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SCIENCE

Central Algarve karst system tufa-related dynamics, Portugal

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ABSTRACT

Geomorphological mapping is a powerful instrument improving the geomorphological interpretation and understanding of the processes and forms used in landscape studies, with the ability of organizing different thematic layers in the same map. The presented map provide relevant information about the different geomorphological units of the central Algarve (i.e. the Carboniferous flysch mountains; the Barrocal, with marly and karstified subunits), where a karst system is prominent. Solution karst morphologies and large dry areas are common in the elevated areas of the Barrocal, suggesting deep circulation of groundwater. These recharge areas feed the perched aquifers of the area, where discharge is controlled by the impervious lithologies (clay-rich strata of the turbidites, marls and argilites) in the valley bottoms or other leaks in dammed aquifers. In springs related to the main aquifers tufa are actively being formed and, close coupled to spring location, different tufa depositional systems develop.

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Karst; carbonate tufa; travertine; geomorphological mapping; Algarve; Portugal

1. Introduction

Geomorphological mapping aims to present a balanced representation of Earth surface processes, with information arranged by relevance according to the generally accepted graphic semiology that enhances the analyzed processes. Geographic information systems (GIS) significantly aid the process of data processing and management (Griffiths, Smith, & Paron, 2011).

This map aims to represent the main geomorphological elements of the central Algarve, relevant to the interpretation of the karst of the *Barrocal* (Portuguese noun formed from *barro* – mud – and *cal* – lime). The karst geomorphology is exposed under the geological, hydrological and geomorphological constraints, expressing the distribution and patterns of the studied landforms (Cunha, 1988; Ford & Williams, 2007; Guerreiro, 2015).

Karst landscape is characterized by deep groundwater circulation, developed as a consequence of the solution of limestone, dolomitic limestone and evaporitic terrains (Cunha, 1988; Ford & Williams, 2007). Consequently, in these areas the epikarst is dry and characterized by the development of solution morphologies that promote an extensive and fast infiltration of the meteoric water in the form of karren, dolines, polja, swallow holes and caves – these promote effective deep circulation. In contrast, lower borders of karst terrains and areas of high phreatic level present discharge points – karst springs and ponor – often related to the precipitation of carbonate tufa due to epiphreatic CO_2 losses (Guerreiro, 2015).

Geomorphological information is important for hydrogeomorphological research in karst areas, since the karst geomorphology is central to understanding the hydrogeological systems. It can contribute to a determination of the presence of lithologies and their landscape settings, that control the recharge (e.g. soluble lithologies in high areas), flow (e.g. confined aquifers, tectono-karst corridors) and discharge areas (e.g. valleys intersecting soluble lithologies and carbonate tufa deposits) of the karst aquifers.

This technique is a useful tool not only for geomorphological and hydrogeological research but also for land planning and land use management (e.g. preventing aquifer contamination and overexploitation).

The main objectives of the map *Geomorphology of the Central Algarve* (Main Map), *Portugal* are to: (1) define the diversity and extent of the geomorphology; (2) locate carbonate tufas and the recharge/discharge areas of the hydrogeomorphological system; (3) identify the relationship between lithologies and the distribution of karst morphology; (4) establish the main denudation surfaces of the Central Algarve and (5) recognize the structural morphology and the influence of neotectonic activity.

2. Methods

Geomorphological map production requires the combination of different methods and data sources, that can be summarized by the following steps: (*i*) interpretation of stereoscopic aerial-photos at the scale of 1:15 000

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(films 85.36 and 85.18 from 1985; and film 86.13 from 1986; both from the *Instituto Geográfico Português*) supported by the use of aerial and satellite images available on *Google Earth* and the digital elevation model (DEM) produced from 1:25,000 national topographic maps with a 10 m contour interval (*Carta Militar de Portugal*, sheets number 597, 598, 606 and 607) and (*ii*) landforms were digitized using *Esri ArcGIS 10.1* using the DEM.

