

Neotectonic structures affecting Plio-Pleistocene sediments in Boliqueime and Quarteira areas

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Introduction. Regional geological setting

The Algarve region, the southernmost area of the Portuguese mainland, is located close to the Azores-Gibraltar plate boundary, which extends from the Azores islands to the Gulf of Cadiz. This tectonic setting explains the regional seismicity and the neotectonic activity, evidenced by numerous earthquakes and by Pliocene to Pleistocene deformation (Dias, 2001, Dias and Cabral, 2000, 2002a,b). The earthquake activity comprises important historical and instrumental events located at the northern edge of a wide belt of seismicity that extends approximately from the Gorringe submarine ridge (SW of Algarve) to the Straits of Gibraltar (Fig. 1). Large historical earthquakes have occurred in the Atlantic SW of Algarve, as the 1755 “Lisbon earthquake” (estimated MW= 8.7), in an area that also experiences important instrumental seismicity. Significant seismic activity also occurs near the littoral and onshore, including some historical events that have caused substantial damage, as in Portimão (1719, IMM max. IX), Tavira (1722, IMM max. X), and Loulé-Tavira (1856, IMM max. VIII), and scattered low magnitude instrumental seismicity (Carrilho, 2005).

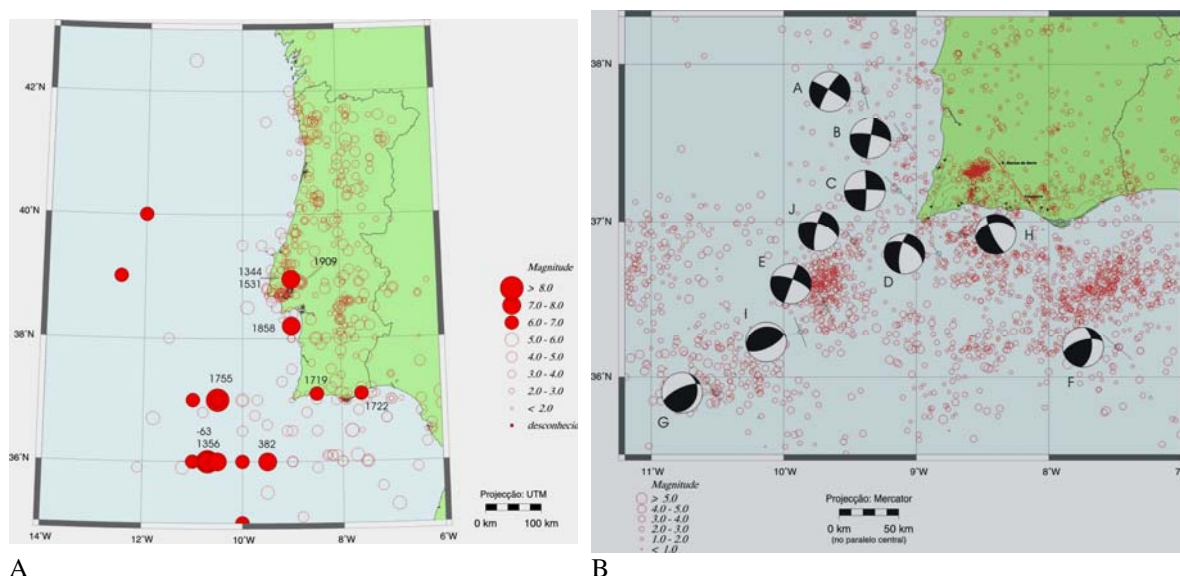


Fig. 1 – A, Historical and instrumental seismicity in mainland Portugal, 63 BC – 1960 AD; B, recent instrumental seismicity in the Algarve region (IM bulletins, 1995-2003) and focal mechanisms with horizontal projection of P axes (Carrilho, 2005); S. Marcos-Quarteira fault in red.

