**Natural Hazards
and Earth
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Seismo-electromagnetic phenomena in the western part of the Eurasia-Nubia plate boundary

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Abstract. This paper presents a work that aims to monitor seismo-electromagnetic phenomena in the Western Part of the Eurasia-Nubia Plate Boundary. This region has a significant tectonic activity combined with relatively low electromagnetic noise levels, rendering high quality seismo-electromagnetic measurements possible. An overview of the seismicity of this region is presented and the research plan is discussed accordingly.

1 Introduction

It is known that low-frequency (ultra (ULF), very (VLF), and low-frequency (LF)) electromagnetic waves produce more convincing earthquake precursors (compared to higher frequencies) because of less contamination, large skin depth, and low attenuation, Chauhan et al. (2009). Thus, two seismo-electromagnetic phenomena (SEM) will be considered: ULF electromagnetic field emissions, Telesca et al. (2008), and VLF/LF radio broadcastings, Biagi et al. (2009). With respect to the ULF measurements, magnetometers are planned to be installed in the South of Iberian Peninsula supported by the existing networks of seismic research and a portable ULF station is also under consideration. Regarding the VLF/LF radio broadcastings, a receiver is presently under installation at the University of Évora to monitor radio signals from up to 10 VLF/LF transmitters to study the seismic activity in the Western Part of the Eurasia-Nubia Plate Boundary (WENP) region. The system inte-
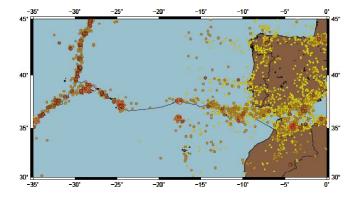
grates the International Network for Frontier Research on Earthquake Precursors (INFREP). Details about this network are presented in other paper submitted to the same issue, and in this context it will not be restricted to WENP region. Furthermore, these measurements are expected to be complemented with the monitoring of the atmospheric electrical field and the radon levels, since these parameters can provide crucial insights into the physics of SEM phenomenology, Smirnov (2008) and Harrison et al. (2010).

With the development of this research plan it is aimed the collection of novel SEM data emerging from the seismic activity in the WENP region. We expect to address the time variations of the electromagnetic properties of the crust/plate with the strain field, and its relation with composition, temperature and stress fields. Moreover, the interplay between atmospheric (and solar) perturbations with crust perturbations will be monitored, to observe geomagnetic perturbations at different locations.

In this paper, we describe the seismicity of the WENP region, the micro-seismicity of the South of Portugal, and the SEM monitoring future research plan, together with a summary of the expected results.

2 Seismicity of WENP region

The western part of the Eurasia-Nubia plate boundary (WENP) starts in the Azores archipelago and goes to the Strait of Gibraltar. This region encloses the transition from an oceanic boundary (between the Azores and the Gorringe Bank), to a continental boundary where Iberia and Africa meet, Grandin et al. (2007a). In the oceanic part, from the Azores archipelago to the Azores-Gibraltar fault

Fig. 1. Seismicity of the western part of the Eurasia-Nubia plate boundary for the period 01/01/1973–17/06/2010 ($M \geq 3.0$, USGS Data File). Small yellow circles represent seismic events with $3 \leq M < 4$, small light brown ones correspond to $4 \leq M < 5$, mean orange circles signify $5 \leq M < 6$, and big red hollow circles stand for $6 \leq M < 9$.

approximately 12° W, the plate boundary is very well delimited. But, from 12° W to 3.5° E, the boundary is more disperse and embraces a larger area of deformation, this region comprises the Iberia-African area and prolongs to the western part of Algeria, Buforn et al. (2004), Borges et al. (2007, 2008) and Bezzeghoud et al. (2008, 2010). The WENP region can be separated into six fundamental zones (from the Mid-Atlantic Ridge in the west to Algeria in the east) with different seismtectonic behaviors: zone I – The Azores region; zone II – The central region; zone III – The Ibero-Maghrebian region. In Fig. 1 a picture of this region is presented, Bezzeghoud et al. (2008, 2010).

