

Neotectonic activity on the Carcavai fault zone (Algarve, Portugal)

Actividade neotectónica da falha de Carcavai (Algarve, Portugal)

R. Ressurreição^{1*}, J. Cabral², R.P. Dias¹, J. Carvalho¹, C. Pinto¹

Recebido em 24/02/2011 / Aceite em 08/06/2011

Disponível online em Outubro de 2011 / Publicado em Dezembro de 2011

© 2011 LNEG – Laboratório Nacional de Geologia e Energia, IP



Artigo original
Original article

Abstract: Studies performed on the Carcavai fault zone, Eastern Algarve, revealed several deformational features in Plio-Quaternary sediments with potential neotectonic implications. These features include fracturing (faults and joints) and clastic dikes, located along the Carcavai fault. Most of the fractures appear to be the expression of the fault activity affecting the Plio-Quaternary sediments. This is suggested by a consistent strike, subparallel to the major tectonic structure, and by the location pattern. Evidences of the fault activity were also identified in the Mesozoic and Paleozoic rocks, though the age of that deformation is poorly constrained. It consists in the presence of zones of intensely brecciated rock and of adjoining coarse sedimentary deposits probably related to the dismantling of a fault scarp. The acquired data point to a late hercynian structure, reactivated as a left-lateral strike-slip fault with a thrust component during the Plio-Quaternary.

Keywords: Neotectonics, Carcavai Fault, Clastic dikes, Plio-Quaternary.

Resumo: Estudos levados a cabo na zona da falha de Carcavai, localizada no sotavento Algarvio, revelaram a ocorrência de diversas estruturas de deformação em sedimentos plio-quaternários com possíveis implicações neotectónicas. As estruturas consistem em fracturas (falhas e diaclases) e filões detríticos, localizados ao longo da falha de Carcavai. A maioria das fracturas aparenta ser a expressão da actividade da falha nos sedimentos plio-quaternários, o que é sugerido pelo consistente padrão direccional, subparalelo ao acidente principal, assim como pelo padrão de distribuição geográfica. Foram também observadas evidências da actividade da falha nas rochas do Paleozóico e do Mesozóico materializadas por zonas intensamente fracturadas e pela existência de depósitos grosseiros compatíveis com o desmantelamento de uma escarpa de falha vizinha. Contudo, a idade dessa deformação está mal constrangida devido à ausência de marcadores cronológicos mais recentes. Os dados adquiridos sugerem que se trata de uma estrutura tardi-hercínica herdada, posteriormente reactivada como desligamento esquerdo com componente de movimentação inversa durante o Plio-Quaternário.

Palavras-chave: Neotectónica, Falha de Carcavai, Filões detríticos, Plio-Quaternário.

Kreemer & Holt, 2001; Sella *et al.*, 2002; Calais *et al.*, 2002; Calais *et al.*, 2003; Fernandes *et al.*, 2003; Nocquet & Calais, 2004; Stich *et al.*, 2006). This direction coincides with that of the maximum horizontal compressive stress (SHMax), inferred from focal mechanisms, borehole ovalization, and active faults kinematic data (Ribeiro *et al.*, 1996; Borges *et al.*, 2001; Carrilho, 2005) (Fig. 1). According to some authors (Cabral, 1995; Ribeiro *et al.*, 1996; Ribeiro, 2002), an incipient subduction zone is nucleating along the continental margin of SW Iberia. Gutscher *et al.* (2002) support the existence of a subduction zone dipping towards E in the Gibraltar region, evidenced by seismic tomography studies, showing the presence of a cold dense body from the surface to depths in the order of 700 m.

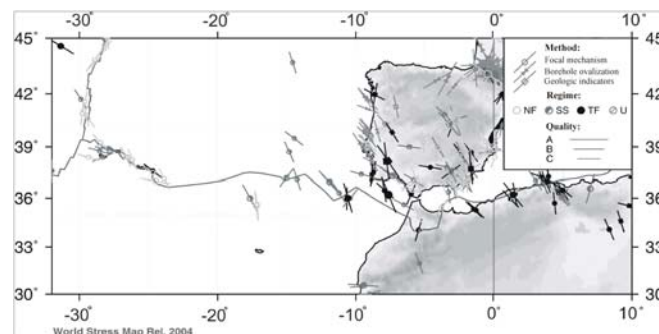


Fig. 1. Stress state indicators on the AGFZ (World Stress Map, Reinecker *et al.*, 2004, adapted from Carrilho, 2005).

Fig. 1. Indicadores do estado de tensão na ZFAG (World Stress Map, Reinecker *et al.*, 2004, in Carrilho, 2005).

In the Gulf of Cadiz, the AGFZ is distributed through numerous structures, with a special relevance for the set of oblique thrusts trending NNE-SSW, such as the Horseshoe and Marquês de Pombal faults, and for reactivated WNW-ESE faults, with dextral strike-slip kinematics (Rosas *et al.*, 2009; Terrinha *et al.*, 2009; Zitellini *et al.*, 2009).

This geodynamic environment explains the neotectonic activity in the Algarve region, which is expressed by vertical crustal movements and brittle and ductile deformation affecting Plio-Quaternary sediments (Dias, 2001; Dias & Cabral, 2002a).

The Algarve region experiences important seismicity, with historical and instrumental earthquakes of high magnitude. This seismicity is mostly concentrated in the offshore, at the Gulf of Cadiz region (Fig. 2). Onshore there is also a significant seismic activity, but of lower magnitude, suggesting that the deformation

¹LNEG, Apartado 7586, 2721-866 Alfragide, Amadora, Portugal;

²Geology Department/LATTEX-IDL, Faculty of Sciences, Lisbon University.

*Autor correspondente / Corresponding author: ricardo.ressurreicao@lneg.pt

1. Introduction

The Algarve region is located near the eastern sector of the Azores-Gibraltar Fracture Zone (AGFZ), which is the boundary between the Eurasia and Nubia lithospheric plates. It is characterized by a 4mm/yr rate of NW-SE to WNW-ESE convergence between these two plates, in the Gulf of Cadiz area (Argus *et al.*, 1989; DeMets *et al.*, 1994; Sillard *et al.*, 1998;

