The Lower Tagus Valley Fault Zone:
Overview, New Insights and Future Challenges

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SUMMARY
The Lower Tagus Valley Fault Zone (LTVFZ) is the tectonic feature located within the Lower Tagus valley (LTV) usually associated with at least two historical earthquakes in the region. Geomorphic features recently identified and observed during field mapping surveys in this study along the Lower Tagus floodplains indicate recent faulting. Evidence was mainly observed on the Quaternary and Holocene alluvial deposits along the northwestern portion of the Lower Tagus Valley, which generally show linear features indicative of left-lateral displacements. The magnitude estimate for the LTVFZ is at least M7.0 based on the length of the mapped active fault trace. Two new relative ages of the deformation are established on preliminary trenching results on the northern region. Recurrence interval will be determined upon receipt of results from sample processing for OSL dating.

Considering the above results, more mapping efforts are underway to investigate the northern and southern extent of the LTVFZ. Other sites for trenching activity are also being explored to determine other possible previous events to improve recurrence interval for the LTVFZ. Based on the above activities, ground shaking-related evidence like paleoliquefaction is also being considered to resolve other prehistoric earthquake events for the LTV.

Keywords: Lower Tagus Valley Fault Zone, active fault, geomorphology, paleoseismology

1. INTRODUCTION

Lisbon sits squarely in the damage range of the LTVFZ, the recently characterized active fault in the western part of the LTV (Besana-Ostman et al., 2012), which is left-lateral and about 80km long. Its northernmost point is in Atalaia and extends southward into Alhandra (Figure 1). The LTVFZ's last devastating quake occurred about 100 years ago. In terms of regional tectonics, the study area has very low regional slip rates mainly due to a relatively slow plate interaction between African and Eurasian plates in the SW Iberian region. Little is known about the seismogenic structure(s) of the LTV region partly because of the thick Cenozoic sediment cover and the very scarce instrumental seismicity of significant magnitude in the region. The existence of a major variscan fracture of crustal scale along the LTV has been assumed since the work of Arthaud and Matte (1975) as supported by deep seismic profiles of Mendes-Victor et al. (1980). Insights into the internal structure of the sedimentary cover was discerned from seismic reflection profiles in the 80's that lead to the suggested transpressional model for the active tectonics of the LTV source zone (Vilanova and Fonseca, 2004). This study presents recent results of some researches undertaken to ascertain the location, extent, recurrence interval and magnitude estimate for LTVFZ.

2. HISTORICAL EARTHQUAKES

There is a series of less known moderate to strong earthquakes with epicenters within 50 km from Lisbon that caused major destructions along the LTV region throughout the historical times. The earliest mention of earthquake destructions in Lisbon were in 63 AD through a Dominican friar named Bernardo de Brito and in 1344 when Pope Clement VI reprimanded the Portuguese king due a strong earthquake that caused damages to the Lisbon Cathedral. In 1356, more reports and accounts showed that the Lisbon Cathedral was again destroyed, which was rebuilt from the 1344 earthquake. Although geologists in the region regard the 1356 event as a distant offshore earthquake (Moreira, 1984), Oliveira (1986) assigned the 1344 quake to the LTV source zone.

Aside from these, the earliest descriptions of damage distribution with reasonable details attributed to the LTV source zone is the 1531 Lisbon earthquake with an estimated magnitude M6.5 to 7 (Justo and Salwa, 1998). The first major 1531 shock was on January 7, which caused many villagers throughout the country to seek refuge in the fields. Nineteen days later, a second major shock caused widespread destruction along the LTV region. Damages and observed destructions produced an intensity distribution shown in Figure 2A. On the other hand, the most recent major earthquake that affected Lisbon is the April 23, 1909 Benavente event (Choffat and Bensaude, 1912; Fonseca and Villanova, 2010). In this event, many towns located on the southern margin of the Tagus about 50km NE of Lisbon were mostly damaged. The earthquake caused several casualties, destroyed buildings and houses, many cracks in the alluvial plain and sand ejections but no ground rupture (Choffat and Bensaude, 1912). Isoseismals for 1909 are also shown in Figure 2B. Note that a modern estimate of the moment tensor for 1909 using instrumental records gave a reverse mechanism with a NE-SW strike, compatible with the orientation of the LTV fault zone, and magnitude M_w=6.3 (Stich et al., 2005).