2.1 The Azores region

The seismicity of the Azores is related with the triple point: Eurasian, African and American plate boundaries (Fig. 1). Typically, it presents a complex seismicity composed of moderate magnitudes and shallow depth ($h < 40$ km) events. In fact, just two earthquakes with $M_s \geq 7$ occurred, the first at east of Santa María Island (8 May 1939) and the second between Terceira and Graciosa Islands (1 January 1980). Actually, the major seismic activity is developed on the Mid-Atlantic Ridge and the North Azores fracture zone, and goes on into the Terceira Ridge. Furthermore, it is known from historical seismicity that large earthquakes occurred in Azores (with maximum modified Mercalli intensities of X), Nunes and Ribeiro (2001).

In short, the seismicity of this region trails much the trend of the islands: roughly ENE from the Mid-Atlantic Ridge to Terceira Island, the 1980 and 1998 earthquakes took place in this zone; and SE from Terceira Island to San Miguel Island, where the 1997 shock appended. Seismic activity then vanishes at 24° W where the Terceira Ridge joins with the Gloria fault that is believed to be seismically dormant, as shown in Fig. 1.
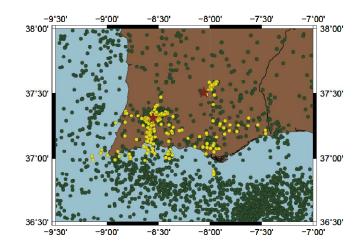
2.2 The central region

The central region, also represented in Fig. 1, is normally accepted to be an extension of the East Azores Fracture Zone that starts in the Gloria Fault, between the longitudes 23° W and 11° W and coincides with the previously defined zone III. The East Azores rupture zone, whose direction is around EW, is evidently pertained by the ocean bottom topography, until 18° W longitude. From this longitude a complex bathymetry is observed where it is difficult to identify a comprehensible alignment, since it is fulfilled by large submarine mountains and abyssal plains. Along this fracture, various NS similar fractions are recognized with profiles containing significant recent scarps, Searle (1980). Besides, Gloria Fault is a right lateral transform fault, Buforn et al. (1988a) that seems to be presently inactive (Fig. 1). This is probably due to the high return period of earthquakes of high magnitude that can be more than 80 years which is comparable with the existence time of instrumental data from this region, Argus et al. (1989). Moreover, numerous seismic events occurred in the east of the island, Nunes and Ribeiro (2001). As a matter of fact, the occurrence on 25 November 1941, of a $M_s = 8.4$ earthquake with epicenter placed at the eastern end of the Gloria Fault, claims in support of this interpretation. The strong magnitude event and the associated seismic deformation could be a consequence of the relative and long standing quietness of this fault.

Summing up, the Gloria Fault is characterized by a seismic gap that extends from the 23° W to 20° W. From this longitude to the 11° W, it presents an EW orientation that engaged different earthquakes, as the strong magnitude events occurred on the 20 May 1931 ($M_s = 7.1$), 25 November 1941 ($M_s = 8.4$) and 25 May 1975 ($M_s = 7.9$), Bezzeghoud et al. (2008, 2010).

2.3 The Ibero-Maghrebian region

This part of WENP can be subdivided into three parts: zone A – Gorringe Bank to Cádiz; zone B – enclosing Betic, Rif Cordilleras and Alboran Sea; zone C – northwest Algeria and Tell Mountains. Similar division was made in Buforn et al. (2004), Bezzeghoud et al. (2008, 2010). In effect, intermediate depth activity, $40 < h < 150$ km, is located in regions A and B and the deep earthquakes, $h \sim 650$ km, are located to the south of Granada, an example of such events is the recent $M_s = 6.3$ earthquake on 11 May 2010 with 623 km depth that as a result of being so deep are not of interest for SEM monitoring. The zone intricacy reflects its bathymetry, seismicity, stress regime and tectonics. Indeed, the bathymetry evidences the Gorringe Bank, the Horseshoe Abyssal Plain and the Guadalquivir bank (located west of the Strait of Gibraltar) with a number of seamounts, banks and submarine ridges with important regional crustal thickness variations, Torné et al. (2000), as fundamental aspects. Besides, in land the main geological features are the Betics, the Rif Cordilleras and the Tell Mountains that are a

