). Panel (e) has been added to the original view and shows the residual of the linear relationship between Guam Z/H ratio and ΣK_p . See text and Thomas et al. (2009b) for details.

Fig. 2a. Temporal evolution of the ULF polarization ratio Z/H at Biak and Darwin in the period November 1995 - March 1996 as reported by Hayakawa et al. (2000) (a reproduction of Hayakawa et al., 2000, Fig. 3). EQ refers to the earthquake date. Dashed green circles highlight the increases of the Biak polarization ratio claimed to be related to the seismic activity. For a better display, the original pale yellow lines of the polarization ratio running averages are changed in red. The ± 5 -day running average of ΣK_p is superimposed onto the Biak panel as well. The upper little panel has been added to the original view and shows the residual of the linear relationship between Biak Z/H ratio and ΣK_p .

Fig. 2b. Temporal evolution of the ULF wave activity of the geomagnetic field components H and Z at the stations of Biak (blue) and Darwin (red) in the period November 1995 - March

1996 as reported by Hayakawa et al. (2000) (a reproduction of Hayakawa et al., 2000, Fig. 2).

ΣK_p temporal evolution is also shown in the lower panel. EQ refers to the earthquake date.

Fig. 3. Upper panel: 5-day backward running averages of ULF polarization ratios S_z/S_D in the period of Iwateken Nairiku Hokubu earthquake at Matsukawa, Memambetsu and Kanoya stations as reported by Hattori (2004) (a reproduction of Hattori, 2004, part of Fig. 10a). Lower panel: 5-day backward running average (thick red solid line) and daily values (thin red solid line) of Matsukawa polarization ratio. The 5-day backward running average of ΣK_p is superimposed onto the upper panel as well. An enlargement view of the claimed precursory anomaly is added to the original view.

Fig. 4. Lower panel: 5-day running average of the ULF polarization ratio Z/G at Kamo station as reported by Kopytenko et al. (2001) (a reproduction of Kopytenko et al., 2001, Fig. 6). Middle panel: seismic activity during April-May 1998. Upper panel: temporal evolution of ΣK_p . In the lower panel the 5-day running average of ΣK_p is superimposed on the original view.

Fig. 5a. Twenty days running averages of the geomagnetic field components Z and G , and the polarization ratio Z/G at the stations of Molchikoshi (M), Seikoshi (S) and Kamo (K) as reported by Ismaigullov et al. (2001) (a reproduction of Ismaigullov et al., 2001, part of Fig. 6). The vertical dashed line represents the beginning of the 2000 Izu swarm. The ± 10 -day running average of ΣK_p is reported onto the Z/G ratios panel as well.

Fig. 5b. Three days running average of the ratio Z/G during the period of the Izu swarm 2000 (upper panel) at Kamo (K) and Kakioka (KK) stations as reported by Ismaigullov et al. (2003)

(a reproduction of Ismaigullov et al., 2003, part of Fig. 2). The 3-day running average of ΣK_p is superimposed onto the Z/G panel as well.

Fig. 6a. Temporal evolution of $\sqrt{Z/G}$ during the period 25 June 2000 - 18 February 2001 at Karimshino observatory as reported by Molchanov et al. (2003) (a reproduction of Molchanov et al., 2003, Fig. 2). The geomagnetic K_p index and the seismic activity K_s index (yellow stars) are reported as well. Green circles highlight the $\sqrt{Z/G}$ increases claimed to be related to five strong earthquakes (yellow stars with a red dot). The K_p index temporal evolution is also superimposed onto each polarization ratio panel (red step-line). See text for details.

Fig. 6b. Daily values of the ratios Z/G, panel a), and 1/G, panel b), at Karimshino observatory as reported by Molchanov et al. (2003) for the same period of Fig. 6a (a reproduction of Molchanov et al., 2003, Fig. 3). The geomagnetic K_p index and the seismic activity K_s index (yellow stars) are reported as well. Daily values of K_p (ΣK_p) are also superimposed on each polarization ratio panel (red step-line). See text for details.

Fig. 7. Temporal evolution of the polarization ratio $R=Z/H$ during the period 10 June - 20 August 2004 at the SEGMA station of Castello Tesino (CST) as reported by Prattes et al. (2008) (a reproduction of Prattes et al., 2008, Fig. 4). The red vertical line refers to the Bovec earthquake date. ΣK_p and the geomagnetic field components, Z and H, are shown as well. K_p temporal evolution (black step-line) is also reported onto the polarization ratio panel.

Fig. 8a. Geomagnetic field anomaly associated with the Kagoshimaken-Hokuseibu earthquake (M6.5 and M6.3) as reported by Hattori (2004) (a reproduction of Hattori, 2004, Fig. 8). (a) regional seismicity; (b) 10-day backward running average of the ratios S_Z/S_G for the stations of Tarumizu, Chichijima and Darwin; (c) temporal evolution of ΣK_p . The 10-day backward running average of ΣK_p (black line) is reported in the middle panel as well.

Fig. 8b. 10-day backward average of the geomagnetic field spectral intensities S_Z and S_G as reported by Hattori et al. (2002) during the same period of Fig. 8a (a reproduction of Hattori et al., 2002, part of Fig. 6). See text for details.

Fig. 9. Temporal evolution of the ratio Z/G at Lumping station before the Chi-Chi earthquake as reported by Akinaga et al. (2001) (a reproduction of Akinaga et al., 2001, Fig. 2). The ± 5 -day running average of ΣK_p is also superimposed onto the original view both with a descending axis (red line) and with an increasing axis (sky-blue line) to show the strange correspondence between Z/G and ΣK_p : negative up to April 1999 and positive later.

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823 >The reliability of magnetic ratio changes as earthquake precursors are investigated.

824 >Nine cases are considered which include seventeen earthquakes.

825 >In the analysis running averages of the ΣK_p geomagnetic index are taken into account.

826 >These increases are actually caused by the normal geomagnetic activity variation.

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ACCEPTED MANUSCRIPT