The ALERT-ES Project: an Earthquake Early Warning System for S. Iberia

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SUMMARY:

The main goal of the ALERT-ES project ("Sistema de Alerta Sísmica Temprana: Aplicación al Sur de España") is to study the feasibility of an Earthquake Early Warning System (EEWS) for SW Iberian Peninsula applied to the potentially damaging earthquakes that occur in the region of Cape S. Vicente-Gulf of Cadiz. This area is characterized by the occurrence of large earthquakes with damage in SW Iberia, such as those of 1755 Lisbon (Imax=X) and 1969 S. Vicente Cape (Ms=8,1). The project has two different parts: the development of algorithms for the rapid estimation of the magnitude from the very beginning of P-waves for S. Vicente Cape-Gulf of Cadiz earthquakes and the development of the corresponding new software modules, dealing with detection, event declaration and location, and their implementation in *EarthWorm* and *SeisComP* platforms integrated in a real time system. A pilot experience will be carried out in the last months of the project.

Keywords: Earthquakes Early Warning System, S. Iberia, real time

1. INTRODUCTION

South-West Iberia is located at the tectonically complex plate boundary between Eurasia and Africa. Seismicity in this region is characterized by the occurrence of moderate earthquakes at shallow depth (h <40 km), intermediate depth (40-150km) and some very deep shocks (650 km) (Buforn *et al*., 1988, 2004)(figure 1.1). The S. Vicente Cape - Gulf of Cadiz area is located at the plate boundary to the west of South-West Iberia and is the location where the largest shocks affecting this region occur. The 1755 earthquake is the most important example of a large earthquake in this region, which produced very important damage, especially, to the city of Lisbon. But this is not an isolated case. In the last 50 years, in this region, large earthquakes have occurred, such as the Gulf of Cadiz, 1964 (Ms=6.5) and the S. Vicente Cape, 1969 (Ms=8.1). Earthquakes of smaller size in this area, can also produce some damage and a considerable social alert, due to the fact that they are felt in a wide region, as it happened in the 2009 earthquake, Mw=5.5, felt in a wide zone of the SW of the Iberian Peninsula, and as far as Madrid. Another important fact is the occurrence of tsunamis generated by earthquakes in this area, as it was the case in the 1755 earthquake which greatly contributed to the damage of the city of Lisbon and other coastal cities of Portugal and Spain. The 1969 earthquake also generated a small tsunami (Baptista et al., 1996; Fukao, 1973; López Arroyo and Udías, 1972; MartínezSolares and Lopez Arroyo, 2004).

In consequence, this region presents an especial interest for the implementation of an Earthquake Early Warning System (EEWS, Hanka et al., 2010). This is the goal of the ALERT-ES project (CGL2010-19803-C03) supported by the Spanish Ministerio de Ciencia e Innovación and with the participation of three groups: Universidad Complutense de Madrid (UCM, coordinator), Real Instituto y Observatorio de la Armada (ROA, San Fernando, Cádiz) and the Institut Geologic de Catalunya (IGC, Barcelona). Researchers from other institutions also participate in the project, namely: University Federico II (Naples, Italy), École Normale Superieure (Paris, France), Instituto Geográfico Nacional (Madrid), Instituto de Meteorologia (Lisbon, Portugal), Universidade de Évora (Portugal), Universidad de Cadiz (Spain) and GeoforschungZentrum (Germany)