The regional neotectonic activity – intended as the tectonic activity from the upper Pliocene to the Present, is evidenced by vertical crustal movements at the regional scale, a few structures with (rather subtle) geomorphic expression, and by structures at the outcrop scale affecting Pliocene-Pleistocene sediments (Figs. 2 and 3) (Dias and Cabral, 2000; Dias, 2001) These comprise brittle deformation structures (including several faults and a large number of joints), ductile deformation structures (represented by folds) and soft sediment deformation structures. There is however a large uncertainty in the age of the Pliocene and younger sediments used as references for characterizing most of the neotectonic structures, due to the lack of fossils and other datable material, the recurrence of facies and the discontinuous outcrop pattern which makes stratigraphical correlations often difficult.

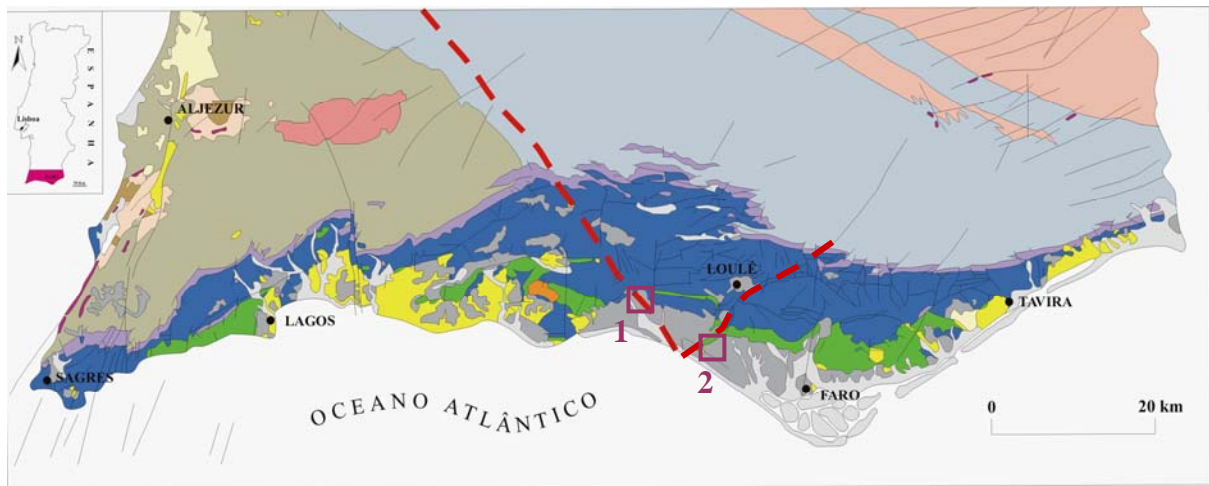


Fig. 2 – Regional geological setting; dashed lines, S. Marcos-Quarteira and Carcavai fault zones (adapted from Dias, 2001); 1, Fonte de Boliqueime area, first stop; 2, Ferrarias area, second stop.