The data were used for the construction of the base map where the main landforms such as valleys, lineaments and the extent of denudation surfaces were represented. Minor landforms, such as dolines, caves, carbonate tufa outcrops and corrosion surfaces, were identified during field surveys and later added to the map.

The symbols, mainly adapted from CNRS (1970), Joly (1997) and Gustavsson, Kolstrup, and Seijmonsbergen (2006), were chosen respecting the hierarchy of the different levels of information gathered. The different elements were represented according to the morphogenesis of erosional landforms (both fluvial – blue – and karst – orange –), depositional landforms (both fluvial – blue – and fluvio-karst/carbonate tufa – green – and dynamic fluvial processes – blue, or green for incrusting springs and streams –); the morphography and morphometry (brown); deformational structure (pink); lithology (color dependent on the stratigraphic age); hydrogeology (white to pale gray) and toponyms and anthropic morphology (dark gray to black) (Table 1).

The geological information used on the geomorphological map was derived from Manuppella (1992) and Manuppella et al. (2006); the data present on the Geology of the Algarve are adapted from the Lithological Map (1982) available on the *Atlas do Ambiente* ({http://sniamb.apambiente.pt/}) and from Dias (2001), Dias and Cabral (2002) and Terrinha et al. (2013).

3. Geology and Geology of the Central Algarve

The Algarve comprises two main geological units (Feio, 1952, 2004): the Carboniferous meta-sedimentary formations of the South Portuguese Zone outcropping in the north; and the Mesozoic and Cenozoic sedimentary sequences of the Algarve basin outcrop in the south (Ribeiro, 2013; Terrinha et al., 2013). The lithological differences and the active erosional processes influenced the evolution of three different geomorphological units: the Serra (Mountains) mainly developed in Carboniferous turbidites; the Barrocal (Mud and Lime) developed essentially in the Mesozoic marls, limestones and dolostones; and the Litoral (Littoral) corresponding broadly to the Cenozoic sedimentary packages (Feio, 1952, 2004) (*Hypsometry of the Algarve* and *Geology of the Algarve* inset maps of the Main Map).

The study area is close to the Nubian-Eurasia plate tectonic boundary, where activity is responsible for the vertical movements, subsidence and tectonic inversion affecting the Algarve since the Triassic, up until the Quaternary (Carvalho et al., 2012; Terrinha et al., 2013). The formations outcropping in the area are deformed by these movements, illustrated by the E–W folding, the frequent faulting and the irregular distribution of different lithologies, leading to diverse hydrogeological conditions in the neighboring terrains and a complex karst system (Figure 1).

The region presents up to six denudational stages above 60 m of altitude, deformed by tectonic and halokinetic processes. These processes promoted the development of stepped denudation surfaces, such as the top surface (roughly developed at Caldeirão Mountain at 350 and 500 m – Figure 2) and the intermediate surface (roughly developed at the Loulé – 200 to 220 m – and the São Brás de Alportel – 240–260 m areas). The surfaces are both southward sloping, often eroded by hydrologic and karst processes related to quaternary climate and eustatic changes (Feio, 1952, 2004; Terrinha et al., 2013).

The highest surface located at ~500 m of altitude on the Caldeirão mountain tops (top surface), and its southern limit is defined by an E–W fault near Alportel stream and a NW–SE fault (outside the map limits) (Feio, 2004). In the study area, the surface was lowered by tectonic movement, with tops at 350 m extending through the Mesozoic terrain.

The intermediate surface is divided to two major tectonic steps, represented at São Brás de Alportel ranging between 240 and 260 m of altitude, and at Loulé and Peral between 200 and 220 m. This surface is affected by the Carcavai and Machados faults, the former with recognized neotectonic activity (Carvalho et al., 2012; Dias, 2001; Ressurreição, 2009; Ressurreição, Cabral, Dias, Carvalho, & Pinto, 2011) (*Plain surfaces and tectonics scheme* support map of the Main Map).

Between 200 and 60 m of altitude the existing surfaces are developed on the southside of the first flexural relief, represented by flat fringes shaped at 150–160 m, 120–130 m, 80–90 m and 60–70 m of altitude.