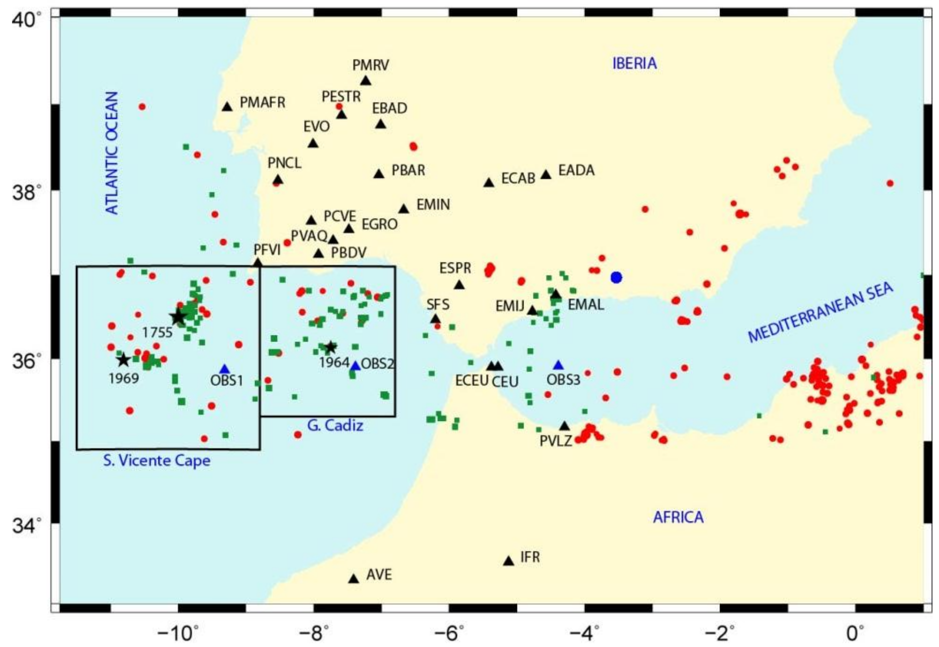

Figure 1.1.- Distribution of epicenters (M>3.5) at shallow (h>40 km, red circles) and intermediate depth ($40<h<150$ km, green circles) for the period 2006-2011 taken from the Instituto GeográficoNacional (IGN) Data File. Black triangles correspond to the broad-band stations and blue triangles to the OBS (FOMAR network). Stars show the epicenters of the largest shocks in this area

The first step in the ALERT-ES project has been the creation of the data base of earthquakes occurred in the S. Vicente Cape - Gulf of Cadiz area. We have selected earthquakes occurred in the period 2006-2011 with magnitude larger than or equal to 3.8 (figure1.1) and recorded at broad-band stations (24 stations) at epicentral distances less than 750 km. Stations used belong to different networks: Western Mediterranean (WM, UCM/ROA), Instituto Geográfico Nacional (IGN) and Instituto de Meteorología (Portugal, IM). The earthquakes, which occur in the above mentioned zone, have foci offshore with a poor azimuthal coverage by seismological stations. In order to solve this problem, three ocean-bottom seismographs (OBS FOMAR Network, figure 1.1) were deployed in April 2011, and recovered in November 2011, with the collaboration of the Spanish Navy. These OBS are of LOBSTER type instruments with hydrophone and a CMG40T (60 seconds) seismometer. The OBS2 was re-deployed but OBS1 and OBS3 had technical problems with the acoustic release. It's planned to deploy them again when repaired. At present, the data-base is composed by 98 earthquakes (60 corresponding to the S. Vicente Cape and 38 to Gulf of Cadiz). The data-base contains more than 1500 records for the Gulf of Cadiz and more than 6000 records for S. Vicente Cape area.

2. ESTIMATION OF P_d AND τ_c PARAMETERS

The second step of the ALERT-ES project is the development of algorithms for the rapid estimation of magnitude from the first seconds of the beginning of recorded P-waves. Generally EEWS use two parameters for the real-time magnitude estimation: τ_c (period) and P_d (peak displacement). We have estimated the values of these parameters for the S. Vicente Cape and tested if the relationships obtained for other regions can be used for the region of our study.

The τ_c parameter (Kanamori, 2005) is defined as:

$$\tau_c = 2\pi \sqrt{\frac{\int_0^{\tau_0} u^2(t)dt}{\int_0^{\tau_0} v^2(t)dt}}$$

Where *u* and *v* are the displacement and velocity respectively, computed over a time window $(0,\tau_0)$ starting at the first-P arrival and τ_0 equal to a few seconds. The τ_c parameter can be considered as representing the average period of the P-wave signal. Several authors have proposed empirical relations between τ_c and magnitude (Kanamori, 2005; Zollo *et al.*, 2010). The peak displacement P_d is defined as the peak displacement of the three first seconds of P-wave (Wu and Zhao, 2006). Zollo *et al.* (2006) have modified the definition of P_d parameter, so that the time window is not fixed to three seconds, and they have normalized the observed P_d to a reference distance. Linear relationships can then be established between P_d and the magnitude M.

