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Holocene Activity of the Porto Alto Fault, Portugal

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SUMMARY

The Lower Tagus Valley area (LTV), where Lisbon is located has been struck by several destructive earthquakes whose sources remain still to be determined. The identification of surface ruptures in the area is a challenging task that requires the use of geophysical techniques. This paper focuses on the identification, for seismic hazard purposes, of faults segments of the Porto Alto fault, one of the most important structures in the LTV. High-resolution P-wave seismic reflection data was acquired to confirm the fault activity in the Holocene but the lack of resolution to detect a fault of maximum 2m anticipated vertical throw in the 50m thick alluvium column was evident. We revisited the site to acquire high-resolution S-wave seismic and GPR data. The seismic profile shows reflectors interruptions in the stacked section, changes in amplitude/shape of the reflection hyperbolae in the shot gathers and coincident low velocity anomalies, indicating the presence of a fault segment at the anticipated location below 25m depth. The GPR profile reaches a maximum depth of about 15m and does not show the presence of any fault. Other geophysical techniques and trenching investigation are under consideration for corroborating the activity of the Porto Alto fault.

Introduction

This paper focuses on the location and characterization of small throw faults in soft sediments in the Lower Tagus Valley (LTV) area for seismic hazard evaluation purposes. The LTV area, where the city of Lisbon is located, is an intraplate region close (about 300 km) to the plate boundary between Africa (Nubia) and Eurasia (Fig. 1a). It has been struck by several destructive earthquakes like in 1344, 1531 and 1909, which caused major loss of lives and significant damages (e.g. Justo and Salwa, 1998). The sources of these events have been attributed to local fault zones based on intensity data but their exact location remains still to be determined. The low slip-rates (0.1-0.4 mm/year) associated to erosion-sedimentation rates make surface ruptures identification a very difficult task. The instrumental seismicity (Fig. 1a), on the other hand, is weak and except for the last decade, is poorly located and cannot be used to identify with precision the seismogenic sources.

Therefore, the use of geophysical techniques for seismic hazard evaluation purposes has been the primary approach in the last decade (e.g. Cabral et al., 2003, Vilanova and Fonseca, 2004; Carvalho et al., 2006; 2008). Oil-industry seismic reflection profiles, which cover a good part of the study area, have been used to identify major fault zones and were followed by high resolution geophysical data acquisition over selected targets (e.g. Carvalho et al., 2006; 2009).

