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Neotectonics of mainland Portugal: state of the art and future perspectives

Neotectónica de Portugal peninsular: estado de la cuestión y perspectivas de futuro

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Abstract

This paper presents a synthesis of the neotectonic studies performed in mainland Portugal that address the "recent" (post Piacenzian, ~3 Ma) tectonic evolution of the Portuguese territory as part of the West Iberian continental margin, specifically in regard to regional seismic hazard evaluation. The interaction of the Iberian microplate with the Nubia plate is identified as the source for the regional neotectonic deformations, which occur at relatively low rates in spite of significant historical seismic activity. In this context of low strain rates expressed by the presence of slow slip rate active faults, it is important to acquire paleoseismic data on the major seismogenic structures to characterize the large earthquakes that they generated in the past, because average recurrence intervals are much longer than the time span covered by the regional historical and instrumental period.

Keywords: Neotectonics, Seismotectonics, Active faults, Seismic Hazard, Portugal

Resumen

Este artículo presenta una síntesis sobre los trabajos de neotectónica que se han llevado a cabo en el Portugal continental como parte del margen continental Iberico occidental, que se centren en la evolución tectónica "reciente" (post Plasenciano, ~3 Ma), en especial aquellos que se centran en la evaluación del peligro sísmico regional. La interacción entre la microplaca Ibérica y la placa de Nubia se caracteriza por ser una fuente de deformaciones neotectónicas que ocurren a velocidades relativamente bajas a pesar de que la sismicidad histórica es significativa. En este contexto de tasas de deformación bajas, reflejadas por la presencia de fallas lentas, es importante adquirir datos paleosísmicos en las principales fallas sismogénicas para así caracterizar los terremotos catastróficos que hayan podido producir-se en dichas estructuras en el pasado. Esto es especialmente importante dado que los períodos de recurrencia de dichas fallas son mucho más largos que el periodo de tiempo cubierto por los datos sísmicos históricos o instrumentales.

Palabras clave: Neotectónica, Sismotectónica, Fallas activas, Peligro sísmico, Portugal.

1. Regional setting

Portugal mainland is located on the Eurasian Plate, close to the West-Iberian continental margin and the Eurasia-Nubia plate boundary (eastern sector of the Azores – Gibraltar fracture zone). The regional geodynamics has been driven by the NW-SE convergence of Eurasia and Nubia, which has occurred at this longitude at an average rate of 4-5 mm/yr for the past 3 Ma, according to the global geological models of plate motions (NUVEL-1A by DeMets *et al.*, 1994, and the more recent MORVEL by DeMets *et al.*, 2010). Space-geodetic observations indicate a significantly different instantaneous interplate motion, with displacement vectors of Eurasia-Nubia rotated anticlockwise relatively to the NW direction of geological models and suggesting a slowing of the convergence rate (Calais *et al.*, 2003; Fernandes *et al.*, 2003; Nocquet and Calais, 2004), though the discrepancy between the geological and GPS data has been reduced in the MORVEL model.

The Eurasia-Nubia plate boundary is clearly discernable at the western and central parts of the Azores – Gibraltar fracture zone, represented by the Terceira Ridge leaky transform, near the Azores archipelago, and by the Gloria transform fault, eastwards up to the Tore Madeira Rise (~20º W). East of the Gloria fault, the plate boundary is poorly established and its nature is matter of debate, as the interplate deformation is apparently distributed across a broad area, over 200 km wide.

Since the late 1990s, a large amount of multi-channel seismic reflection data, along with high-resolution multi-beam swath bathymetry data, have been acquired in the SW Iberian margin in an effort to locate a discrete plate boundary in the Gulf of Cadiz area and, at the same time, to try to identify the source of the great 1755 Lisbon earthquake (estimated M_W 8.5-8.7; Johnston, 1996; Martinez-Solares and López Arroyo, 2004). Several studies (*e.g.* Zitellini *et al.*, 1999, 2001, 2004; Gràcia *et al.*, 2003; Terrinha *et al.*, 2003) revealed a complex structural pattern, with discrete active reverse faults trending NE-SW to NNE-SSW, such as the Gorringe Bank, Marquês de Pombal and Horseshoe faults. There are also E-W to WNW-ESE faults, such as the Guadalquivir Bank and Portimão Bank faults. Multiple rupture on these faults was proposed as a possible source of the 1755 earthquake (Gràcia *et al.*, 2003; Baptista *et al.*, 2003).

Coeval ~E-W extension in the Alboran Basin at a rate of ~2mm/yr (Serpelloni *et al.*, 2007), and left-lateral shear along the NNE trending Trans-Alboran shear zone, are not straightforward in the context of regional shortening, indicating complexity of deformation at the plate borders. In this context, and based upon a number of independent observations such as detailed seafloor morphology, earthquake distribution and seismic profiles (multi-channel reflection, as well as wide angle refraction), Gutscher and others (*e.g.* Gutscher, 2004; Gutscher *et al.*, 2002, 2009) proposed the occurrence of active subduction in the Gibraltar Arc by westward roll-back of an old (Miocene?) plate. In a recent paper, Pedrera *et al.* (2011) question this model, defending that the eastward Gibraltar Arc oceanic subduction system is inactive probably since the Late Miocene. According to these authors, the current tectonic framework in the Gibraltar Arc domain is of continental collision, with the regional intermediate seismicity being associated to part of the old, N30ºE to N40ºE oriented subducted slab, orthogonal to the regional convergence.

New high-resolution multi-beam bathymetry data allowed the recognition of several WNW–ESE trending lineaments in seafloor sediments of the Gulf of Cadiz, and the interpretation of multi-channel seismic reflection profiles showed that they are controlled by underlying deep seated faults (Rosas *et al.*, 2009). Based upon the morphology associated with two of the lineaments and on analogue modelling, the authors conclude that these lineaments correspond to the bathymetric expression of ongoing right-lateral strike-slip reactivation of WNW–ESE pre-existing faults, and estimate an age of ca. 1.8 Ma for this tectonic reactivation. Zitellini *et al.* (2009) extend these lineaments farther west, across the Horseshoe abyssal plain and up to the Hirondelle Seamount; theses authors also interpret them as faults (the SWIM faults) and propose that this newly found set of almost linear and sub parallel, WNW–ESE trending vertical faults that form a narrow band of deformation over a length of 600 km, corresponds to the present Nubia–Europe plate boundary in this region.