We have analyzed more than 900 velocity records corresponding to 60 earthquakes occurred in the S. Vicente Cape region for the period 2006-2011 and recorded at 24 stations at epicentral distances between 70 km and 600 km (figure 1.1). For the determination of τ_c we have used the vertical component of the broad-band records, corrected by the mean and filtered using a high-pass Butterworth filter with corner frequency at 0.075Hz, and finally integrated to obtain the displacements. We have checked time windows from 2 to 4 s.

The P_d parameter has been estimated using the P-wave amplitude observed at the records of the three components at each station. We have corrected by the mean, filtered using the same high-pass filter as before and removed the instrumental response in order to obtain the displacements. In our case, due to the poor azimuthal coverage of the stations, we must introduce a previous correction for the observed peak amplitude according to the focal mechanisms. We have divided the observed P-wave amplitude in each station by the corresponding radiation pattern, using the focal mechanisms of 2007 or 2009 earthquakes (Pro *et al.*, 2012) depending of the location of the epicenter. The focal mechanisms of these two earthquakes are representative for earthquakes of the S. Vicente Cape area. The P_d

amplitudes have been reduced to a hypocentral reference distance of 200 km, in order to find the linear relation between them and magnitude.

Preliminary results for τ_c versus magnitude are shown in figure 2.1 together with data of Japan, Taiwan and Italy (Zollo *et al.*, 2010). From this figure we observe that our data are inside the standard error bounds obtained by Zollo *et al*. (2011) for other regions.