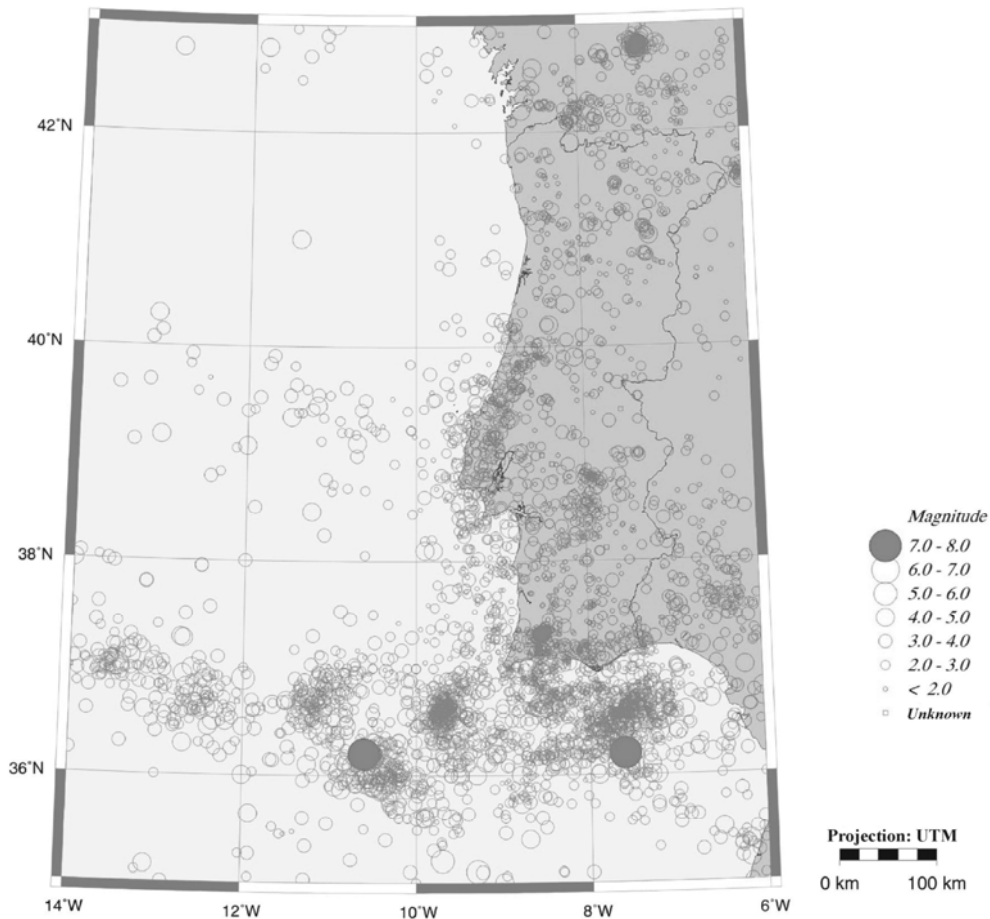


Fig. 2. Instrumental seismicity from 1961 to 2003 (Carrilho, 2005).

Fig. 2. Sismicidade instrumental entre 1961 e 2003 (Carrilho, 2005).

is mainly absorbed by structures located offshore (Dias & Cabral, 1995a, b; Dias, 2001).

The Carcavai fault zone (Carcavai-Vale de Rãs – Manuppella *et al.*, 2007 or Loulé-S. Brás – Terrinha, 1998) (Fig. 3), trending NE-SW, extends onshore for about 20 km, between Quarteira and S. Brás de Alportel (Dias, 2001).

According to Terrinha (1998) this fault is intercepted offshore by the S. Marcos-Quarteira fault. In the NE sector it branches into several minor faults with opposite vergence. It is interpreted by this author as an extensional structure that was subjected to a pre-Miocene tectonic inversion (Terrinha, 1998).

Dias (2001) characterized the Carcavai fault as a left-lateral strike slip fault with a reverse component in the Neogene, presenting neotectonic activity. This activity is evidenced by brittle deformation (faults and joints) and soft-sediment deformation structures (clastic dikes) affecting the sediments of the Ludo Formation (Dias, 2001; Dias & Cabral, 2002a), of Plio-Quaternary age (Moura & Boski, 1999). The clastic dikes were interpreted as seismically induced liquefaction features (Dias, 2001; Dias & Cabral, 2002a; Ressurreição, 2009).

The Carcavai fault can be divided into two sectors (Dias, 2001). A northern sector, extending from S. Brás de Alportel to Areiro, corresponding to a fault zone with numerous branches trending NE-SW to ENE-WSW, and a southern sector, located between Areiro and Quarteira, made up of two branches that

probably merge offshore (Fig. 3). Noiva (2009) identified deformation probably associated with the Carcavai fault offshore, thus supporting its extension to the continental shelf.

In general, the extent, geometry and behavior of this fault were poorly characterized, being these some of the goals of the present study.

2. Geological setting

The study area, located in Eastern Algarve, comprises a great variety of lithologies, from Paleozoic to Cenozoic age.

The Paleozoic rocks outcrop only in the northern area, consisting of flysch sequences of late Carboniferous age that were intensely folded and faulted during the Hercynian orogeny (Manuppella, 1992). To the south, the Mesozoic and Cenozoic sediments crop out.

The Mesozoic basin was formed in a transtensional regime during the opening of the Thetys Sea and the Central Atlantic Ocean, throughout the Jurassic and Early Cretaceous (Terrinha, 1998). Limestones and marls are predominant, dating from Upper Triassic to Lower Cretaceous, however siliciclastic sediments abound in the Triassic. The absence of Upper Cretaceous sediments may be due to an important tectonic inversion event that occurred in Late Cretaceous to Eocene/Oligocene (Terrinha, 1998; Kulberg *et al.*, 1992).

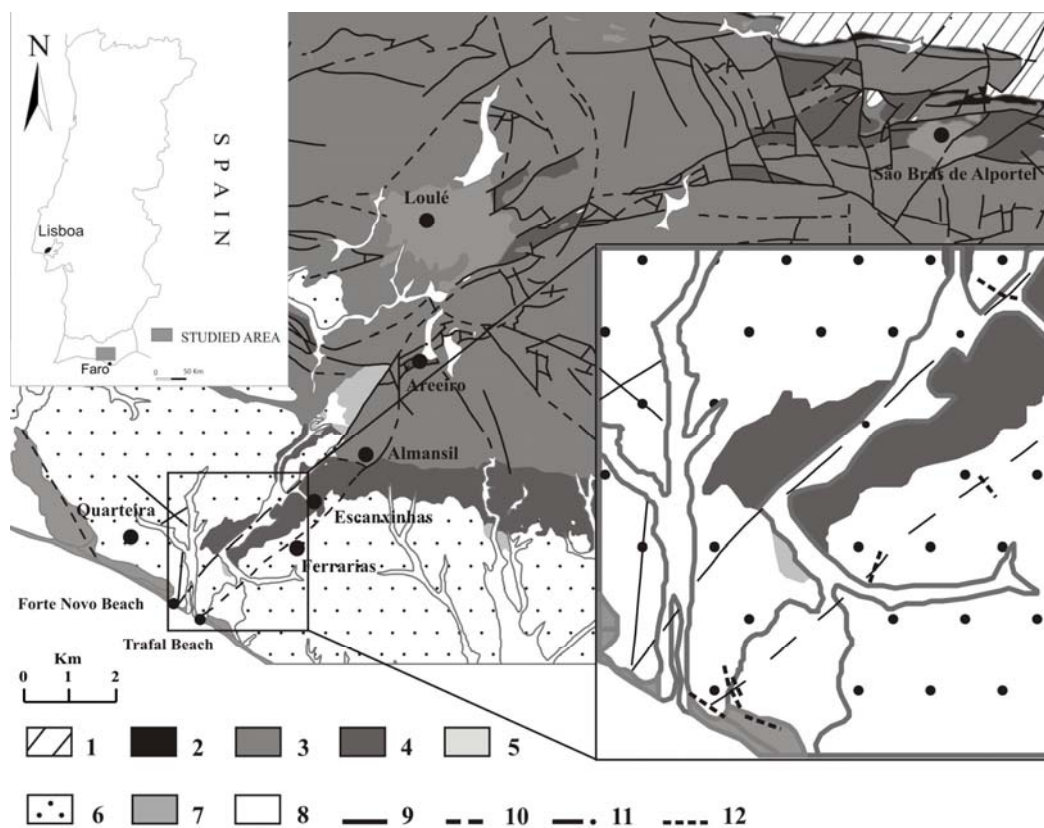


Fig. 3. Study area location (geological map adapted from Manuppella, 1992). 1, Paleozoic; 2, Triassic; 3, Jurassic; 4, Cretaceous; 5, Miocene; 6, Pliocene-Pleistocene; 7, Quaternary; 8, Alluvium; 9, Fault; 10, Probable fault; 11, Hidden fault; 12, Seismic profile.