The level of seismotectonic activity at the West-Iberian continental margin points to an atypical passive margin. An explanatory model argues that this margin is in transition from passive to active convergence (Ribeiro *et al.*, 1996; Ribeiro, 2002). According to this model, Iberia is behaving as a microplate that is rotating clockwise between Africa and Eurasia, inducing convergence across the West Iberia margin at ~1 mm/yr.

As a result of the regional geodynamic setting, mainland Portugal and the nearby Atlantic area experiences moderate levels of seismicity, characterized by relatively frequent M<6 events and the occurrence of occasional large earthquakes, such as the 1969 M_S 7.9 (Fukao, 1973) and 2007 Mw 6.0 (Stich *et al.*, 2007) Horseshoe events, in addition to the more sporadic very large events, such as the 1755 “Lisbon earthquake”.

2. The Neotectonic studies in mainland Portugal

2.1. The early years

Geological studies in Portugal started in the mid 19th century and evolved rapidly; the first draft of the Geological Map of Portugal (1:500,000 scale) was prepared by Carlos Ribeiro and Nery Delgado in 1867, and published in 1876. Early geological studies already included structural characterization, and the structural/tectonic view was notably implemented in the late 19th to early 20th centuries, by Nery Delgado and Paul Choffat, superbly expressed in the study of the Arrábida Chain (south of Lisbon) (Choffat, 1908).

Paul Choffat was interested in the 1755 earthquake and in the relatively intense seismic activity from the second half of the 19th century to early 20th century (*e.g.* Choffat, 1904), which included the 1858 "Setúbal earthquake", referenced in Johnston and Kanter (1990) as one of the largest earthquakes ever registered worldwide in "stable continental crust", with estimated M_W 7.1. In that publication Choffat cited and discussed the intensity distribution of the 1755 and 1858 earthquakes, and of other felt events that occurred in 1903.

On April 23rd, 1909 a violent earthquake took place in the Lower Tagus river valley (M_W = 6.0 to 6.2; Teves-Costa *et al.*, 1999; Dineva *et al.*, 2002; Stich *et al.*, 2005) causing significant damage and 46 fatalities. The town of Benavente, located about 30 km NE from Lisbon on the eastern bank of the Tagus River, was completely destroyed, and other nearby villages were intensely affected (Teves Costa and Batlló, 2010). The occurrence of this event increased interest in the regional seismic activity. The effects of the earthquake were studied by Bensaúde (1910) and Choffat and Bensaúde (1911) who published a comprehensive report. Reference to a geological origin was already considered, as Bensaúde (1910) refered to two probable seismogenic faults as potential sources (Tagus and Sorraia faults), and Dinis (1911) also indicated faults as the source of the "tectonic earthquakes". He proposed that the 1909 event was generated by a "vertical movement" along a NE-SW "line" passing through Benavente.

The following years were marked by a relative stagnation of geological research in Portugal, and particularly of studies with tectonic implications. Some exceptions were the monumental work by Pereira de Sousa (1919-1932) on the 1755 earthquake, or the works by Freire de Andrade (1933, 1937) on the offshore submarine valleys, and by Zbyszewski (1939) regarding the Sado Cenozoic Basin (south of Lisbon). This author refered to significant Pliocene-Quaternary tectonic activity (vertical movements, tilting and faulting).

In the 1940-50's, however, there was a resumption of geological studies addressing "recent" Pliocene to Quaternary tectonic deformations, as exemplified in the works by Teixeira (1944) on the "Plio-Pleistocene tectonics" of NW Iberia, or by Zbyszewski (1948, 1959) concerning "Pliocene salt tectonics in Portugal". This latter author also mentioned several examples of Quaternary tectonic deformations in a synthesis on the "Quaternary of Portugal" (Zbyszewski, 1957). This period corresponds to a renewal of physical geography, and the geomorphology of Portugal was addressed by several geographers who introduced a mobilist view of landscape evolution, relating it with "recent" tectonics and, tentatively, with regional seismicity (e.g. Birot, 1945, 1949; Feio, 1949, 1951a,b; Ribeiro, 1942, 1943, 1949).

2.2.The modern years: 1960 to Present

In the period 1960-80, structural geology and tectonics developed as autonomous disciplines in Portugal. The first modern regional structural study was produced (Ribeiro, 1974), and the introduction of plate tectonics theory allowed for the interpretation and understanding of the present regional tectonic framework. Meanwhile, new techniques in geophysics were also developed, and the national seismic network increased from 3 to 12 analogue stations after the 28th February 1969, M_W 7.8 earthquake (Fukao, 1973), allowing better coverage of the regional seismicity and an improved appraisal of its distribution.

The first reference to "neotectonics" in the Portuguese literature appears in Ribeiro *et al.* (1979), meaning post-Miocene tectonics. A first, small scale, Neotectonic Map of Portugal, showing faults with evidence of "activity in the Quaternary", was published two years later in the scope of a work on geothermal analysis (Ribeiro and Moitinho de Almeida, 1981). However, systematic neotectonic research, specifically oriented to hazard assessment, was initially promoted in the scope of nuclear power plant siting studies in mainland Portugal, sponsored by the Portuguese Electricity Company (Electricidade de Portugal, EDP) and by the Portuguese nuclear regulatory entity (Gabinete de Protecção e Segurança Nuclear, GPSN).

The intention of building a nuclear power plant at the Ferrel site (W coast) led to a detailed neotectonic study of the area, following the criteria of the United States Nuclear Regulatory Commission (USNRC, 1978). The work started in 1979 focused on the characterization of the activity of a local fault (Ferrel fault), including geological mapping at the 1:2,000 scale (Cabral, 1981). The first trench for paleoseismic research in Portugal was then opened, and the Ferrel site was abandoned partly due to the trenching results, which showed evidence of Quaternary activity (Cabral and Ribeiro, 1981, 1986).

J. Cabral, formerly at GPSN, joined A. Ribeiro at the Geology Department of the Faculty of Sciences of Lisbon University (FCUL) in 1982, and started the neotectonic study of NE Trás-os-Montes (NE Portugal) under his supervision (Cabral, 1985). This study, though performed in the scope of a post-graduate thesis, was stimulated by the intention of Spain of building a nuclear plant at Sayago and, later, of implementing project IPES (*Instalación Piloto Experimental Subterráneo*) at Aldeadavila, near the Trás-os-Montes border (Barriga *et al.*, 1988).