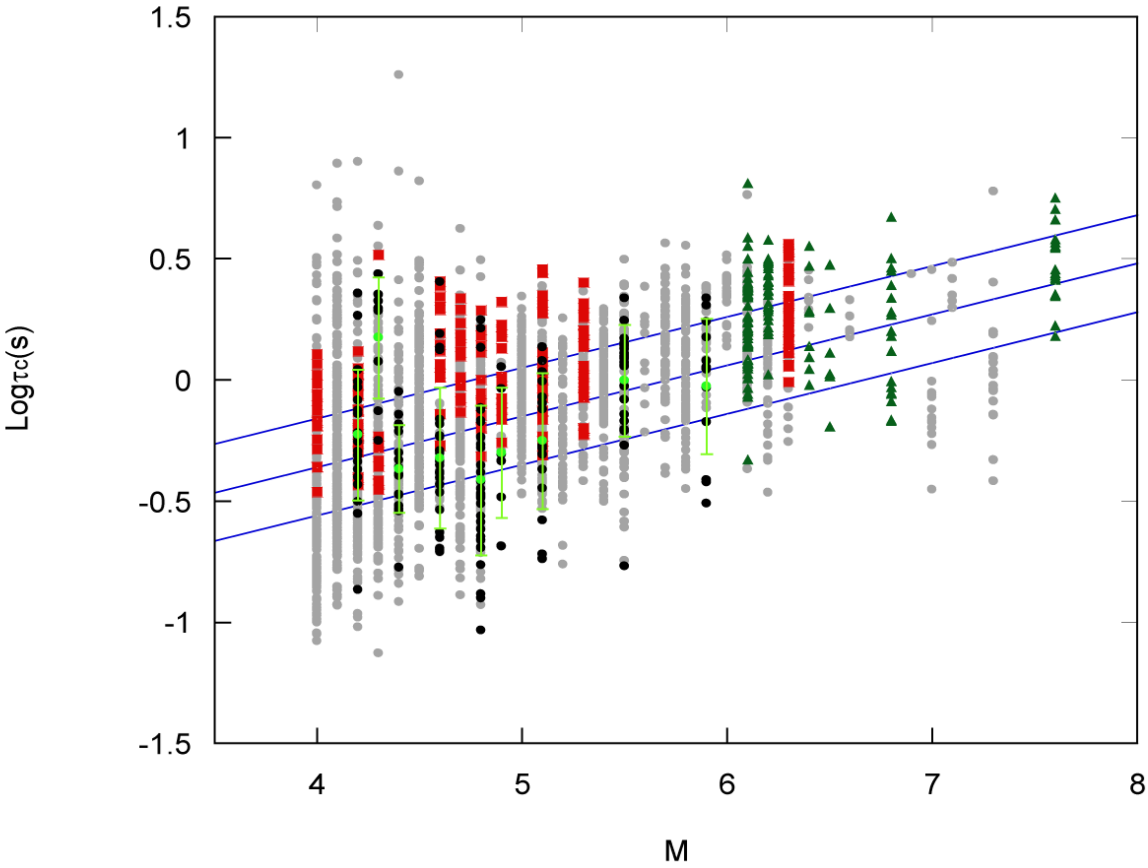

Figure 2.1 Values of τ_c versus magnitude for the S. Vicente Cape region (black circles, mean value green circles) together with values of τ_c for Italy (red squares), Japan (grey circles) and Taiwan (green triangles) taken from Zollo et al, 2010. Blue lines best-fit and misfit standard error bounds

3. PICKING

EEWS must be able to automatically detect, locate and estimate earthquake magnitudes in a few seconds, just after first-P wave arrival and with enough accuracy. In the ALERT-ES project we must first test the different methods for the automatic detection and picking of the seismic phases. Phase detectors and pickers provide also other parameters, like robust onset timing, amplitude information, onset polarization, etc. In order to obtain the earthquake parameters τ_c and P_d, we need to analyze a few seconds signal window just after the P wave arrival, in consequence the onset time of the P wave must be automatically picked with a very small uncertainty, to avoid losing a part of the signal or introducing noise as signal.

Automatic phase picker algorithms are based on the identification of the changes of some characteristic of the incoming signals when the seismic waves arrive, such as the energy, the frequency content, statistical properties (Withers *et al*., 1998). Picking methods are usually applied on the pre-filtered vertical component records.

We have checked more than 10 picking methods based, for example, on the ratio of the short-term and long-term averages of a characteristic function or of an envelope of the seismic signal (Baer and Kradolfer 1987), on the statistical properties of the non-Gaussian signals (Savvaidis *et al*., 2002), on the complex demodulation (Roberts and Christoffersson, 1991), on the Walsh transform (Michael et al., 1982), Hilbert transform (Earle and Shearer, 1994), Fourier transform (Gledhill, 1985) and wavelets transform. Other approaches are based on neural-network analysis, autoregressive methods, fractal dimension and polarization analysis. The *Earthworm*'s automatic picking module (USGS, 2005), based on Allen's algorithm (Allen, 1978), has also been checked. We have applied these methods to the database of ALERT-ES project in order to find the best compromise between the uncertainty on the picks and the velocity and computational efficiency needed for EEWS.

Preliminary results show that Baer &Kradolfer (1987) and Savvaidiset *et al*. (2002) algorithms have a lowest uncertainty on the picks with a small consumption of computational time. The Baer and Kradolfer algorithm show a difference less than 2 samples (0.08 s) between the manual (red) and automatic (black) picking (figure 3.1). The computational time consumption is 52 microseconds per each second. Two different thresholds were used, one for detection and other for picking. For the Savvaidis et al., algorithm the difference is less than 3 samples (0.13 s) and the computational time consumption is 78 microseconds per each second of data.

The *Earthworm*'s automatic picking module has been adjusted in order to detect P-waves with a maximum of a half second of difference from the manual picking. Once the parameters have been adjusted, the configuration of each station has been tested with other records from the database with lower quality (low SNR). From the results obtained we have classified the stations into two groups, according to the time difference between the automatic and the manual picking. Most of the differences correspond to the interval of 0-0.3 seconds with a standard deviation of 0.46 s, lower than 0.5 seconds that was used to configure. Large differences (greater than 1 s) correspond to bad quality records