Another major event in the proximity of Lisbon is the 1858 event. During this earthquake, the town of Setubal was the most devastated with an estimated magnitude of M7.1 (Vilanova and Fonseca, 2007). Despite the absence of mapped ground rupture, the source of this earthquake was assumed to be the southernmost extension of LTV trending almost NS.

3. RECENT RESULTS FOR THE LTVFZ

3.1 Geomorphic Analysis and Field Mapping

Based on geomorphic analyses and field surveys in the Lower Tagus region, at least 45km-long active fault trace was determined from NNE of Entroncamento to Azambuja. The trace has been mapped by analyzing aerial photographs and other remotely-sensed data to identify various geomorphic features like scarps, tectonic bulges, tectonic depressions, and evidence for left-lateral displacement associated with active faulting. The identified trace shows evidence for apparent left-lateral displacement and can be followed for at least 45 km within the valley, transecting the Lower Tagus River, its tributaries, and innumerable terraces.

In Entroncamento area, several river tributaries were diverted due to the tectonic bulges along the fault while an apparent left-lateral displacement is observed on another tributary and a saddle in Atalaia. The clear active fault geomorphology can be followed from this area southwards east of Azambuja. The geomorphic evidence can be likewise identified on the ground where a mole-track-like feature near the western edge of the farm was observed. Unfortunately, towards the south and beyond this town, all evidence is very subtle. This may be attributed to the further sedimentation within the floodplains during the progression of sea level in this area about 7000 BP-1000 BP as shown by (Viz, 2009) coupled with the erosional process and human activities in the last several hundreds of years. Therefore, in this region, most of the identified linear scarps and small linear valleys have high uncertainties that more or less correspond to the boundaries of the farmed regions. Although ocular investigation confirmed the active fault features from Entroncamento to Azambuja, field inspections were very limited and/or even hindered from Azambuja to Alhandra since most places are fenced private lands especially within the sandbars and were generally flooded due to the unusual amount of rain that had prevailed in the last few months in Lisbon.

The newly-mapped trace has a general trend of N20E and is about 40km long from Atalaia to Santarem. Although it is still difficult to ascertain if the mapped trace had ruptured during at least one or all the three historical earthquakes mentioned, geomorphology indicates a most probable Holocene activity based on the transected features. Plot of the mapped trace is shown in Figure 3. It is notable that the mapped trace correlates well with the elongation of the isoseismals for both 1531 and 1909 events. Further details on mapping results are demonstrated by Besana-Ostman et al. (2012).

3.2 S_{mf} Calculations

One of the features we analyzed for LTVFZ is the mountain front sinuosity. Mountain front sinuosity index (S_{mf}) can be measured from landforms that developed and/or were modified by tectonic processes, which provide relevant information about the activity of the related tectonic structures. This technique was applied in areas such as SW USA (Bull and McFadden, 1977; Rockwell et al., 1984), the pacific coast of Costa Rica (Wells et al., 1988) and the Mediterranean coast of Spain (Silva et al., 1992; Silva, 1994; Masana, 1994; Silva et al., 2003) wherein the values are grouped into three classes: Class 1 (<1.4) as an active fronts with high activity, Class 2 (between 1.4 and 2.5) are with medium activity and Class 3 (>2.5) as inactive fronts (Bull and McFadden, 1977). In LTV, the most characteristic landforms are the associated drainage networks and alluvial fan systems measured on a 1:100,000 scale SRTM-derived digital elevation model (DEM) with 90m resolution. Our initial computations for S_{mf} produced a value of 1.39 for the northern segment and 1.47 for the southern segment measured (Figure 4A). These values imply that the northern and southern segments are Class 1 and 2, respectively (Besana-Ostman et al., 2012). For comparison, S_{mf} values for other tectonic structures in Portugal are also measured with results shown in Figure 4B. Interestingly, S_{mf} values for Vilariça and parts of Messejana faults indicate active fronts with high activity. The rest of the measured mountain fronts have medium activity.