Neotectonic research by the Lisbon University team was intensified in 1983, in the scope of new nuclear power plant site selection studies promoted by EDP and GPSN. Studies included regional and detailed research in different areas of Portugal, with an emphasis on major fault zones, *e.g.* the Lower Tagus fault zone (Cabral *et al.*, 1984), the Ponsul fault (Dias and Cabral, 1989), and the Vilariça fault (Cabral, 1989). The results were synthesised in a Neotectonic Map of Mainland Portugal (1:1,000,000 scale) (Cabral and Ribeiro, 1988, 1989), showing "faults with evidence of activity in the last 2 Ma". Data were later updated in a Ph.D. thesis (Cabral, 1993) and published in a memoir (Cabral, 1995), and a compilation and interpretation of present stress indicators in the study region was accomplished (Ribeiro *et al.*, 1996).

Further studies performed by the Lisbon University group and by other teams in the scope of research projects, M.Sc. and Ph.D. theses, have largely increased the knowledge on the active structures in the Portuguese mainland. Many examples may be given, such as for the Penacova-Régua-Verin fault (Baptista, 1998), the Porto-Coimbra-Tomar fault zone (Dinis, 2004; Dinis *et al.*, 2007; Gomes, 2008), the Lower Tagus Valley fault system (Vilanova, 2003; Vilanova and Fonseca, 2004; Cabral *et al.*, 2003, 2004, 2011a,b; Besana-Ostman *et al.*, 2012; Carvalho *et al.*, 2006, 2008; Martins *et al.*, 2009), the Vidigueira-Moura and Alqueva faults (Brum da Silveira, 2002; Brum da Silveira *et al.*, 2009), or faults in the Algarve (southern Portugal) (Dias, 2001; Dias and Cabral, 2002a,b).

3. Methodology and data

As stated above, it is after the early 1980s that the research team from Lisbon University performed studies directed at the neotectonics in mainland Portugal, intended as the study of tectonic deformations occurring since the initiation of the current tectonic regime, characterized by a NW-SE trending S_{Hmax} that results from the Iberia-Nubia convergence along the same azimuth (Ribeiro *et al.*, 1996, Borges *et al.*, 2001).

The timing of onset of the current stress regime is not easy to determine, however, as its orientation is not clearly distinct from the roughly NNW-SSE late Miocene (to early Pliocene?) compressive stress field (Ribeiro *et al.*, 1990; Cunha *et al.*, 2000, 2009). What the geological registry shows is that, where present, Pliocene sediments of Piacenzian age (3.6-2.58 Ma) postdate an intense post-Tortonian (upper Miocene) shortening phase. On the other hand, these and younger sediments of probable Gelasian age (2.58-1.8 Ma, lower Quaternary) that constitute the top of the sedimentary infill in the former Miocene compressive basins are affected by displacement along major faults and show evidence of having been uplifted, suggesting a resumption of the tectonic activity in the Quaternary, making this period (~2.6 Ma) an adequate time frame for the Neotectonic period in mainland Portugal.

The considered neotectonic activity spans a large time interval, based on the current tectonic regime (upper Pliocene to Present), thus requiring the use of relatively old stratigraphic and geomorphic references to recognize and characterize the deformations accumulated since the onset of the neotectonic period – typically fluvial sediments that predate the Quaternary entrenchment of the regional drainage network and correlative raised marine sediments and abrasion platforms, of Piazencian age, along the littoral.

Even though this time window is quite wide comparatively to other periods of neotectonic activity considered for more active regions, it is appropriate for the current geodynamical setting of the Portuguese mainland, where the active faults have slow slip rates and long seismic cycles. It is thus intended to assure the identification of all the potentially hazardous seismogenic sources, including those that take a long time to accumulate geomorphic and/or stratigraphic evidence of activity. It is the same time frame used in the Quaternary Active Faults Database of Iberia (QAFI), where it was chosen for similar reasons (García-Mayordomo *et al.*, 2010).

The neotectonic deformations include two major interrelated components that may be distinguished and independently analysed for methodological purposes: vertical movements of the lithosphere, resulting from large scale folding and isostatic adjustments, and active faulting.

3.1. Vertical movements of the crust

Evidence for almost generalized uplift of the Portuguese mainland territory since the end of the Pliocene is given by the common presence of high sea cliffs and raised marine terraces along the coast, and of a deeply incised drainage network inland (Figs. 1 and 2).

An indirect methodology was thus used for the characterization of the neotectonic vertical movements in the study region, consisting in the recognition of geological and geomorphologic references whose relation to the coeval sea level is reasonably known, so that the primitive height at which they were formed can be estimated and compared with their present elevation (Fig. 3).

This methodology is more rigorous and easier to apply in the coastal area due to the proximity to the reference datum (mean sea level) and the possibility of using directly correlatable geological and geomorphologic markers (marine terraces and abrasion platforms). The existence of several terrace levels at one particular coastal area is evidence for long-term vertical movements affecting the coast. The rationale is that the relict shorelines record both fluctuating Quaternary sea-level highstands and the ongoing tectonic uplift. Worldwide data of Quaternary sea-level changes have been combined to build eustatic sea-level curves that can be used as references for research studies (*e.g*. Shackleton *et al.*, 1984; Haq *et al.*, 1987; Dowsett and Cronin, 1990; Naish and Wilson, 2009; Raymo *et al.*, 2011, for the late Pliocene-early Pleistocene sea-level, and Shackleton and Opdyke, 1973; Bloom *et al.*, 1974; Chappell, 1974; Bender *et al.*, 1979; Bloom, 1980; Chappell and Shackleton, 1986; Siddall *et al.*, 2006, among others, for the Pleistocene eustatic sea-level curves).

The rates of uplift can be quantified by correlation of inner edge elevations (which approximate mean sea level at the time of formation) to sea-level highstands. If the elevation and age of these sea-level highstands are known, then the uplift rate can be calculated for each marine terrace.