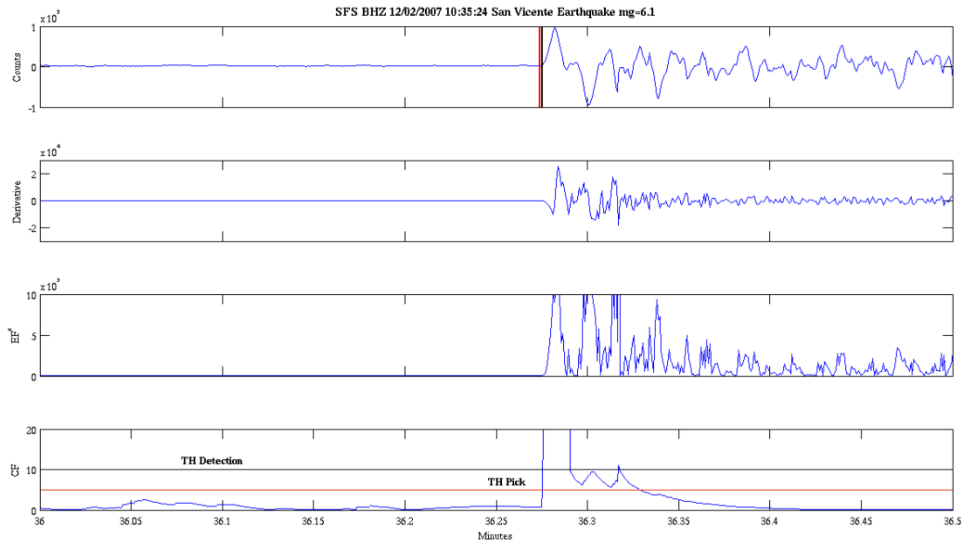

Figure 3.1 Automatic picking (Baer and Kradolfer algorithm) for 2007 S. Vicente earthquake (Mw=5.9)for SFS station. From the top to the bottom BHZ record, its derivative, the square EF function, and the characteristic function CF and the threshold are shown

4. LOCATION AND LEAD TIME SCENATIO FROM EARTHWORM'S MODULE

A stand-alone simulator of the detection and location module used in *Earthworm* (USGS, 2005) has been configured in order to check the quality of the hypocenter estimation and the time necessary to obtain it, comparing with the results obtained with a reference hypocenter (hypocenter determined by IGN). Different tests have been carried out, using different number of stations to detect and locate the events. An example of these estimations is shown for the M=5.5 earthquake of 17 December 2009 offshore S. Vicente Cape. A good estimation of the epicenter can be obtained using 6 stations, 47s after the earthquake occurrence and an alert can be given at that time. In fact, 5 seconds before, using only 4 stations, an alert could be given, but the error in the hypocenter and origin-time is larger. In figure 4.1, we shown the automatic epicenter estimated using 6 stations, very close to the reference (IGN) epicenter. The lead time is estimated supposing that the largest damage is produced by the arrival of the S-waves. The lead-time scenario obtained from the differences between S-wave arrival time and alert-time is also shown. A blind zone, determined by the zone where S-wave arrival time is less than the alert-time (47 s in this case), is represented in figure 4.1with a dashed line circle that reaches the SW of Portugal. So, this region could not have been alerted. Nevertheless, other populated cities such as Faro, Huelva, Cádiz or Seville could have been alerted 10, 40, 55 and 65 seconds before S waves arrivals.

