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ON THE PRESUMED ULF MAGNETIC PRECURSORS OF EARTHQUAKES

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Introduction. During the last twenty years many researchers investigated ULF (Ultra-Low-Frequency) magnetic data in the hope of finding seismogenic signals. After the report of Fraser-Smith et al. (1990) several ULF stations were installed and many papers documented the observations of pre-earthquake magnetic anomalies. These claims motivate the belief that one day short-term earthquake prediction based on magnetic data may become a routine technique. Short-term earthquake prediction has been the topic of several scientific debates but at present the entire subject remains still controversial. In order to be useful, short-term prediction requires reproducible earthquake precursors which provide information regarding intensity, location and time of the predicted earthquake together with error estimates for each parameter. Thus, a serious problem concerns the identification of reliable earthquake precursors. Recently, some researchers have given rise to a re-examination process of dubious earthquake precursors and published their findings. For example Masci (2010, 2011a), by means of global geomagnetic Kp index time-series, demonstrated that many presumed magnetic seismogenic signatures are not related to the subsequent earthquakes but are normal variations driven by the geomagnetic activity level. More precisely, as pointed out by Masci (2011a, 2012a), since the Kp index is representative of the geomagnetic field average disturbances over planetary scale, we should not expect that a good correlation between an ULF parameter of the geomagnetic field and Kp will always and everywhere exist during a long-time range. On the contrary, if a close correspondence between these changes of an ULF geomagnetic field parameter and Kp exists during a period of time, this indicates that the changes are part of normal global geomagnetic field variations driven by solar-terrestrial interactions and cannot be described as earthquake-related signals.

Here, some examples of questioned earthquake precursors are reported hoping to shed light on the usefulness of the ULF magnetic measurements to study the occurrence of pre-earthquake seismogenic signals. In addition, the results of the analysis of magnetic data from the Geomagnetic Observatory of L'Aquila during the period of the 2009 L'Aquila seismic sequence are reported as well.

Brief history of ULF magnetic precursors. The history of ULF earthquake magnetic precursors can be summarized as follow:

i. Fraser-Smith *et al.* (1990) documented the occurrence of possible ULF magnetic earthquake precursory signals before the Loma Prieta 1989 earthquake. Campbel (2009) and Thomas *et al.* (2009a) put into question the seismogenic origin of this precursor. Fraser-Smith *et al.* (2011) reaffirmed the possibility that the Loma Prieta precursor may have a seismogenic origin.

ii. After Fraser-Smith *et al.* (1990) many ULF stations were installed in order to investigate the occurrence of earthquake precursors and a huge number of papers claimed the observation of magnetic ULF earthquake-related signatures using different methods of analysis.

iii. Recent studies gave rise to a re-examination process of presumed earthquake precursors and demonstrated that many of these precursors are normal signatures induced by the normal geomagnetic activity.
The starting points of the re-examination process are:
- Any potential anomaly, before to be considered a reliable earthquake precursor, should be excluded as a random anomaly or as an anomaly related with other possible sources, both natural and artificial.
- According to the normal scientific process, further independent confirming measurements are required before such magnetic field changes can be referred to definitively as precursors.

In the following sections, some examples of the results obtained by different methods which are considered useful tools to study the presence of ULF magnetic precursors of earthquakes are reviewed.

Fractal analysis. Several researchers documented the observation of pre-earthquake magnetic anomalies by means of the investigation of changes in the fractal parameters (i.e., the spectral index, the fractal dimension, and the multi-fractal parameters) of the geomagnetic field components. Recently, the studies by Masci (2010, 2012c) demonstrated that the changes of the fractal characteristics of the geomagnetic field components, which previous papers claimed to be due to seismogenic signals, were actually normal disturbances induced by the variation of the global geomagnetic activity level. Fig. 1a shows the changes of the spectral index β of the geomagnetic field H component during the period of the 8 August 1993 Mw7.7 Guam earthquake as reported by Hayakawa *et al.* (1999). The authors attribute the decrease of β, which started few months before August 1993, to the preparatory process of the Guam earthquake and consider it as a possible precursory signature. In Fig. 1a ΣKp index ±5-day and ±15-day running averages time-series has been superimposed onto the original view. The Fig. shows that there is a strong correlation between β and ΣKp both over short time scale (see the ±5-day running average) and over long time scale (see the ±15 running average). Thus, it is clearly evident that the gradual decrease of β before the Guam earthquake was induced by the normal geomagnetic activity and cannot be connected to the subsequent seismic event. See Masci (2010) for details.