In what concerns mainland Portugal, several sectors of the coastal area present a discontinuous series of variably wide, although predominately narrow, upper Pliocene to Quaternary marine terraces and/or wave-cut platforms located at altitudes ranging from near present sea level to a few hundreds of meters. When preserved, the terrace sediments are generally thin, commonly composed of a lower pebbly layer overlain by beach sands, rarely containing shells and fragments of marine fossils, and often buried by eolianites and/or colluvial deposits of sand and gravel from the adjacent paleo-sea cliffs. Taking the elevation and estimated age of beach sediments and/or correlative abrasion platforms at several places (200-350 m, attributed to the Piacenzian, ~3 Ma; 70-80 m, attributed to the Lower Pleistocene, ~1 Ma; 35-40 m, attributed to MIS 7, ~200-250 ka; and 20-25 m, attributed to MIS 5e, ~125 ka), relatively constant, long to shorter term average uplift rates of 0.1-0.2 mm/yr are inferred. Detailed studies of vertical movements of the crust based upon raised marine terraces are presently being performed for the southwestern region of mainland Portugal and the preliminary results yielded similar uplift rates for the Upper Pleistocene (Figueiredo *et al.*, 2011). Major uncertainties rely upon the coeval eustatic sea levels, the constraining of the paleo-shore lines and of their present elevation, and the age of the littoral references.

Inland, away from the coast and from direct connection to sea level as the reference datum, erosion surfaces and sediments of exoreic fluvial origin were used as markers for inferring the regional vertical movements. In mainland Portugal, the valleys of the major rivers typically show flights of downward-stepping terraces with variable sedimentary fills, documenting long periods of valley incision that alternate with shorter periods of predominantly lateral erosion and minor aggradation. In this context, the rationale is that the fluvial terraces may serve as references to evaluate rates of fluvial incision at the long term, which is considered a reasonable proxy for regional uplift (*e.g*. Merrits *et al.*, 1994; Burbank and Anderson, 2001; Hancock and Anderson, 2002).

When using the river terraces, uncertainties are higher than for the littoral references, as besides the common uncertainties in the age of the references and in the contemporary base level, there is the interference of climatic factors on river erosion and sedimentation, and variable river gradient, as well as the capacity of response of the river to the main external controlling mechanisms (tectonics, climate and sea-level). In fact, it is assumed that the elapsed time is long enough for the river to incise and regularize its longitudinal profile to the lowering base level that results from the continental uplift, that is, it is assumed that the incision rate balances the uplift rate of the continent. As Burbank and Anderson (2001) stressed, it must also be assumed that the longitudinal gradient of the modern and ancient valley floors were similar, and differences in former and present base levels small comparatively to the amount of uplift. River incision is thus more appropriate for long term evaluation of the continental uplift, except in the river-mouth areas, where the response to relative sea-level change is rapid.

The long term uplift rates obtained for the inland areas, averaged for the last ~3 Ma, are in general similar to those inferred for the littoral (0.1-0.2 mm/yr) (Cabral, 1995; Cunha *et al.*, 2005, 2008, 2010). We may conclude that the uplift rates estimated for the Portuguese mainland are low comparatively to uplift rates recognized in other regions subjected to active tectonics, although the rates obtained at the coastal region are high comparative-

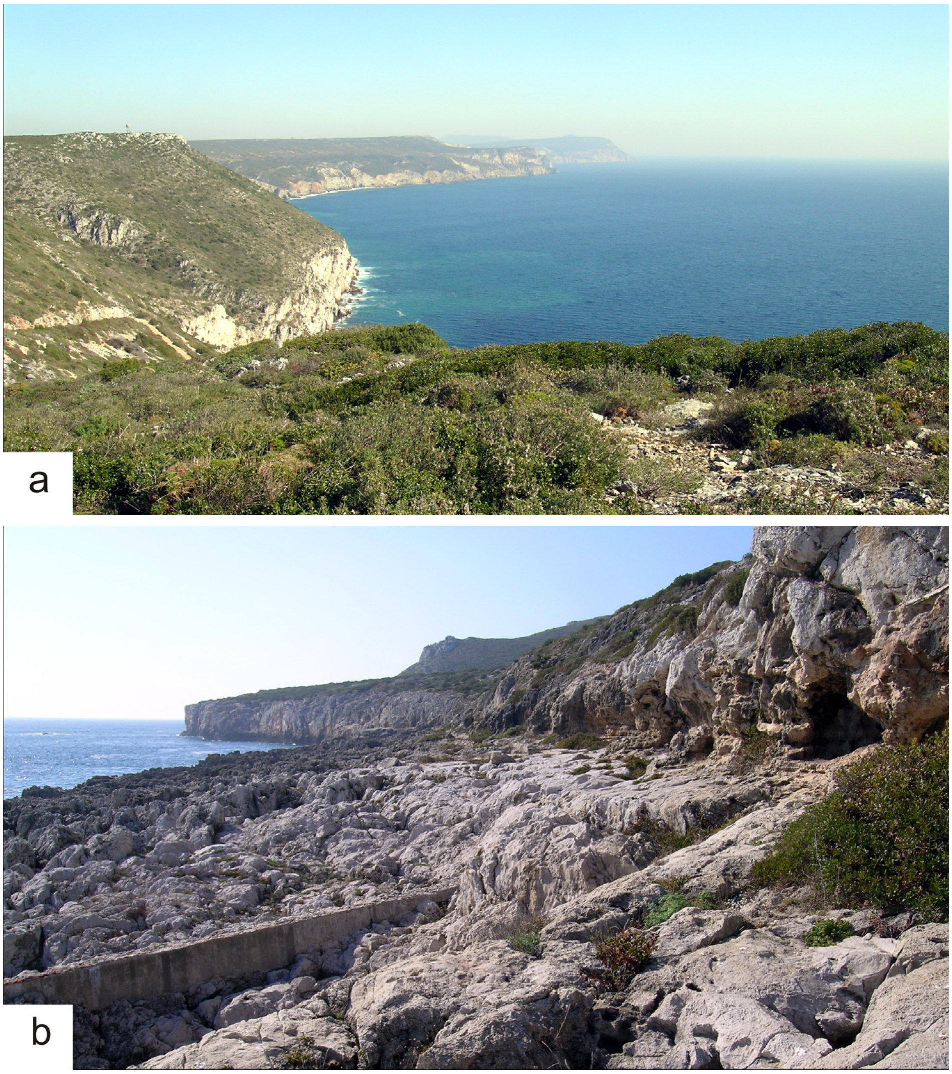

Fig. 1.- a - View towards the east of the high sea-cliffs bounding the Miocene Arrábida fold and thrust belt, located to the south of Lisbon. The erosion surface at the top is at ~200 m a.s.l. and truncates folded Jurassic limestones; it post dates the Tortonian folding, though its age is still poorly constrained; b - View towards the west of a raised marine terrace located at ~10 m a.s.l. at the foot of the former sea-cliffs; the age of this rocky platform, with some beach sands and eolianites still preserved, is matter of debate, as radiocarbon dates obtained for sea-shells from the sediments yield ages close to 35 ka (Ramos Pereira *et al.*, 2007), implying abnormally high uplift rates to explain the present elevation.