consequence of the collision between Eurasia and Africa, and form the Alpine domain. In the Gibraltar western part, from Gulf of Cádiz to Gorringe bank, epicenters are scattered in an EW direction, across about ~100 km wide, with foci at shallow and intermediate depth. Four significant earthquakes have occurred in this region in the last 50 years: one in the Gulf of Cádiz (15 March 1964; $M_s = 6.4$) and three probably along the Horseshoe fault, at west of the San Vicente Cape (12 December 2009, $M_w = 5.6$; 2 February 2007, $M_w = 5.9$; 28 February 1969, $M_s = 8.0$), Udías et al. (1976), Buforn et al. (1988b), Bezzeghoud et al. (2010). Since 2003, an increase in the seismicity of the area enclosing the Gorringe Bank and the Horseshoe Fault (Zone A) has been observed. In particular, the East of 16° W region is controlled by a transpressive tectonic regime, with a very low convergence rate of 5.5 mm/yr trending NW to NNW, Bezzeghoud et al. (2008, 2010). Such regime conforms the observed maximum horizontal stress direction, Borges et al. (2001) and Bezzeghoud et al. (2008, 2010). Moreover, in this region, the limit between plates occupies a large area with a disseminated deformation that even reaches a NS width of 300 km close to the Iberia continental margin. Actually the seismicity is spread, even though a vast number of events are concentrated along a ~100 km extensive band, trending ESE-WNW from 16° W to 9° W. In the area, sequences of topographic configurations tending WSW-ENE appear, Borges et al. (2007), Bezzeghoud et al. (2008, 2010). Parallel to the San Vicente canyon, the Horseshoe scarp and the Marquês de Pombal scarp since, at least, the Miocene have undergone deformations. This hypothesis is corroborated by the incidence of oceanic earthquakes with abnormally large magnitude inside the area of dispersed seismic activity alike the 1969 earthquake, with $M_s = 8.0$, and the historical 1755 Lisbon earthquake, Grandin et al. (2007a, 2007b). On the other hand, historical earthquakes with maximum intensity of IX or X occurred W of San Vicente Cape (Lisbon earthquake in 1755), southern Iberia (1829 and 1884) and in northern Morocco (1909). At least, seismic activity with magnitude range from 3.5 to 5 at intermediate depth ($40 < h < 150$ km) is further present in this region, as extensively described in literature, Munuera (1963), Hatzfeld (1978), Grimison and Cheng (1986), Buforn et al. (1988b, 1991a, 1991b, 1997, 2004), Seber et al. (1996), Serrano et al. (1998), Bezzeghoud et al. (2008, 2010). Particularly in the area A, intermediate-depth shocks are diffuse over a ~100 km broad belt (between 36° N and 37° N) that goes EW from 8° W to 11° W. Nevertheless, a large amount of foci (the majority, in fact) at intermediate depth is found in area B, at the eastern side of the Strait of Gibraltar in a thin NS trending band less than 50 km wide concentrated at 4.5° W and expanding from 35° N to 37° N. Therefore, the distribution of intermediate-depth earthquakes is different in area A (EW propensity) from that of area B (NS trend). No intermediate depth seismicity is observed east of 3° W in Spain, Morocco or Algeria.