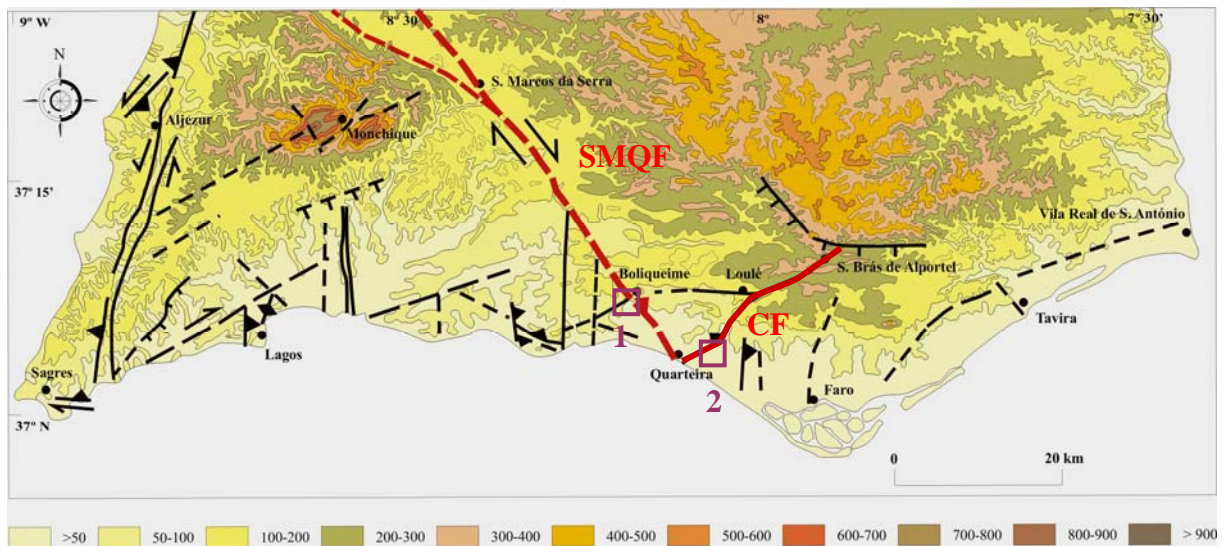


Fig. 3 - Map of the main active faults identified in the Algarve Region and the regional hypsometry (Adapted from Dias, 2001); SMQF, S. Marcos Quarteira fault; CF, Carcavai fault. 1, Fonte de Boliqueime area, first stop; 2, Ferrarias area, second stop.

Vertical movements of the crust are evidenced by the presence of an E-W elongated relief, 100 km long (the “Serra Algarvia”), which decomposes into two bulges: the Monchique mountain (903 m in the Foia) and the Caldeirão mountain (589 m in Pelados), separated by a NW-SE elongated fault controlled depression (S. Marcos - Quarteira fault) (Fig. 3). This relief evolved from an uplifted polygenetic erosion surface cut mainly on the Variscan basement, which was last retouched in the (Late?) Pliocene to Quaternary (Dias and Cabral, 1997, 2000, 2002b; Dias, 2001).

Brittle deformation structures that have been observed affecting the Pliocene to Quaternary cover sediments are characterized by a great number of outcropping fractures. These have diversified orientations and kinematics, evidencing reverse, normal and strike-slip offsets, although reverse fault geometry is predominant. In addition to these faults, an intense fracturing of indeterminate kinematics (probably corresponding mostly to joints) was observed in distinct areas, showing a heterogeneous spatial distribution. These fractures are generally almost vertical, with a large dispersion in trend. Ductile deformation structures affecting the Pliocene to Quaternary cover sediments are represented by folds at the mesoscopic scale.

Many of these folds and fractures (faults and joints) have been interpreted as non-tectonic but resulting from the evolution of an underlying cryptokarst developed on Miocene and Mesozoic limestone basement rocks, mainly in the areas where the fracturing shows larger scattering and smaller offsets (Dias and Cabral, 2002a; Dias, 2001). Effectively, the spatial distribution of the fractures is heterogeneous. In some places the cover sediments are strongly fractured along relatively confined zones located nearby or on the prolongation of hidden regional structures and this fracturing is thus interpreted as a distributed surface expression of active structures in the underlying Miocene and Mesozoic basement rocks. However, in other areas the Pliocene-Pleistocene

sediments present a scattered fracture pattern which can hardly be related to any hidden underlying tectonic structure, and that probably results, in most cases, from the underground evolution of the karst morphology that the cover sediments fill up.

When the interaction between the fractures affecting the sedimentary cover and the Miocene or Mesozoic underlying limestones could not be directly observed at the outcrop, two criteria were used in order to infer a non-tectonic origin: a) geographical dispersal, concerning fractures lacking a clear relationship to known regional active structures; b) directional scattering. It is expected that the fracturing on the cover sediments that is triggered by the solution of underlying limestones presents dip-slip normal fault geometry at the upper level. However, many fractures with reverse fault geometry were also observed, that are explained by the following mechanisms: a) fault plane rotation by the continuing sediments subsidence; in this process, early generated sub-vertical fractures rotate as the karst pit infill subsides; b) imposed geometric control by upwards fault propagation from nearly vertical to overhanging cavity walls; c) extensional faulting of sheared steeply dipping sedimentary layers that line sub-vertical cavity walls (Riedel type shears); d) pervasive sediment failure in response to stretching induced by the lowering of the cavity floor.



Fig. 4 – Karst pit in Miocene limestones filled with intensely deformed Pliocene sands, at Praia da Rocha beach, Portimão.