Some planar levels can be found along the main streams of the area. However their relationship with the levels described above is not clear. Some of these plain surfaces are devoid of fluvial deposits and therefore they cannot be termed terraces.

Three streams with marked fluvial levels are represented in this map: the Seco River, the Algibre Stream and the Alportel Stream. The modern alluvium corresponds to the A level, and the older levels are organized from B to E. The most complex system is found on the Seco River, with five distinct levels present. The alluvium, filled with fluvial deposits and evidence of calcrete formation processes, is overlain by thin layers of carbonate cemented coarse calciclastic deposits. The E level represents the uppermost fluvial deposits, represented by a thick sequence of alluvial plain carbonate tufa (Figure 3).

Table 1. Thematic elements used on the geomorphological map.

	Symbology			Color	Information source				
Thematic layers	•	⊦	□		A	B	C	D	E
Morphogenetics									
Fluvio-karstic features	✓		✓	Orange			✓		✓
Deposition features			✓	Blue, green			✓		✓
Dynamic actors	✓	✓		Blue, green	✓				✓
Elevation									
Morphometry	✓	✓		Brown	✓				
Morphography		✓	✓	Yellow, brown	✓		✓		✓
Structure									
Tectonics and lithology	✓		✓	Red, gray		✓			
Strutural morphology		✓		Pink	✓	✓	✓	✓	
Other elements									
Toponymy and anthropic morphology	✓	✓	✓	Black	✓		✓	✓	✓

Notes: Symbology, • – points; ⊦ – polyline; □ – polygon; information source, A – 1/25 000 topographical maps; B – Geological maps 1/50 000 and 1/100 000; C – aerial photography; D – satellite imagery and E – field surveys and GPS.

Outcropping in the northern mountainous area, the Carboniferous basement is represented by high slope gradients – the steepest of the area – often above 20° (northern area of the slope gradient map). These friable and frequently impervious rocks (aquiclude) are easily eroded under the high drainage density (usually above 4 km/km^2, reaching 9.2 km/km^2).

The oldest lithologies of the Meso-Cenozoic basin are the easily friable Triassic sandstones and Lower Jurassic clays, evaporites and volcanic rocks (basalts and basic pyroclasts of the Central Atlantic Magmatic Province), outcropping along an E–W depression on the mountain edge and forming the main control on the hydrography of the area.

The karst developed on the Mesozoic limestone and dolostone is a landscape unit represented in the Main Map. The recharge areas of the karst aquifers are mostly located in the E–W relief of the Mesozoic folded sequences, where the karstified limestones and dolostones outcrop and promote deep circulation. The drainage density is usually low in the karst terrains (<2 km/km^2), in contrast with densities up to 6.5 km/km^2 on the marly terrains.

The karren, including giantkarren, and doline fields and swallow holes promote fast infiltration, feeding the aquifers and springs located in the valleys that cut the system of cascade-like perched aquifers (Figure 4(a) and 4(b)). This area is usually covered by xerophitic shrubland (maquis and garrigue) and bare rock.

Aquifer damming is the most common process for the origin of karst springs in the area, ensured by the presence of aquitard formations, such as the Olho de Paris and the Olho de Alfarrobeira springs. Some springs are related to the differences in the solubility