Summarizing, the seismic activity of the Iberia-African re-

Fig. 2. Yellow circles represent the micro-seismicity ($1 < M < 3$) of the South of Portugal acquired with the network described in Rocha et al. (2008), for nearly 4 years of observation. Green circles stand for the seismic records from IM database from 1961–2009. The red stars show the planned locations to host the ULF three-component magnetometers.

gion is dominated by the incidence of moderate magnitude earthquakes, the majority with shallow depth focus in the range $0 < h < 40$ km. Nevertheless, significant seismicity at intermediate depths, $40 < h < 150$ km, with an EW trend and concentrated in Gulf of Cádiz is also present. Yet, another intermediate depth seismicity spot, between 36° N and 37° N, appears in a 100 km wide area, and it also generates very deep earthquakes ($h \sim 650$ km), Buforn et al. (1991a, 1997).

3 Micro-seismicity of the south of Portugal

The study of the micro-seismic activity of the south of Portugal is recent, but is revealing rather interesting results. The data here analysed were acquired using both the Portuguese national network supported by Instituto de Meteorologia, IP Portugal (IM) and a seismic monitoring network installed on purpose to this study in the mentioned region, Rocha et al. (2008). In Fig. 2 the micro-seismicity, $M < 3$, of this region is presented. It appears that the seismicity in both regions is characterized by low magnitude events, Bezzeghoud et al. (2008). It is clearly possible to define in the region of Monchique epicenter alignments that suggest a correlation with two possible faults newly discovered in this area, Rocha et al. (2008). In the NW region of Almodôvar, it is possible to define a trend of the distribution of epicenters that may indicate the occurrence of an uncharted fault in this zone.

Interestingly, the field compression is in agreement with the regional stress field expected for this region and the resulting collision between the Eurasian plate and African.

3.1 Almodôvar region

The obtained results show the occurrence of reduced magnitude events. Using the proper programs of localization, Klein (1978), and relocation, Waldhaus (2001), it was possible to define a zone of seismic activity in Almodôvar region (see Fig. 2). The seismicity detected in the region of Almodôvar has a tendency according to NE-SW orientation, which becomes more evident with the epicenter redistribution, obtained after the relocation.

3.2 Monchique region

The studies undertaken allowed the identification of a relevant seismic activity, with typical magnitudes $1 < M < 3$ and constrained between 5 and 15 km depth, around the Monchique region. The seismicity map obtained after the relocation using the previous programs defines a clear alignment of the seismic epicenters in this region, which can be related with two probable faults recently indentified in this area, Rocha et al. (2008). The faults have ENE-WSW and NNE-SSW directions.
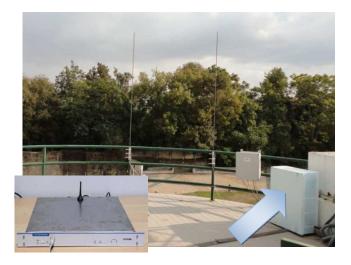
4 SEM monitoring study

As already pointed out in the introduction the present study integrates two main types of SEM phenomena, one dedicated to the recognition of ULF electromagnetic fields, and the other to the detection of VLF/LF radio broadcasting anomalies, both related with seismic activities. It has three structural objectives: (1) establish an Iberian monitoring network of seismic related ULF electromagnetic emissions, possibly integrated in the existing seismic networks, Caldeira et al. (2007), and the Western Mediterranean Broad-Band Seismological Network (WMBB), Martin et al. (2007); (2) extend the international INFREP network with a new receiver, whose installation is already in progress, in the University of Évora; (3) contribute to the increase of both seismic related ULF and VLF/LF world database. Moreover, these measurements are expected to be complemented with the monitoring of the atmospheric electrical field and the radon levels, since these parameters can give crucial insights into the physics of SEM phenomenology. In this way, multi-parameter assessment of the preparatory stage of the earthquakes is envisaged.

