Is the Vila Franca de Xira fault still active? A shallow seismic reflection shear-wave study in an intraplate environment

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Abstract

The V. F. Xira fault (VFXF) is considered to be the most probable source of several destructive earthquakes that caused significant damage and loss of lives in Lisbon, Portugal and surrounding cities. The fault outcrops in Miocene sediments but is not seen to affect Quaternary terrains. The combination of low slip-rates in the area with erosion/sedimentation rates prevents the identification of active faults in the region. Our goal is to confirm if this fault has been active and to improve seismic hazard assessment in the LTV area. Previous P-wave seismic reflection data indicated the possibility of two shallow fault segments affecting the Holocene alluvium close to the VFXF outcrop. Due to the lack of resolution of this data to detect a small throw (< 2m) fault, the site was revisited with a high-resolution shallow S-wave reflection profile to confirm the fault segments but results were not completely conclusive. Here, we present reprocessed S-wave data and results of full-elastic seismic modelling to confirm the presence of the suspected faults. Clear indications of faulting were found: change of the shape and the amplitude of the reflection hyperbolae, discontinuities in the reflectors in the stacked section, shear-wave velocity dropping in anticipated the damage zones, and weak fault plane reflections. The results are analyzed further through seismic modeling. We conclude that the shallow fault segments affect the entire thickness of the Holocene alluvium and that the VFXF is active.

Introduction

The Vila Franca de Xira fault (VFXF), which has recently been proposed as a segment of a larger fault zone (Carvalho et al., 2008), has been suspected to be the possible source of several destructive earthquakes that caused significant damage and loss of lives in Lisbon, Portugal and surrounding cities. In the last 1000 years, events with estimated magnitudes above 6 have struck the region in 1344, 1531 and 1909. The fault is seen to affect Miocene sediments but not Quaternary terrains. The combination of low slip-rates in the area (< 0.5 mm/year) with high erosion/sedimentation rates erases the signatures of surface ruptures and blankets the Lower Tagus Valley (LTV) area with a 50 m thick alluvium cover preventing the identification of active faults in the region. The goal of this work is to confirm this fault has been active into the Holocene and therefore a very likely possible source for these earthquakes; understanding the activity of this fault is imperative for a proper seismic hazard and risk analyses in the LTV area.

In the last two decades geophysical methods have been used to locate and characterize the seismogenic sources of this region (Cabral et al., 2003; Carvalho et al., 2006; 2008). Primarily relatively deep seismic reflection profiles, acquired for the oil-industry during 1950-1981, have been used for this purpose. Although these datasets have allowed determination of the main seismogenic sources in the region, yet due to a lack of resolution resulting from the unfavorable acquisition geometry and acquisition parameters of the oil-industry data, these works had to be followed by shallow high-resolution geophysical work (Carvalho et al., 2006; Cabral et al., 2011).

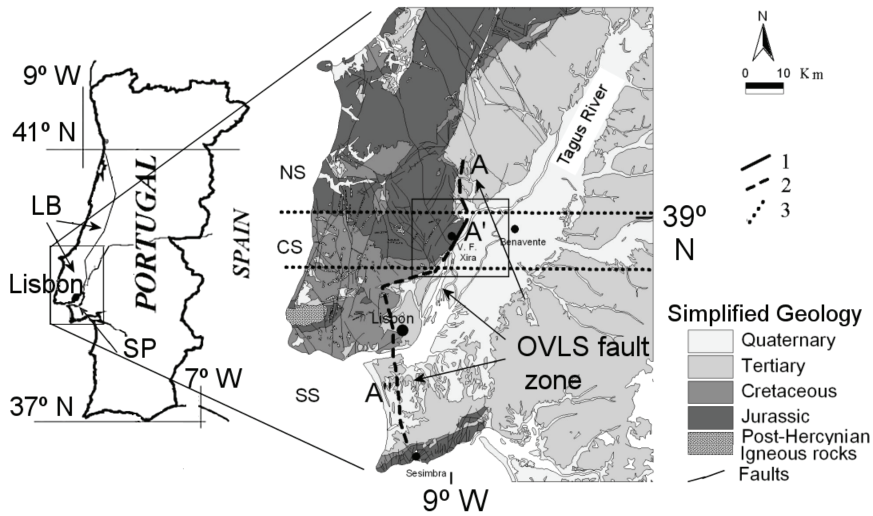

***Figure 1** Location of the VFXF and a simplified geological map (Oliveira et al., 1992). The segments of the OVLS fault zone are shown (A,A', A''). 1- outcrop of the OVLS fault, corresponding to the VFXF; 2- course of the OVLS fault zone inferred from seismic reflection and potential-field data; 3- delimitation of the OVLS fault zone segments based on geological and seismic reflection data (after Carvalho et al., 2008); NS- northern sector; CS- central sector; SS- southern sector; SP- Setúbal Peninsula; LB- Lusitanian Basin. Square indicates location of this study.*