Fig. 3. Localização da área de estudo (geologia adaptada de Manuppella, 1992). 1, Paleozóico; 2, Triássico; 3, Jurássico; 4, Cretácico; 5, Miocénico; 6, Pliocénico-Plistocénico; 7, Quaternário; 8, Aluvião; 9, Falha; 10, Falha provável; 11, Falha oculta; 12, Perfil sísmico.

The Cenozoic is characterized by sediments of lower and middle Miocene (sandy limestones), upper Miocene (silts and sands) (Cachão, 1995; Cachão *et al.*, 1998; Pais *et al.*, 2000) and the Pliocene-Pleistocene sediments of Ludo Formation (sands and gravels) (Moura & Boski, 1999). This work gives a special attention to the Ludo Formation sediments (Fig. 4) because of their neotectonic implication as stratigraphical markers for recognizing and characterizing the younger deformation.

3. Neotectonic activity of the Carcavai fault

3.1. Southern sector of the Carcavai fault

In this sector of the Carcavai fault zone, the neotectonic deformation is essentially expressed by intense fracturing affecting the Plio-Quaternary sediments of the Ludo Formation, and by the occurrence of clastic dikes.

The western branch has a regular NE-SW direction and, for most of its length it coincides with the Carcavai creek which is adapted to the fault zone due to the presence of more easily erodible, intensely fractured rocks. This causes an absence of fault outcrops in the southern part of this branch, because it is covered by recent alluvial sediments, with the exception of the exposures at the Forte Novo beach cliffs (Fig. 3).

At this location, intense jointing affects the Plio-Pleistocene sediments (Fig. 5), materialized by planes trending NNW-SSE to

NNE-SSW (Dias, 2001). Dias (2001) also reported the existence of two fault planes (N23°E, 52°W, and N23°E, 55°W), but it wasn't possible to quantify the offset due to the lack of sedimentary reference markers. At about 600 m to N, in the Quarteira Camping area, two similar outcrops were identified, but with joints trending preferentially N-S.

At Escanxinhas area, E of the Carcavai creek (Fig. 3), the Ludo Formation sediments cover the cretaceous rocks through an unconformity marked by a well-developed karst, at an elevation of 30 m. W of the creek, this surface can be observed at an elevation of 50 m, suggesting activity of the western branch of Carcavai fault zone causing a vertical offset of 20 m in Plio-Quaternary times (Fig. 6).

North of Almansil, the published geological maps indicate the presence of Miocene rocks (Galvana Limestones and Galvana Conglomerates) affected by the Carcavai fault. According to Manuppella *et al.* (2007) the genesis of the Galvana Conglomerates unit is related to the important compressive tectonic events that occurred during late Tortonian.

In this sector, the eastern branch the Carcavai fault zone trends NE-SW until N of Almansil, where it changes orientation to N-S and joins the western branch (Fig. 3). The fault is here expressed as a discontinuous band of deformation, from Trafal beach to S of Almansil. This deformation consists of intense fracturing, with joints and faults (predominantly reverse faults) (Fig. 7), and clastic dikes (Fig. 8). Many of the identified features have orientations and distribution consistent with that of the Carcavai fault (Fig. 9).

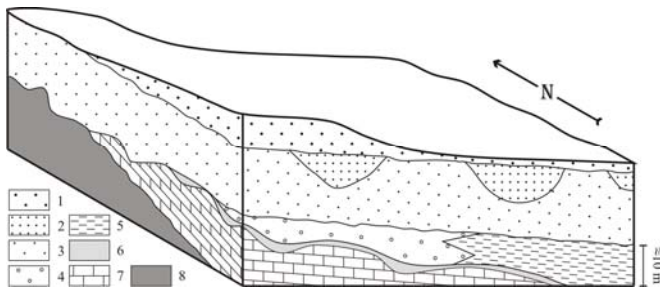


Fig. 4. Schematic block diagram showing the spatial relation between the Ludo Formation Members and the Meso-Cenozoic rocks (Moura *et al.*, 1998, in Dias & Cabral, 2002b). 1, Gambelas sands and gravels (Pleistocene); 2, Ludo sands (Pliocene-Pleistocene); 3, Quarteira sands (Upper Pliocene); 4, Falésia sands (Lower Pliocene); 5, Monte Negro sands (Lower Pliocene); 6, Cacela clayey silts (Miocene); 7, Lagos Portimão Formation (Miocene); 8, Mesozoic.

Fig. 4. Modelo esquemático representando a relação espacial entre os membros da Formação do Ludo e o substrato Meso-Cenozóico (Moura *et al.*, 1998, in Dias & Cabral, 2002b). 1, Areias e cascalheiras de Gambelas (Pleistocénico); 2, Areias do Ludo (Pliocénico-Pleistocénico); 3, Areias de Quarteira (Pliocénico superior); 4, Areias da Falésia (Pliocénico inferior); 5, Areias de Monte Negro (Pliocénico inferior); 6, Siltes argilosos de Cacela (Miocénico); 7, Formação de Lagos Portimão (Miocénico); 8, Mesozóico.

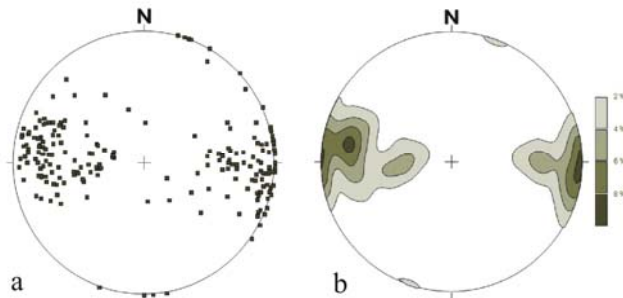


Fig. 5. Stereographic plot of fractures (mostly joints) affecting the Ludo Formation sediments, at Quarteira region ($n=225$) (Dias, 2001): a) poles to the planes, and b) density contour diagram of the poles to the planes.

Fig. 5. Projecção estereográfica de fracturas (maioritariamente diaclases) a afectar os sedimentos da Formação do Ludo na região de Quarteira ($n=225$) (Dias, 2001): a) pólos dos planos, e b) diagrama de contornos de densidade dos pólos dos planos.

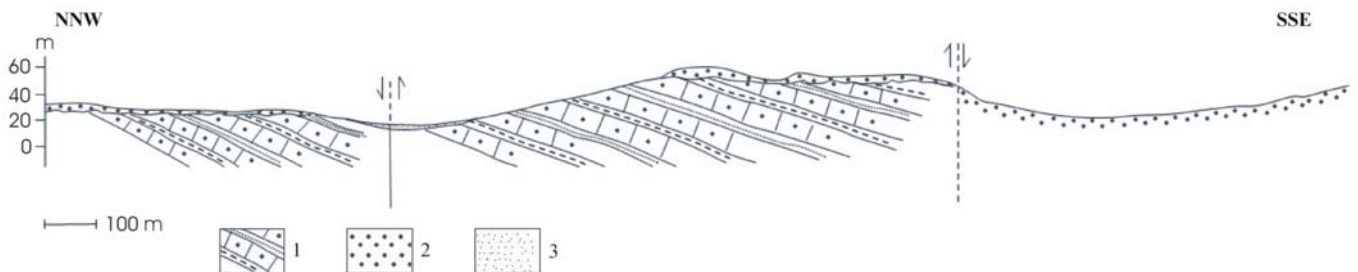


Fig. 6. Geologic cross section made at Ferrarias area, across the eastern and western branches of the Carcavai fault. 1, Cretaceous; 2, Pliocene-Pleistocene (Ludo Formation); 3, Holocene (alluvium) (Ressurreição, 2009).