Soft sediment deformation structures due to liquefaction resulting from palaeoearthquakes (palaeoseismites) have also been identified in several areas, consisting in convolute folding of sandstone and conglomerate layers, fractures filled with collapsed sediments due to sudden opening (neptunian dikes), and detrital dikes (Rodríguez-Pascua, 1998; Dias and Cabral, 2000a; Dias, 2001). These structures may result from ground motions related to strong distant earthquakes, but the proximity of many of the seismites to known faults suggests a relationship to moderate to high magnitude ($M \geq 5.5$) events generated by these faults. This pattern is compatible with the regional seismicity although some of the palaeoseismites point to a higher level of local earthquakes magnitude (Dias & Cabral, 2000a, Dias, 2001).

The S. Marcos Quarteira and Carcavai fault zones

In this field trip we intend to show some aspects of tectonic structures and palaeoseismites that affect Pliocene to Quaternary sediments outcropping in the central Algarve region and that are probably related to tectonic activity of the S. Marcos-Quarteira and Carcavai (Loulé) faults (Figs. 2, 3 and 5).

The S. Marcos-Quarteira fault is a NW-SE trending structure that extends from S. Marcos da Serra, at the N, to Quarteira, at the S, along approximately 40km, probably prolonging to the immersed area. It is a major regional tectonic structure inherited from the Variscan Orogeny, which controlled the evolution of the Algarve transtensional basin during the Mesozoic, separating it in two blocks that evolved differently. It was reactivated during Cenozoic tectonic phases and, since the Neogene, it controlled the evolution of the regional landscape, namely of the Serra de Monchique and Serra do Caldeirão mountains, located West and East of the fault, respectively (Figs 1 and 2).

Although relatively evident on satellite imagery, it is difficult to recognize and follow the fault trace on the ground, generally evidencing deformation distributed over a wide zone. It was reactivated in the Plio-

Quaternary, probably as a predominantly right lateral (?) strike slip fault zone. Though there aren't any known major related earthquakes, the S. Marcos-Quarteira fault shows some control on the regional seismicity pattern, evidencing some aligned epicenters and apparently working as the NE boundary of an area of higher seismicity at the SW (Fig.1). The neotectonic activity of the S.Marcos-Quarteira fault is better evidenced in the Boliqueime area, where will be the first field trip stop. Details are described below.

The Carcavai fault zone is a NE-SW structure that passes near Loulé (Figs. 2, 3 and 5) affecting mostly sediments of the Mesozoic Algarve Basin. Field studies taken on the Carcavai fault zone revealed several deformational features on Plio-Quaternary sediments with potential neotectonic implications (Dias, 2001, Ressurreição, 2009). These features include fracturing and clastic dikes, located along this structure.

The dikes were previously interpreted as seismically induced liquefaction features, although they consist in atypical forms, of a fine grained body of sediment intruding sands. The pattern of abundance and strike, as well as evidences of upwards direction of transport of sediments support this interpretation. Most of the fractures seem to be the expression of the fault activity on the Plio-Quaternary sediments. This is suggested by a consistent strike pattern, subparallel to the major structure, and location pattern. The data and regional geological setting point to a left-lateral strike-slip fault with an increasing thrust component, from late Mesozoic/early Cenozoic times to the Present.