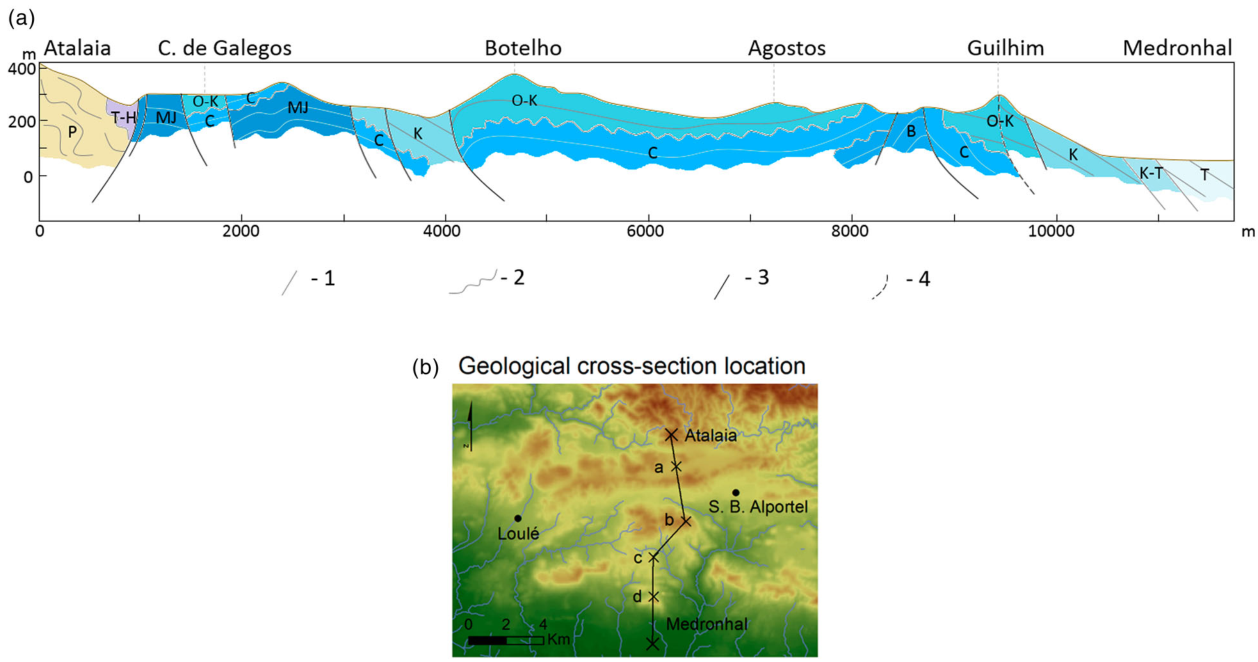

Figure 1. (a) N–S geological section found in the Guilhim-Campina de Galegos area (adapted from Manuppella (1992), Terrinha et al. (2002) and Ramos, Fernández, Terrinha, Muñoz, and Arnaiz (2015)). (b) Location map of the Figure 1 geological section. Notes: K-T – Kimmeridgian-Tithonian; K – Kimmeridgian; O-K – Oxfordian-Kimmeridgian; C – Callovian; B – Bathonian; MJ – Middle Jurassic (indiferentiated); T-H – Triassic-Hettangian; P – Paleozoic; 1 – lithology limit; 2 – angular discordance; 3 – fault; 4 – probable fault; a – Campina de Galegos; b – Botelho; c – Agostos; d – Guilhim.

Figure 2. Top surface of Caldeirão Mountain (~500 m of altitude) and lower block of the top surface (~350 m of altitude).

rate between karst lithologies (distinct limestone formations, or between lime and dolostone formations), such as the Olho da Várzea spring.

Despite the presence of important incrusting springs in the Alface area, the outcropping lithologies found in the adjacent high areas are mainly marls and marly limestones. This suggests an artesian connection between the Bathonian-Callovian formations in the Colmeal-Alface to others further north in the São Romão-Vilarinhos area, explaining the artesian incrusting springs found in Bordeira.

Knowledge of the geomorphological evolution of the karst regions is improved through analysis of carbonate tufa deposits that record climate variability, the chronology of incision periods and related environments (e.g. Vázquez-Urbez, Pardo, Arenas, and Sancho (2011) and García-García, Pla-Pueyo, Nieto, and Viseras (2014)).

The fluvial tufa deposits are associated with low gradient valleys or paleo-surfaces located south of the Algibre flexure, sometimes with cascades resulting from tufa accumulation in rocky areas or knick-points (Guerreiro, Cunha, & Ribeiro, 2011). The incrusting springs located on high gradient streams of low discharge promote the formation of perched springline tufa (Olho de Paris spring) or transition models (modern Alface tufa) (Guerreiro, Cunha, & Ribeiro, 2011). (Figure 4(c)).