Fig. 6. Corte geológico efectuado sobre a região de Ferrarias, interceptando os ramos ocidental e oriental da falha de Carcavai. 1, Cretácico; 2, Pliocénico-Pleistocénico (Formação do Ludo); 3, Holocénico (aluvião) (Ressurreição, 2009).

At the Trafal beach cliff (Fig. 3), the Plio-Pleistocene sediments show intense jointing and some reverse faults trending NNE-SSW to NE-SW (Dias, 2001).

A few kilometers northwards, at Ferrarias (Fig. 3), there are several outcrops with potential neotectonic interest. Figure 10 shows an outcrop where three fault surfaces produce an accumulated reverse separation of 1.80 m on a pebble layer of the Ludo Formation. A drag fold in the coarse grained sediments, compatible with reverse slip, can also be seen. The fault surfaces show the particular characteristic of coinciding with thin detrital dikes filled with lutite sediment.

From Almansil to the N, where the two branches merge, deformation affecting Cretaceous and Jurassic rocks was identified. This deformation consists essentially of zones of intensely fractured rock and rotated bedding.

3.2. Northern Sector of the Carcavai fault

Along the northern sector of the Carcavai fault zone, only Mesozoic and Paleozoic rocks crop out and there are no Plio-Pleistocene sediments to be used as markers. So, evidence of neotectonic activity is scarce or even inexistent.

From S to N, the fault gradually changes its direction to ENE-WSW, and turns into a more complex and diffuse structure. Between Loulé and S. Brás de Alportel (Fig. 3) the fault zone becomes wider, consisting of a set of alternating horsts and grabens formed during the extensional events that affected the Algarve Basin in the Mesozoic (Terrinha, 1998). The fault strands that limit these structures were later reactivated as thrusts during the late Mesozoic and Cenozoic tectonic inversion episodes (Terrinha, 1998), probably with a strike-slip component.

Fault activity affecting the Mesozoic and Paleozoic rocks in this sector is evidenced by intense fracturing and the presence of fault breccias. However it is not possible to date this activity due to the absence of chronologic markers.

N of Almansil (Fig. 3), there are some outcrops showing coarse sediment containing striated pebbles (Fig. 11). The outcrops are difficult to interpret because the sediment is affected by a well developed calcrete. Nevertheless it may correspond to sediment formed by the dismantling of a nearby fault scarp, probably of the same age of the Galvanas Limestones Unit.

A wide fault zone affecting Jurassic carbonate rocks was observed at a trench located E of Loulé (Fig. 3), open for building purposes. At this site we could identify intense fracturing of the Jurassic limestones and marls, with numerous striated fault surfaces that can be grouped in two major sets trending approximately NE-SW to NNE-SSW and E-W (Fig. 12).

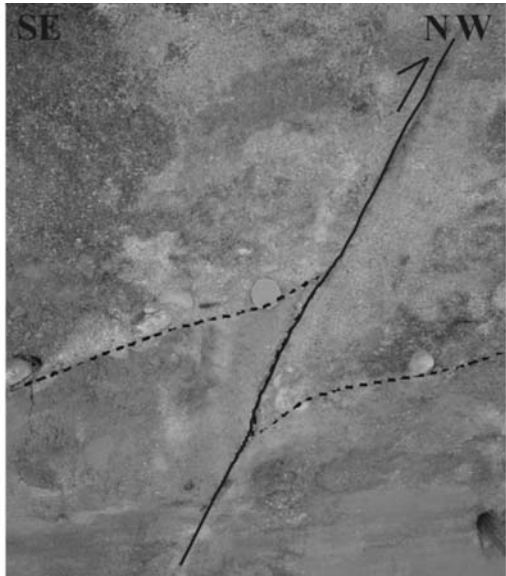


Fig. 7. Reverse fault causing an offset of 12 cm in a pebble bed of the Ludo Formation sediments, located near Ferrarias.

Fig. 7. Falha inversa provocando um rejeito de 12 cm num nível grosseiro da Formação do Ludo, localizada próximo de Ferrarias.

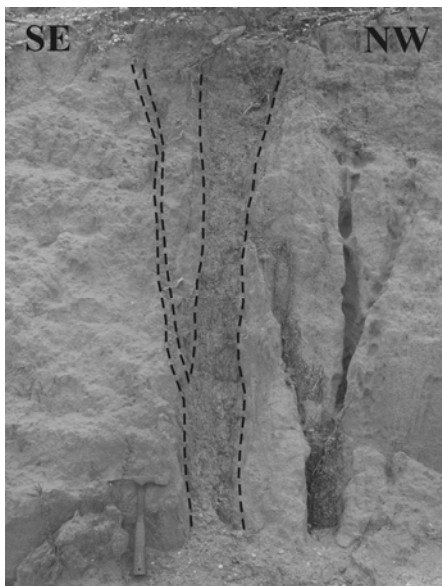


Fig. 8. Fine grained clastic dike in the Ludo Formation sediments, at Ferrarias, trending (N56°E, 84°SE). In the SE wall there is an upwards branching into a thin dike.

Fig. 8. Filão detrítico composto por sedimento de granulometria fina, intercalado nos sedimentos da Formação do Ludo, em Ferrarias. Apresenta uma atitude (N56°E, 84°SE). Na parede SE da estrutura observa-se uma ramificação para um filão de fina espessura.

There is also a third set of surfaces trending N-S but apparently of less importance. Many of these fault surfaces are covered with reddish clay, which seems to be the residual product of the

weathering of the carbonate rocks. This clay is striated too (Fig. 13), indicating fault activity posterior to the weathering process. Samples of this clayey veneer were collected for X-Ray diffraction analysis, revealing a mineral assemblage of illite and kaolinite. The chronological significance of this will be discussed in the Discussion chapter. At this site the fault zone also shows a fault breccia made up of angular fragments of different carbonate lithologies within a clayey matrix.

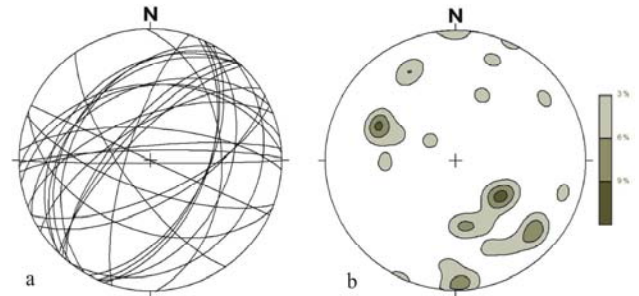


Fig. 9. Stereographic plot of faults affecting the Ludo Formation sediments, along the eastern branch (n=29): a) planes, and b) density contour diagram of the poles to the planes.

Fig. 9. Projecção estereográfica dos planos de falhas a afectarem os sedimentos da Formação do Ludo, ao longo do seu ramo oriental. (n=29): a) planos, e b) diagrama de contornos de densidade dos pólos dos planos.



Fig. 10. Reverse faults affecting the Ludo Formation sands, at Ferrarias, presenting an accumulated offset of 1.80 m distributed between three fault planes. The dashed lines represent the base of a pebble bed (Ressurreição, 2009, Ressurreição *et al.*, 2009).

Fig. 10. Falhas inversas a afectar as areias da Formação do Ludo em Ferrarias, mostrando um rejeito acumulado de 1,80 m distribuído entre três planos de falha. A linha a tracejado representa a base de um nível de seixos. (Ressurreição, 2009, Ressurreição *et al.*, 2009).

Other similar outcrops were identified NE of this location, showing the same fracturing patterns. N of São Brás de Alportel, at the prolongation of the Carcavai fault (Fig. 3), several fault planes affecting the Triassic and Paleozoic rocks were observed.

