Research paper

# Identification and characterization of fluid escape structures (pockmarks) in the Estremadura Spur, West Iberian Margin

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D. Duarte [a], *, V.H. Magalhães [a, b], P. Terrinha [a, b], C. Ribeiro [c], P. Madureira [c, d], L.M. Pinheiro [e], O. Benazzouz [e], J.-H. Kim [f, g], H. Duarte [h]

[a] Portuguese Institute for the Sea and Atmosphere (IPMA), Marine Geology and Georesouces Division, 1749-077 Lisbon, Portugal
[b] Instituto Dom Luiz Associated Laboratory (IDL), Lisbon, Portugal
[c] Geosciences Department, School of Sciences and Technology, Évora University, Portugal
[d] Portuguese Task Group for the Extension of the Continental Shelf (EMEPC), Paço d'Arcos, Portugal
[e] Department of Gesciences and CESAM, University of Aveiro, Portugal
[f] Royal Institute for Sea Research, Department of Marine Microbiology and Biogeochemistry P.O. Box 59, NL-1790 AB Den Burg, The Netherlands
[g] Korea Polar Research Institute, 26 Songdomirae-ro, Yeonsu-gu, Incheon 21990, South Korea
[h] GeoSurveys Portugal—Consultants in Geophysics, Aveiro, Portugal

## ARTICLE INFO

## ABSTRACT

Located on the West Iberian margin, between Cabo Carvoeiro and Cabo da Roca, the Estremadura Spur is a trapezoidal promontory elongated in an east-west direction, extending until the Tore seamount. Recently a field with more than 70 pockmarks was discovered in the NW region of the Estremadura Spur outer shelf (Lourinhã Monocline). Pockmarks are the seabed culminations of fluid migration through the sedimentary column and their characteristic seabed morphologies correspond to cone-shaped circular or elliptical depressions. The characterization of these features and the understanding of the associated fluid escape process are the main objectives of this work. Here we characterize these structures to understand their structural and stratigraphic control based on: 1) Seismic processing and interpretation of the high resolution 2D single-channel sparker seismic dataset, 2) Bathymetric and Backscatter interpretation and 3) ROV direct observation of the seafloor.

The analysis of the seismic profiles allowed the identification of six seismic units, disturbed by the migration and accumulation of fluids. The Estremadura Spur outer shelf has been affected by several episodes of fluid migration and fluid escape during the Pliocene-Quaternary that are expressed by a vast number of seabed and buried pockmarks. At present, the pockmarks are mainly inactive, as the seabed pockmarks are covered by recent sediments. It is concluded that the migration of fluids to the seabed occurred over the Pliocene-Quaternary, as indicated by the buried pockmarks at different depths below the seabed. The vertical stacking of various pockmarks suggests a cyclical fluid flow activity that can possibly be the result of the eustatic sea level variations and the subsequent changes of the hydrostatic pressure.

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## 1. Introduction

Pockmarks are crater-like features found on the seabed with round to oval shape, steep flanks, and a relatively flat bottom. It is widely accepted that pockmark craters are the seabed expression of fluid migration pathways through the sedimentary column (Judd and Hovland, 2007). Cathles et al. (2010) suggest that these features form abruptly, when local accumulations of overpressured pore-fluids erupt through the surface sediments, and that they are thereafter maintained by slow pore-water and gas seepage. When the fluid migration ceases, the pockmarks are eventually buried by sediments. Although fluid flow is a common process in sedimentary basins of passive continental margins, fluid escape processes and structures have barely been reported in the West Iberia Margin (WIM).

The Estremadura Spur pockmarks field, detected during the acquisition of a seismic reflection sparker survey under the scope of the PACEMAKER project (Kim et al., 2016) is the first documented

evidence of fluid seepage in the Lusitanian Basin, a Mesozoic rifted basin containing promising hydrocarbon occurrences. The Estremadura Spur is an east-west elongated trapezoidal shape promontory, located on the West Iberian margin (between the Cabo Carvoeiro and the Cabo da Roca), extending offshore until the 500 m below sea level (bsl) bathymetric isoline (Fig. 1). Pockmarks in the WIM have only been reported in the Galicia Margin, approximately 300 km to the north (García-Gil et al., 2015).

Gas seepage has also been reported in estuarine and submarine deltaic environments of the Ria de Vigo (García-García et al., 2004, 2003, 1999; Judd and Hovland, 2007; Martínez-Carreño and García-Gil, 2013), the Aveiro Estuary (Duarte, 2009; Duarte et al., 2007), and in the Tagus submarine delta (Noiva et al., 2014). In the Gulf of Cadiz area that straddles across the Africa-Iberia transpressive plate boundary and Gibraltar arc subduction roll-back (Gutscher et al., 2012, 2002; Zitellini et al., 2009) various fluid migration structures have been found, such as, pockmarks, mud and salt diapirs and mud volcanoes (León et al., 2010; Magalhães, 2007; Magalhães et al., 2012; Pinheiro et al., 2003; Hensen et al., 2015). In this work we describe the pockmark field of the Estremadura Spur and discuss the fluid migration process, age and implications on the active tectonics of the WIM.

