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The Vale de Santarém Neogene trough in the seismotectonics framework of the Lower Tagus Valley (Portugal)

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Abstract: Vale de Santarém is a small valley near the Tagus River, 60 km NNE of Lisbon, in an area of important seismicity. It is located in the Lower Tagus Cenozoic Basin, astride a narrow WNW-ESE tectonic trough where a thick Pliocene sedimentary sequence is preserved. Tectonic control is evidenced by faults bordering the trough, which have controlled sedimentation. It is aligned with the Rio Maior Pliocene basin, located 20 km NW, suggesting a WNW-ESE fault zone beneath the Neogene sedimentary cover, which was reactivated in Plio-Pleistocene (?) times, generating the small tectonic basins at the southern and northern tips. The interference of this structure with the active NNE-SSW faults of the Tagus Valley may cause segmentation of these faults, with implications for the expected seismogenic sources and the regional seismic hazard.

Keywords: Vale de Santarém, tectonic basin, seismotectonics, Lower Tagus Valley, Portugal.

The study area is located on the western Portuguese mainland and involves the highly developed and populated region of Lisbon. It is located a few hundred kilometres north of the Eurasian (Iberia)-Africa plate boundary (the Azores-Gibraltar fracture zone), in the Lower Tagus River Valley (LTV) (Carvalho *et al.*, 2006). This valley is located in the Lower Tagus Cenozoic Basin (LTCB), a NE-SW trending trough filled with up to about 2 km of sediments of Cenozoic age, which resulted from tectonic inversion of the Mesozoic Lusitanian Basin, located to the west, predominantly under the action of a Miocene compression (Fig. 1a).

The study region is presently characterized by the occurrence of a low, diffuse seismicity, though it has been affected by a few historical earthquakes that caused many casualties, serious damage and economic losses. Besides the action of large earthquakes generated in the southwestern offshore area, such as the one on November, 1st 1755, one of the largest earthquakes ever recorded (estimated magnitude ≥8.5, Martins and Mendes-Víctor, 1990; Zitellini *et al.*, 1999; Baptista *et al.*, 2003; Gràcia *et al.*, 2003), connected with the seismicity of the Iberia–Africa plate boundary, the study region records significant intraplate activity, witnessing important historical and instrumental earthquakes that periodically affect this area, such as the events in 1344, 1531 and 1909, with assigned magnitudes of 6 to 7 (Martins and Mendes-Víctor, 1990; Cabral *et al.*, 2003).

The 1344 and the 1531 earthquakes are poorly located because of the scarcity of historical descriptions,