Polarization ratio. Many researchers consider the investigation of the magnetic field polarization ratio as a key parameter that allows us to distinguish the normal ULF geomagnetic field pulsations from other signals such as the possible seismogenic emissions. The magnetic polarization ratio is defined as the ratio between the integrated (in a fixed range of frequency) power of the vertical component Z and one of the horizontal components H and D (see Hayakawa *et al.*, 1996). Thomas *et al.* (2009b) and Masci (2011a, 2012a, 2012b) showed that presumed seismogenic magnetic pre-earthquake polarization ratio variations were normal signals induced by the solar-terrestrial interaction. According to Masci (2011a), the variation of the geomagnetic activity level which induces changes in several geomagnetic parameters (e.g., the polarization ratio) is a key parameter for the interpretation of the observed magnetic anomalies. For example, when the geomagnetic activity decreases, the geomagnetic field horizontal components decrease more than the vertical component, therefore the polarization ratio increases. In contrast, an increase of the geomagnetic activity causes an increase in the geomagnetic field horizontal components that is larger than the increase of the vertical component, thus the polarization ratio decreases. In summary, there is an inverse correspondence between the polarization ratio changes and the variations of the geomagnetic activity.

Fig. 1b shows the polarization ratio analysis of magnetic data from the station of Castello Tesino during the period of the 12 July 2004 M5.5 Bovec earthquake. According to Prattes *et al.* (2008) the ULF geomagnetic field polarization ratio at Castello Tesino, the closest station to the earthquake epicentre, shows significant increases the period before the earthquake occurrence. Masci (2011a) superimposed Kp index time-series onto the original view by Prattes *et al.* (2008). Taking into