The most representative karst depressions are the doline fields located at Campina de Galegos, Goldra–Gorjões, Santa Bárbara de Nexe (relict) and adjacent to the Fojo polje (Figure 4(d)). Despite the subterranean discharge of the Fojo polje it has been considered a doline (e.g. Crispim, 1982). This depression is developed in the limestone core of an

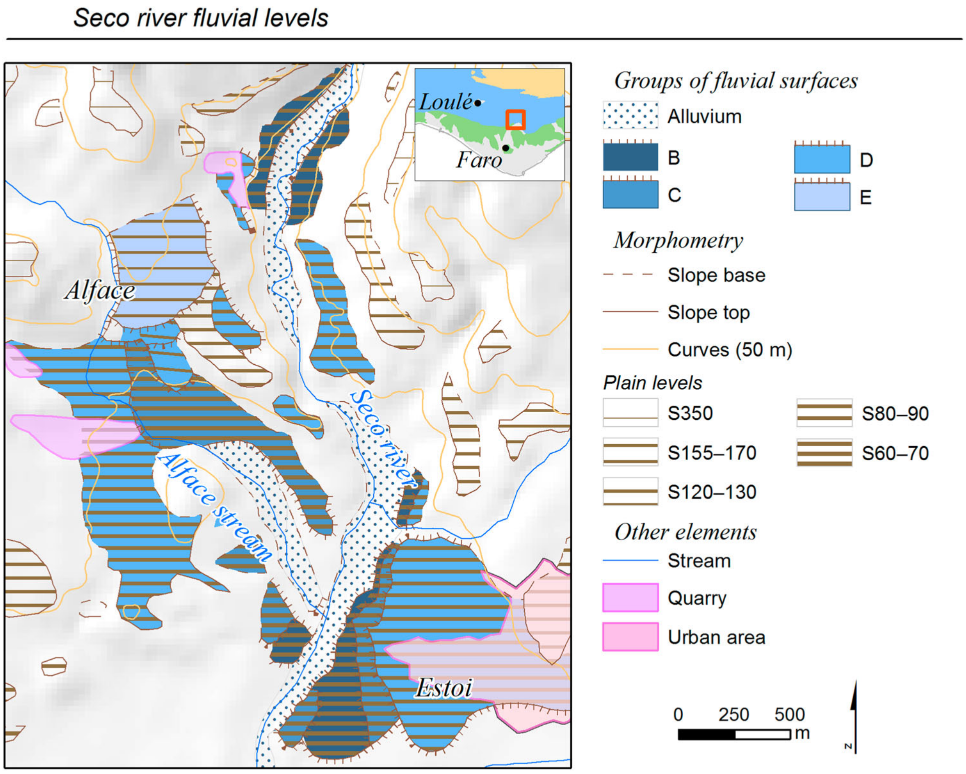

Figure 3. Seco river fluvial levels 210 × 150 mm (300 × 300 DPI).

Figure 4. (a) Malhada Velha giant karren; (b) Karren and solution fissures filled by terra rossa in the Peral quarries (beside the Fojo polje); (c) Paris spring carbonate tufa platform and tufa barrier; (d) Campina de Galegos paleo corrosion surface, nowadays a doline field. Notes: TB – Tufa barrier; TP – Tufa platform; DF – Campina de Galegos doline field.

anticline, covered by younger marls and marly limestones leading to its identification as a polje.

The Santa Bárbara de Nexe dolines are developed in the S80–90 surface. The southern limits is a limestone bar where chemical weathering is incipient. Nowadays, these dolines are degraded and the limestone bar cut by the fluvial erosion.

The biggest karst feature mapped is the Campina de Galegos-Almargens corrosion surface; it is at present under the influence of denudation processes, such as the mechanical weathering (riverine incision) and the chemical solution (karstification – dolines and karren) (Figure 4(d)). The denudation surfaces identified in high resolution stereoscopic analysis allowed the reconstitution of a paleosurface developed along the Mercês stream valley in the west and, probably, in the Carboniferous terrains in the north.