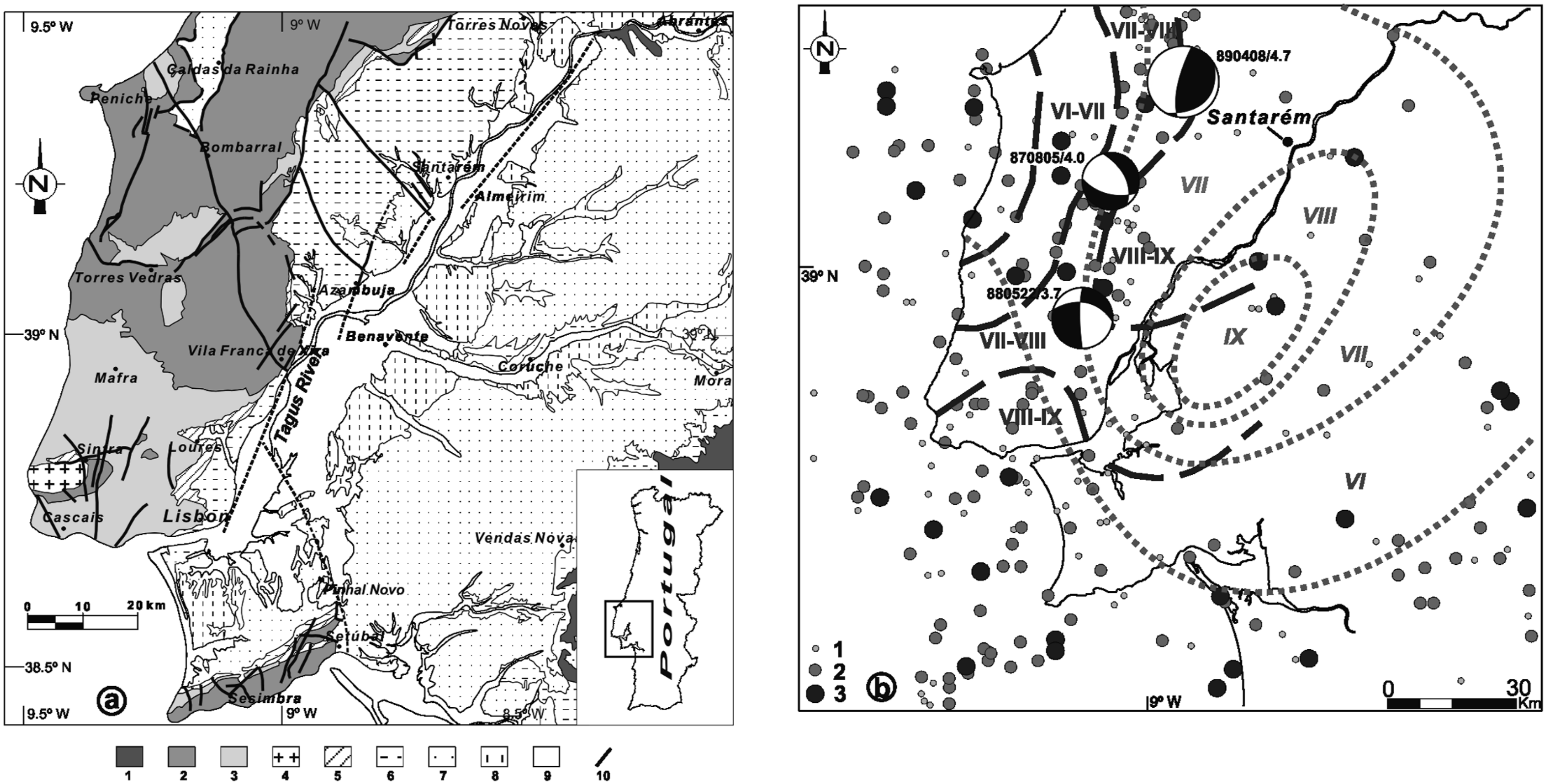

Figure 1. (a) Geological Map of the Lower Tagus Valley Region, adapted from "Carta Geológica de Portugal", 1: 500 000 scale (Oliveira *et al.*, 1992). Key – 1: Paleozoic basement; 2 and 3: Jurassic and Cretaceous sediments of the Lusitanian Basin, respectively; 4: Sintra Late-Cretaceous intrusive massif; 5, 6 and 7: Paleogene, Miocene and Pliocene sediments of the Lower Tagus basin, respectively; 8 and 9: Pleistocene and Holocene fluvial sediments of the Tagus river, respectively; 10: mapped fault (adapted from Cabral *et al.*, 2003, 2004; Carvalho *et al.*, 2006), (b) epicentre distribution of instrumental seismicity in the Lower Tagus Valley Region and adjacent areas for the period 1915 to 2004, from the International Seismological Centre, on-line Bulletin,http://www.isc.ac.uk/bull, International Seismological Center, Thatcham, United Kingdom, 2001. Symbol dimension is proportional to magnitude: 1: M2; 2: 2<M3; 3: M>3 (<4). Seismic intensities (I MM) and isoseismal lines for the earthquakes in 1531 (dashed lines, adapted from Oliveira and Sousa, 1991) and 1909 (dotted lines, intensity in italics, adapted from Moreira, 1984). Focal mechanism from Borges *et al.*, 2001.