3.3 Initial Trench Excavations

Trenching of a fault is probably the most common and high potential technique for investigating an active fault with surface rupture. In Pombalinho, we found a fault scarp transecting a Holocene terrace where we made initial excavations. The walls of the excavated trench are shown in Figure 5. The sedimentary succession exposed in the trench revealed several packages composed of horizontally stratified unconsolidated sand and clay. These layers showed deformation by both faulting and liquefaction. The pattern of deformation and the 8m wide zone of deformation showed strike-slip faulting accompanied by several centimeter vertical displacements (Besana-Ostman et al., 2011). Ages of the deformation will be determined from the results of the C14-dating being undertaken for the collected organic samples.

3.4 Magnitude Estimate

Considering the length of the mapped LTVFZ, the most probable magnitude estimate can be calculated using the magnitude-rupture length regression relations $Mw = 5.16 + 1.12 \log(SRL)$ for strike-slip faults, where SRL is surface rupture length (Wells and Coppersmith 1994). Based on this empirical relation, the northern and southern segments could be expected to produce an Mw 6.9 and Mw 7.0 earthquake, respectively. In case the whole fault extent were to rupture, the resulting magnitude would be Mw 7.3 (Besana-Ostman et al., 2012). This magnitude is higher than previously suggested for 1909 and 1531 events. Moreover, with this magnitude estimate and assuming a 2m lateral displacement for a single event, a recurrence interval of 20,000 years is calculated and a net slip rate of 0.1 mm. However, if 1.1 mm of net slip as indicated by Negredo et al. (2002), the resulting recurrence interval is 1,800 years.

4. FUTURE CHALLENGES

4.1 Future Active Fault Mapping

With the newly-established active fault trace for the LTVFZ and knowing that fault length is directly correlated with the earthquake magnitude that can be generated on that structure, the knowledge about the extent of an active fault is critical for seismic hazard analysis. Consequently, to ascertain the potential earthquake magnitudes and taking into account a long return period or clustering for large earthquakes in SW Iberia, active fault mapping will be pursued and refined. Additional morphometric index like valley index will also be calculated using DEM and be correlated and compared with S_{mf} values. We also hope to recalculate S_{mf} values for all structures in Portugal as higher resolution SRTM-derived DEM becomes available.

Further and more detailed mapping is underway using high-resolution LiDAR and continuous analysis of other available data. Over the years, advancements in LiDAR hardware & software and better understanding of the technology have greatly improved the usefulness of LiDAR as a valuable surveying and mapping tool. Recently, LiDAR is also emerging as an attractive alternative to the traditional technology for large-scale geospatial data capture. And since surficial geological mapping in the heavily vegetated terrain has always been difficult for the geologists, LiDAR-based mapping of superficial geology provides a very powerful tool for identifying the variety of surficial deposits and landforms in this diverse landscape. Under Project FINDER, the northern extent and more details in the LTVFZ will be mapped and identified using a powerful laser mounted on an aircraft over mountainous terrain to virtually deforest the landscape and reveal details of the topography, including the traces of active faults. This LiDAR data is currently being acquired and initial results will be presented during the convention.

Moreover, more trench excavations are scheduled to be dug to address the issue of recurrence interval especially for the northern segment of LTVFZ. With the acquisition of older aerial photographs and higher resolution data like LiDAR, we hope to identify better trench sites that could provide more deformed layers with datable materials. During our recent trench excavations, typical issues that we faced were the massive clay deposit, extensive agriculture activity and relatively shallow water level within the valley. Holocene deposits within the LTV are predominantly comprised of sand particles and clays. Based on trenches excavated in other regions, it was noted that ground ruptures are known to 'heal' on massive sand layers within a year of displacement. Thus, such deformation will be very challenging to find with the absence of other distinctive layers. It was noted, however, that extensive liquefaction deformations were observed on several layers and sites.