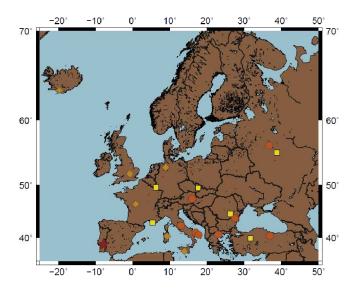### 4.1 Observation of ULF magnetic field emissions

The detection of ULF electromagnetic fields aims to equip seismic stations, in the south of Iberian Peninsula with three-component ULF magnetometers of type LEMI-30 (produced by the Lviv Centre of Space Research, Ukraine) as commonly used in ULF research, Chauhan et al. (2009). A possible location for the initial two equipments is presented in Fig. 2. According to the micro-seismicity previously presented, the following potential regions have been selected:

(1) offshore zone with intermediate and strong magnitude – between Gorringe Bank, the Horseshoe Fault and the Gulf of Cádiz; (2) onshore zone with low magnitude – Algarve and south Alentejo (between Monchique and Almodôvar). An important point is that the sensors are installed in specific sites that exhibit significant seismic activity and, simultaneously, low electromagnetic noise levels. These conditions favour detection of SEM phenomena. Moreover, preference will be given to places that already host seismic stations . A portable three-component ULF magnetometer, most probably the LEMI-18 model, will be used in the search for the proper location, by monitoring the electromagnetic activity of the region of interest. Once a specific site is chosen it will be employed in calibration procedures. Nonetheless, this portable magnetometer could also be used for in-situ aftershock studies, typically $M \sim 3 - 5$, once the mainshock epicentre has been correctly identified. Special attention will be given to man-made noise sources, such as electricity transmission grids, factories, roads, etc., that must be clearly identified to ensure the reliability of the acquired data, Prattes et al (2008) and Bleier et al. (2009). Our ULF study will be focused on the analysis of low magnitude earthquakes (LME) with $M \leq 4$. These events are frequent in the South of Portugal, but have been almost completely disregarded in literature, as will be discussed in the next session. Finally, the magnetometers will integrate the South European GeoMagnetic Array (SEGMA) array.

4.2 Observation of VLF/LF radio signals

The recognition of VLF/LF radio broadcasting anomalies is already being performed through two antennas (one for each band) connected to a receiver built by Elettronika (Italy), which is able to acquire up to 10 signals (distributed in these bands). This equipment is frequently employed in similar experiments, Biagi et al. (2009). In Fig. 3 a photograph of the apparatus installation in the University of Évora (38°34′ N, 7°54′ W, 300 m a.m.s.l.) is presented. The system was recently installed in the context of the present project and is in operation since 1 September 2010. The receiver integrates the International Network for Frontier Research on Earthquake Precursors (INFREP), shown in Fig. 4, and is expected to monitor signals emitted from active transmitters to study the seismic activity in the WENP region. In fact, the relevant issue when choosing a transmitter is that the radio path from the transmitter to the receiver crosses the epicentral area, Biagi et al. (2008, 2009), so three transmitters out of the ten being examined (already monitored by other INFREP receivers) are located in: Sicily (Italy), 37°07′ N/1°26′ E; Sardinia (Italy), 40°54′ N/09°42′ E; Monaco (France), 43°47′ N/06°09′ E. Once we assure a proper functioning of the system, three frequencies that are now being monitored will possibly be substituted by three other emitters in the west of the Iberian Peninsula: Ponta Delgada (Azores-Portugal),
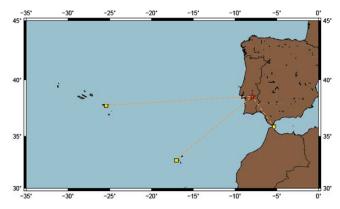
Fig. 3. Photograph of the VLF and LF antennas and the box where receiver is kept (pointed with the blue arrow) at the University of Évora. The inset shows the front panel of the receiver.

Fig. 4. Representative map of the INFREP showing the location (orange circles) of the five VLF/LF receivers presently in operation. Some transmitters, whose signals are sampled by the different receivers, are also indicated (light brown diamonds represent VLF transmitters and yellow squares LF ones). The new receiver under installation in Mitra (Évora) is pointed with a red star.

Funchal (Madeira-Portugal), Ceuta (Spain). Figure 5 shows the location of the mentioned emitters and the receiver. It is expected that the receiver is able to detect anomalies related with high magnitude earthquakes (HME), $M \geq 5$, in Europe. The data acquired with this equipment will be available to the INFREP community according to the regulation of the network.