4. Conclusions

The geomorphological map of the Central Algarve has revealed a heterogeneous distribution of landforms, even within the Meso-Cenozoic outcrop of the Barrocal area, with important contrasts between the morphological features developed on the limestone and the marly terrains.

The use of the lithological base map contributes to a better understanding of the hydrogeological behavior of the area, and the location and functioning of the main basins, including the recharge and discharge areas, which are an important constraints on carbonate tufa distribution.

The carbonate tufa depositional systems are also dependent on the morphology of the substratum, especially on the geomorphological position of the spring and the adjacent streams. From the analysis of the geomorphological map it is clear that there is a relationship between slope and fluvial influence controlling carbonate deposition: perched springline carbonate tufas are found on the left margin of the Mercês stream where surficial drainage is poor and the longitudinal gradient of the stream is steep while at Cadouço and São Lourenço streams, with higher discharge and lower gradients, carbonate fluvial deposits produce tufa-related waterfalls.

Geomorphological studies of the central Algarve are still at an earlier stage, with most karst relief poorly described or unknown. The geomorphological map has assisted the geomorphological characterization, which enabled the identification and interpretation of karst structures and denudation surfaces.

Some structures become recognizable on the geomorphological map (e.g. Santa Bárbara de Nexe dolines), and alternative explanations for the tectonic sectioning or depression evolution was clarified (e.g. the S200–220Loulé and S240–260São Brás de Alportel denudation surfaces and the Fojo polje).

Software

This map was prepared using *Esri ArcGIS 10*, including the data editing and processing and map.

Disclosure statement

No potential conflict of interest was reported by the authors.

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References

Carvalho, J., Matias, H., Rabeh, T., Menezes, P. T. L., Barbosa, V. C. F., Dias, R., & Carrilho, F. (2012). Connecting onshore structures in the Algarve with the southern Portuguese continental margin: The Carcavai fault zone. *Tectonophysics*, *570–571*, 151–162.

CNRS. (1970). *Légende pour la carte géomorphologique de la France au 1/50 000* (Centre National de Recherche Scientifique. RCP 77). Paris: Editeur scientifique. 75 p.

Crispim, A. J. (1982). *Morfologia cársica do Algarve* (BSc scientific trainee report). Lisbon: Faculdade de Ciências da Universidade de Lisboa. 171 p.

Cunha, L. (1988). *As Serras Calcárias de Condeixa-Sicó-Alvaiázere – Estudo de Geomorfologia* (PhD thesis). Faculdade de Letras da Universidade de Coimbra, Coimbra. 329 p.

Dias, R. (2001). *Neotectónica da região do Algarve* (PhD thesis in Geology). Universidade de Lisboa, Lisbon, 369 p.

Dias, R., & Cabral, J. (2002). Neotectónica da região do Algarve. *Comunicações do Instituto Geológico e Mineiro*, *89*, 190–208.

Feio, M. (1952). *A Evolução do Relevo do Baixo Alentejo e Algarve* (PhD thesis in Geography). Faculdade de Letras da Universidade de Lisboa, Lisbon. 186 p.

Feio, M. (2004). Capítulo II – O Baixo Alentejo e as serras envolventes. In M. Feio & S. Daveau (Eds.), *O Relevo de Portugal – Grandes Unidades Regionais II* (pp. 21–32). Coimbra: Associação Portuguesa de Geomorfólogos.

Ford, D., & Williams, P. (2007). *Karst Hydrogeology and Geomorphology*. Wiltshire, UK: John Wiley & Sons. 562 p.

García-García, E., Pla-Pueyo, S., Nieto, L. M., & Viseras, C. (2014). Sedimentology of geomorphologically controlled Quaternary tufas in a valley in southern Spain. *Facies*, *60*, 53–72.

Griffiths, J. S., Smith, M. J., & Paron, P. (2011). Introduction to applied geomorphological mapping. *Developments in Earth Science Processes*, *15*, 3–11.