Ground penetrating radar and seismic reflection method have been two of the most commonly used methods for shallow fault location and characterization. Here, following the location of the VFXF in reprocessed oil-industry profiles, P-wave high-resolution seismic reflection data were acquired over the Holocene alluvium (Carvalho et al., 2006). The lack of resolution and relative insensitivity to subtle changes in the subsoil for P-wave data in the shallowest 50 m highlighted the need to revisit the site and acquire S-wave seismic reflection profiles. These more recent surveys suggested that two major fault segments affect the alluvium Holocene cover (Carvalho et al., 2009). Here, we present the reprocessed S-wave data and the results of full-elastic seismic modeling in order to confirm the presence of the previously suspected fault segments in the Holocene alluvial sediments, indicating that the VFXF is an active fault and the very probable source of the earlier mentioned major earthquakes.

Shear wave data acquisition and processing

The shear wave profile was acquired with a layout of 48 40Hz horizontal geophones with 36 active channels and 12 roll-along channels. The source to the nearest geophone offset was 5 m. To avoid spatial aliasing of the surface waves, a receiver spacing of 0.75 m was chosen through walkaway noise tests. The seismic source used was a wooden beam pressed with the wheels of a jeep and hit from the side. More details of the acquisition parameters can be found in Carvalho et al. (2009).

The raw shot gathers show clear reflection events at 200 ms and 400 ms. The original data processing flow with post-stack migration (Carvalho et al., 2009) was carried out; the nominal CMP stack fold was 18. However, for each shot, all of the 48 channels were actually acquired. The use of all 48 channels resulted in a split-spread geometry and a varying CMP fold along the profile, but a higher nominal fold.