Fig. 5. Map of the planned VLF/LF radio broadcast system: three transmitters (represented by yellow squares) located at Azores (Portugal), Madeira (Portugal) and Ceuta (Spain), and the receiver (shown as a red star) installed at Évora (Portugal).

4.3 Observation of the Atmospheric Electrical field

Investigation of AE anomalies related with seismic activity is by now being preformed through a vertical component of the atmospheric electrical field (VAE) sensor, Keithley Electrometer model JCI 131, installed at the University of Évora (in the same coordinates as the VLF/LF system). This equipment has been in operation during the period of December 2003 to October 2004 and from February 2005 until now. It is prepared for continuous monitoring of the VAE and works in four scales: 2, 20, 200 and 2000 kV/m with automatic commutations, respectively with the correspondent sensitivity thresholds of 0.1, 1, 10 and 100 kV/m. Figure 6 presents a picture of the apparatus. Inspection of the data collected until now is revealing interesting results presented in a paper submitted to this issue, Silva et al. (2010). In the future, it is planned that more VAE sensors could equip the seismic stations that will receive ULF magnetometers, in order to achieve multiple-parameter monitoring.

4.4 Monitorization of the atmospheric Radon levels

The Radon levels are monitored using, for the moment (the acquisition of new equipments is being considered), a "Radon Thoron Daughters Meter model 4S" built by Silena (a former Italian company) that uses alpha spectrometry and has a sensitivity of $3.7\,\mathrm{Bq/m^3}$ of equilibrium equivalent radon concentration (1 mWL), and an electronically-regulated flow-rate of 3 l/min with 5% precision. The apparatus is now under installation at the University of Évora in the same place of the VAE sensor and VLF/LF system to allow multiple parameter assessment of the region. Precursor anomalous Radon levels have been reported for various seismic events, Toutain et al. (1999). Thus monitoring such levels deserves attention by itself. Even so, their direct correlation with SEM could open new insights into the physical

Fig. 6. Photograph of the VAE sensor installed at the University of Évora. The inset is a zoom into the head of the instrument.

mechanisms behind SEM that are the main purpose of this project. Similarly to the VAE sensors, new Radon detectors could, in the future, equip the seismic stations that will host ULF magnetometers.

5   Discussion

With this research effort, it is likely that new SEM data linked with seismic activity in the WENP region could emerge and contribute to a better understanding of SEM phenomena. Furthermore, such data could be used in the following objectives: (1) perform the correlation between the ULF and VLF/LF radio signals, for different seismic events, with the atmospheric electrical field and the radon levels; (2) theoretical modelling of the observed phenomena; (3) extend the empirical magnitude versus distance diagram for the detection of abnormal ULF signals preceding HME presented by Hattori et al. (2004) to LME (working below the present detection threshold). In fact, since LME were not considered in the former diagram, the extension of such diagram could provide valuable information about the ULF precursory emissions. Moreover, the study of Gladychev et al. (2010) reveals that observation of LME is feasible if the seismic epicentre is sufficiently close to the ULF station; (4) Explore VLF/LF radio anomalies correlated with HME earthquakes and also LME, already below the empirical threshold for its detection (similar to the ULF case) discussed by Rozhnoi et al. (2004); (5) Search for a relation law between the strength

of SEM anomalies and the magnitude and/or local (referred to the place where the sensors will be installed) ground motion of the impending LME. This objective could give an important insight into the driving mechanisms of these phenomena and present a decisive contribution to the development of this field. Obviously, the SEM perturbations caused by LME will be, in principle, very faint and their detection and discrimination from other possible signal sources will represent a real challenge.

As a final remark, it is important to mention that laboratorial experiments concerning the electrical properties of the rocks (for the moment the study is focusing on granitic rocks), which may contribute to a better understanding of SEM phenomena, are already being undertaken.

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