4. Seismic data acquisition

In order to confirm the existence of the eastern branch of the southern sector of the Carcavai fault, as well as to study the geometry of the fault zone at depth, geophysical data were acquired. In areas where the location of the fault was uncertain, EM and seismic reflection profiles with a coarse spatial sampling were carried out. After accomplishing a more precise location of the fault zone, and in places where geological evidence suggested

the presence of the structure, seismic reflection profiles with a tighter spatial resolution were acquired.

A fixed spread with 48 channels, 50 Hz vertical receivers and a 250 Kg accelerated weight-drop seismic source were used. Shots were fired inside the receiver layout and two end shots with half the receiver spacing. The sensors spacing varied from 7.5 m at Trafal, 5 m at Palmeiras and 2.5 m at Ferrarias (Fig. 3). A sampling rate of 0.25 ms was used to allow a refraction interpretation of the reflection shot gathers (not presented here).



Fig. 11. Conglomerate cropping out N of Almansil, probably generated by dismantling of a fault scarp related to the Carcavai fault.

Fig. 11. Conglomerado aflorante a N de Almansil, provavelmente resultante do desmantelamento de uma escarpa de falha gerada pela falha de Carcavai.

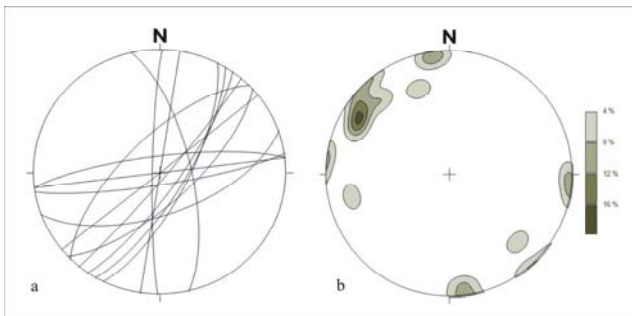


Fig. 12. Stereographic plot of planes from a fault zone, at Goncinha-Loulé (n=15) (Ressurreição, 2009): a) planes, and b) density contour diagram of the poles to the planes.

Fig. 12. Projecção estereográfica dos planos de uma zona de falha, em Goncinha-Loulé (n=15) (Ressurreição, 2009): a) planos, e b) diagrama de contornos de densidade dos pólos dos planos.

The data were processed with a commercial application (SPW) and the following main steps were applied: pre-processing (Yilmaz, 2001), deconvolution, velocity analysis, NMO correction and stack, 2 iterations of residual statics (surface consistent), integral DMO (id.) and phase-shift or split-step migration.

After migration, FX deconvolution, spatial noise filter (Hornbostel, 1991), frequency and coherency filters were applied to enhance signal to noise ratio and spectral whitening (40-80 Hz) to increase the frequency content of the data. Finally, the profiles were depth converted using interval velocities derived from the stacking velocities using Dix equation. Final time migrated and depth converted sections of the seismic profile carried out at the Ferrarias area are presented in Figure 14. Depth

sections are shown with a horizontal/vertical exaggeration of 1.5:1.

5. Discussion

In the Carcavai fault zone, the neotectonic activity is essentially expressed by fracturing (faults and joints) and seismites, affecting the Ludo Formation sediments.

The observation of deformation in sediments overlying carbonate rocks can induce the investigator wrongly. In fact, Dias & Cabral (2002b) reported several shear structures with normal and reverse kinematics affecting the Plio-Quaternary sedimentary

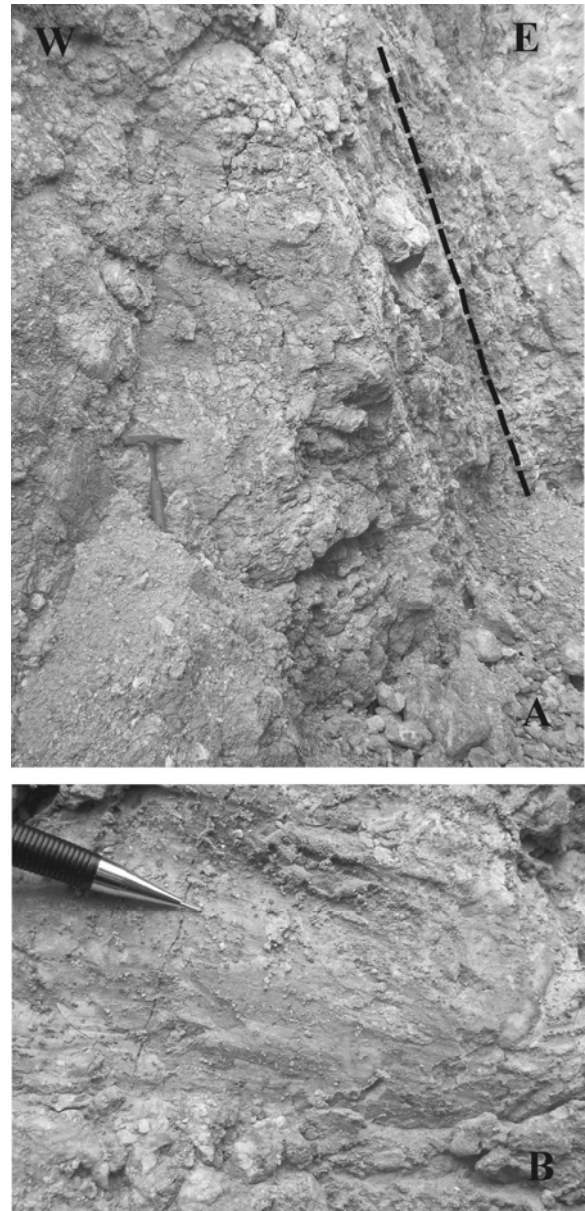


Fig. 13. Fault zone at Goncinha-Loulé. A, general view of fault planes trending E-W (where the hammer is placed) and NNW-SSE (dashed line). B, striated E-W plane. The pencil indicates the dip direction of the striae (Ressurreição, 2009).

Fig. 13. Zona de falha em Goncinha-Loulé. A, aspecto geral dos planos de falha E-W (onde se encontra colocado o martelo) e NNW-SSE (linha a tracejado). B, plano estriado de direcção E-W. A lapiseira indica a atitude das estrias (Ressurreição, 2009).

cover in the Algarve region. These structures result from underground karst evolution in the underlying carbonate rocks, where the progressive dissolution or sudden collapse of caves generate folds and shear fractures in the overlying sediments, in a process with no tectonic implications (Dias & Cabral, 2002b).

Therefore, it is necessary to use some criteria to distinguish the features formed by this process from those of tectonic origin, namely by evaluating the geographical and directional pattern of the structures and their eventual relationship with known nearby active faults, though the trend of the karst structures may also be passively driven by inactive tectonic structures, because pre-existent fractures facilitate the circulation of water, thus promoting the carbonate dissolution (Dias & Cabral, 2002b).

The acquired data doesn't show any significant neotectonic activity related to the eastern branch of the southern sector of the Carcavai fault zone. At the cliffs of Forte Novo beach, where the fault is signaled in the geological maps (Fig. 3), intense fracturing was observed but only two fractures with recognizable offset were identified. The dominant N-S direction of the fractures, distinct from the generally observed NE-SW trend, is probably the consequence of a locally rotated stress field caused by an interference with the nearby S. Marcos-Quarteira fault.