## 2. Geological setting

The Estremadura Spur is the morphologic expression of an East-West striking anticline pop-up structure formed during the Alpine orogeny in the Lusitanian Basin and WIM mostly in Miocene times (Fig. 1). The Estremadura Spur anticline extends offshore for more than 300 km from the coastline to abyssal depths and is topped by a polygenic erosive surface that corresponds to the edge of the continental shelf reaching atypical depths of 500 m bsl (Fig. 1). The northern boundary of the Estremadura Spur is the Nazaré canyon, associated to the Nazaré Fault, with a headscarp lying at 70 m bsl.

The Lusitanian Basin and WIM resulted from intra-continental rifting of Pangea in Triassic through Early Cretaceous times (Kullberg et al., 2013). The sedimentary record starts with continental siliciclastic deposits of Triassic-Hettagian age evolving to a sedimentation in a transitional environment. By the end of the Lower Jurassic the sedimentation in the basin is marine with the deposition of limestones and marls throughout the Middle and part of the Upper Jurassic. The Upper Jurassic-Lower Cretaceous sedimentation is siliciclastic and carbonated. The Cenomanian (marls topped by reef limestones) is topped by the Lisbon magmatic complex, the last of three magmatic events that occurred during rifting (Mata et al., 2015). The age of oceanic break up off the Estremadura Spur and the ocean-continental transition structure are still controversial but apparently occurred during Early Cretaceous times (Kullberg et al., 2013). During the Cenozoic the WIM was affected by periods of compression and tectonic inversion, forming folds and thrusts with approximate W-E orientation, related to the Alpine orogeny (Pyrenean and Betic events), resulting in the uplift of some regions of the margin, such as the Estremadura Spur. The peak of deformation, with maximum compression of NW-SE direction, occurred in the Late-Miocene (Cunha et al., 2012; Pais et al., 2012).

The study area lies within the Estremadura Spur where outcrops of folded Jurassic and Cretaceous are unconformably covered by Neogene units. The superficial part of the Neogene has been described as the Lourinhã Monocline consisting of ~40 m thick package of Pliocene and Quaternary age (Badagola et al., 2006).

The edge of the continental shelf of the Estremadura Spur is irregular as attested by the Nazaré canyon and has minor gullies on its edge. The continental shelf break lies at depths varying from approximately 140 m—400 m bsl, which is interpreted as a result of Pliocene-Quaternary differential tectonic movements across faults (Badagola et al., 2006). Pliocene-Quaternary movements have also been reported on the nearby coast associated to deformation of salt diapirs (Benedetti et al., 2009). Previous published works on the morphology and tectonics of the continental shelf of central and
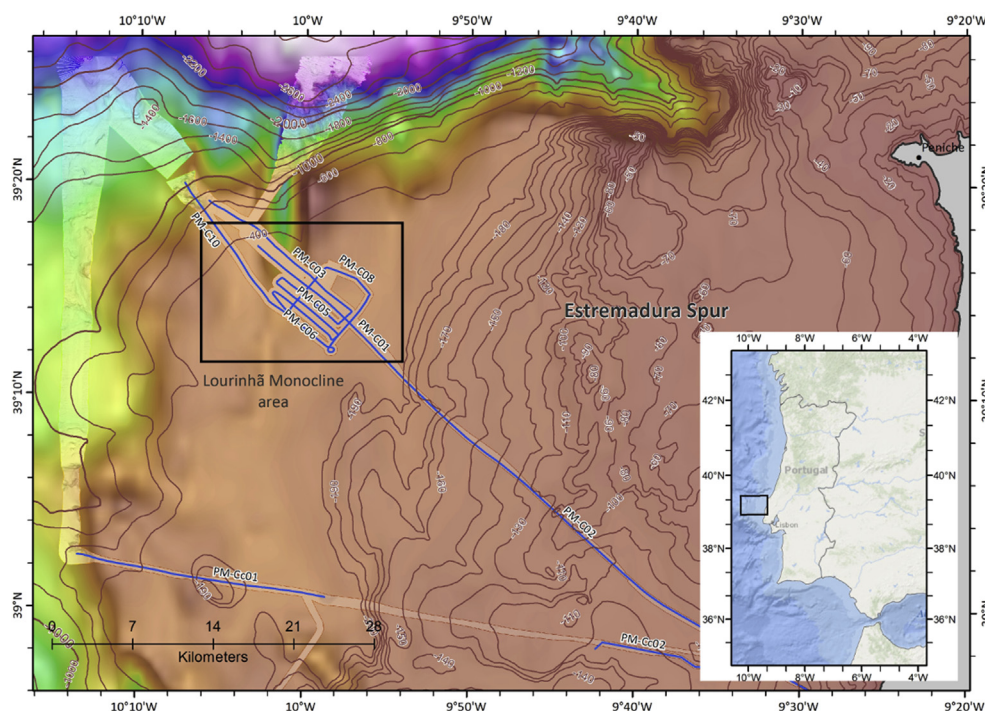


