A FALHA DE PINHAL NOVO – ALCOCHETE NO CONTEXTO DA NEOTECTÓNICA DO VALE INFERIOR DO TEJO

The Pinhal Novo-Alcochete fault zone in the seismotectonic framework of the Lower Tagus Valley (Lisbon Region)

C. Moniz (1), J. Cabral (2)

(1) Unidade Geologia, Hidrogeologia ,Geologia Costeira, Laboratório Nacional de Energia e Geologia. catarina.moniz@lneg.pt
(2) Departamento de Geologia e Instituto Dom Luiz, Faculdade de Ciências da Universidade de Lisboa. Campo Grande, 1749-016 Lisboa. jcabral@fc.ul.pt

Resumen/resumo: A Zona de Falha de Pinhal Novo-Alcochete (ZFPNA) é uma importante macroestrutura da região de Lisboa. A ocorrência de sismos históricos revela a presença de falhas sismogénicas regionais, caracterizadas por taxas de movimentação baixas (0,05-0,1 mm/ano). A ZFPNA está identificada principalmente por dados de sub-superfície. Tem direcção NNW-SSE e geometria ramificada, com uma zona de deformação atingindo 1,5 km de largura. Funcionou como bordo da Bacia Lusitana (BL) neste sector, implicando um enraizamento profundo no soco paleozóico. Foi reactivada em desligamento no Miocénico, como rampa lateral da estrutura em dobras e cavalgamentos da Arrábida, por acção de uma compressão NNW-SSE que inverteu a BL. O deslocamento de horizontes estratigráficos superficiais reconhecidos em perfis de reflexão sísmica e sondagens indica actividade tectónica fini-neogénica a quaternária, corroborada por evidências geomorfológicas. A dimensão estimada da ZFPNA indica um sismo máximo expectável de M 6-7, com intervalos médios de recorrência na ordem de 3.000 a 11.000 anos

Palabras clave: Falha de Pinhal Novo-Alcochete, Vale Inferior do Tejo, Falhas activas, Sismotectónica

Abstract: *The Pinhal Novo-Alcochete Fault Zone (PNAFZ) is a major tectonic structure of Lisbon Region, located in the southern area of the Lower Tagus valley. Historical earthquakes evidence the presence of regional seismogenic faults, characterized by low slip-rates (0.05-0.1 mm/yr). The PNAFZ has been recognized mostly by sub-superficial data. It trends NNW-SSE, with a branched geometry up to 1.5 km wide. The fault worked as eastern border of the Mesozoic Lusitanian Basin (LB) in this sector, implying that it roots deeply in the Paleozoic basement. It was reactivated with strike-slip motion in the Miocene, as a lateral ramp of the Arrábida fold and thrust structure, under a NNW-SSE compression that tectonically inverted the LB. Offset of uppermost horizons in seismic reflection profiles and boreholes indicates late Neogene-Quaternary tectonic activity under the present stress field, corroborated by geomorphic evidence. A maximum M 6-7 earthquake is inferred from fault dimension, with probable average recurrence of 3,000-11,000 yrs.*

Key words: *Pinhal Novo-Alcochete Fault, Lower Tagus Valley, Active Faults, Seismotectonics.*

Regional setting: The Pinhal Novo-Alcochete Fault Zone (PNAFZ) is a major tectonic structure of Lisbon Region, located ca. 12.5 km east of the city. It is sited in the Tagus Cenozoic Basin, in the eastern zone of the Setúbal Peninsula, southern area of the Lower Tagus Valley, where mostly Pliocene and Quaternary sediments outcrop except in the Arrábida Chain at the S (Figure 1). The occurrence of important historical earthquakes in this area indicates the presence of active seismogenic faults, though characterized by low slip-rates (0.05-0.1 mm/yr) (Cabral, 1995; Cabral et al., 2004).