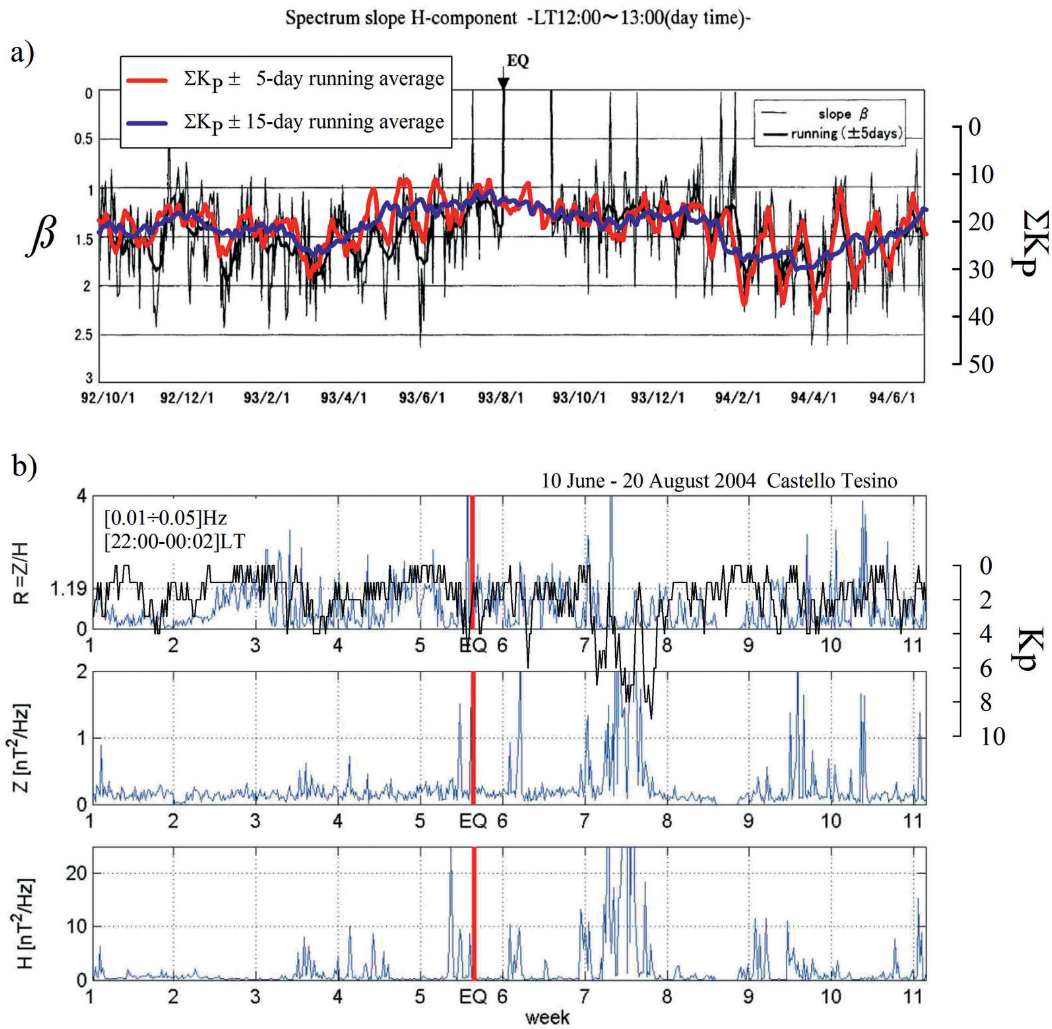

Fig. 1 – (a) Spectral exponent β of the geomagnetic field H component from Guam Observatory compared with the geomagnetic index ΣKp time-series. EQ refers to the time of the Guam earthquake. (b) Polarization ratio R=Z/H during the period 10 June-20 August 2004 at the station of Castello Tesino as reported by Prattes et al. (2008). The red vertical line referes to the time of the 2004 Bovec earthquake. The geomagnetic field components, Z and H, are shown as well. Kp index (black step-line) is also superimposed onto the polarization ratio time-series.

account the Kp behaviour, it is clearly evident that before the Bovec earthquake there is a close inverse correspondence between the polarization ratio and the geomagnetic activity. This correspondence can also be found during the period following the date of the earthquake, but not during week 7. However, since week 7 is a period characterized by a high level of geomagnetic activity, as expected the polarization ratio has on average low values because the horizontal component amplitude increases dominate the lower vertical component increases. In summary, the polarization ratio increases which occurred before the Bovec earthquake were undoubtedly induced by changes of the geomagnetic activity level.

Principal component analysis. Fig. 2a shows the increases (see the black envelope curve) before the IZU swarm 2000 of the third Principal Component Analysis eigenvalue λ_3 of the geomagnetic field H component. Hayakawa (2011) claims that these λ_3 increases are related to the