Fig. 1.- Vista hacia el este de los acantilados que limitan el pliegue y el cinturón de cabalgamientos Miocenos de la Arrabida, situados al sur de Lisboa. La superficie de erosión a techo tiene una altura de 200m y trunca calizas Jurasicas plegadas. Dicha erosión es posterior al plegamiento Tortoniense aunque su edad es poco conocida. b – Vista hacia el oeste de la terraza marina levantada situada a 10 m del nivel del mar, al pie de los antiguos acantilados. La edad de esta plataforma rocosa, con arenas de playa y eolianitas preservadas, está en discusión dado que las dataciones radiométricas de caparazones marinos en sedimentos aportan una edad de 35 ka (Ramos Pereira *et al.*, 2007), lo que implica unas tasas de levantamiento anómalamente altas.

ly to other passive continental margins. A synthesis of the vertical movements in the last 3 Ma (upper Pliocene and Quaternary) is presented in Figure 4, showing overall uplift, higher in the northern sector.

3.2. Active faults

Besides the vertical deformations of the crust, neotectonic activity in mainland Portugal is also expressed by

Fig. 2.- Upstream view, towards the west, of the Douro River valley near S. João da Pesqueira (NE Portugal) showing the deep entrenchment of the river, which flows at ~90 m a.s.l., incised on the bordering plateaus at an elevation of 500-600 m.

Fig. 2.- Vista, aguas arriba (hacia el W), del río Duero cerca de S. João da Pesqueira (NE Portugal) mostando profundo encajamiento. El flujo se produce ~90 m por debajo de las mesetas colindantres, con una elevación de 500-600 m.

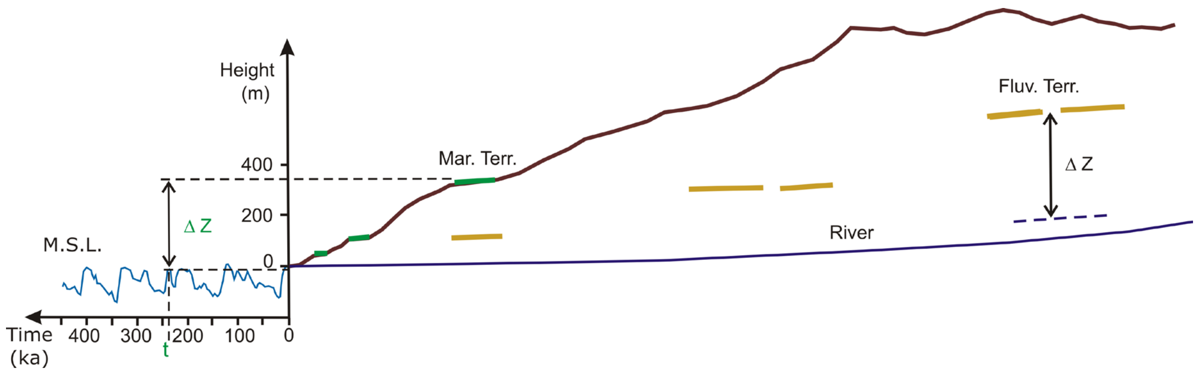

Fig. 3.- Schematic drawing to illustrate the methodology used for the characterization of the neotectonic vertical movements in mainland Portugal. (Fluv. Terr., fluvial terrace; Mar. Terr., marine terrace; M.S.L., eustatic mean sea level; eustatic sea level curve adapted from Siddal *et al.* (2005). Uplift = ΔZ; uplift rate = ΔZ/age of reference).

Fig. 3.- Esquema que ilustra la metodología usada para la caracterización de los movimientos neotectónicos verticales en Portugal continental. Fluv. Terr., terraza fluvial; Mar. Terr., terraza marina; M.S.L., elevación media del nivel del mar; curva eustática del nivel del mar adaptada de Siddal *et al.* (2005). Levantamiento = ΔZ; tasa de levantamiento = ΔZ/edad de referencia.

the occurrence of active faults, that is, of faults evidencing slip in the current tectonic regime so that recurrent movements are expectable in the (relatively) near future. As discussed above, for the study region this means faults evidencing movements in the Quaternary (past ~2.5 Ma).

Active faulting was strongly conditioned by reactivation of pre-existent structures under a NW-SE compression, namely Variscan faults in the Paleozoic basement that had already been reactivated in previous deformational phases of the Alpine orogenic cycle, faults in Mesozoic extensional basins, and faults in Tertiary compressive and strike-slip basins, often rendering neotectonic reactivation difficult to distinguish from previous Neogene faulting which occurred in a rather similar stress field.

The criteria used for recognizing fault activity comprised structural/stratigraphic cross-cutting evidence and geomorphologic evidence. The first consisted of identifying faults affecting sediments dating from the neotectonic period considered, thus requiring the presence of sediments of Quaternary age. A major problem is that widespread erosion induced by uplift, low sedimentation and slow slip rates make "young" (Upper Pleistocene to Present) faulted sediments rare, so that cross-cutting evidence for recent activity is almost totally absent. The sediments affected by neotectonic faulting are usually deficiently dated and generally attributed to the upper Pliocene-lower Quaternary, thus proving evidence only for the longer term (~2.5 Ma) activity.

The geomorphologic criterion used to assess activity is the faults' morphotectonic expression; faults with preserved scarps, or faults producing river deflections, or deforming terraces and other reference surfaces of Quaternary age are considered active. A major problem in the application of this criterion consists in the difficulty of differentiating geomorphic features that effectively point to youthful activity, from other very similar features that result from erosional effects related to differential erosion between basement rocks and faulted Tertiary sediments, often preserved in tectonic basins that have been affected by intense exhumation due to the deep incision of through flowing, or nearby major rivers.