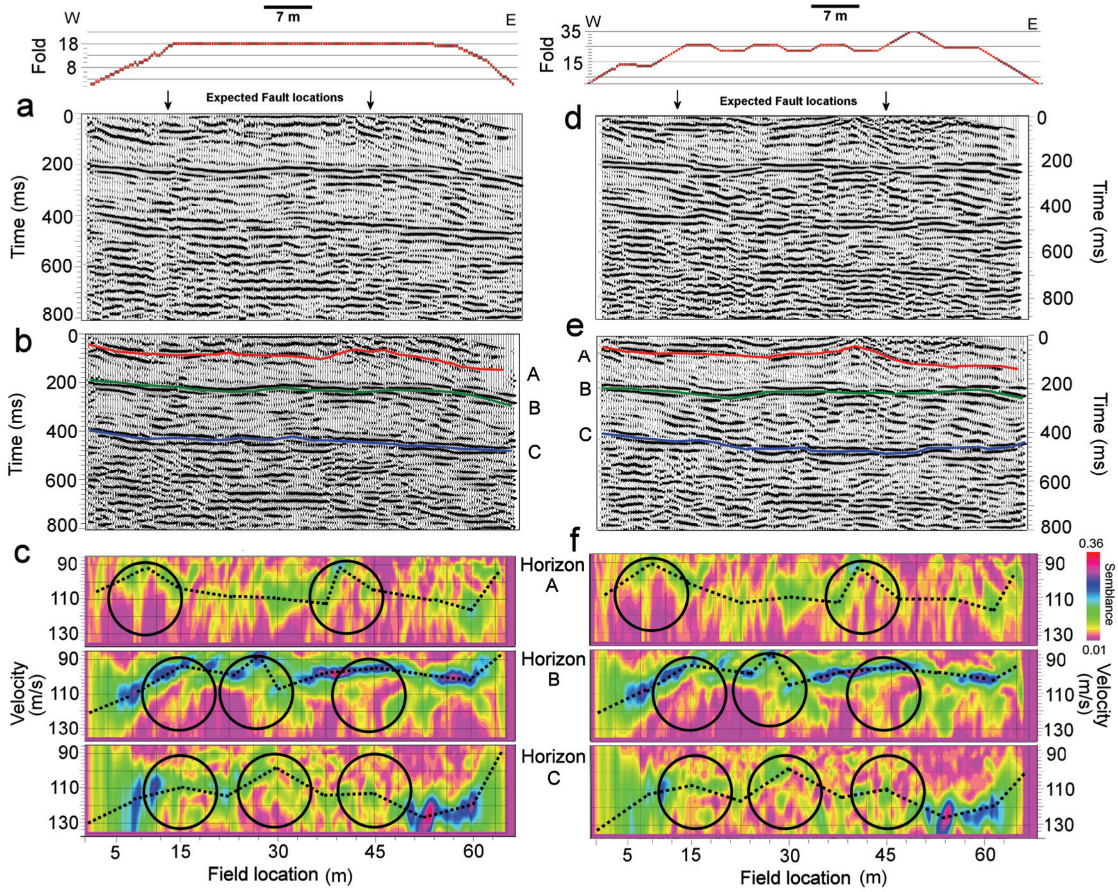

***Figure 2** Reprocessed S-wave stacked sections for an end-on geometry with a constant CMP fold (a)-(c) and split-spread with a variable CMP fold (d)-(f) geometries: (a/d) unmigrated, (b and e) poststack time-migrated; (c and f) HOVA velocity fields for the 3 reflectors marked in (b and e); the circles mark the anomalous changes in the velocity. Arrows indicate the locations of the anticipated fault segments based on previous studies. The CMP fold distribution is shown at the top.*

Both datasets (corresponding to end on geometry with a constant CMP fold and a split-spread geometry with variable CMP folds) were reprocessed separately using the original processing flow. Horizon velocity analysis (HOVA) was performed (Fig. 2), in combination with pre-stack time migration (PSTM) using a Kirchoff algorithm (Fig. 3). In absence of VSP, the time-stacked section was depth converted using an 1D average of the HOVA velocity field. The fault interpretation is overlaid in the depth section of Fig. 3. The latter was based not only on the stacked data but also on analyses of shot gather, common-offset gathers, velocity analysis and independent well data.

Clear indications of faulting were found: a change of shape and amplitude of the reflection hyperbolas, discontinuities in the reflectors in the stacked section, local changes in velocity and scattering behavior (visible in common-offset sections not shown here) at coincident locations. Well data located a few hundred meters from the two ends of the profile show a significant change in depth of the base of Holocene at a distance of about 800 m (Carvalho et al., 2009). All these evidences (but no fault plane reflection) points to the existence of shallow fault segments at this location. However, the question rose as to why no clear fault plane reflection was visible? Can it be the ragged nature of the fault segments that interfered destructively? Or is it due to the limited width of the fault segments? Or otherwise, can the ductile nature of the soft, wet sediments that produce little contrast between the fault zone and adjacent sediments be responsible for this lack of fault-plane reflections? These questions led us to perform the seismic modeling, which we present in the next section.

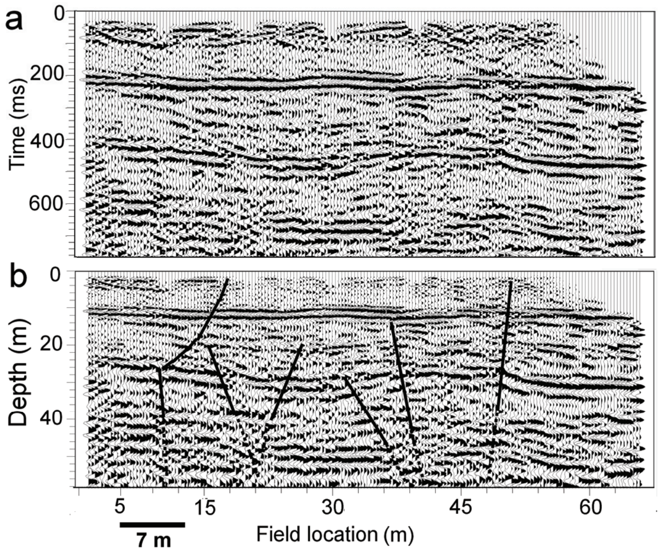

Figure 3 *Reprocessed shear wave profile acquired at V. F. Xira alluvial plain using an end-on geometry with a constant CMP fold, HOVA and PSTM (a) and depth conversion using an 1D average of the HOVA velocity field (b).*

Data interpretation and modelling

The model used in this study is based on well data and the interpretation of the S-wave stacked section which is depth converted using the RMS velocities. Well data includes geological log and SPT data located about 300m from both ends of the seismic profile. This model is in good agreement with the general stratigraphic model for the Quaternary in this area (Vis, 2009).