Considering the above predicament, we hope to introduce the geoslicer in LTVFZ studies. Geoslicer is comprised of a sampling box and a shutter typically made of stainless steel (Nakata and Shimazaki, 1997). During excavation, the sampling box will be driven vertically into the ground by using a hammer, vibrator or body-weight followed by its shutter sliding along the thin slits attached to both sides of the box. The box is pulled out containing sediments with undisturbed features. This method is far more effective at depths beyond conventional sampling method such as boring sticks, and hand augers that will allow three-dimensional observation of structures of the sediments. The geoslicer could extract sizeable samples using a vibrator from alluvial lowlands, sand dunes, tidal flats, swamps and even from lake bottoms. Collected sections can be taken to a laboratory in the sampling box for close examination or can be displayed at a meeting or even stored for future re-examinations. In order to get deeper and wider outcrops, the geoslicer may employ sheet piles commonly used at construction sites as sampling boxes.

Finally, considering the results of initial trenching activities undertaken during this study, other landforms like sandbars and Holocene terraces will be utilized as a possible source of evidence of ground shaking-related features liquefaction. We highly suggest that paleo-liquefaction studies should be implemented and be given a serious consideration for moderately-sized events within the LTV. We will attempt to utilize the geoslicer to extend the reach of the traditional trench as well as on future paleoliquefaction studies in this region.

4.2 Seismic Hazards Assessments

Accurate information on fault location would allow for increased precision in the measurement of distance between a seismogenic source and a particular site. The new information about the location of the LTVFZ is our small contribution to geophysicists and engineers to calculate better the potential of ground shaking level at a given point in LTV in the event of a future earthquake. Using the new length and location information, better parameters can be used in hazards assessment for the cities within LTV. Finally, we hope that the new facts on LTVFZ will not only help in the future hazards assessment and disaster mitigation efforts in Portugal but also bring about new studies of active faults for the whole country.

5. SYNOPSIS

In the case of LTV in Portugal, we identified the active fault trace associated with the LTVFZ. The active trace is about 80km long left-lateral fault that extends from Atalaia to Alhandra. The available isoseismal data from historical records, though very limited, indicate a gross NE-SW trend. Its shape likewise indicates a most probable NE-SW rupture propagation, which correlate with the trend of the mapped active trace. Moreover, morphometric index S_{mf} indicates high tectonic activity for the northern segment. Initial trench excavation showed faulting and liquefaction deformations.

Considering the currently defined length and possible segments for LTVFZ, further studies are proposed and underway to determine the recurrence interval of LTVFZ in various sites. Determination of its extension north of Entroncamento and south of Azambuja are also of an utmost importance for further research to establish the characteristic of the major earthquake for the LTV. Other future studies will also include additional research on valley index, high-resolution LiDAR, more excavations, geoslicer and paleoliquefaction.

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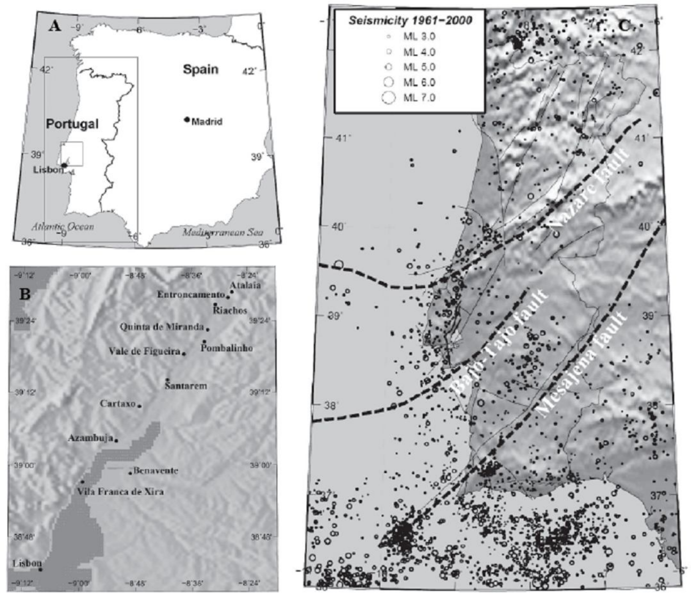


Figure 1. A. Map showing the location of Portugal in the Iberian Peninsula. The study area (small rectangle) is shown in B with names of towns along the Lower Tagus valley and land background based on the 90-m resolution SRTM-derived DEM. Dark gray areas indicates water. C. Plot of seismicity from 1961 to 2000 seismicity (circles). The faults identified by Carvalho et al (2006, 2008) and the main Quaternary active faults in the 1:1,000,000 scale geological map of Portugal are shown as thick black and thin black lines, respectively. The thicker dashed lines represent the Nazare, Bajo-Tajo, and Mesejena faults as plotted by Jimenez-Munt et al. (2004). Adapted from Besana-Ostman et al. (2012).