having been positioned in the LTV based upon the destruction that they produced in the Lisbon area. The most recent major earthquake, whose epicentre was located NE of Lisbon near the village of Benavente occurred on April 23rd 1909. In this area the shock was registered with the maximum intensity of IX (MM) (Bensaúde, 1910; Choffat and Bensaúde, 1911; Choffat and Bensaúde, 1912; Moreira, 1984; Oliveira, 1986). Teves-Costa *et al.* (1999) calculated a moment magnitude of 6.0 for this earthquake, based upon analogue seismograms recorded in the Strasbourg and Uppsala seismic stations, and Stich *et al.* (2005) calculated a focal mechanism for the event, obtaining a reverse fault solution with nodal planes oriented 051°, 52° SE and 242°, 38° NW. The focal mechanism thus suggests an ENE-WSW trending source fault in the LTV fault system. The doubtful epicentre location and the interference of site effects and possible rupture directivity make it difficult to correlate this event with any known regional tectonic structure.

The occurrence of earthquakes indicates seismogenic faults in the study region that are still poorly constrained, due to the low slip-rates and the presence of a thick Holocene sedimentary cover that conceals many of the structures in the underlying Mesozoic and Paleozoic basement. Moreover, the available data regarding hypocentre depths (mostly between 10 and 20 km) show that the seismicity in the LTV is developed in the upper crust and is mostly generated by structures present in the Paleozoic basement under the Cenozoic and Mesozoic basins, which thus rupture several kilometres below the Cenozoic sedimentary cover.

Regional structural setting

The LTCB is undoubtedly a sedimentary sink intensely affected by tectonics, which acted mainly from the Neogene to the Quaternary, whose evolution was controlled by the NNE-SSW structural trend of the Lusitanian Basin. NW dipping pre-existent normal faults of Mesozoic age were affected by tectonic inversion in the Cenozoic and moved as oblique slip reverse faults that transferred Mesozoic rocks of the Lusitanian Basin to the NW over Cenozoic sediments of the LTCB to the SE (Cabral *et al.*, 2003; Carvalho *et al.*, 2006) (Fig. 1a).

The Vila Franca de Xira and Azambuja faults are two important structures with this trend that have been recognized in the LTV (Fig. 1a). The first outcrops on the right bank of the Tagus River about 25 km north of Lisbon, and shows the best morphological expression in the LTV as an east facing fault scarp. It consists of a NNE-SSW oriented complex fracture zone recognized by geological outcropping and from deep seismic reflection data and aeromagnetic data interpretation (Carvalho *et al.*, 2006). It is partially hidden under recent alluvium of the Tagus River and is intersected by a transverse NW-SE fault system, being offset through a left-lateral step-over.

The Azambuja fault, located about 15 km further NE, is another regional NNE-SSW trending structure showing geomorphologic and structural evidence of Pliocene to Quaternary activity (Cabral *et al.*, 2004). It presents a 15 km long fault scarp, downthrowing to the east a Lower Pleistocene erosion surface. Near the village of Azambuja, where the fault crosses the Tagus River bank, the vertical offset has a maximum value of around 80 m decreasing progressively northwards.

Besides the presence of major NNE-SSW "longitudinal" faults, there is geological evidence, as well as gravimetric and deep seismic reflection data, evidencing the presence of a system of WNW-ESE to NW-SE trending "transverse" faults that have made apparently a significant contribution to the overall structure of the LTCB and must be considered in the evaluation of the regional seismogenic potential (Carvalho, 2003; Cabral *et al.*, 2003; Carvalho *et al.*, 2006).

The Vale de Santarém structures

In this study we focused attention on the most conspicuous outcropping example of the "transverse" fault system in the LTV, which is the Vale de Santarém tectonic basin (Fig. 2). The area of Vale de Santarém had never previously been studied in detail and the aim of this work is to provide a better understanding of the possible behaviour of the "transverse" structures in the case of activity of the main, NNE-SSW trending faults.