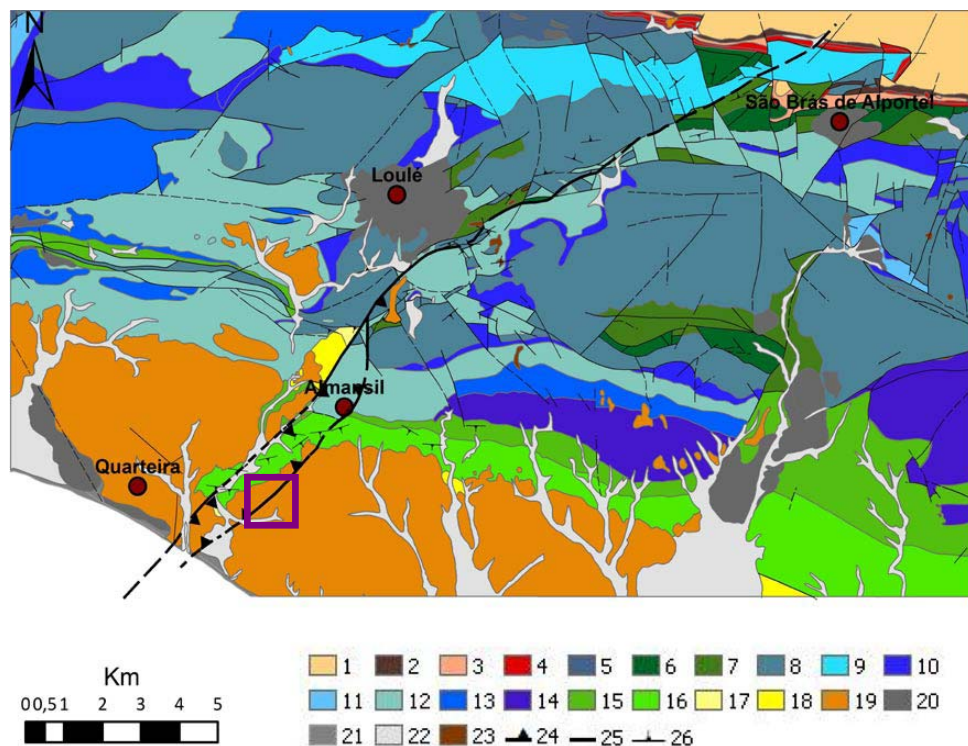


Fig.5 – Probable fault trace of the Carcavai fault. Geological map adapted from Manuppella *et al.* (1992 e 2007). 1, Paleozoic; 2, Triassic; 3 to 14, Jurassic; 15 and 16, Cretaceous; 17 and 18, Miocene; 19, Plio-Quaternary; 20 to 22, Quaternary; 23, Volcanic rocks; 24, Fault with reverse component; 25, Fault with strike slip component; 26, Bedding (after Ressurreição, 2009). Square, Ferrarias area, second stop.

First stop: Neotectonic structures related to the S. Marcos-Quarteira fault at the Boliqueime area

As stated above, the neotectonic activity of the S.Marcos-Quarteira fault is better evidenced near Fonte de Boliqueime, along an area of approximately 4 km², where related deformation has been recognized affecting several sedimentary units of probable Pliocene and Quaternary age, namely the “Falésia Sands”, the “Boliqeime Sands” and the “Barrancosa Sands” (Figs. 2, 3 and 6).

The “Boliqeime Sands” unit corresponds to an informal sedimentary unit composed of brownish detrital siliciclastic sediments, with yellowish and pinkish beds, over 15m thick. They comprise a sequence of alternating thin (centimetric to decimetric) beds of fine sand, silt and clay, with some interbedded pebble layers, and present calcareous crust, testifying a fluvio-lacustrine palaeoenvironment. They reach a maximum height of 70m and overlay a preexistent paleorelief. A Pleistocene age is attributed based upon the stratigraphical distribution of the identified ostracode species. They comprise 19 limnic species, being 2 exclusively fossil.

Most of the species that were identified have a Pleistocene-Holocene age, though 5 have a wider time distribution (middle Oligocene, Miocene and Pliocene). The coexistence of all the species, the presence of *Vestalenula pagliolii*, and the good preservation, points to a Pleistocene age (Cabral et al., 2003, 2005).