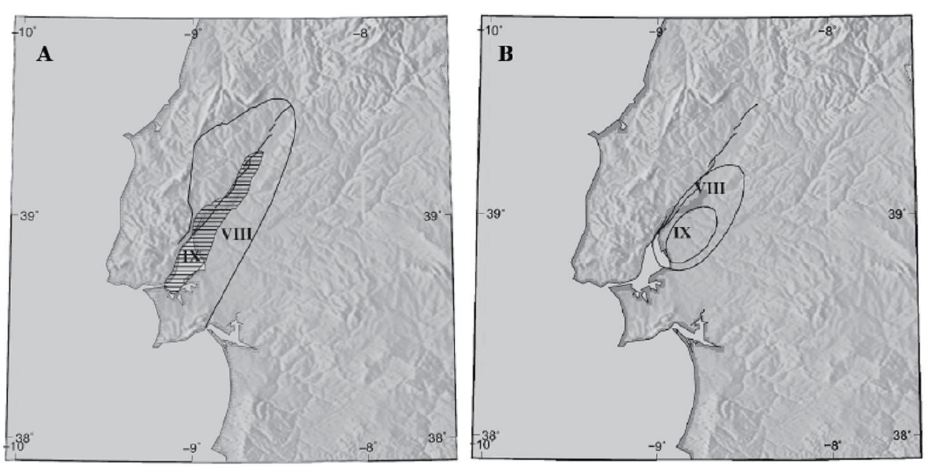
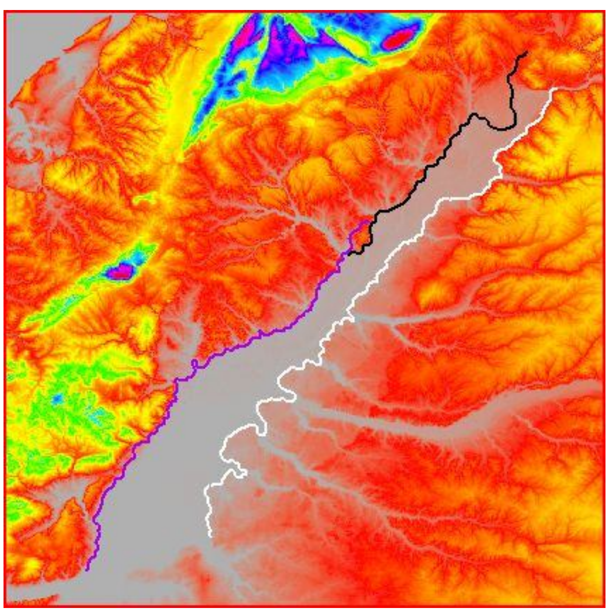


Figure 2. A. Isoseismals for the 1531 earthquake simplified from Justo and Salwa (1998). B. Isoseismals for the 1909 earthquake according to Chofat and Bensaude. The trace of LTVFZ is shown in black line according to Besana-Ostman et al. (2012).

Figure 2. The mapped LTVFZ trace plotted on Google Earth together with regional geology, 1909 epicenter according to Stich et al. (2005), and other structures in the area.