Guerreiro, P. (2015). *Tufos calcários no Algarve Central. Geomorfologia, sedimentologia e paleoambientes* (PhD thesis). Universidade de Coimbra, Coimbra.

Guerreiro, P., Cunha, L., & Ribeiro, C. (2011). Geomorphological settings and tufa models in Algibre flexure (Algarve, Portugal). *Rendiconti Online della Società Geologica Italiana*, *16*, 19–20. [Abbadia San Salvatore (Siena, Itália): International School of Travertine & Tufa.]

Gustavsson, M., Kolstrup, E., & Seijmonsbergen, A. C. (2006). A new symbol-and-GIS based detailed geomorphological mapping system: Renewal of a scientific discipline for understanding landscape development. *Geomorphology*, *77*, 90–111.

Instituto Geográfico do Exército. Cartas Militares de Portugal à escala 1:25 000 № 597, 598, 606, 607. 2005 and 2006 ed.

Joly, F. (1997). *Glossaire de Géomorphologie – Base de Donnés Sémiologiques pour la Cartographie*. Paris: Armand Colin. 324 p.

Manuppella, G. (1992). *Carta Geológica da Região do Algarve. Escala 1:100 000*. Lisboa: Serviços Geológicos de Portugal.

Manuppella, G., Bartolomeu, A., Rodrigues, A., Leal, J. G., Ramalho, M., Rocha, R., … Dias, R. P. (2006). *Carta Geológica de Portugal. 53-A (Faro). Escala 1:50 000*. Edited by G. Manuppella. Instituto Nacional de Engenharia, Tecnologia e Inovação, I. P., Departamento de Geologia. Ministério da Economia e da Inovação.

Ramos, A., Fernández, O., Terrinha, P., Muñoz, J., & Arnaiz, A. (2015, June 1–4). *On the nature of the Iberia-Africa boundary in the Gulf of Cadiz – Evidence for transpression and implications*. 77th EAGE Conference & Exhibition 2015, Madrid, 4 p.

Ressurreição, R. (2009). *Estudos de Neotectónica na Falha de Carcavai (Algarve): Contribuição para a Caracterização desta Estrutura e de Paleossismitos Prováveis Associados* (MSc thesis). Faculdade de Ciências da Universidade de Lisboa, Lisbon, 121 p.

Ressurreição, R., Cabral, J., Dias, R. P., Carvalho, J., & Pinto, C. (2011). Neotectonic activity on the Carcavai fault zone (Algarve, Portugal). *Comunicações Geológicas*, *98*, 5–14.

Ribeiro, A. (2013). Evolução geodinâmica de Portugal; os ciclos ante-mesozóicos. In R. Dias, A. Araújo, P. Terrinha, & J. C. Kullberg (Eds.), *Geologia de Portugal no contexto da Ibéria. Vol. I. Geologia Pré-mesozóica de Portugal* (pp. 15–57). Portugal: Escolar Editora.

Terrinha, P., Ribeiro, C., Kullberg, J. C., Lopes, C., Rocha, R., & Ribeiro, A. (2002). Compressive Episodes and Faunal

Isolation during Rifting, Southwest Iberia. *The Journal of Geology*, *110*, 101–113.

Terrinha, P., Rocha, R., Rey, J., Cachão, M., Moura, D., Roque, C., … Youbi, N. (2013). A Bacia do Algarve: estratigrafia, paleogeografia e tectónica. In R. Dias, A. Araújo, P. Terrinha, & J. C. Kullberg (Eds.), *Geologia de Portugal no contexto da Ibéria. Vol. 2. Geologia Meso-Cenozóica de Portugal* (pp. 29–166). Portugal: Escolar Editora.

Vázquez-Urbez, M., Pardo, G., Arenas, C., & Sancho, C. (2011). Fluvial diffluence episodes reflected in the Pleistocene tufa deposits of the river Piedra (Iberian range, NE Spain). *Geomorphology*, *125*, 1–10.