**Fig. 1.** Geographic location of the Estremadura Spur with the indication of the Lourinhã Monocline pockmark field (black rectangle) and the PACEMAKER seismic lines (blue lines). The coordinate system used was WGS 84. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

northern Portugal were based on low resolution bathymetry (Badagola et al., 2006; Badagola, 2008; Mougenot, 1989; Rodrigues, 2001).

## 3. Materials and methods

### 3.1. Acoustic data

Multibeam bathymetry, acoustic backscatter and high-resolution seismic data were collected during the PACEMAKER research cruise carried out between 21 and 23 March 2011 on board the RV Pelagia. The multibeam echosounder system used was the Kongsberg EM300 (30 kHz). Final products of the multibeam data are a high-resolution bathymetric map (with cell-size of 10 m) covering and area of 53 km$^2$ and the correspondent backscatter imagery.

Fourteen 2D high-resolution seismic profiles were acquired with a 1 kJ sparker seismic reflection system. This data was processed using the SPW software package (Seismic Processing Workshop, from Parallel Geoscience Corporation). The seismic raw data in SEG-Y format was first imported into SPW, followed by the picking of the seafloor reflection, data sorting, spectral analysis, and Butterworth band-pass filtering. The data was also corrected for swell and tide statics. Then, the data was processed with source signature deconvolution, to increase the vertical resolution of the seismic section and attenuate the multiples. An early mute was applied to eliminate the relative contributions of the direct arrivals and the noise present in the water column. Finally, the seismic section was migrated to correctly position the seismic events at their correct subsurface location. Migration was performed with the 2D Stolt algorithm at a constant velocity of 1500 m/s. The data trace spacing was 2.2 m. Before inserting the data into an interpretation package, the navigation was corrected for offset and layback. The geographic coordinates were converted to Universal Transverse Mercator (UTM zone 29N) and the trace headers of the seismic data were exported as ASCII files.

The interpretation of the seismic reflection data was performed using the software SeisWorks (OpenWorks) from Landmark Graphics Corporation. The interpretation was based on the methodology developed by Mitchum et al. (1977a, 1977b, 1977c).

### 3.2. Underwater videos

During the EMEPC/PEPC/LUSO/2015 cruise on board of the NRP Almirante Gago Coutinho, between 27 May and 3 June 2015, direct observations of the seafloor in two selected areas were conducted and recorded on video using the Estrutura de Missão para a Extensão da Plataforma Continental (EMEPC) Remotely Operated Vehicle (ROV) Luso.

## 4. Results

### 4.1. Bathymetry and backscatter

The study area is located on the NW edge of the Estremadura Spur outer shelf, at water depths ranging between 240 and 350 m, within the Lourinhã Monocline partially covered by ~40 m of clastic Pliocene and Quaternary sediments (Badagola et al., 2006). The seafloor is a gently dipping (0.5°) featureless seabed - except for the presence of crater-like, circular to oval depressions - limited by the shelf break, at 400 m bsl. The continental slope is quite steep (~5°) as depths vary from 400 m to more than 2000 m bsl on a section of 20 km. In the area surveyed during the PACEMAKER campaign that covered an area of approximately 52 km$^2$, 76 shallow round depressions were identified in the bathymetry. These depressions

have depths of 2–17 m, with diameters ranging from 30 m up to 400 m and border slopes of more than 3°. In plan view they have circular, sub-circular and elliptical shapes, while in cross-sections they have 'U' and 'V' shaped profiles (Fig. 2). The edge of the depressions at the present day seafloor has a slight to nil positive relief with respect to the regional bathymetry, with maximum heights of 17 m.

Based on the multibeam backscatter three different seafloor areas were defined (Fig. 3): i) Area 1, is characterized by a heterogeneous distribution of the backscatter intensity, with predominant low-backscatter areas and clusters of high-backscatter spots more abundant at the north-west sector of the covered area; ii) Area 2 displays a monotonous low backscatter pattern with occasional intermediate intensity spots; iii) Area 3 exhibits a spotted backscatter pattern with prevalence of high-backscatter facies.

Some of the round depressions that are observed in the bathymetry (Fig. 2) are also visible in the backscatter imagery, and those are characterized by a high-backscatter signal in the central part of the depressions (Fig. 3). The crater-like depressions display a geometry which is compatible with pockmarks.