A

Fault	Lmf	Smf	Class	Kinematic
LTVFZ (N)	41.08977	1.396193	I	LL
LTVFZ (S)	69.29127	1.475516	II	LL/rf
LTVFZ (PN)	39.62231	1.384825	I	
LTVFZ (EF)	89.88897	1.762515	II	R
Vilarica (N)	56.50501	1.392555	I	LL
Vilarica (C)	68.54933	1.11190	I	LL
Vilarica (SE)	89.51457	1.192953	I	LL
Vilarica (SW)	106.9709	1.540776	II	T
Penacova	221.1838	1.490318	II	LL
Ponsul (N)	48.27547	1.698882	II	RF
Ponsol (S)	71.13974	1.479651	II	RF
Nazare (N)	90.89797	1.442697	II	LL
Nazare (S)	67.6656	1.480885	II	LL
Aljezur (N)	35.45892	1.65237	II	LL/rf
Aljezur (S)	12.22804	1.473279	II	LL/rf
Messejana (P1)	75.31972	1.478905	II	LL
Messejana (P2)	43.88635	1.504902	II	LL
Messejana (P3)	41.10461	1.598064	II	LL
Messejana (P4)	32.90106	1.34527	I	LL
Messejana (P5)	28.10038	1.727505	II	LL
Messejana (P6)	22.33175	1.543702	II	LL
Messejana (S1)	20.74761	1.551895	II	LL
Messejana (S2)	34.00317	1.418074	II	LL
Messejana (S3)	26.90766	1.745815	II	LL
Messejana (S4)	43.33552	1.58374	II	LL
Messejana (S5)	63.84332	1.398299	I	LL
Messejana (S6)	42.01602	1.546141	II	LL

B

Figure 4. a. Map showing the traces (black, purple and white) measured to determine initial values of S_{mf} for the LTVFZ and b. S_{mf} for other identified structures for Portugal. Each value corresponds to a segment or portion of the structure depending on the geometry. Adapted from Besana-Ostman et al. (2011)

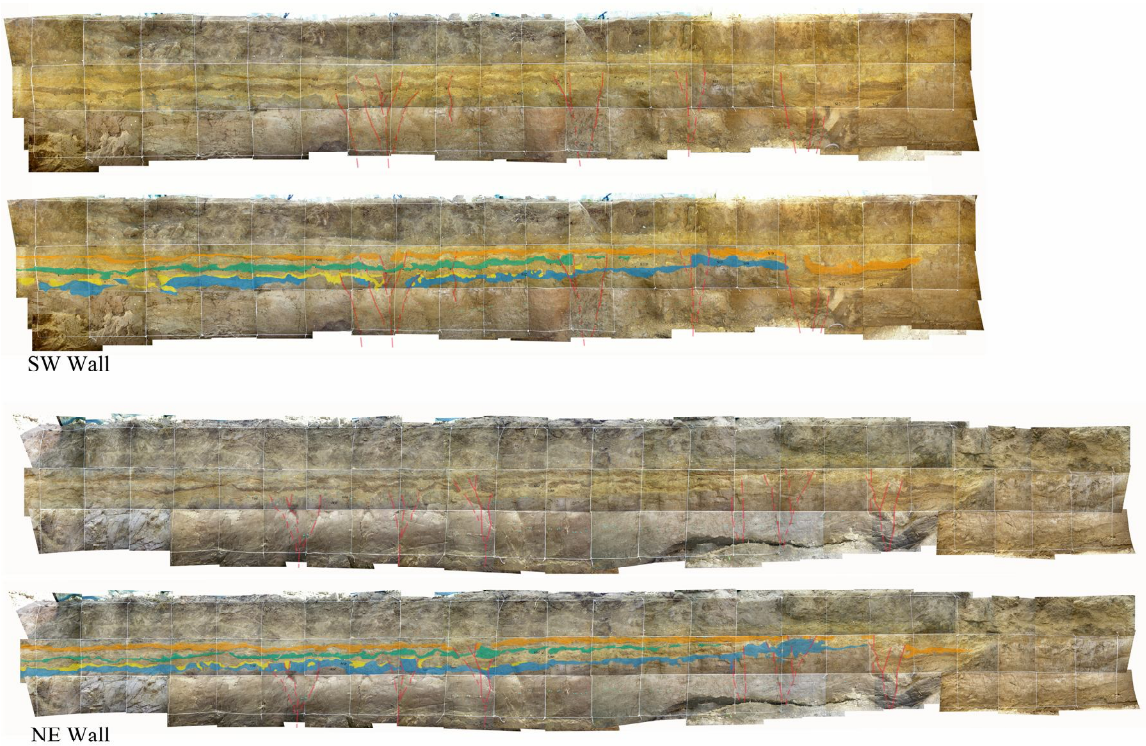


Figure 5. Photo showing one of the excavated trenches in Pomnalinho. Adapted from Besana-Ostman et al. (2011)