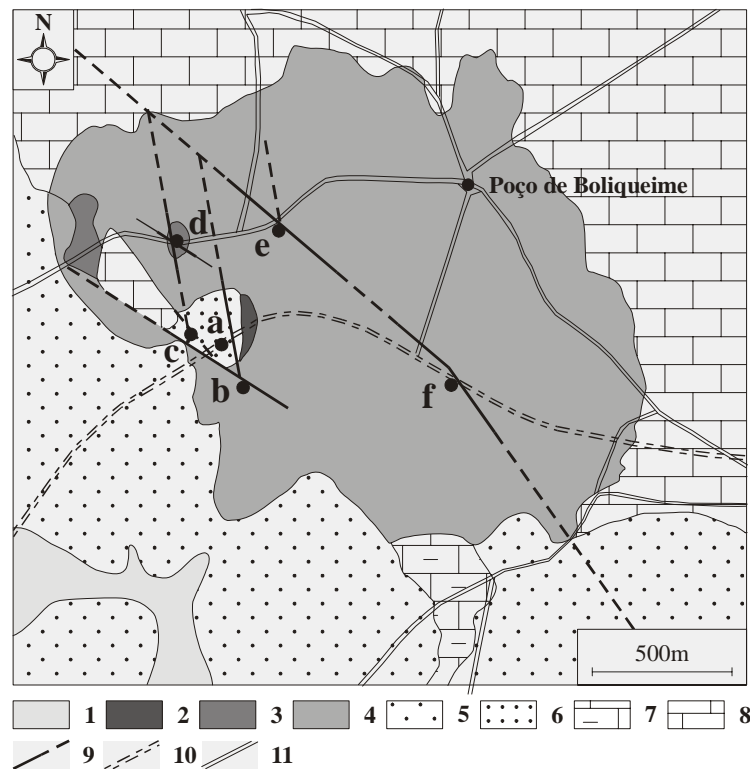


Fig. 6 - Location map (see regional location in Figs. 2 and 3). 1, alluvium; 2, fluvial terrace deposits; 3, Barrancosa Sands; 4, Boliquireime Sands; 5, Faro-Quarteira Sands; 6, Falésia Sands; 7, Miocene limestones; 8, Jurassic limestones; 9, fault and probable fault; 10, railway; 11, road.

The “Boliquireime Sands” unit overlays Jurassic limestones at the N and E, Miocene limestones at the S, and siliciclastic Pliocene sediments of the “Faro-Quarteira Sands” and of the “Falésia Sands”, at the S and the W. Locally overlaying the “Boliquireime Sands” occurs a sandy, reddish unit named “Barrancosa Sands”. A younger gravelly unit outcrops encased both on the “Boliquireime Sands” and the “Barrancosa Sands”, probably consisting of a fluvial terrace deposit of the Quarteira creek.

Barrancosa railway outcrop

At the railway near Barrancosa (Fig. 6-a, Fig. 7) the cover sediments are well exposed and the outcrops evidence a steep faulted contact between the “Boliquireime Sands”, at the W, and the “Falésia Sands” at the E (F1 on Fig. 8). The fault trends (N55W, 78SW), with striae pointing to nearly dip slip normal movement. W of the fault the “Boliquireime Sands” dip towards the SW: they trend (N55W, 88SW) near the fault, and (N57W, 25SW) 40m distant (bottom panel, Fig. 8). E of the fault, the “Falésia Sands” trend (N35W, 17NE) and increase their dip towards the E (top panel, Fig. 8).

Several minor faults affect these sediments, trending N-S to N50°W, and dipping predominantly to the W, producing centimetric vertical offsets on the bedding (maximum of 25cm) (F2-F6, top panel, Fig.8). The geometrical relationship with the bedding suggests that these faults were generated primarily as normal faults and were later rotated by the eastwards tilting of the sediments. The upper stereonet plot in Fig. 8 shows F1 and the minor faults (F2-F6), and the lower stereonet plot shows only the minor faults (F2-F6), rotated to remove the effect of the eastwards tilting of sediments that likely postdated faulting. These minor faults are sealed by the youngest, pebbly unit (Fig. 8), consisting probably of a fluvial terrace of the Quarteira creek (T, top panel, Fig. 8). S of the railway the “Boliquireime Sands” dip towards SW suggesting that the main fault continues southwards (Fig. 6).



Fig 7 – Barrancosa railway outcrop, northwestern side.