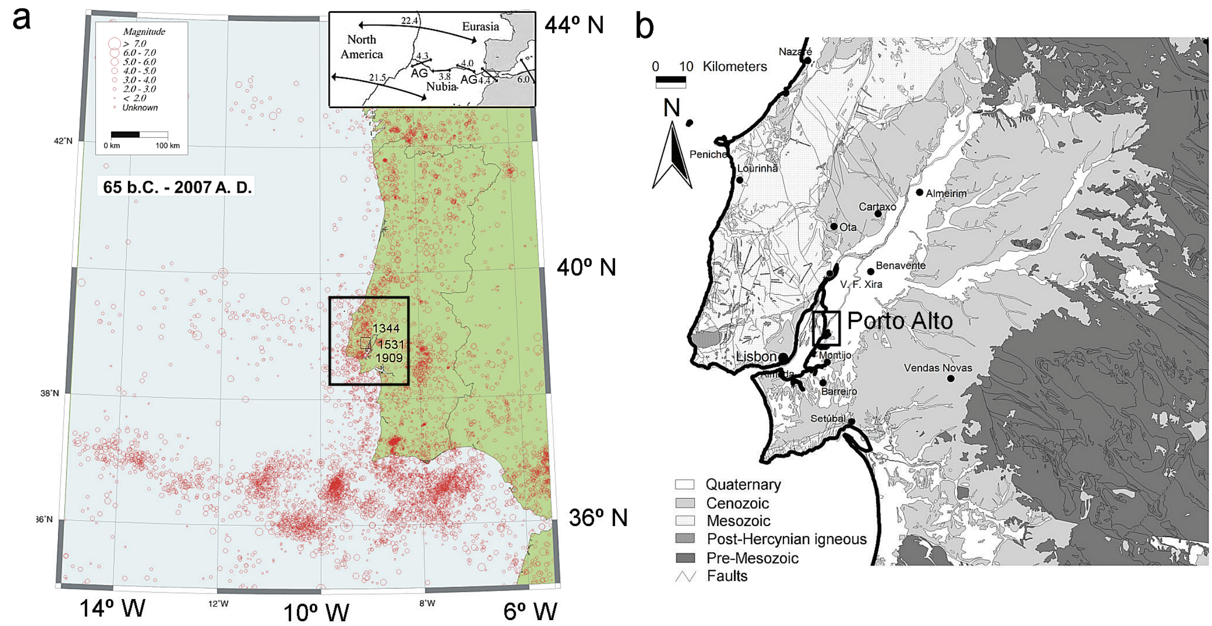

Figure 1 *(a) and (b) Seismicity of the study area (after Instituto de Meteorologia) with general location of "local" earthquakes of 1344, 1531, 1909 and inset showing tectonic setting of the study area. Square indicates location of geological map shown in (b). (b) Simplified geological map of the LTV region (after LNEG, 2010). Square indicates location of the study area.*

The Porto Alto fault zone is one of the most important fault zones in a regional framework. It was clearly identified on oil industry data (Fig. 2a), and a site close to Porto Alto (Fig. 2b and 1b) was chosen for acquiring high-resolution P-wave seismic reflection and vertical electrical soundings data (Carvalho et al., 2006), since the upper 100ms in the oil-industry data are poorly imaged due to the used acquisition geometry. The lack of resolution in the Holocene sediments to resolve a fault of maximum 1m to 2m anticipated vertical throw was evident even in the so-called high-resolution P-wave dataset. However the data indicated that the fault was present below the 50m thick Holocene cover and could be affecting this column of sediments till a depth of about 20m.

In this research, we have revisited the site to acquire high-resolution S-wave seismic and ground penetrating radar (GPR) data. In the last decades, advantages of the S-wave reflection method to map in great details shallow faulting have been recognized (e.g., Goforth and Hayward, 1992; Ghose and Goudswaard, 2004; Pugin et al., 2009, Harris, 2009). Two key advantages with S waves compared to P-waves at shallow depths are superior resolution due to considerably low S-wave velocities in soft sediments and the sensitivity of S waves to subtle changes in the soil type (Ghose and Goudswaard, 2004). Full elastic modelling of S-wave shot gathers in a similar environment (Ghose et al., in prep.) show that it is possible to image our target with the proposed acquisition parameters.