### 4.2. Seismic interpretation

Interpretation of the seismic reflection profiles was crucial for the understanding of the crater-like depressions, their relationship with the sub-seafloor geology and their classification as pockmarks. Detailed seismostratigraphic interpretation allowed to propose a chrono-stratigraphic model in an area without wells and also revealed acoustic features possibly related to fluid flow and trapped fluids.

#### 4.2.1. Seismostratigraphic interpretation

The seismostratigraphic interpretation allowed the identification of six seismic units (U1 to U6) bounded by seismic horizons (M to H5) that mark the main geologic discontinuities or variations in seismic facies, as summarised in table of Fig. 4 and in the seismic profile of Fig. 5.

#### 4.2.2. Seismic evidence for fluid flow

Hydrocarbon seepage can be recognized on seismic data, because it often causes mechanical and/or compositional changes in the geological sequences that can produce a detectable acoustic anomaly. Evidence for fluid flow or the presence of gas in sedimentary sequences is inferred from the observation of morphological features (e.g. pockmarks) and of geophysical indicators, such as gas chimneys, acoustic turbidity and blanking (Duarte et al., 2007; Judd and Hovland, 2007). Gas chimneys are vertical to near-vertical zones associated with upward fluid migration through a fracture network; some lateral diffusion can also occur from the chimneys within the host sedimentary sequences (Duarte et al., 2007; Judd and Hovland, 2007; Ligtenberg, 2005). Acoustic turbidity (AT) appears on shallow seismic reflection profiles as a disturbance on the seismic record masking all seismic reflections of the deeper layers. Sometimes, coherent reflections can still be followed, despite the reduced amplitude of the acoustic turbidity areas. Acoustic blanking (AB) is defined by a transparent or signal-starved domain (usually vertical) in the seismic profiles, often close to the seabed (Judd and Hovland, 2007).