The village of Vale de Santarém is located in a small valley on the right bank of the Tagus River, about 60 km NNE of Lisbon. This valley partially coincides with an approximately 7 km long and 1 km wide tectonic basin, where an abnormally thick sedimentary sequence of Pliocene age is preserved. The tectonic origin can be recognized by the presence of a major WNW-ESE trending steep fault that borders the basin on the south, and of another sub-parallel subsidiary fault on the northern side (Fig. 2). Both faults have downthrown the intermediate block during the

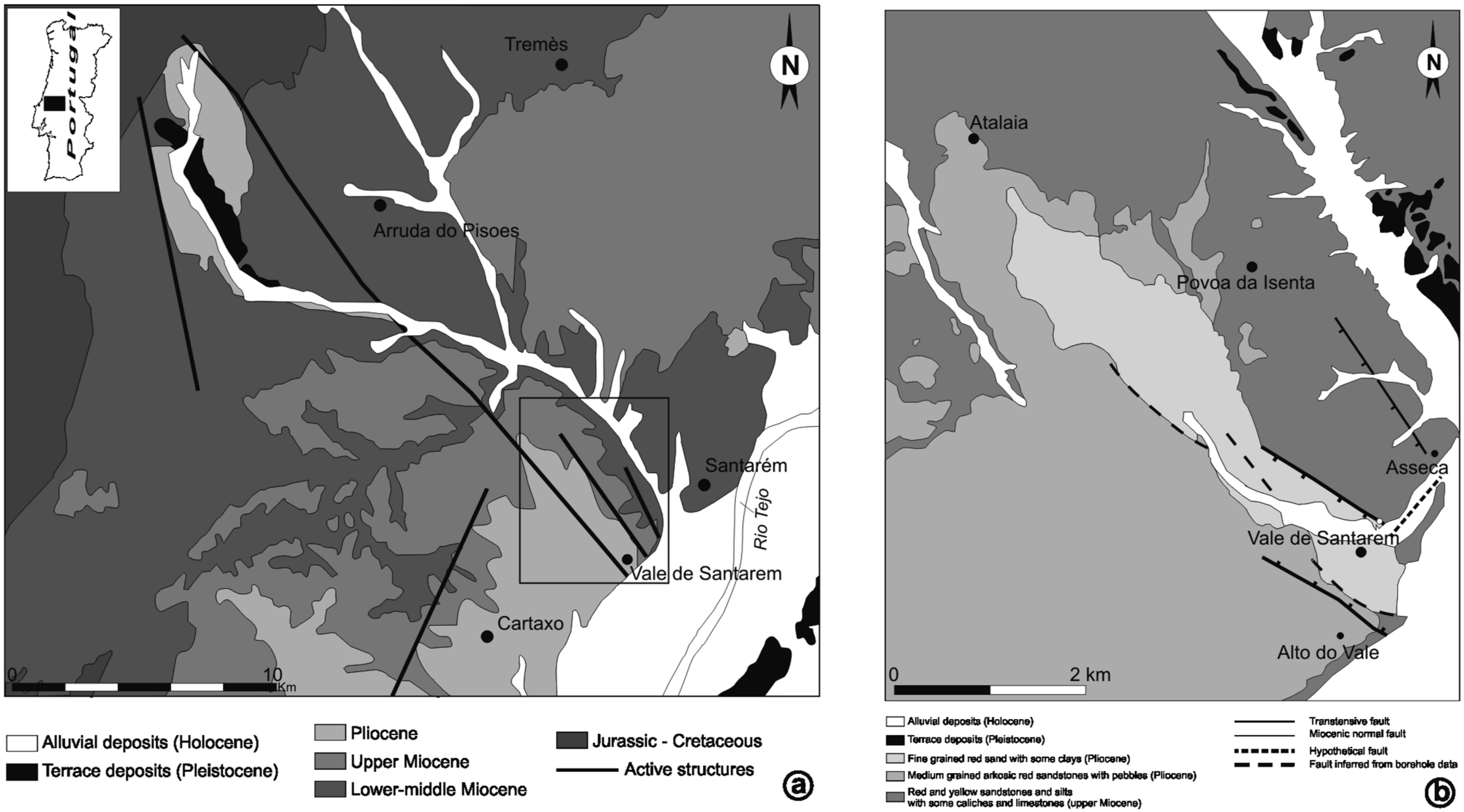

Figure 2. (a) Geological Map of the Lower Tagus Valley Region, adapted from “Carta Geológica de Portugal”, 1: 500 000. Frame: studied area detailed in figure 2b, (b) geological map of Vale de Santarem.

Pliocene, partially controlling the sedimentation, which shows particular facies evidencing a continental confined environment.

The Pliocene deposits preserved in the Vale de Santarém tectonic trough, as well as other fluvial deposits of similar age located outside this basin, mainly to the south, unconformably overlie sediments of Valesian age (Upper Miocene). These are fluvial and lacustrine continental deposits showing a variety of facies, including predominantly white, yellow or red sands and variably consolidated arkosic sandstones, some pebbly horizons, silty and clayey layers, as well as limestone and marls with caliches.