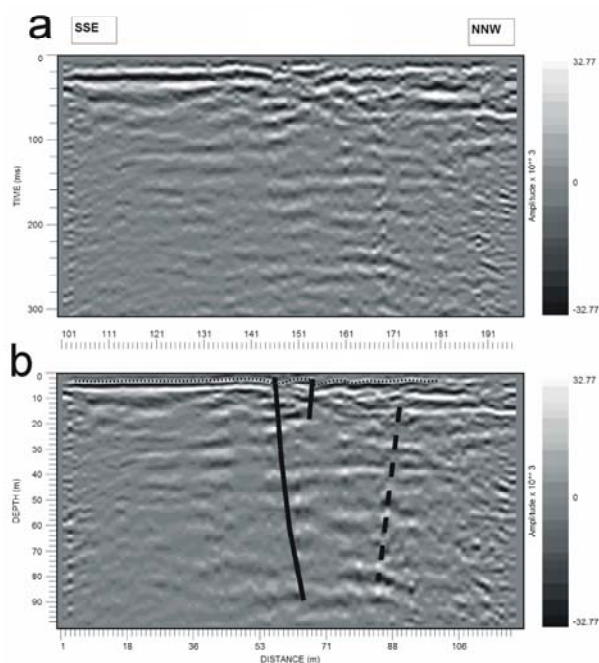


Fig. 14. Time migrated (a) and depth converted (b) seismic reflection stacked sections acquired at Ferrarias. The depth converted seismic section shows fault interpretation (adapted from Carvalho *et al.*, in press). The dotted line represents the contact between Cretaceous (below line) and Plio-Pleistocene sediments (above line).

Fig. 14. Seções sísmicas migradas em tempo (a) e convertidas para profundidade (b) adquiridas em Ferrarias. As seções convertidas em profundidade mostram a interpretação estrutural (adaptado de Carvalho *et al.*, in press). A linha a ponteados representa o contacto entre o Cretácico (abaixo da linha) e os sedimentos Plio-Pleistocénico (acima da linha).

Figure 6 shows a vertical offset of the Plio-Quaternary sediments basal unconformity surface of about 20 m, with relative rising of the southeastern bloc. This figure is also useful to infer the fault's western branch. In the continuation of the cross-section towards SE, it would be expected to observe this unconformity surface at an elevation close to 45 m, but in that direction we find the Plio-Quaternary sediments cropping out

down to an elevation of at least 20 m, suggesting the presence of another fault to the E, which downthrows this unit. According to Carvalho *et al.* (in press) the geophysical data support this inference, showing, however, a smaller vertical offset of about 10 m. So, it seems that there is an elevated bloc between the western and eastern branches of the S sector of the Carcavai fault. Figure 15 presents a geologic cross section, made on the basis of a set of geo-electric boreholes, which also supports that conclusion. Considering that the Carcavai structure probably behaves as a strike-slip fault with a reverse component, the inferred vertical offset does not allow to estimate the fault slip rate, because the horizontal displacement is not known, thus only allowing a minimum estimate.

Although the presence of underlying carbonate rocks is propitious to underground karst evolution, the deformation band referred above, identified along the eastern branch of the fault, from Praia do Trafal to Almansil (Fig. 3), may be the surface expression of the Carcavai fault activity. This is suggested by the consistent geographical and directional pattern of the deformation features, as well as the reverse kinematics of most of the identified fault surfaces, consistent with the regional stress regime and the Carcavai fault behavior. Probably, many of the identified reverse faults have a significant strike-slip component, not recognizable, which is supported by dips exceeding 45° presented by most of them.

The seismic profiles interpretation revealed several fault surfaces at the expected location of the Carcavai fault zone. Several reverse faults were detected as well as some structures showing a normal kinematic component, cutting the uppermost sediments (Plio-Quaternary?). Where it was possible to calculate the vertical offset of the faults, a 10 m vertical separation affecting these sediments was estimated (Carvalho *et al.*, in press).

In the published geological maps (Manuppella, 1992; Manuppella *et al.*, 2007), two Miocene geologic units – the Galvana Limestones and the Galvana Conglomerates – are represented N of Almansil. Their restricted geographic position next to the Carcavai fault suggests that they were conditioned by the tectonic activity of this fault. In fact, the irregular geometry of the fault points to the generation of a pull-apart basin associated to left-lateral strike-slip movement, where the Miocene sediments were deposited.

The Galvana Limestones unit does not correspond to a sediment resulting from fault scarp erosion. According to Pais (1982) & Manuppella *et al.* (2007), it was deposited in a proximal marine environment, as shown by the identified fauna. Therefore it must have been deposited over a large area, then eroded, staying preserved in small tectonically depressed areas.

Conversely, the Galvana Conglomerates unit may have a tectonic origin associated with the Carcavai fault activity. According to Pais (oral com.), the age ascribed to this sedimentary unit is doubtful and may be younger than the Upper Miocene, carrying possible neotectonic implications.

The fault zone identified E of Loulé, already described above, might also be of neotectonic interest. The striated clay that veneers the fault surfaces in the studied outcrop may have two possible origins: It can be the product of chemical weathering of the Jurassic limestones, or be the accumulation along the fracture surfaces of the clay content of the Ludo Formation fine grain sediments, that was leached down by infiltration waters. In fact, the clay content of kaolinite and illite is similar, but in different proportions: the Ludo Formation sediments are richer in kaolinite and the clay contained in the fractures has more illite. This may be caused by the content in Mg of the Jurassic dolomitic rocks. To consider this second explanation it must be assumed that the

Jurassic rocks were covered in the past by the Plio-Quaternary sediments, which seems probable because these cover sediments were observed at a nearly similar altitude in other places in the region.

Despite the uncertainty in assigning an age to the observed deformation, that outcrop provided good kinematic criteria. The fracturing pattern is compatible with simple shear fractures for a left-lateral strike-slip fault, with R planes (NE-SW), P planes (ENE-WSW) and R' planes (N-S).

The identified striae are consistent with this interpretation.

North of S. Brás de Alportel region (Fig. 3), the Carcavai fault could not be tracked, with the exception for the faults

affecting the Triassic and Paleozoic rocks, referred above. The regional geologic map (Manuppella, 1992) shows several ENE-WSW to NE-SW trending faults crossing the Paleozoic. There is also a set of earthquake epicenters in Eastern Algarve, whose source structures were not identified (Fig. 2) that may be related with the Carcavai fault, suggesting its extension towards NE, which has implications on its seismogenic potential.

Figure 16 shows the suggested trace for the Carcavai fault and its kinematic behavior.