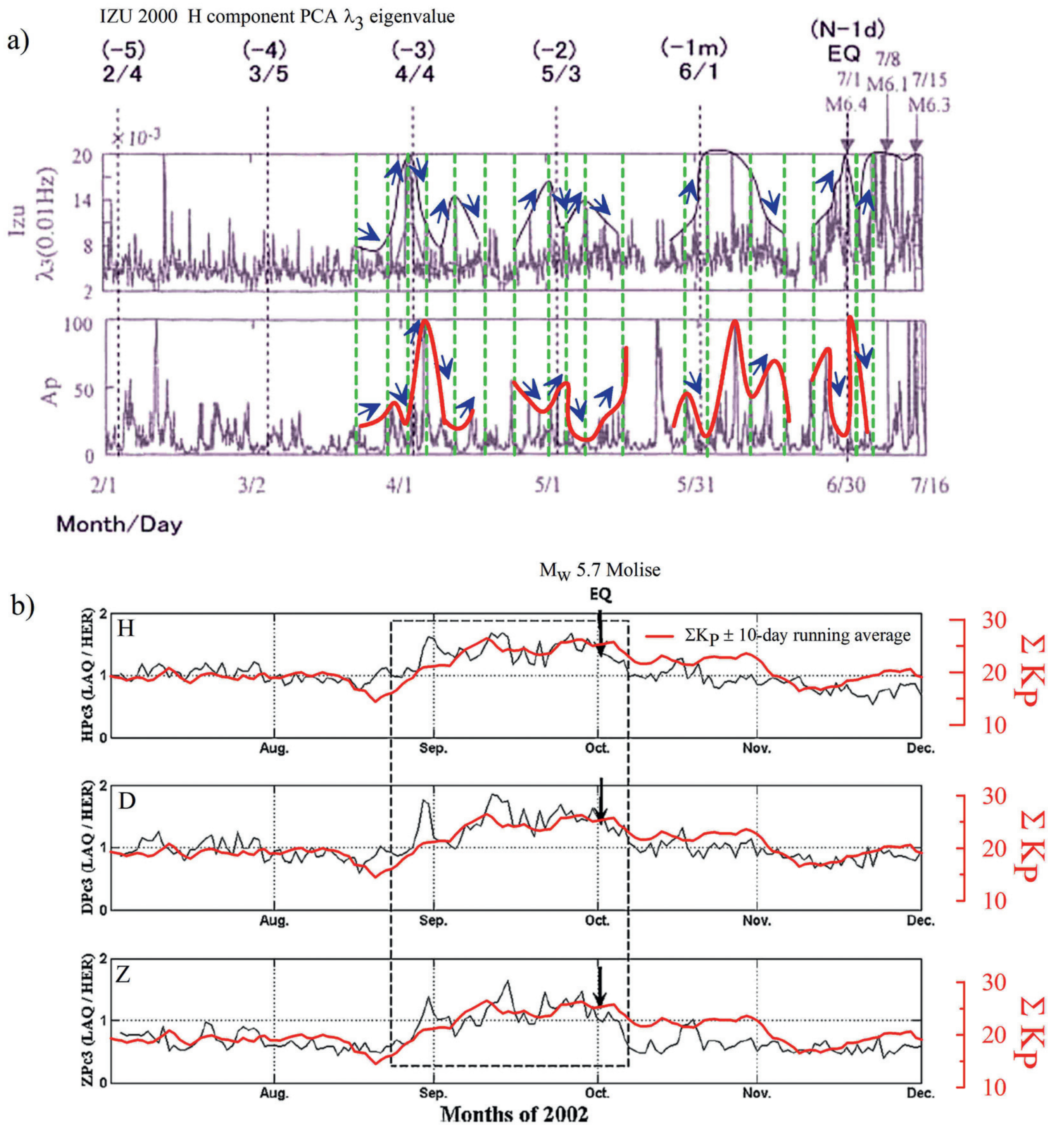

Fig. 2 – (a) Third Principal Component Analysys eigenvalue λ_3 of geomagnetic field component H at the frequency of 10mHz and Ap index time-series during the period of the Izu swarm 2000 as reported by Hayakawa et al. (2011). The thick black line represents the envelope curve of λ_3 peaks as reported in the original figure. The thick red line was added onto the original view and refers to the envelope curve of Ap peaks. Blue arrows highlight the inverse correspondence existing between the variations of the two evenlope curves in the majority of the periods delimited by vertical dotted green lines. (b) Daily values of Pc 3 amplitude ratios between the pair of coniugate station LAQ and HER for the geomagnetic field components H, D, and Z at the time of the Molise 2002 earthquakes as reported by Takla *et al.* (2011). ΣKp±10-day running average is also superimposed onto each panel of the original view.

seismic activity, as well as correlated with the effect of Earth's tides (see Hayakawa, 2011 for details). The Principal Component Analysis of ULF magnetic data is based on the following points: 1) the first eigenvalue λ_1 is related to signals caused by solar-terrestrial interaction; 2) the second eigenvalue λ_2 is a combination of artificial signals and earthquake-related signals, even if the influence of artificial signals is more intense; 3) the third eigenvalue λ_3 is a combination of artificial signals and earthquake-related signals even if the second one seems to be more pronounced (see

Hattori *et al.*, 2004 for details). In my opinion λ_3 could be contaminated by magnetospheric signals as well. Unfortunately, previous authors do not investigate in deep this possibility. In Fig. 2a the envelope curve of the Ap geomagnetic index has been drawn onto the original view. Vertical dotted green lines and blue arrows highlight the changes of the trend (increase or decrease) of the envelope curves during different periods of time. As a matter of fact, we can note that the two envelope curves of λ_3 and Ap show an inverse correspondence; more precisely, on average λ_3 decreases (increases) when Ap increases (decreases). The inverse correspondence is evident in the majority of the periods delimited by the dotted green lines. The correspondence fails just during few periods. In any case, the selection of the peaks used to draw the envelope curves could influence their shape. In summary, the inverse correspondence between the Ap index and λ_3 suggests us that a possible relation between λ_3 and the global geomagnetic activity may exist. Therefore, connecting the λ_3 increases with the earthquakes occurrence is just an oversimplified assumption. See Masci (2011b) for details.