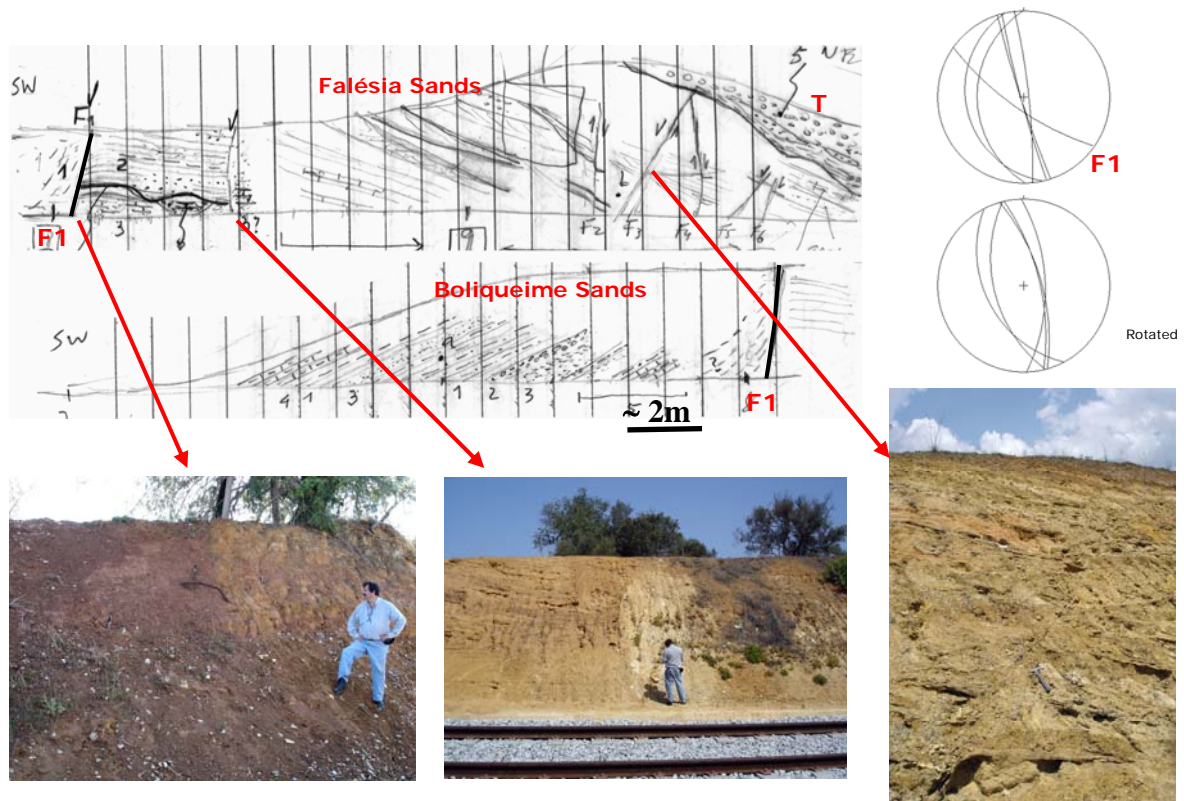


Fig 8 - Railway outcrop; interpretative sketch and photos.

Boliqeime National Road EN-125 outcrop

One of the most interesting fault outcrops can be observed at the EN-125 road-cut near Fonte de Boliqeime (km 79,5 Fig. 6-e), where Pleistocene sediments are intensely deformed, as shown in Fig. 9. The deformed sediments correspond to the “Boliqeime Sands” unit, comprising sandstones, pelitic and lacustrine marly layers, with interbedded conglomerates. As referred above, these sediments probably correspond to a fluvio-lacustrine palaeoenvironment, and have been dated as Pleistocene by their content of several ostracode species (Cabral et al., 2003, 2005). Besides being affected by faults, the detrital deposits are folded and in certain areas show convolute bedding suggesting liquefaction and fluidization of water saturated sediments, which produced fluid escape structures, probably during Magnitude >7 earthquakes (Dias, 2001).

Despite the absence of clear kinematic indicators, the geometry of the main faulted contact (N55°W, 80-85°SW) suggests the occurrence of strike-slip movement (Fig. 9). The presence of several low angle, SW verging, reverse faults immediately to the NE (Fig. 9) may be explained by strain partitioning in a right lateral transpressive regime. The small size of the folding and the low dip of the reverse faults, which activated bedding surfaces, point to the presence of a very shallow decollement rooted immediately to the E.

Attending to the location and strike, these meso-scale faults are interpreted to be correlative to the S. Marcos-Quarteira fault zone, possibly reflecting local compression at a restraining bend of the NW-SE trending right-lateral strike-slip fault (Fig. 3).