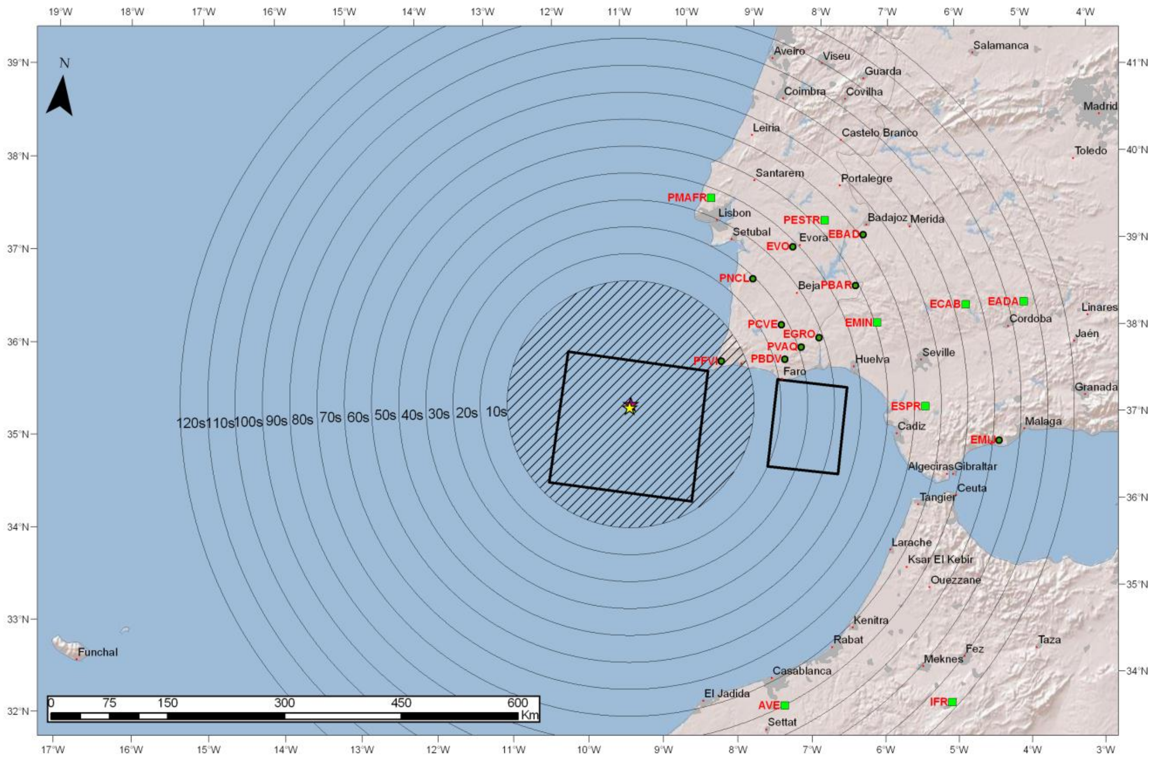

Figure 4.1.- Lead time scenario for a M5.5 earthquake, obtained from an automatic detection and location performed with 6 stations. Automatic epicenter (purple star) and reference epicenter (yellow star) are shown, together with , blind zones(dashed line circle) and lead times . Stations with median time picking differences <0.1s are shown as green circles, and stations with larger differences as green squares

5. PRESTO: APPLICATION TO S. IBERIA

PRESTO (Probabilistic and Evolutionary Early Warning System; Zollo *et al.*, 2009, Satriano *et al.*, 2010) has been developed by the RISC LAB of the Federico II University (Naples, Italy) as part of an EEWS program for the Southern Apennines region (Italy). In this region a modern strong motion network is deployed and shocks occur inside of the network at epicentral distances less than 50 km. However, in the S. Vicente and Gulf of Cadiz areas the situation is quite different. Earthquakes occur off-shore at epicentral distances larger than 100 km and are recorded at broad-band seismic stations (velocity instruments), deployed on land with a large azimuthal gap to the west.

In consequence, the application of PRESTO system to S. Vicente Cape-Gulf of Cadiz is a good test to estimate its robustness in another context. We have used the standard configuration and 4 picks to declare an event, for selected events of S. Vicente Cape taken from the data base. Specific crustal models for this area have been used (Gonzalez *et al*., 1996). Preliminary results are shown in figure 5.1 for the Mw=5.9 earthquake of 12 February 2007. The event is detected 43 seconds after the origin-time, although the location found is wrong due to two false picks (EADA and PVLZ stations, figure 5.1A). A new location is obtained after 51 seconds using 6 stations (figure 5.1B). A good hypocentral location is finally obtained after 55 seconds, from 8 picks associated to the event, but the magnitude is still underestimated (M=5.6, figure 5.1C). Finally, almost 1 minute after the origin-time, a good location and magnitude estimation is obtained (figure 5.1D). According to these results the time available for early warning is 14 seconds for Huelva, 23 seconds for Cadiz and 33 seconds for Seville and in consequence an EW alert would be useful. Other PRESTO configurations will be tested in the future.