A series of "U" and "V" shaped depressions affecting the seafloor were identified on the seismic sections. Based on their dimensions, geometry, and disturbance of lateral continuity of seismic horizons these features are interpreted as seafloor pockmarks produced by fluid seepage. The seafloor pockmarks are more frequent in the area with steeper slopes (>0.5°) where the seismic unit U6 is absent. At least three levels of buried pockmarks (one of these levels is seen at
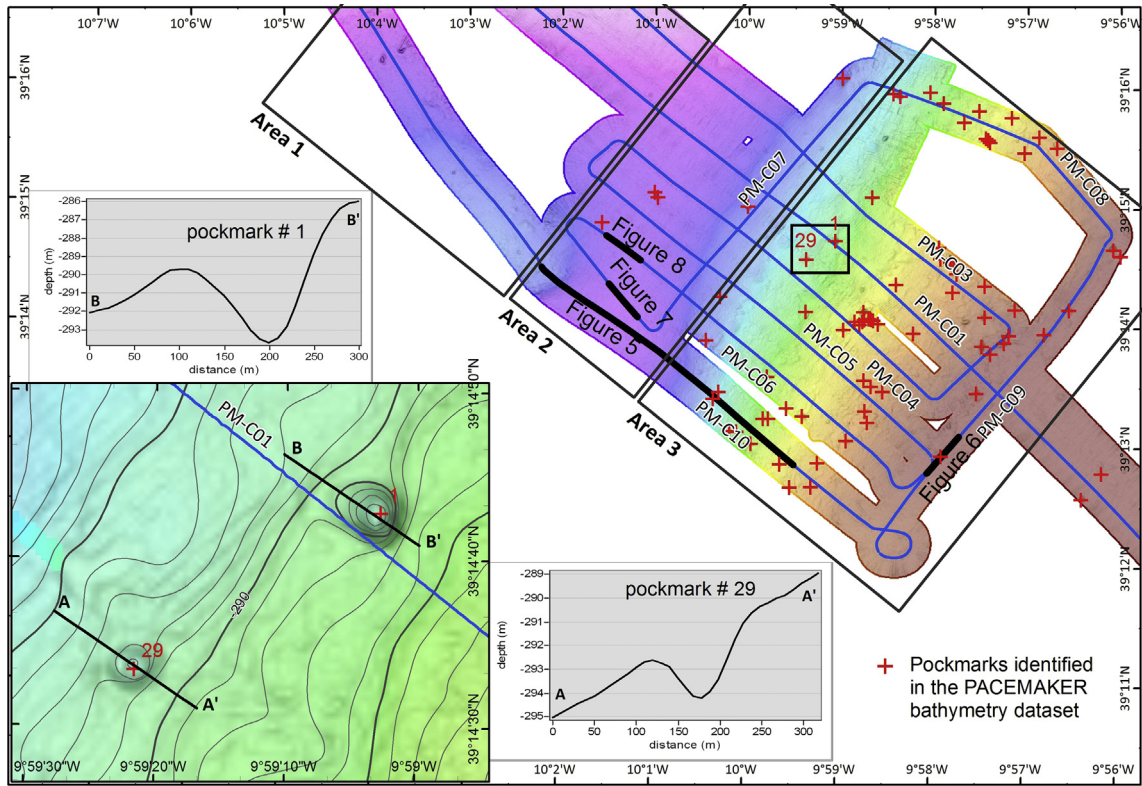
**Fig. 2.** Lourinhã Monocline seafloor bathymetry and detail of a region with two depressions and topographic profiles of these features. Vertical exaggeration of profiles is approximately 25x.
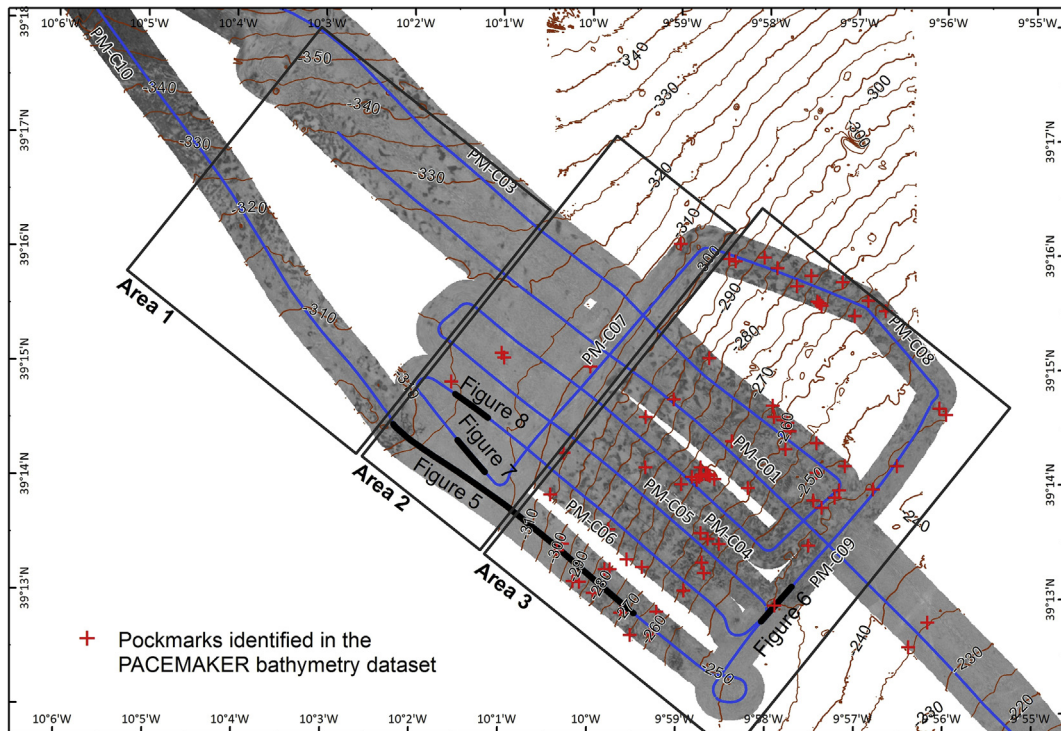


**Fig. 3.** The Lourinhã Monocline area of the Estremadura Spur (black rectangle in Fig. 1) with the multibeam derived backscatter imagery (lighter grey: low backscatter; darker grey: high backscatter). Equidistance: 5 m.
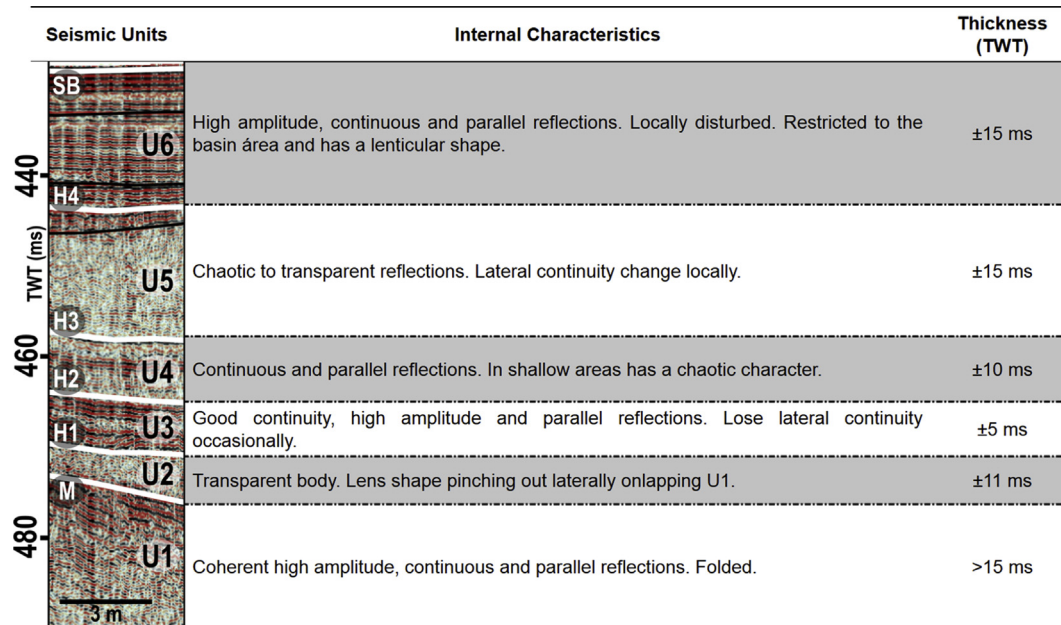
**Fig. 4.** Principal features of the seismic units identified in the PACEMAKER dataset (the dotted lines mark discontinuities in the seismic sequence).