The PNAFZ has been identified and characterized mostly by indirect, sub-superficial data. It trends NNW-SSE and shows a complex, branched geometry, extending over a deformation zone up to 1.5 km wide. It was generated as an extensional structure at the eastern border of the Mesozoic Lusitanian Basin (LB) in this sector, implying that it is rooted deep in the Paleozoic basement. It was later reactivated in the Miocene under the action of a NNW-SSE compression that produced tectonic inversion of the LB. Reactivation occurred with strike-slip motion, in thin-skin tectonics above a decollement horizon of evaporitic rocks of Lower Jurassic age, when the fault worked as a lateral ramp of the Arrábida fold and thrust belt, thus behaving as a strain accommodation structure of the Arrábida thrusting (Ribeiro et al., 1990)

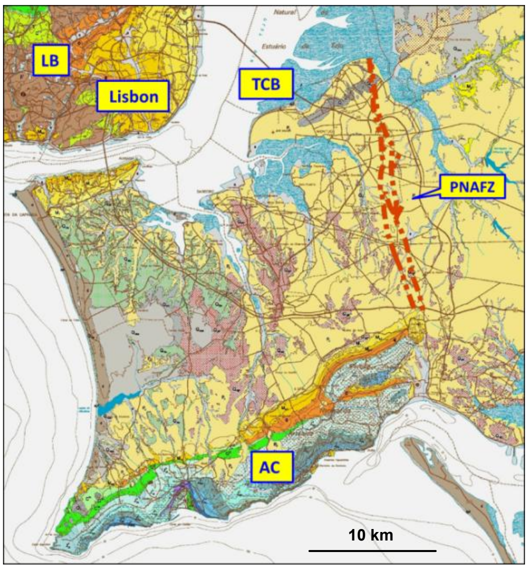

Figure 1: AC, Arrábida Chain, LB, Lusitanian Basin, PNAFZ, Pinhal Novo-Alcochete Fault Zone, TCB, Tagus Cenozoic Basin. Adapted from Carta Geológica da AML, Folha S, 1:100 000, LNEG (INETI), 2005.

Offset of uppermost horizons recognized in seismic reflection profiles and in boreholes in the area, particularly of the basal unconformity of the Pliocene sediments, indicates late Neogene to Quaternary tectonic activity of the PNAFZ under the present stress field, which is supported by geomorphic evidence.

Regional seismicity: Instrumental seismic activity in the study region is low and diffuse. It has been monitored until 1998 by a sparse national network, which does not allow an accurate location of older events. The available focal depths (mostly below 5 km) indicate that seismicity extends through the upper crust and that it is usually generated by faults in the Paleozoic basement, which rupture well below the Mesozoic and the Cenozoic sedimentary cover that outcrops in the area. In spite of the low instrumental seismicity, some M 6-7 destructive historical earthquakes have occurred in the region, as in 1344, 1531, 1858 and 1909. The overall earthquake activity thus represents a serious seismic hazard for this densely populated region.

The most interesting earthquake for the PNAFZ is the 11th November 1858 event, which occurred south of the Tagus River valley, having significantly affected the town of Setúbal where it damaged most of the buildings. A maximum intensity of IX MM has been estimated for the epicentral area, located offshore near the coast S of Setúbal (Oliveira, 1986) (Figure 2).

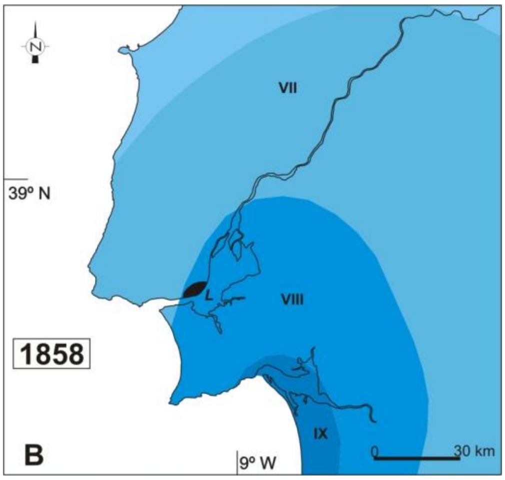

Figure 2: Isoseismal lines (IMM) of the 1858, Setúbal earthquake. Adapted from Oliveira (1986).