The Pliocene sediments outcropping inside the small tectonic basin show two distinct facies, one consisting of well sorted, medium to fine grained red sands with oblique laminations, often consolidated, showing some white areas due to near surface leaching of iron oxides, and another consisting of medium to coarse grained, consolidated, arkosic red sands with quartz pebbles; a brown coal layer was observed underlying fine sands on the northern side of the valley. Fifteen boreholes have been drilled in the Pliocene infill of the Vale de Santarém trough for lignite prospecting, with an average depth of 45 m and a maximum of 110 m (Pais *et al.*, 1999). The boreholes have cut through whitish quartz sands with interbedded thin clay layers rich in organic matter, and layers of lignite and diatomite, showing a maximum thickness of about 70 m. South of the southern fault that borders the tectonic trough, the Pliocene basal unconformity rises to an elevation of about 50 m, showing a syn- to post-Pliocene vertical throw of several tens of meters in this fault.

The Vale de Santarém Pliocene basin is an asymmetric, southwestwards tilted, tectonic trough, generated by two subvertical NW-SE/WNW-ESE trending faults approximately 0.75-1 km apart, the southern one being the major structure. On the north side of the valley a faulted contact was observed between Miocene sandstones and Pliocene clays and sands, locally featuring normal (fault dip: 230/78) or reverse (fault dip: 040/70) fault movement component. On