Fig. 7) are identified, located at various depths within seismic units U2 to U6, with geometries and sizes similar to the ones found on the seafloor. These buried structures are inactive at present-time, since the pockmarks are filled with sediments.

The largest depression has a diameter of 147 m and a depth of approximately 4 m (Fig. 6). This depression was interpreted as resulting from fluid escape because there is obvious sediment volume loss underneath it as sea floor and unconformities are not parallel and there is vertical and horizontal disruption of the seismic horizons.

In all the seismic profiles, areas of acoustic disturbed reflections are clearly identified, not only in the chaotic and transparent units U2 and U5, but also as lateral interruptions of the continuous and coherent reflections in units U4 and U6. It is possible to observe these features in Fig. 8 with 1.5–5 ms of vertical dimension. Vertical to sub-vertical columnar zones of acoustic wipe out and seismically transparent features are observed (Fig. 8), more frequently, in the sector where the Pliocene-Quaternary sequence is thicker. These vertical structures terminate at seabed pockmarks or at buried pockmarks. The majority of these structures seems to have their origin at unit U1, although some rare ones originate in the younger units. Larger vertical zones of acoustic anomaly (near 16 m of vertical dimension), characterized by loss of lateral coherency and low amplitude of the reflections, are also observed crossing the seismic sequence (Fig. 8) and ending near the seabed. The reflections of the host sedimentary package are usually offset or deformed (localized folds and collapse structures, synclines) close to these features.

### 4.3. Seafloor direct observations with ROV

Direct observation of the seafloor and video recording both outside and inside the depressed areas identified in the bathymetry was done during Remote Operated Vehicle (ROV) Luso dives in two selected locations between 280 and 300 m bsl. These observations showed that the seafloor is composed by non-consolidated fine to coarse sandy sediments with well consolidated rock fragments dispersed at the seafloor or forming small clusters (Fig. 9). These rock clasts are more frequent along the slopes of the depressions and the preliminary observations of the hand specimens indicate

that they are black coloured carbonate breccias. The ROV Luso observations, inside depressions with high backscatter anomalies has provided no evidences for seepage activity or authigenic carbonate crusts or concretions at the seafloor. The base of the observed depressions was instead found to be covered by clastic sediments and bubbling was not observed at the seafloor in these sites.

## 5. Discussion

### 5.1. Seismic chronostratigraphy

Due to the inexistence of wells available for correlation in the area it was not possible to directly calibrate the seismic data and develop an age model for this sedimentary package. Hence, chronostratigraphic constraints are made by comparing the seismic stratigraphic record with the regional geology and published onshore and offshore geological maps (Badagola et al., 2006; Badagola, 2008; LNEG, 2010).

The acoustic basement corresponds to outcropping units of folded Jurassic and Cretaceous rocks. The older seismic unit (U1) displaying geometrically organized seismic reflections was folded and eroded prior to the deposition of U2, possibly by transpressive kinematics associated with the possible vertical (strike-slip) fault (seen in the seismic profile PM-C10; Fig. 5). Considering the Middle Miocene age of the peak of the alpine compression in the WIM, U1 is probably of Miocene age topped by the M unconformity. Accordingly, seismic units U2 to U6, in which tectonic folding is milder are of probable Pliocene through Holocene age.