Ratio between conjugate stations. Takla *et al.* (2011) show anomalous variations of Pc 3 before two Mw5.7 earthquakes which occurred respectively on 31 October and 1 November 2002 in the Molise region, Italy. The authors compare geomagnetic field data from the stations of L'Aquila (LAQ) and Hermanus (HER), which is the almost conjugate point of L'Aquila. According to the authors, in conjugate stations the Pc 3 pulsations have the same amplitude, therefore the anomalous increase of the ratio LAQ/HER during October 2002 (see Fig. 2b) is related to the Pc 3 amplitude increase at LAQ station caused by the preparatory process of the Molise earthquakes. As a matter of fact, Fig. 2b shows that the Pc3 LAQ/HER ratio is close related to the long-term variation of the geomagnetic activity (see ΣKp ±10-day running average which was superimposed onto the original view). This correlation suggests that the Pc3 ratio increase which occurs during October 2002 could be somehow related to the increase of the global geomagnetic activity level. Namely, it is well known that in conjugate stations the Pc3 pulsations were excited synchronously but their amplitudes are not always equal even if they may be of the same order of magnitude. As a consequence, we should not expect that in conjugate stations the Pc 3 amplitude ratio is always almost constant. Bearing in mind these considerations, we can suppose that the increase of LAQ/HER ratio during October 2002 may be related to a residual signal caused by the different amplitude of Pc 3 in the two conjugate stations. In conclusion, the Pc 3 ratio increase occurred on October 2002 seems to be induced by the raise of the global geomagnetic activity. As a consequence, the Pc 3 increase cannot be undoubtedly associated with the preparation process of the Molise earthquakes.

L'Aquila 2009 earthquake. On 6 April 2009 a seismic sequence culminated with the Mw6.3 main shock which heavily damaged the town of L'Aquila. The characteristics of the L'Aquila 2008-2009 seismic sequence are that the earthquakes were shallow and very close to the INGV (Italian Istituto Nazionale di Geofisica e Vulcanologia) Geomagnetic Observatory of L'Aquila. The epicentre of the main shock was only 6 km further from the observatory. These characteristics could justify the observation of possible seismogenic electromagnetic signals also providing an opportunity for a careful investigation of the reliability of the methodologies adopted in previous studies which have documented the observation of magnetic earthquake precursors. Masci and di Persio (2012) investigated the possible occurrence of magnetic precursors of L'Aquila earthquake using ULF magnetic data coming from the INGV Geomagnetic Observatory of L'Aquila. Magnetic data (1 Hz sampling rate) are analyzed in the range of frequency [3–100]mHz. The time window [22:00–02:00]UT (LT=UT+1) has been chosen to minimize the background noise level. The authors investigated the occurrence of changes in the magnetic polarization ratio and the variations of the fractal characteristics of the geomagnetic field components. They did not found any seismogenic signatures of L'Aquila earthquakes. Fig. 3 shows an example of the polarization ratio analysis (frequency band [5–15] mHz) and fractal dimension analysis (geomagnetic field H component; Higuchi method) as reported by Masci and Di Persio (2012). The seismic activity (Ml) of L'Aquila area and the ΣKp time-series are shown as well. We can note that the fractal dimension ranges from 1 to 2; this means that the time-series under examination, i.e. the geomagnetic field, is analogous to the fractional Brownian motion (fBm) model. Fig. 3 does not show anomalous changes both in the