Fig. 9 - Deformed “Boliqueime Sands” at the EN 125 road outcrop

Second step: Neotectonic structures related to the Carcavai fault near Ferrarias

Ferrarias (near Quarteira; Figs. 3 and 5) is located close to the eastern branch of the NE-SW trending Carcavai fault (Fig. 5). Neotectonic activity in this area is indicated by a zone of disturbed sediments of the “Faro-Quarteira Sands” unit of late Pliocene age, composed of siliciclastic reddish sandstones and conglomerates, which shows several intrusions of intensely deformed silt and clay. The presence of the detrital dykes is not conclusive as palaeoseismicity evidence, because they can result from the infilling of opened fractures by sediments, or bioturbation. However, the downwards increase in thickness of several of the detrital dykes, the presence of striated surfaces in the dike walls and particle alignment in the intruded material, as well as vertical offsets observed in a few cases (Fig. 10) suggest that the fine materials were intruded through predominantly opening mode-mode fractures, after a process of liquefaction and lateral spreading associated to seismic events of moderate to large magnitude (Dias and Cabral, 2000; Dias, 2001; Ressurreição, 2009).

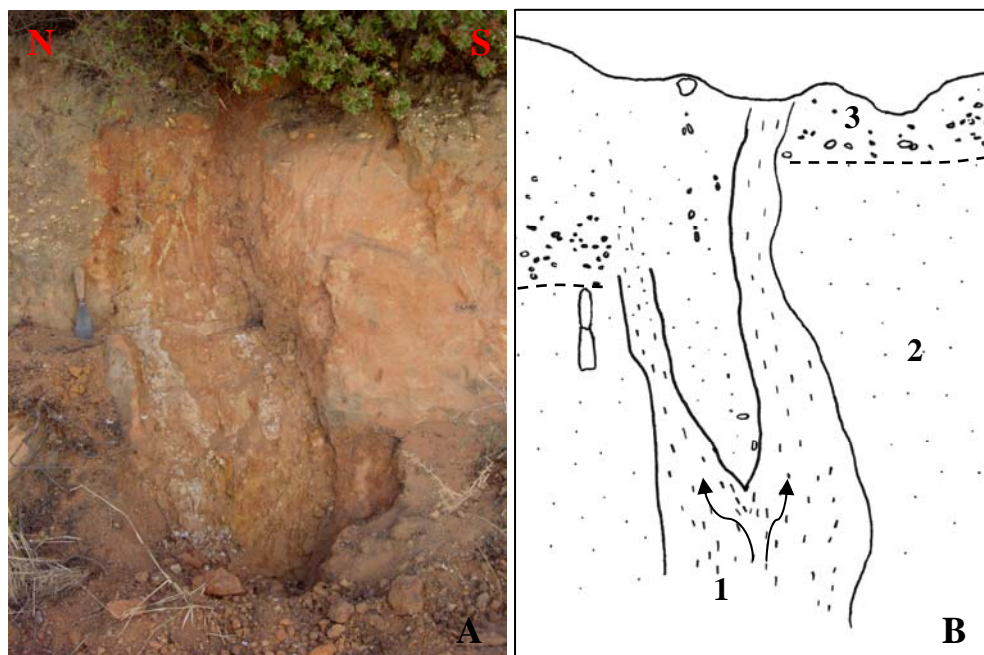


Fig. 10 - Example of a detrital dike intruding sediments of the “Faro-Quateira Sands” unit at Ferrarias. The dike trends (N45°E, 90°SE) and produces a vertical offset of approximately 30cm on a pebbly layer.

A few thin dikes appear to exploit small faults evidencing reverse movement component, which trend subparallel to the Carcavai fault (Fig. 11).



Fig.11 - Example of thin detrital dikes intruding fractures evidencing a reverse dip slip movement component. The dike at the right side (NW) is 4cm thick and trends (N65°E, 68°N); together with a nearby fault, trending (N45°E, 66°NW), they produce an offset of 1.30m on a pebbly layer (85 and 45cm respectively). The dike at the left trends (N30°E, 40°N) and displaces the pebble layer with a dip offset of 50cm.

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