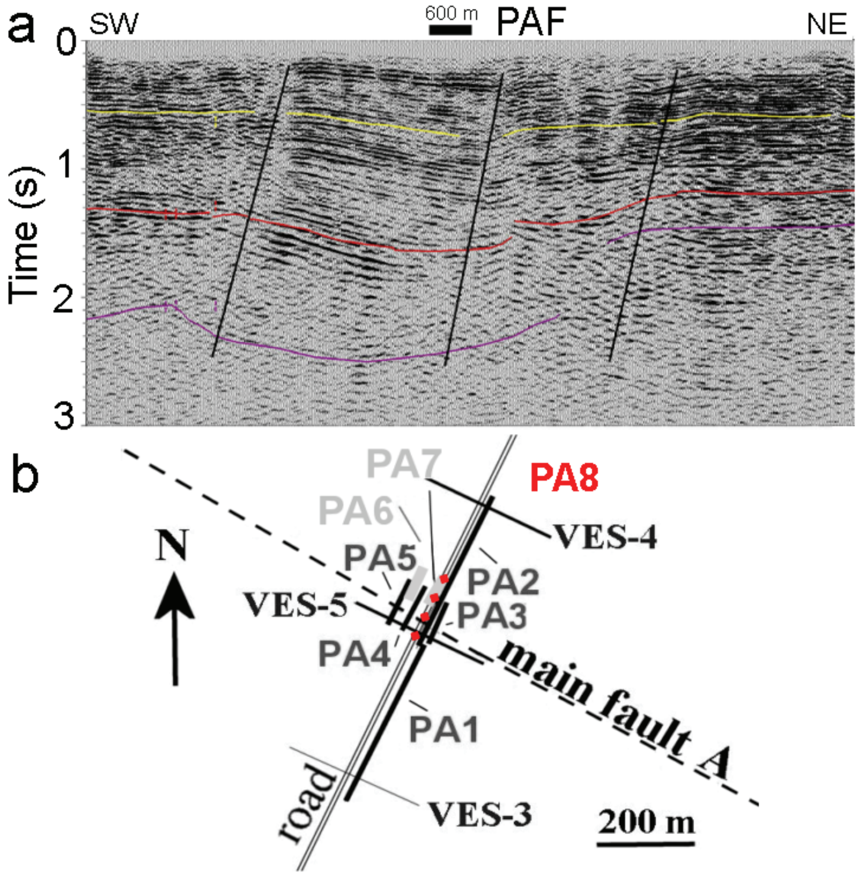

Figure 2 *(a) Oil-industry seismic reflection profile where the fault zone was firstly identified. Interpretation after (Pinto, 2011.) PAF- Porto Alto fault. yellow line- Upper Miocene; red line- base of Cenozoic; purple line- near top of Palaeozoic. (b) Location of previous shallow P-wave reflection and VES studies (in black) and S-wave reflection (gray) and GPR (red) profiles carried out in this research.*

Methodology

Figure 2 shows the detailed location of all previously acquired shallow P-wave and VES profiles, the two more recent S-wave reflection profiles (PA6 and PA7), and the GPR (PA8) profile. The GPR profile was coincident with one of the S-wave profiles (PA7). All profiles are located in agricultural plain where alluvium sediments of the Tagus river are deposited in the last 15 kyears (Carvalho et al. 2006). The maximum thickness of these soft sediments reaches about 50-60m. These units host a few aquifers and the water table is about 1m deep.

The previous shallow P-wave seismic reflection data (Carvalho et al., 2006) indicated two major fault segments in this area, the eastern one approaching the surface. This shallow fault segment is the target of the present studies. Our goal is to investigate if the Holocene alluvium is affected by this faulting.

We have performed walk-away noise tests to optimize the acquisition parameters for this site. The location is so chosen as to cross in the middle the anticipated fault segment. The geophone spacing was 0.5 m in the walkaway test. With 1.0 m minimum source-receiver offset the walkway data are acquired using 96 geophones located ahead the source. From the maximum frequency and the minimum velocity observed in the walk-away data, we have optimized the geophone spacing for the final reflection profiling at 0.75 m to ensure no spatial aliasing in the acquired data.