There is one reference of a tsunami having affected the town harbor (Moniz, 2010), though further research on this subject is still needed. If so, the rather localized effect points to some submarine slope failure as the triggering mechanism, possibly in the nearby Setúbal submarine canyon. This event is referenced by Johnston and Kanter (1990) as one of the worldwide largest earthquakes ever occurred in “stable continental crust”, assigning a magnitude MW of 7.1, which is probably overestimated. This moderate to large size earthquake may have been generated by the prolonging of the PNAFZ S of Setúbal. A M 3.6 earthquake has recently occurred (20 Feb. 2014) in the same area (Figure 3), whose focal mechanism is roughly compatible with the proposed southward prolonging of the fault (Figure 4).

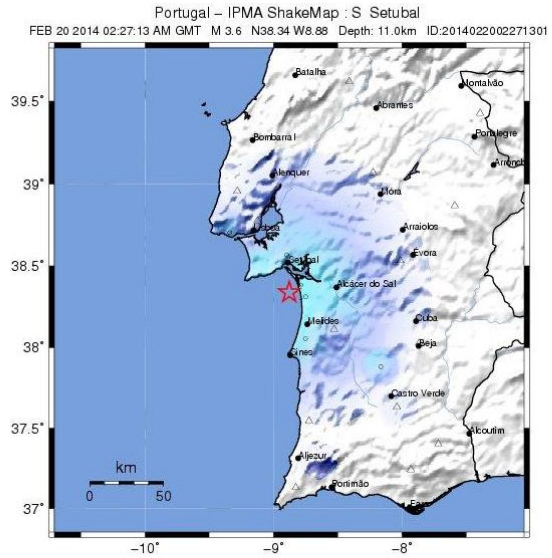

Figure 3: Location map of the February 20, 2014, M 3.6 event, with Instrumental Intensity III-IV shown. (http://shakemap.ipma.pt/).

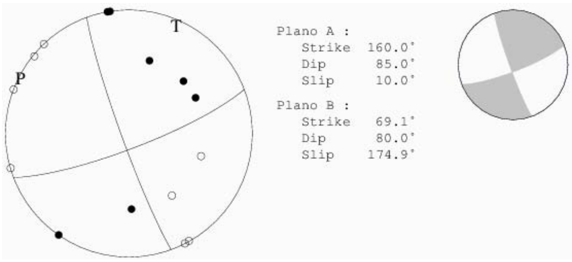

Figure 4: Focal Mechanism of the February 20, 2014, M 3.6 event, 15 phases, best solution (F. Carrilho, IPMA, personal communication).

Underground evidence of fault activity. Seismic reflection and borehole data: The PNAFZ is barely expressed at the surface geology, as it is buried under a thick sedimentary cover comprising some Pleistocene coarse deposits and Pliocene sands and clays, of probable Piacenzian age, that occur along most of the Setúbal Peninsula. These unconformably overlay shallow marine Miocene sediments and continental Paleogene deposits, which cover Mesozoic sediments of the LB located below. Though being mainly a concealed, blind structure, the PNAFZ has been recognized for quite a long time through subsurface information, mostly seismic reflection data for oil exploration, evidencing the presence of a salt wall intruding the fault zone.

Offset of the uppermost horizons recognized in seismic reflection profiles and in boreholes for oil and groundwater exploration in the area, particularly of the basal unconformity of the Pliocene sediments, indicates late Neogene to Quaternary tectonic activity of the PNAFZ

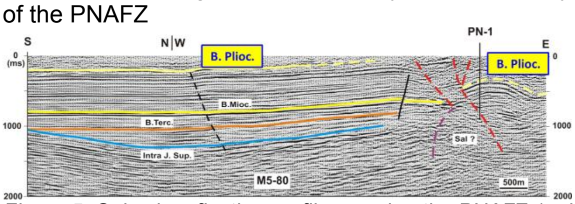

Figure 5: Seismic reflection profile crossing the PNAFZ (red dashed line); offset of the Base of Pliocene horizon is evident, with folding and downthrowing to the E; PN-1, Pinhal Novo oil exploration well. (Moniz, 2010).