Fault activity in mainland Portugal shows a predominance of ~E-W to NE-SW faults with prevailing reverse movement component, and ~N-S to NNE-SSW faults with prevailing left-lateral strike-slip movement component, which were reactivated during the Quaternary under the action of a NW-SE S_{Hmax}. Examples of the first set of structures are the north-verging Seia-Lousã fault (Cabral, 1995; Ribeiro *et al.*, 1996; Sequeira *et al.*, 1997) (Fig. 5a), that corresponds to the north boundary fault of the Portuguese Central Cordillera, the south-verging Ponsul fault (Dias and Cabral, 1989; Cabral, 1995; Cunha *et al.*, 2005, 2008), located south of the Central Cordillera, and the Vidigueira-Moura fault (Brum da Silveira, 2002; Brum da Silveira *et al.*, 2009), located in Alentejo (southern mainland Portugal). Examples of the second set of structures are the NNE-SSW Penacova-Régua-Verin and Manteigas-Vilariça-Bragança left-lateral strike-slip faults, located in northern Portugal (Baptista, 1998; Baptista *et al.*, 1997, 1998; Cabral, 1989, 1995; Cunha and Pereira, 2000; Rockwell *et al.*, 2009) (Fig. 5b).

As a result of the performed studies, a synthetic map of active faults in mainland Portugal (1:1,000,000 scale) was published in 1988 (Cabral and Ribeiro, 1988, 1989), revised in 1995 (Cabral, 1995), and successively updated (Fig. 6). Estimated long term (~2.5 Ma) average slip rates range between 0.005 and 0.3-0.5 mm/yr, corresponding mostly to low activity rates. Thus, as referred above, "young" (Upper Pleistocene to Present) faulted

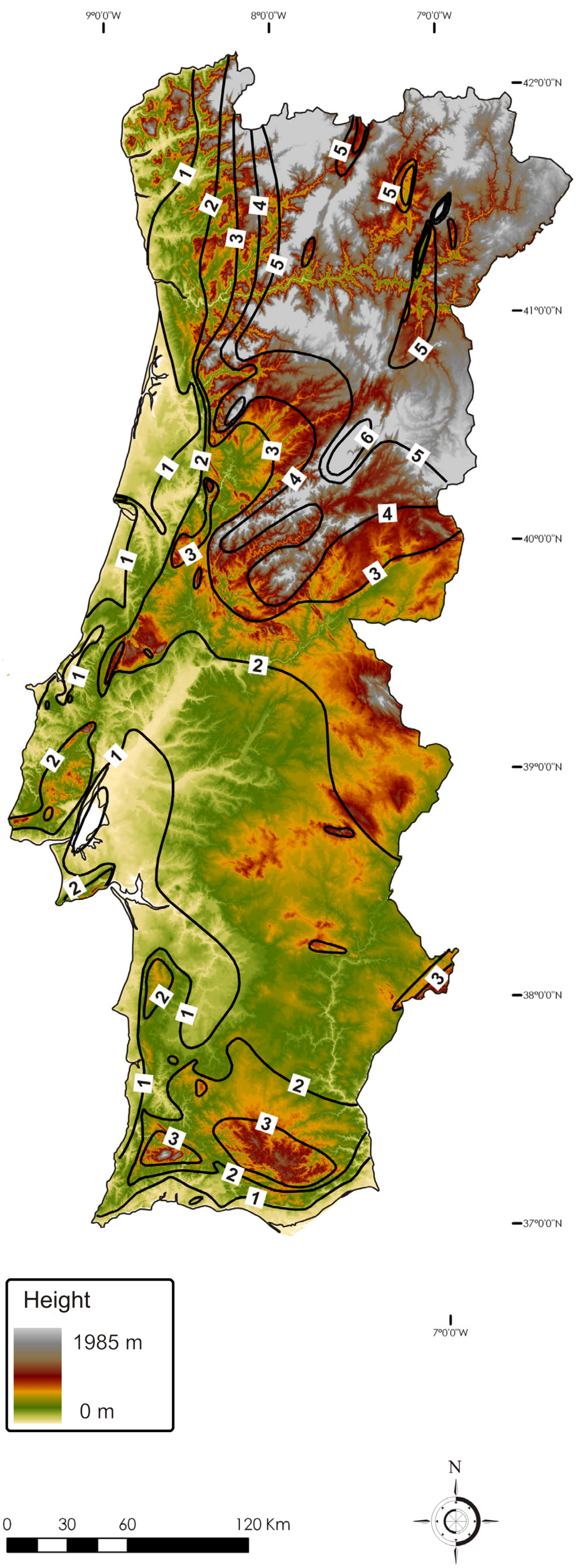

Fig. 4.- Map of neotectonic vertical movements in mainland Portugal based upon uplift values inferred from raised marine terraces and the drainage network entrenchment, as explained in the text (adapted from Cabral, 1995). Movement accumulated approximately in the last 3 Ma; uplift isolines in hundreds of meters. Relief obtained from 200 m grid digital terrain model. This output should be envisaged as a rough approximation, particularly for the inland areas, where long term entrenchment may be considerably delayed relatively to the regional uplift.

Fig. 4.- Mapa de movimientos neotectónicos verticales en el Portugal continental basada en valores de levantamiento obtenidos en terrazas marinas y en valores de encajamiento de la red de drenaje (adaptado de Cabral, 1995, ver texto). El movimiento ha tenido lugar aproximadamente durante los últimos 3 Ma. Isolíneas del levantamiento en centenares de metros. Relieve obtenido del modelo digital del terreno con un paso de malla de 200 m. Este resultado debería ser considerado como una aproximación, especialmente en lo que se refiere a las zonas lejos de la costa, donde el encajamiento de largo término podría estar considerablemente desfasado respecto del levantamiento regional.

sediments are rare and, though some geomorphic features indicate youthful activity, most result from, or are enhanced by erosive effects due to the generalized fluvial entrenchment. The youngest documented deformation so far is along the Vilariça fault and dated at 15,000-10,000 years ago, obtained in the scope of paleoseismic studies performed by Rockwell *et al.* (2009).

4. Present and futures perspectives

In 2004, the research project "Seismotectonics GIS Database for Mainland Portugal" was implemented with the intention of promoting the revision, enlargement and integration of all the data pertaining to the Seismotectonics of the Portuguese mainland and adjacent area. The overall purpose was to construct a GIS database built upon the current European procedures envisaging its integration in a European database. The database included information on upper Pliocene-Quaternary crustal vertical movements, active fault geometry, kinematics, and seismogenic potential, archeoseismological records, stress indicators, and seismicity (Silva *et al.*, 2008).