Full elastic modeling was carried out using the in-house modeling software developed at Delft University of Technology (Thorbecke and Draganov, *in press*). We have modeled only the SH-wave response because in the field we acquired only the transverse horizontal component data. A dipole source oriented transverse to the line of receivers with a fundamental frequency of 40 Hz is used.

We have tried first to model the major seismic reflection events present in the field data. This can be done quite successfully, though due to the local surface conditions, the surface waves and refracted events are stronger in the modeled data. We next introduce a fault segment representing by a thin rectangular zone with low velocity and extending from a depth of 4 m until a depth of 30 m. We experimented varying a few key fault parameters, to understand their effects on the shot gathers (see Carvalho et al., 2012, this conference).

Figure 4 shows the raw field-observed shot gathers together with the modelled ones at two source locations. A fault width of 0.4 m, a velocity contrast of 10 m/s between the damage zone and the adjacent sediments (considering a 10% drop in S-wave velocity drop in the damage zone) and a vertical spacing of fault plane irregularities (undulations/roughness) of 4 m are used in modelling. Based on modelling results we can explain the near-absence of fault-plane reflections in the field data.

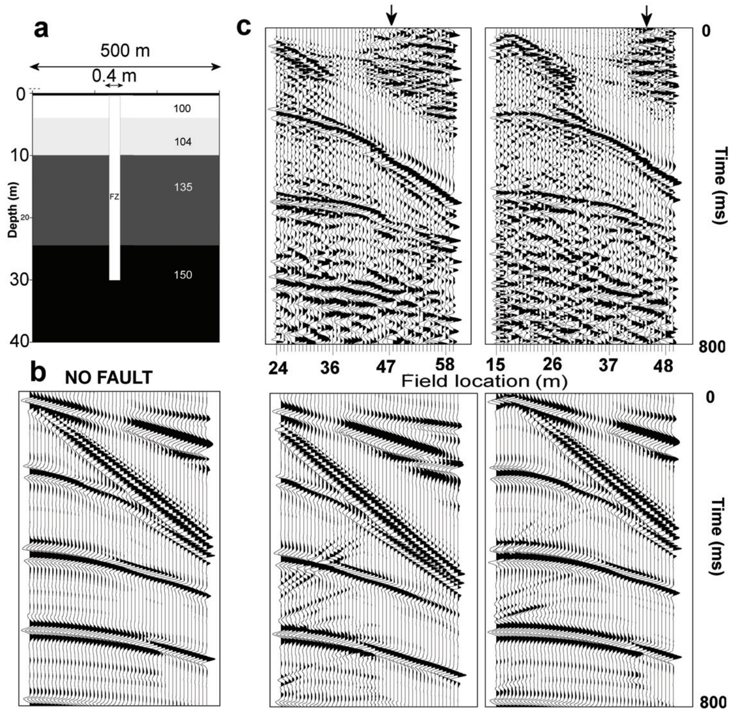

Figure 4 *(a) Velocity structure used in modelling; numbers indicate SH velocity in m/s ; (b) synthetic shot gather with no fault; (c) comparison of SH-wave field data with modelled shot gathers at two different shot locations. Arrow indicates position of the interpreted fault segment.*

Conclusions

We found evidences in our seismic shear wave field data that support the existence of shallow fault segments at the V. F. Xira site. The evidences point to a small vertical throw fault in unconsolidated soft sediments, recognizable by a change in the shape/attitude of the reflection hyperbolae, shear-wave velocity drops and scattering in the damage zones, and very weak fault plane reflections. The results are supported by seismic modelling, carried out using reasonable fault parameters for such tectonic/geological environments. The results support the conclusion that the fault segments affect the entire thickness of the Holocene alluvium, and that the VFXF zone is still active and is the most probable source of the 1344, 1531 and 1909 earthquakes.

Acknowledgements

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