Geomorphic evidence of fault activity: The underground evidence for the Plio-Quaternary activity of the PNAFZ is further supported by geomorphic evidence, namely the presence of an elongated relief located astride the fault zone, and the occurrence of asymmetric drainage (Figure 6).

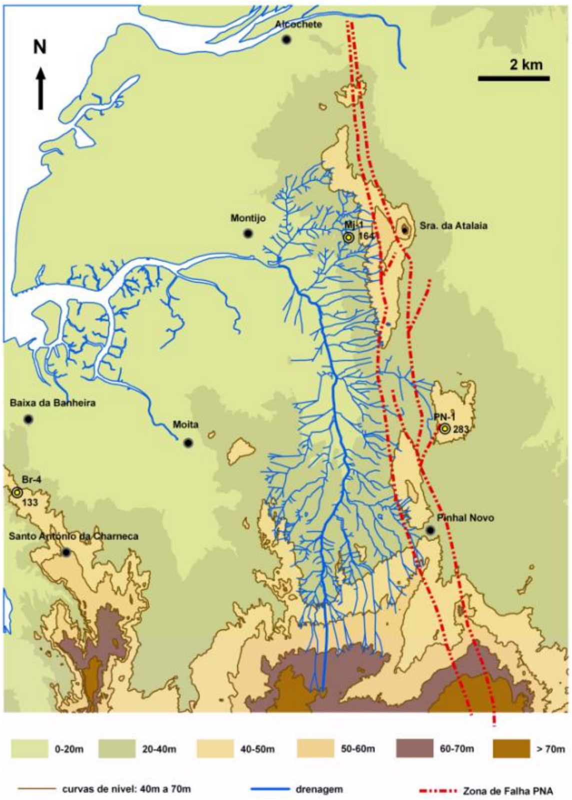

Figure 6: Hypsometric map of the study area, evidencing the relief along the surface trace of the PNAFZ (red dashed line), and the strongly asymmetric drainage to the west. (Moniz, 2010).

This elongated relief can hardly be explained by erosional processes as it is developed on the Pliocene sands and clays that outcrop regionally. It apparently corresponds to an uplifted ridge related to the PNAFZ activity, distorting the drainage network at the western side, which shows anomalous geomorphic indexes (Pinter, 1996), namely an Asymmetry Factor (AF) of 70 and a Transverse Topographic Symmetry Factor (T) of 0.42, with both asymmetry vectors pointing towards 265º, perpendicularly to fault zone trend.

Seismogenic potential of the PNAFZ: Evaluation of the maximum expectable earthquake was based on an estimative of the fault dimensions. Two values were considered for the maximum rupture length: 20 km based upon the known geological evidence, and 30 km assuming the conservative hypothesis that the fault extends either N, connecting to other faults of the Lower Tagus Valley system located NE of Lisbon, or continues southwards, along the eastern border of the Arrábida fold and thrust belt (Figure 7). The down-dip width of the fault (W) was estimated from the rupture length (L) using a fault Aspect Ratio for strike-slip faults by Peruzza and Pace (2002), namely $W \approx L/3+2{,}38 \approx$ 9-12 km, which is compatible with depth data of the instrumental seismicity. A rupture area A was thus obtained comprised between 180 km^2 and 360 km^2. The magnitude of the maximum earthquake was then obtained using the regressions M_W/L and M_W/A of Wells and Coppersmith (1994).

- $M_W = 5{,}08 + 1{,}16 \log L$ (Wells e Coppersmith, 1994) →
  - L = 20 km → $\boldsymbol{M_W = 6{,}6}$
  - L = 30 km → $\boldsymbol{M_W = 6{,}8}$
- $M_W = 4{,}07 + 0{,}98 \log A$ (Wells e Coppersmith, 1994) →
  - A = 180 km^2 → $\boldsymbol{M_W = 6{,}3}$
  - A = 360 km^2 → $\boldsymbol{M_W = 6{,}6}$

Slip rate and recurrence: The currently available geological data does not allow estimating the slip rate of the PNAFZ. However, in order to make a rough assessment of the recurrence interval of the maximum expectable earthquake, it was assumed that the PNAFZ has a slip-rate of v = 0.05-0.1 mm/yr, similar to the slip rates that have been estimated for other regional active structures (Cabral, 1995; Cabral et al, 2004).