A review and update of all the information pertaining to the active faults in mainland Portugal was performed in the scope of that project, and it is presently being completed and inserted into larger databases of active faults, namely at the Iberian scale (Active Faults Database of Iberia, García-Mayordomo *et al.*, 2010) and the European scale (SHARE European-scale seismic source model, Nemser *et al.*, 2010).

The low slip rates indicate long recurrence times for maximum (M 6-7) earthquakes (*ca*. 5,000 - 200,000 years), stressing the shortness of the historical record as well as the need to refine the geological (neotectonic/ paleoseismological) data. There is also a need to collect

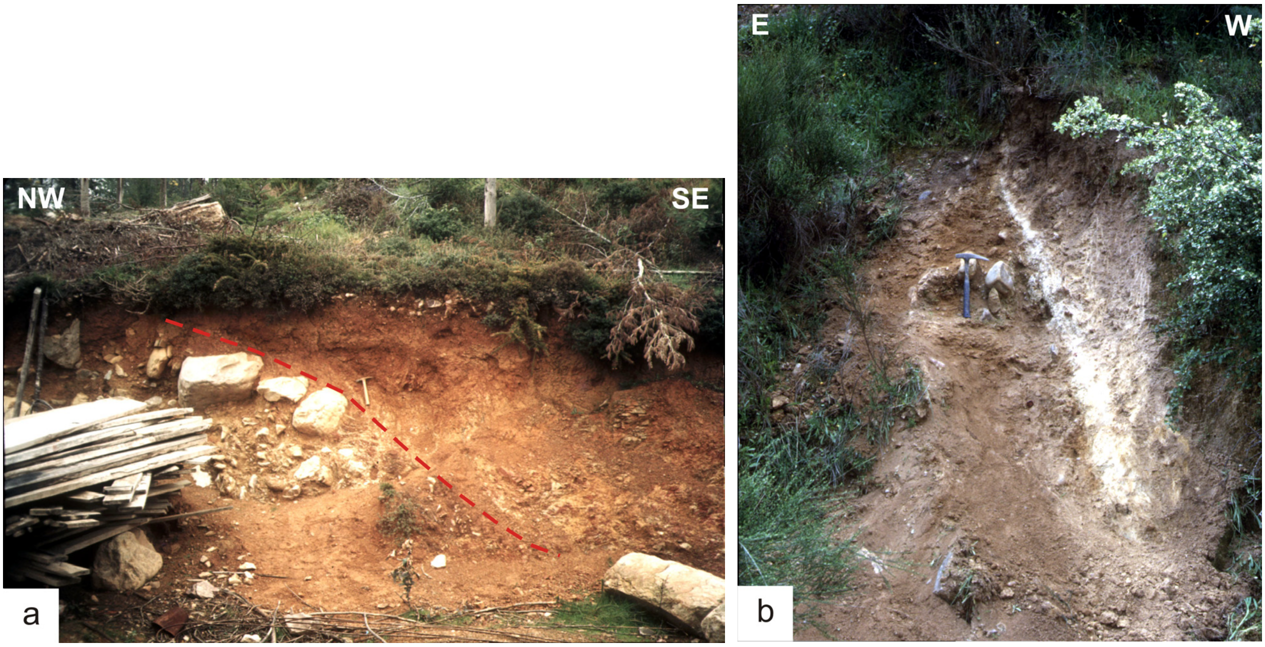

Fig. 5.- a - Outcrop of the Seia-Lousã reverse fault, at the N boundary of the Portuguese Central Cordillera (near Carvalhal), showing Cambrian schist (SE) thrusted over fan-conglomerates of probable Piacenzian age (?) (NW); b - Outcrop of the Manteigas-Vilariça-Bragança strike-slip fault near the Douro river (Pocinho), showing Variscan granite (W) in fault contact with river terrace deposits of probable Upper Pleistocene age (200 – 100 ka) (E).

Fig. 5.- a - Afloramiento de la falla inversa de Seia-Lousã, en el límite septentrional de la cordillera central Portuguesa (cerca de Carvahal) que muestra esquistos Cámbricos cabalgando sobre conglomerados aluviales de probable edad Piaccenciana (NW); b - Afloramiento de la falla de Manteigas-Vilariça-Bragança cerca del río Duero (Pocinho) que muestra el granito varisco (Oeste) en contacto por falla con depósitos de terraza de probable edad pleistocena superior (200 – 100 ka) (Este).

further archaeoseismological evidence, as a tool for detecting and characterizing past earthquakes.

In spite of the early paleoseismic studies performed at the Ferrel site (Cabral and Ribeiro, 1981), until the late 1990's the neotectonic studies in mainland Portugal have favoured the regional coverage of faults that exhibit upper Pliocene to Quaternary activity, rather than conducting detailed research regarding the seismogenic behaviour of particular structures. The reason was to obtain a most complete database of active or potentially active structures.

However, the lack of paleoseismic data emerged as a major drawback, when knowledge of the most recent fault activity and earthquake potential was needed for specific seismic hazard evaluations. In order to obviate this problem, two research projects were submitted in 1998 for studying the seismic hazard in the Lower Tagus Valley (projects TAGUS, PI J. Fonseca, and SHELT, PI J. Cabral), which comprised a significant component of paleoseismological research. Paleoseismic results on the Lower Tagus fault system were published by Fonseca *et al.* (2000), Vilanova (2003) and Vilanova and Fonseca (2004), and these were contested and interpreted as having landslide origin by Cabral and Marques (2001) and Cabral *et al.* (2002, 2003, 2011a), while the palesoseismic research performed by the SHELT group yielded inconclusive results (Cabral *et al.*, 2011b).

Paleoseismological research in the Manteigas-Vilariça-Bragança fault was started by Rockwell and collaborators in 2004-05, in the scope of studies for the construction of two nearby dams (the Sabor river dams), and the results were published in 2009 (Rockwell *et al.*, 2009). Several trenches were excavated at 3 sites and, according to those authors, the following evidence was found (from N to S): at the Vilariça site, a fault was uncovered left-laterally displacing late Pleistocene channel deposits (18 ka/~6.5 m, 23 ka/~9 m), evidencing a slip-rate of 0.3-0.5 mm/yr; at the Vale Meão site, the main fault in the Variscan basement rocks was found propagating into late Pleistocene sediments with small reverse offsets (strike-slip unknown), evidencing 2 (possibly 3?) events in the past 14.5 ka, yielding an average recurrence period of ~5-7 ka. However, the 2 to 3 events appeared probably clustered between 14.5-11 ka, implying a recurrence period <2 ka during that period. A small offset rill located 2.2 km to the SSW suggested 2-2.5 m of left-lateral displacement in the last event. At the Longroiva site the study was inconclusive due to the lack of young sediments. The fault segment length and the observed strike-slip displacements argue for earthquakes in the M7+ range.