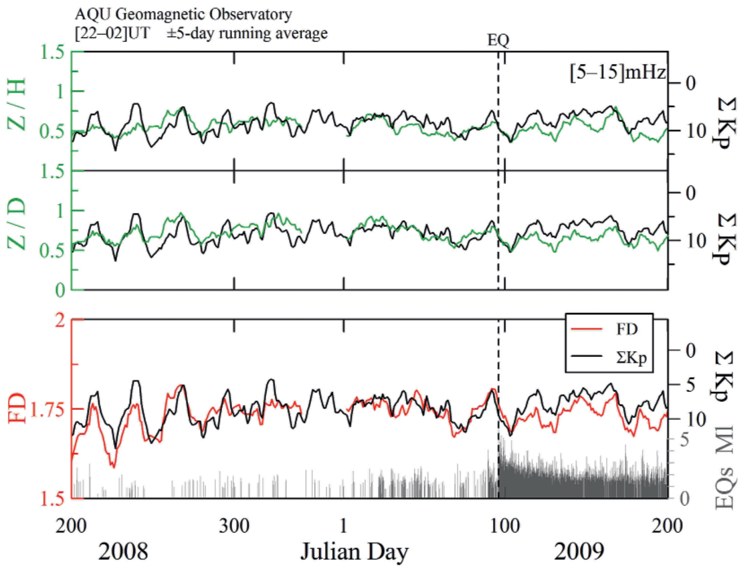

Fig. 3 – Geomagnetic field polarization ratios (Z/H and Z/D) in the frequency band [5-15] mHz and Higuchi fractal dimension (FD) of the geomagnetic field H component compared with ΣKp. The seismicity (Ml) of the L'Aquila area is reported as well.

polarization ratio and in the fractal dimension that could be reasonably related to L'Aquila seismic sequence. On the contrary, we can note that the fractal dimension and ΣKp show a strong inverse correlation. However, if we take into account the fractal dimension time-series in the same manner as it has been done in previous studies, we note an increase of the fractal dimension which starts about the middle of March 2009. Later, just after the main shock, the fractal dimension decreases. In addition, in Fig. 3 we can also note that the fractal dimension increase seems to be related to the rise in the seismic activity during March 2009. However, Fig. 3 clearly shows that the fractal dimension increase which occurs during the period before the main shock is closely related to a decrease in the geomagnetic activity level. Thus, the simultaneous increase of fractal dimension and the seismic activity is just a coincidence. In summary, the possible correlation between fractal dimension increase and the seismic activity is not supported by the analysis.

The inverse correlation between the geomagnetic field fractal dimension and the geomagnetic activity can be explained as follow. The increase of the fractal dimension before the earthquake suggests that the magnetosphere has a transition from a more ordered state toward a less ordered state since a higher fractal dimension means a lower degree of organization. This finding is confirmed by the corresponding decrease of the ΣKp index, which indicates that the magnetosphere evolves toward a lower degree of organization (see e.g. Balasis *et al.*, 2009). On the contrary the subsequent decrease of the fractal dimension, and the corresponding ΣKp increase, suggests that the magnetosphere evolves towards a higher degree of organization.

Fig. 3, as expected, shows that an inverse correlation also exists between the polarization ratios (Z/H and Z/D) and the geomagnetic activity. In conclusion, within the limits of the analyses by Masci and Di Persio (2012) no earthquake-related signal can be identified during the period of L'Aquila seismic sequence.

Conclusions. All the examples here reported do not show strong evidence of correlation between the presumed magnetic precursors and the subsequent earthquakes. Conversely, there is a close correspondence between the presumed precursors and the normal global geomagnetic activity level. Thus, previously reported associations with the preparation process of the earthquakes occurrence are not correct. In my opinion, the authors documented the observation of sismogenic pre-earthquake magnetic signals without properly investigate the influence of other possible ULF sources, as well as the geomagnetic activity which is the main source of ULF signals. In summary, the methodologies which were used in investigating ULF seismo-magnetic signals show some problems of fundamental importance. In addition, I would like to emphasize that, a single analysis by itself cannot establish if an anomaly is a seismogenic signature, or is just a chance event caused by other sources, either natural or artificial. Consequently, a more careful approach should be adopted before claiming that any ULF pre-earthquake anomalous observation is a precursory signal so as not to create illusions of a future development of short-term earthquake prediction capabilities based on ULF magnetic precursors.

At this stage, questions of fundamental importance should be: The ULF magnetic earthquake precursors are fact or fiction? Additional scientific and economic efforts in this field of research are justified?

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