Using the relationship between M_W, slip rate (v) and recurrence interval (Ti) proposed by Slemmons and Depolo (1986), the following values were obtained:

- ***v*** = 0,05 mm/yr
  - $\boldsymbol{M_W = 6{,}3 \rightarrow T \sim 6ka}$
  - $\boldsymbol{M_W = 6{,}6 \rightarrow T \sim 9ka}$
- ***v*** = 0,1 mm/yr
  - $\boldsymbol{M_W = 6{,}3 \rightarrow T \sim 3ka}$
  - $\boldsymbol{M_W = 6{,}6 \rightarrow T \sim 5ka}$

Slightly different values of the maximum earthquake recurrence time are obtained using the relationship between the maximum expected seismic moment M_o^e and the geologically assessed moment rate M_o^g (Wesnousky, 1986):

M_W	A (km^2)	V (mm/yr)	M_o^e (Nm)	M_o^g (Nm yr^{-1})	T_i (yr)
6.3	180	0.05	2.3×10^{18}	2.7×10^{14}	8.500
		0.1		5.4×10^{14}	**4.300**
6.6	360	0.05	6.4×10^{18}	5.4×10^{14}	**11.900**
		0.1		1.1×10^{15}	5.800

Conclusions: The PNAFZ is a concealed, still poorly known tectonic structure located near Lisbon that belongs to the Lower Tagus Valley fault system. It worked as an extensional fault in the Mesozoic, and was reactivated in the Miocene, as a lateral ramp of the Arrábida thin-skinned fold and thrust belt. We propose that the PNAFZ was again reactivated since the upper Pliocene as a deep-seated left lateral strike-slip fault (thick-skinned tectonics) under the current stress regime, which is characterized by a NW-SE trending maximum horizontal compressive stress (Figure 7).

Estimation of the maximum earthquake points to a magnitude comprised between 6 and 7. Estimation of the average recurrence intervals is very imprecise due to the lack of a slip rate. Assuming a value similar to slip rates that have been estimated for other regional active structures, average return periods of 3,000 to 12,000 yrs are obtained. These large return periods may explain the absence of significant related instrumental seismicity,

The PNAFZ thus shows the potential and is a likely candidate for generating strong earthquakes, with large return periods, in the study region, though its seismogenic nature still needs to be proven. The 1858 Setúbal historical earthquake may have been produced by a southern segment of this fault zone.

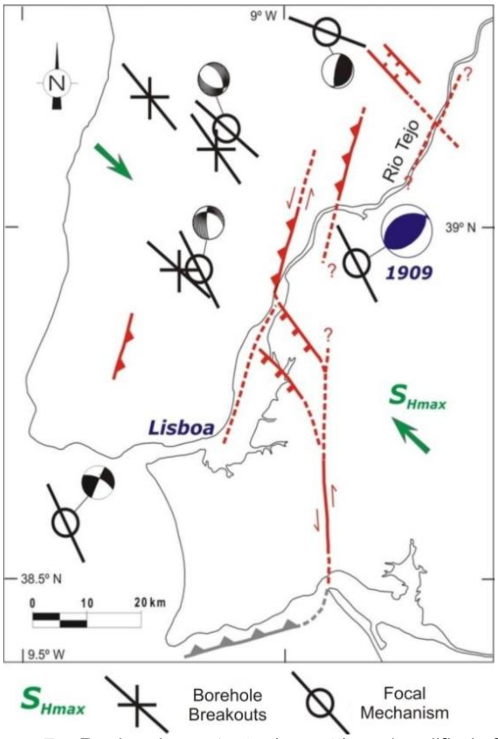

Figure 7: Regional neotectonic setting (modified from Cabral et al., 2003)

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