Taking into consideration the exposed onshore geology some constraints can be made regarding the age of the post-Miocene seismic units. In the nearby region of Lisbon no Zanclean sedimentation is recorded (Pais, 2002), this observation points of a Late Pliocene (Piacenzian) age to the U2 unit representing a hiatus in the sedimentary record of approximately 1.5 Ma in between U1 and U2. The discontinuity between U2 and U3 can be speculatively attributed to the important low-stand period at the Pliocene-Pleistocene transition or Lower to Middle Pleistocene (Gelasian-Middle) age for the U3 to U5 units (Haq et al., 1987). The transition of U5 to U6 corresponds to a discontinuity possibly related to the Last Glacial
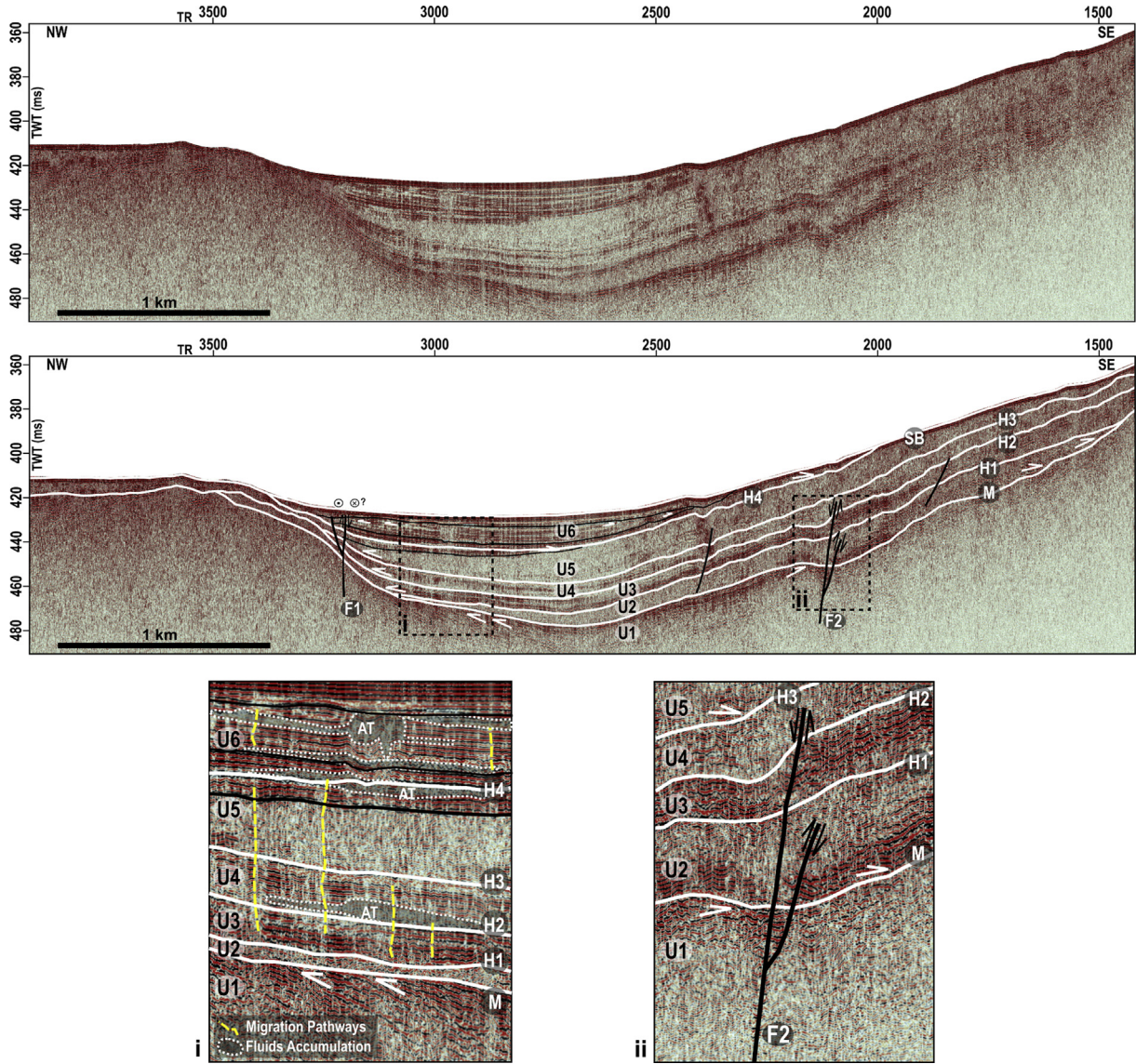
**Fig. 5.** Interpretation of the seismic profile PM-C10. **Black letters**: seismic units. **White letters and white lines**: seismic horizons. **Black solid lines: fault planes. Black doashed lines**: possible fault planes. **White arrows**: toplap and onlap terminations. TR: traces; TWT (ms): two-way time in ms. i, ii: details of the profile. AT: acoustic turbidity; Yellow dashed arrows: migration pathways (for location see Fig. 2).

Maximum, being therefore U6 considered as Upper Pleistocene to Holocene age.

### 5.2. Evidence for fluid migration and pockmarks

The occurrence of a large number of morphologic features interpreted as pockmarks based on the multibeam bathymetry and backscatter images (Figs. 2 and 3) is the first direct evidence of the occurrence of fluid seepage in the Estremadura Spur. However, direct observation made with the ROV Luso did not show obvious signs of fluid seepage at the seafloor, such as bubbling or water turbidity.