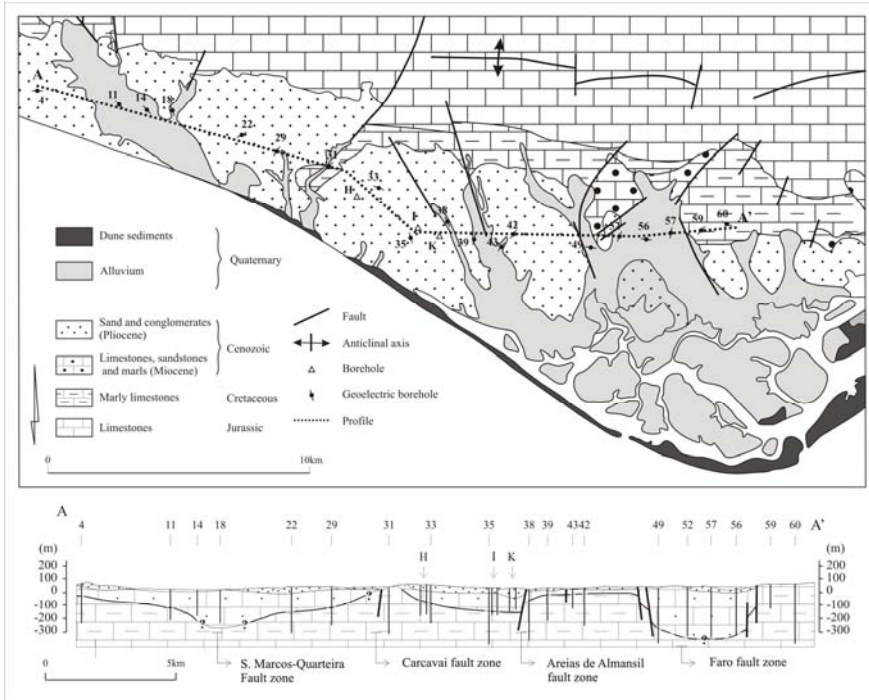
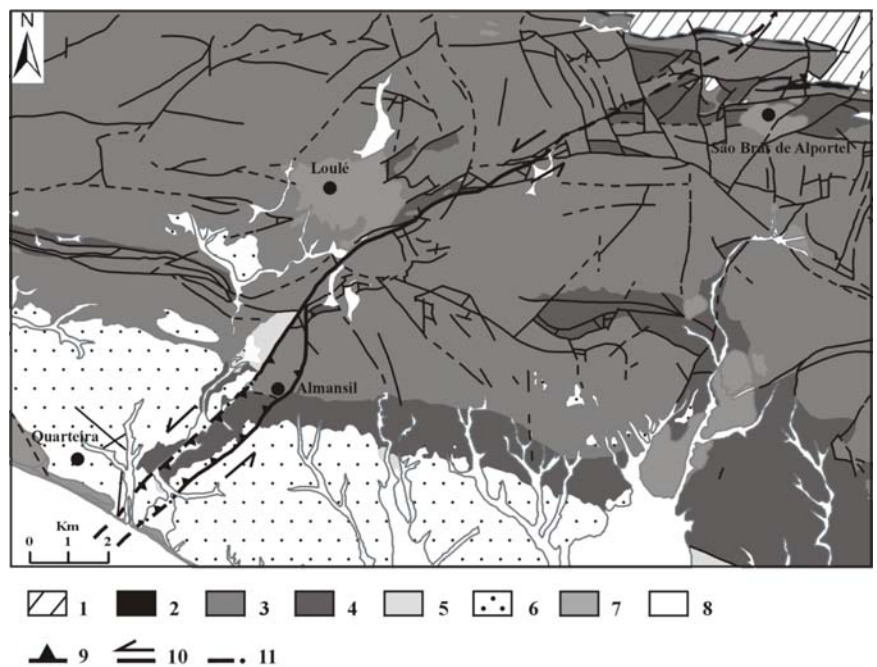


Fig. 15. Geologic map of the Quarteira-Faro region showing the localization of geo-electric boreholes, and geologic cross section with the fault zones identified in the area (adaptated from Geirnaert *et al.*, 1982; Dias, 2001).

Fig. 15. Mapa geológico da zona de Quarteira-Faro com a localização de sondagens geo-eléctricas e corte geológico evidenciando as zonas de falha indentificadas na área (adaptado de Geirnaert *et al.*, 1982; Dias, 2001).

Fig. 16. Proposed trace for the Carcavai fault zone (geological map adapted from Manuppella, 1992). 1, Paleozoic; 2, Triassic; 3, Jurassic; 4, Cretaceous; 5, Miocene; 6, Pliocene-Pleistocene; 7, Quaternary; 8, Alluvium; 9, reverse fault; 10, strike-slip fault; 11, hidden fault.

Fig. 16. Traçado proposto para a zona de falha de Carcavai (cartografia geológica adaptada de Manuppella, 1992). 1, Paleozóico; 2, Triássico; 3, Jurássico; 4, Cretácico; 5, Miocénico; 6, Pliocénico-Plistocénico; 7, Quaternário; 8, Aluvião; 9, falha inversa; 10, falha de deslizamento; 11, falha oculta.



6. Final comments

The Carcavai fault is probably a late-Variscan fault reactivated during the Mesozoic extensional phases of the development of the Algarve's Basin, and latter during the tectonic inversion phases that affected this Basin still in the Mesozoic and in the Cenozoic.

From the acquired data we can infer that the Carcavai fault is a structure with neotectonic activity (intended as tectonic activity since the Pliocene), with a low activity rate, probably behaving as a left lateral strike-slip fault with a reverse component. Taking its mapped length, we infer that it has the potential to generate high magnitude (>6) seismic events. This is consistent with evidence of surface faulting and the generation of structures interpreted as seismically induced liquefaction features, such as the described clastic dikes. The total length of the fault zone, more than 20 km, is still unknown, as it continues offshore (Noiva, 2009) and probably also to the NE.

Due to the lack of a value for the horizontal offset of the Carcavai fault, and its dominant strike-slip kinematics, the estimated slip rate of 0.01 mm/yr and average recurrence interval of 60,000 years represent minimum values calculated from the vertical component of displacement.

Acknowledgements

This work was financed by the ERSTA (Estudo do Risco Sísmico e de Tsunamis do Algarve) protocol established with ANPC (Autoridade Nacional de Protecção Civil).

We thank G. Manuppella and his collaborators for indicating us places with evidences of neotectonic activity, and for the availability of his personal cartographic documents.

We would also like to thank J. Pais and J. Madeira for critically reviewing the manuscript.