Two research projects were submitted in 2006 to further implement paleoseismic studies in mainland Portugal, namely project RETURN, coordinated by J. Fonseca, and project PALEOSISPOR, coordinated by J. Cabral. Further investigations were performed on the Vilariça fault in the scope of PALEOSISPOR, and the results supported the recent activity at the Vale Meão site, pointing to strike-slip surface faulting affecting late Pleistocene fluvial terrace sediments (Cabral *et al.*, 2010; Perea *et al.*, 2010). Paleoseismic studies have also been performed on the NNE-SSW trending S.Teotónio–Aljezur–Sinceira strike-slip fault system, located near the SW coast, pointing to seismogenic activity during the Pleistocene (Figueiredo *et al.*, 2008, 2009a,b, 2010a,b). Active tectonic studies also continued in the Lower Tagus valley region in the scope of project RETURN and of a new project submitted in 2009 (project FINDER, PI G. Besana-Ostman), resulting in the recognition of geomorphic expression of recent faulting in the area (Besana-Ostman *et al.*, 2010, 2012).

Albeit the efforts that have been undertaken in the past few years, the amount of paleoseismic data from faults in mainland Portugal is still very small and insufficient for adequately addressing regional seismic hazard assessment, stressing the need to perform further paleoseismic investigations and making this a priority issue.

Another critical subject for the refinement of the neotectonic data in Portugal pertains to the difficulty in dating the stratigraphical and geomorphological references used for characterizing the deformations, which frequently are beyond the limit of ^{14}C, and even of optically stimulated luminescence (OSL) due the natural radiation high dose rates. Further implementation of OSL dating, and particularly the introduction of cosmogenic radionuclide dating (CRN), is essential to surpass that limitation and to better characterize the timing of the neotectonic movements (uplift/subsidence and fault slip) and to estimate strain rates.

Finally, a network for continuous GPS monitoring of regional tectonic deformations should be established in mainland Portugal. Observations have already been performed in the Lower Tagus Valley and the Algarve (southern Portugal) regions, but consistent results have not yet been obtained. Monitoring areas should be enlarged in order to enclose major active structures, as the Penacova-Régua-Verin and the Vilariça faults, and the

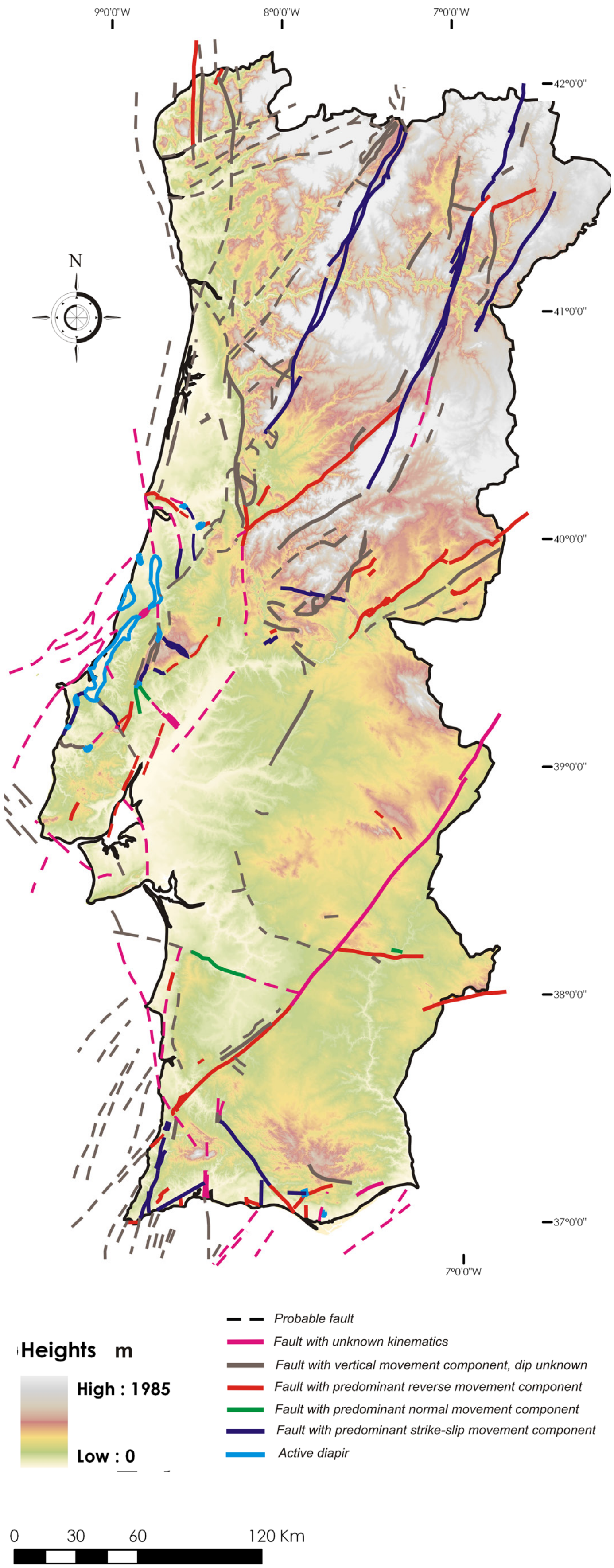

Fig. 6.- Map of faults in mainland Portugal (onshore area) evidencing activity in the last ~3 Ma; modified from Neotectonic Map of Mainland Portugal, 1:1,000,000 scale (Cabral and Ribeiro, 1988; Cabral, 1995).

Fig. 6.- Mapa de fallas en el Portugal continental (zona emergida) que pone en evidencia la presencia de actividad tectónica en los últimos ~3 Ma; modificado del Mapa Neotectónico de Portugal Continental, a escala 1:1,000,000 (Cabral and Ribeiro, 1988, Cabral, 1995).

expected slow strain rates argue for the urgency in starting measurements, as it will take years to adequately characterize velocities.

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