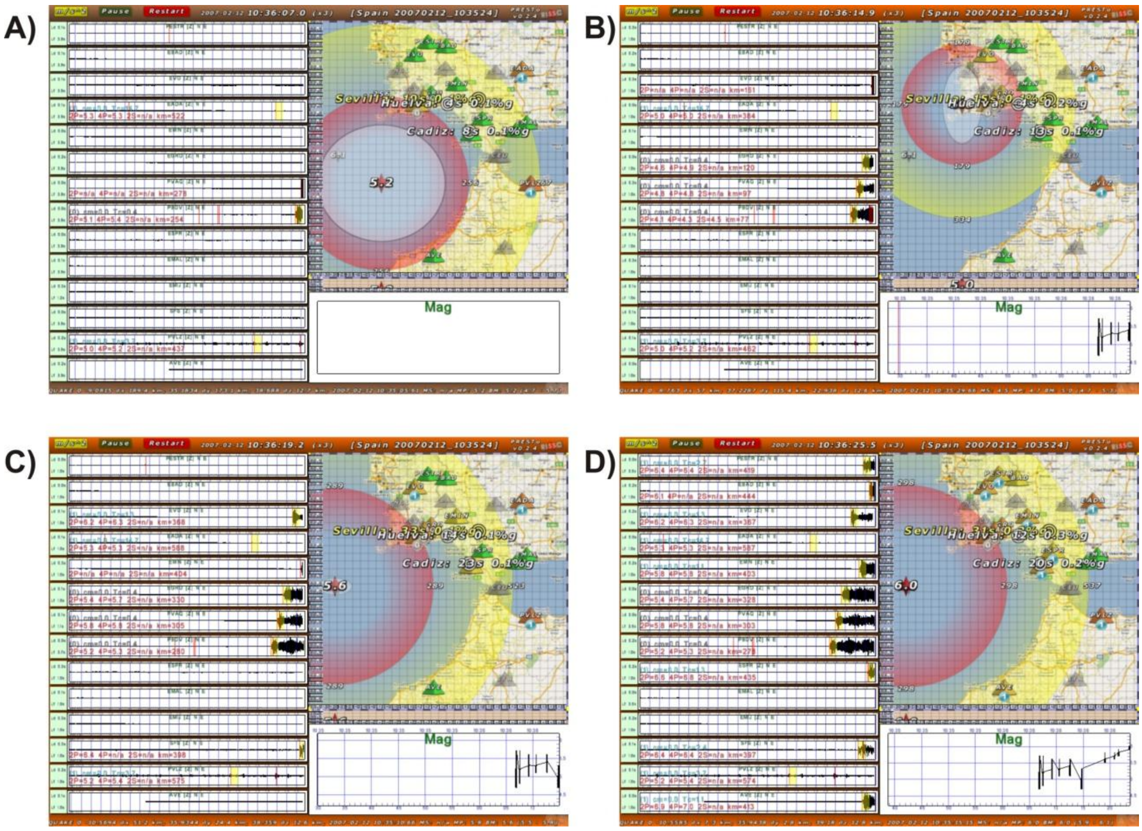

Figure 5.1.- Application of PRESTO system to the 2007 S. Vicente earthquake (Mw=5.9). At each step stations used on the locations are shown at left with a yellow mark. At right the epicenter determined by PRESTO is shown as a red star together the magnitude estimated.

5. CONCLUSIONS.

Preliminary results for the ALERT-ES project show that the relationships between τ_c and magnitude obtained for different regions, may be applied to earthquakes occurred in S. Vicente Cape region. Different algorithms have been checked for automatic picking. Best results have been obtained for the Baer and Kradolfer (1987) and Savvaidis *et al*. (2002) algorithms with differences less than 0.08s and 0.13s between automatic and manual picking. The *Earthworm*'s methodology has also been checked and configured for the region, in order to obtain differences less than 0.5s between automatic and manual picking. Different scenarios of lead-time to warn population of different nearby cities have been also obtained with automatic *Earthworm* location routines. Finally we have tested the PRESTO system for selected earthquakes occurred in this area, with the standard configuration. Preliminary results, show a useful scenario of alert-times with the automatic location and magnitude estimation in the application to the 2007 (Mw=5.9) S. Vicente Cape earthquake.

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