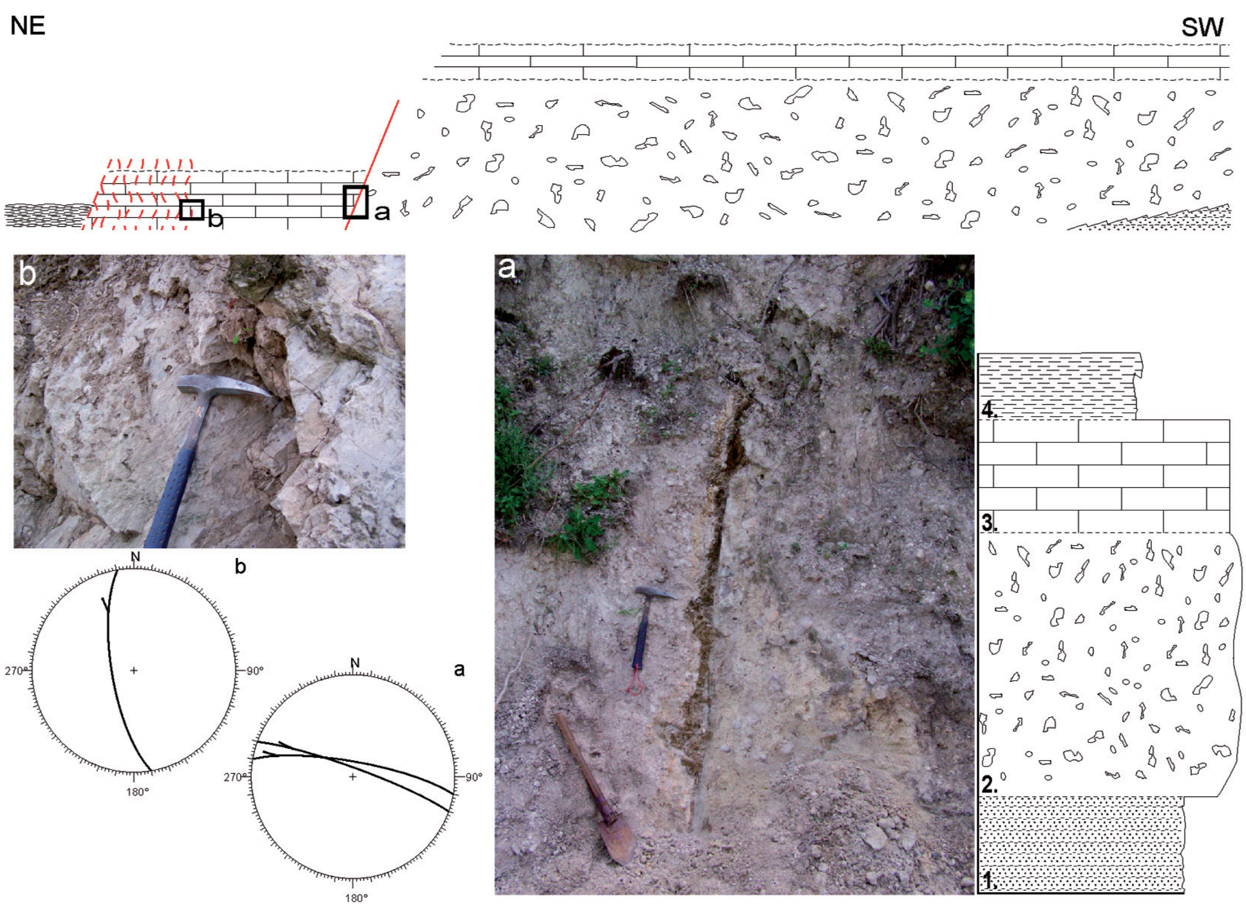

Figure 3. Outcrops of southern fault of Vale de Santarém fault system

the SW side, the major boundary fault outcrops in a railway cutting, well expressed in the Miocene sediments as ca. 15 m of intense fracturing and brecciation (Fig. 3). Some (dubious) striations observed in a faulted contact between limestone and a gravelly layer suggests an oblique left-lateral transtensive regime. Further NW, this structure was observed affecting the overlying Pliocene sediments (dip: 040/70, dip: 060/70).

The Vale de Santarém structure is aligned with another Pliocene tectonic trough located about 20 km to the NW, the Rio Maior basin (Figs. 1 and 2). This suggests the presence a continuous, WNW-ESE trending fault zone beneath the Neogene sedimentary cover of the LTCB which was reactivated, mainly near its extremities, in Plio-Pleistocene times, with scissor-like displacement, downthrowing to the NE, at the southern tip, where it interferes with the "longitudinal" fault system of the LTV, and downthrowing to the SW at Rio Maior, where it interferes with another major NNE-SSW trending structure, the Porto de Mós-Rio Maior fault zone.

Based upon borehole data, the interference of the WNW-ESE structures with the NNE-SSW LVT fault system can cause segmentation of these "longitudinal" faults, with consequences in terms of expected maximum magnitudes and regional seismic hazard evaluations. These considerations have to be further explored in detail in order to improve the present study.

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