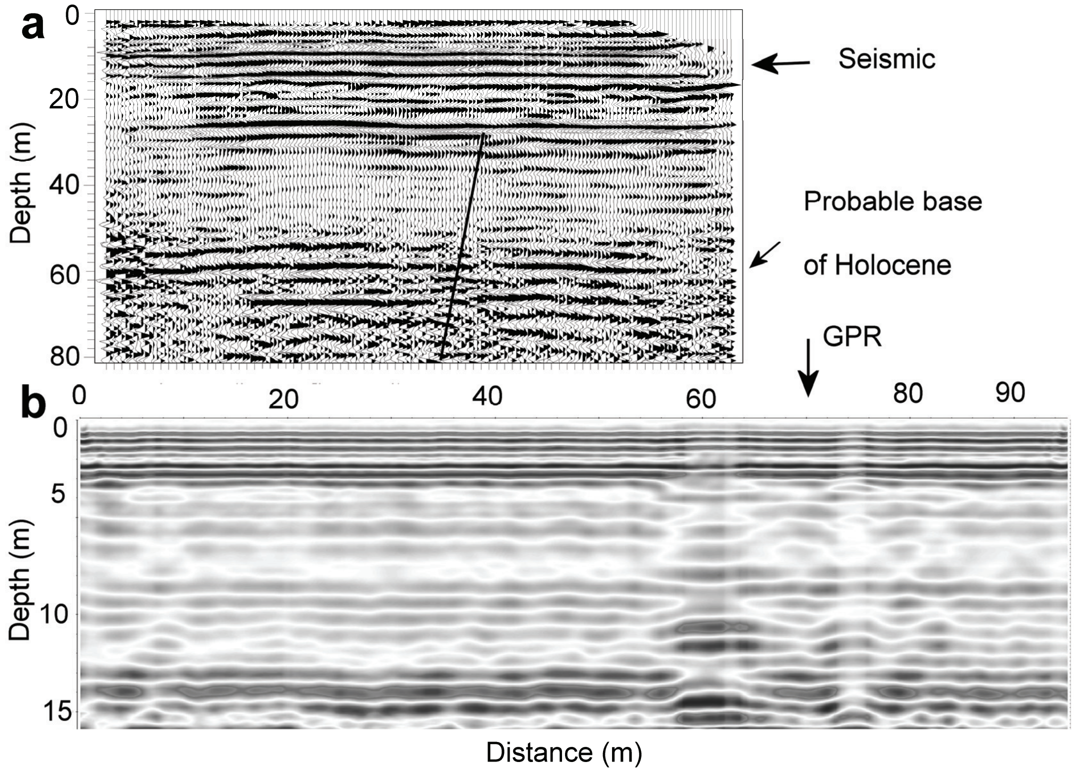

Figure 3 *(a) Depth converted PSTM stacked shear wave section for profile PA7, using 1D average velocity from HOVA. The fault interpretation is superimposed.(b) Coincident GPR profile PA8.*

A wooden beam pressed with the wheels of a heavy jeep and hit from the side has served as the S-wave source. We have hit both ends of the sledgehammer S-wave source to eliminate P-wave contamination but little is observed in the raw data which is due to the relatively hard, dry top surface condition and the soft soil beneath.

With 36 active receiver channels and 12 roll-along channels in inline end-on geometry, equal source and receiver intervals of 0.75 m and minimum source-receiver distance of 5m, two parallel S-wave reflection lines are shot. With this geometry we achieved a nominal fold of 18. Maintaining a constant CMP fold along the profile allows us to discard any possible artefacts related to the uneven/varying stack fold and locate evidences of subtle faulting in the seismic reflection data.

The processing sequence was the following: geometry installation, vertical stacking, trace editing, gain correction, bandpass filtering, first arrival muting, deconvolution and spectral whitening, velocity analysis, NMO correction, CMP stacking, surface consistent static corrections and velocity analysis and prestack time Kirchoff migration (PSTM). In absence of VSP, the time sections have been converted to depth using a representative 1-D interval velocity field obtained from the stacking velocity field. The result is shown in Figure 3 with fault interpretation overlaid.

To confirm the interpretation in Fig. 3 we have also looked for evidences of faulting in the shot gathers and searched for low velocity anomalies. For this purpose constant velocity panels were analysed and Horizon Velocity Analysis (HOVA) was performed for 4 selected seismic horizons. Previous modelling in a similar geological environment located about 30km from this site showed that very few fault plane reflections are expected and that a change in amplitude/shape of the reflection hyperbolae in the shot gathers is an indication of faulting. These signals were found for the fault marked in Fig. 3.

Ground Penetrating Radar Data

The GPR profile was acquired along a single profile of 95.2m long with the GSSI SIR-3000 acquisition system attached to a shielded antenna with a center frequency of 100 MHz. Data was collected using a horizontal sampling of 50 traces per meter and a time window of 350ns. Post-acquisition data processing involved zero time adjustment, band pass filtering between 20 and 200 MHz, horizontal trace to trace averaging (5 traces), and the application of automatic gain control (AGC). An average velocity of 0.1 m/ns was used for depth estimation. The result is shown in Fig.3b. No evidence of faulting was found at the depth reached in agreement with the seismic interpretation.

Conclusions

We have found consistently in the shot gathers and in stacked sections changes in amplitude/shape of the reflection hyperbolae, low-velocity anomalies and interruptions of the reflectors at a particular location, which we associate with the presence of a fault segment below 25m depth. The two shear-wave profiles show disturbances at this location, which is also the previous anticipated fault location based on shallow P-wave reflection surveys. GPR data that reaches a maximum depth of about 15m, does not show the presence of a fault at this location. Electrical tomography studies, other geophysical techniques, and trenching investigation are now being considered for corroborating the presence and the Holocene activity of the Porto Alto fault zone.

Ackowledgements

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