References

- Argus, D. F., Gordon, R. G., Demets, C., Stein, S., 1989. Closure of the Africa-Eurasia-North America plate motion circuit and tectonic of the Gloria fault. *Journal of Geophysical Research*, **94**, 5585-5602.
- Borges, J. F., Fitas, A. J., Bezzeghoud, M., Costa, P. T., 2001. Seismotectonics of Portugal and its adjacent Atlantic Area. *Tectonophysics*, **331**, 373-387.
- DeMets, C., Gordon, R. G., Argus, D. F., Stein, S., 1994. Effect of Recent Revisions to the Geomagnetic Reversal Time Scale on Estimates of Current Plate Motions. *Geophysical Research Letters*, **26**, 1921-1924.
- Cabral, J., 1995. Neotectónica em Portugal Continental. *Memórias do Instituto Geológico e Mineiro, Memória*, **31**, Lisboa, 241.
- Cachão, M., 1995. Utilização de nanofósseis calcários em biostratigrafia, paleoceanografia e paleoecologia. Aplicações ao Neogénico do Algarve (Portugal) e do Mediterrâneo Ocidental (ODP 653) e à problemática de *Coccolithus pelagicus*. *Unpublished PhD Thesis*, Fac. Ciências da Univ. de Lisboa, Lisboa, 450.
- Cachão, M., Boski, T., Moura, D., Dias, R. P., Silva, C. M., Santos, A., Pimentel, N., Cabral, J., 1998. Proposta de articulação das unidades sedimentares neogénicas e quaternárias do Algarve (Portugal). *Actas do V Congresso Nacional de Geologia, Comunicações do Instituto Geológico e Mineiro*, Lisboa, **84**, A169-A172.
- Calais, E., Nocquet, J.-M., Jouanne, F., Tardy, M., 2002. Current strain regime in the Western Alps from continuous Global Positioning System measurements, 1996-2001. *Geology*, **30**, 7, 651-654.
- Calais, E., DeMets, C., Nocquet, J.-M., 2003. Evidence for a post-3.16-Ma change in Nubia-Eurasia-North America plate motions? *Earth and Planetary Science Letters*, **216**, 81-92.
- Carrilho, F., 2005. Estudo da Sismicidade da Zona Sudoeste de Portugal Continental. *Unpublished MSc Thesis*, Fac. Ciências da Univ. de Lisboa, Lisboa, 147.
- Carvalho, J., Ramalho, E., Dias, R. P., Pinto, C., Ressurreição, R., *in press*. A Geophysical Study of the Carcavai Fault Zone, Portugal. *Pure and Applied Geophysics*. DOI : 10.1007/s00024-011-0318-y.
- Dias, R. P., 2001. Neotectónica da Região do Algarve. *Unpublished PhD Thesis*, Fac. Ciências, Univ. Lisboa, Lisboa, 369.
- Dias, R. P., Cabral, J., 1995a. Actividade Neotectónica no Algarve. *Comunicações do 8.º Congresso do Algarve*, 7 a 9 de Abril, Vilamoura, 337-345.
- Dias, R. P., Cabral, J., 1995b. Actividade Neotectónica na região do Algarve. IV Congresso Nacional de Geologia, Resumos alargados, Universidade do Porto-Faculdade de Ciências Museu e Laboratório Mineralógico e Geológico, 14 a 18 de Dezembro, Porto, *Memórias*, **4**, 247-251.
- Dias, R.P., Cabral, J., 2002a. Neotectonic activity of the Algarve region (S of Portugal). *Comunicações do Instituto Geológico e Mineiro*, **89**, 193-208.
- Dias, R. P., Cabral, J., 2002b. Interpretation of recent structures in an area of cryptokarst evolution – Neotectonics versus subsidence genesis. *Geodinamica Acta*, **15**, 4, 233-248.
- Fernandes, R. M. S., Ambrosius, B. A. C., Noomen, R., Bastos, L., Wortel, M. J. R., Spakman, W., Govers, R., 2003. The relative motion between Africa and Eurasia as derived from ITRF2000 and GPS data. *Geophysical Research Letters*, **30**, 16.
- Geirnaert, W., Van Beeres, P. H., De Vries, J. J., Hoogeveen, H., Geoelectric survey of the miocene aquifer between Quarteira and Olhão, Algarve, Portugal, In *Hidrogeologic studies in the East Algarve, Portugal*. (W. Geirnaert P. H. Van Beeres, J. J. De Vries, Eds.). (A contribution to the III Semana de Hidrogeologia, Lisboa, Portugal 1982), 2-22.
- Gutscher, M.A., Malod, J., Rehault, J.-P., Contrucci, I., Klingelhoefer, F., Mendes-Victor, L., Spakman, W., 2002. Evidence for active subduction beneath Gibraltar. *Geology*, **30**, 1071-1074.
- Hornbostel, S., 1991. Spatial prediction filtering in the t-x and f-x domain, *Geophysics*, **56**, 2019-2026.
- Kreemer, C., Holt, W. E., 2001. A no-net-rotation model of present day surface motions. *Geophysical Research Letters*, **28**, 23, 4407-4410.
- Kullberg, J. C., Pais, J., Manuppella, G., 1992. Aspectos gerais da tectónica alpina no Algarve. *Ciências da Terra*, Lisboa, **11**, 293-302.
- Manuppella, G., 1992. Carta Geológica da Região do Algarve, escala 1/100 000, Notícia Explicativa. *Serv. Geol. Port.*, Lisboa, 15.
- Manuppella, G., Ramalho, M., Telles Antunes, M., Pais, J. (2007). Notícia explicativa da Folha 53-A (Faro), na escala 1/50 000. *Serv. Geol. Port.*, Lisboa, 52.
- Moura, D., Boski, T., 1999. Unidades litostratigráficas do Pliocénico e Plistocénico no Algarve. *Comunicações do Instituto Geológico e Mineiro*, **86**, 85-106.
- Nocquet, J.-M., Calais, E., 2004. Geodetic measurements of crustal deformation in the Western Mediterranean and Europe. *Pure and Applied Geophysics*, **161**, 661-681.
- Noiva, J., 2009. Caracterização de estruturas tectónicas activas da região sul de Portugal com recurso a ferramentas SIG: o caso da falha de São Marcos-Quarteira. *Unpublished MSc Thesis*, Universidade Nova de Lisboa, 98.
- Pais, J., 1982. O Miocénico do Litoral sul Português. Ensaio de Síntese. *Estudo Complementar para obtenção do grau de Doutor*, Universidade Nova de Lisboa, Lisboa, 47.
- Pais, J., Legoinha, P., Elderfield, H., Sousa, L., Esteves, M., 2000. The Neogene of Algarve (Portugal). *Ciências da Terra*, Lisboa, **14**, 277-288.
- Ressurreição, R., 2009. Estudos de Neotectónica na falha de Carcavai (Algarve): contribuição para a caracterização desta estrutura e de paleossismos prováveis associados. *Unpublished MSc Thesis*, Faculdade de Ciências da Universidade de Lisboa, 121.
- Ressurreição, R., Cabral, J., Dias, R., 2009. Estudos de Neotectónica na falha de Carcavai (Algarve): evidências de deformação em sedimentos plio-quaternários. In: Boski, T.; Moura, D.; Gomes, A. (Eds), *Livro de Resumos, VII Reunião do Quaternário Ibérico, CIMA*, Faro, 59-62.
- Ribeiro, A., 2002. *Soft Plate and Impact Tectonics*. Springer-Verlag, Berlin, 336.
- Ribeiro, A., Cabral, J., Baptista, R., Matias, L., 1996. Stress pattern in Portugal mainland and the adjacent Atlantic region, West Iberia. *Tectonics*, **15**, 2, 641-659.
- Rosas, F. M., Duarte, J. C., Terrinha, P., Valadares, V., Matias, L., 2009. Morphotectonic characterization of major bathymetric lineaments in Gulf of Cadiz (Africa-Iberia plate boundary): Insights from analogue modeling experiments. *Marine Geology*, **261**, 1-4, 33-47.

- Sella, G., Dixon, T., Mao, A., 2002. REVEL: a model for Recent plate velocities from space geodesy. *Journal of Geophysical Research*, **107**, 30.
- Sillard, P., Altamimi, Z., Boucher, C., 1998. The ITRF96 realization and its associated velocity field. *Geophysical Research Letters*, **25** (17), 3223-3226.
- Stich, D., Serpelloni, E., Mancilla, F.L., Morales, J., 2006. Kinematics of the Iberia-Maghreb plate contact from seismic moment tensors and GPS observations. *Tectonophysics*, **426**, 295-317.
- Terrinha, P. A. G., 1998. Structural Geology and Tectonic Evolution of the Algarve Basin, South Portugal. *Unpublished PhD Thesis*, Imperial College, London, 430.
- Terrinha, P., Matias, L., Vicente, J., Duarte, J., Luís, J., Pinheiro, L., Lourenço, N., Diez, S., Rosas, F., Magalhães, V., Valadares, V., Zitellini, N., Roque, C., Mendes-Victor, L., MATESPRO Team, 2009. Morphotectonics and strain partitioning at the Iberia-Africa plate boundary from multibeam and seismic reflection data, *Marine Geology*, **267**, 3-4, 156-174.
- Yilmaz, Ö., 2001. *Seismic Data Analysis*. Society of Exploration Geophysicists, Tulsa, **II**, 10, 2027.
- Zitellini, N., Gràcia, E., Matias, L., Terrinha, P., Abreu, M.A., DeAlteriis, G., Henriot, J.P., Dañobeitia, J. J., Masson, D.G., Mulder, T., Ramella, R., Somoza, L., Diez, S., 2009. The quest for the Africa-Eurasia plate boundary west of the Strait of Gibraltar, *Earth and Planetary Science Letters*, 28.