Nevertheless, the vertical to sub-vertical columnar zones of acoustic wipe out, seismically transparent features and acoustic blanking localized underneath buried pockmarks or pockmarks lying at the seafloor are interpreted as fluid migration pathways. Three types of conduits are visible in the seismic profiles: pipes, chimneys, and wide acoustic disturbed zones. The pipes correspond to sub-vertical narrow zones, acoustically transparent or with reflectors of reduced amplitude. They are approximately 10 m wide extending across all the seismic sequence (Figs. 7 and 8) and are most probably related to the upward migration of fluids along localized faults or along hydraulic fractures caused by the fluid overpressure in the host strata. The chimneys correspond to wider zones of disrupted or attenuated upward convex bending reflections with approximately 55 m wide in the upper part, narrowing downwards to approximately 19 m and about 31 m height. The reflections in the host strata bend upwards near these chimneys (Fig. 9). Wider acoustic blanking zones (Fig. 9), cut the seismic sequence and were interpreted as having been caused by upwards direct diffuse fluid migration through the sediments and accumulation (Duarte et al., 2007; Judd and Hovland, 2007; Ligtenberg, 2005).

In the seismic dataset, layer parallel acoustically disturbed zones were also identified. These zones developed concordant with the stratigraphic units and are characterized by the loss of lateral coherency and low amplitude of the reflections (previously referred as acoustic turbidity). This disturbance is probably caused by fluid
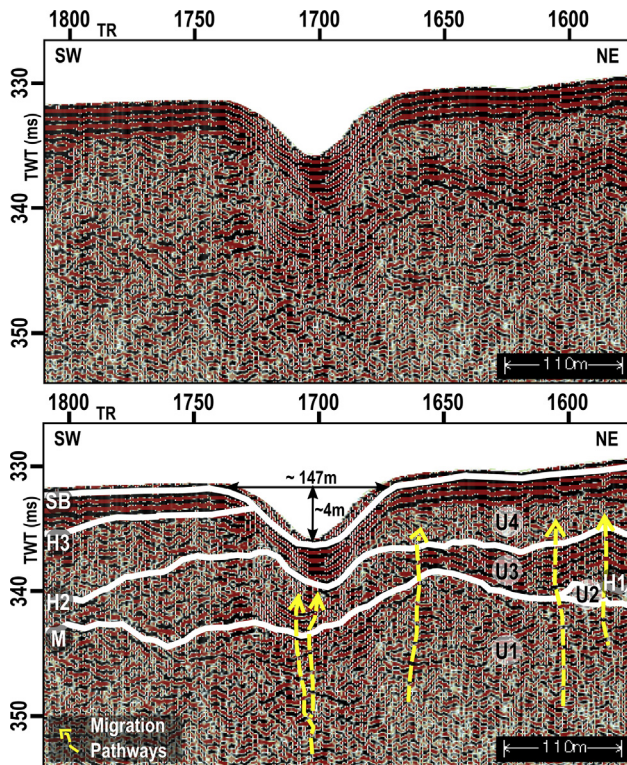
Fig. 6. Detail of seismic profile PM-C09 showing a pockmark at the seabed (Fig. 2 for location).

accumulation along these sedimentary units (Figs. 7 and 8).

Although gas hydrates are frequently found associated with pockmarks in other regions of the world (Barnes et al., 2010; Chand et al., 2008; Gay et al., 2007, 2006; Judd and Hovland, 2007; Pinheiro et al., 2003), in the Estremadura Spur no evidence or indications of their presence were identified in the sedimentary sequence.

### 5.3. Fluid seepage history

Fluids tend to move towards lower hydraulic heads, i.e. towards locals of lower confining pressure. The fluids capacity to move upwards or laterally is controlled by the nature of the sedimentary deposits namely their porosity and permeability, especially by faults and fractures that might constitute preferential migration pathways. Impermeable layers serve as seals; they constrain fluid migration pathways changing their trajectories or inducing the development of fluid pressures above the expected hydrostatic values and sediment yielding point causing hydraulic fracturing.

Several geological processes may trigger vertical fluid migration and subsequent expulsion associated with the excess pore-fluid pressure. These processes include tectonic deformation, rapid sediment loading, earthquake wave propagation and sea level changes (Kopf, 2002; Talukder, 2012) and therefore recurrence or cyclicity in the flow can be expected. The presence of pockmarks at the seabed and buried pockmarks at various depths within the Pliocene-Quaternary seismic units (U2 to U6), and the existence of migration pathways visible in the seismic sequence (Figs. 6–8), indicate that the migration of fluids in the Estremadura Spur was intermittent, possibly occurring in recurrent episodes, at least since the Late Pliocene. The two most likely processes that can have triggered the fluid flow and seepage, and the consequent pockmark formation are periodic sea level changes and seismicity. Sea level
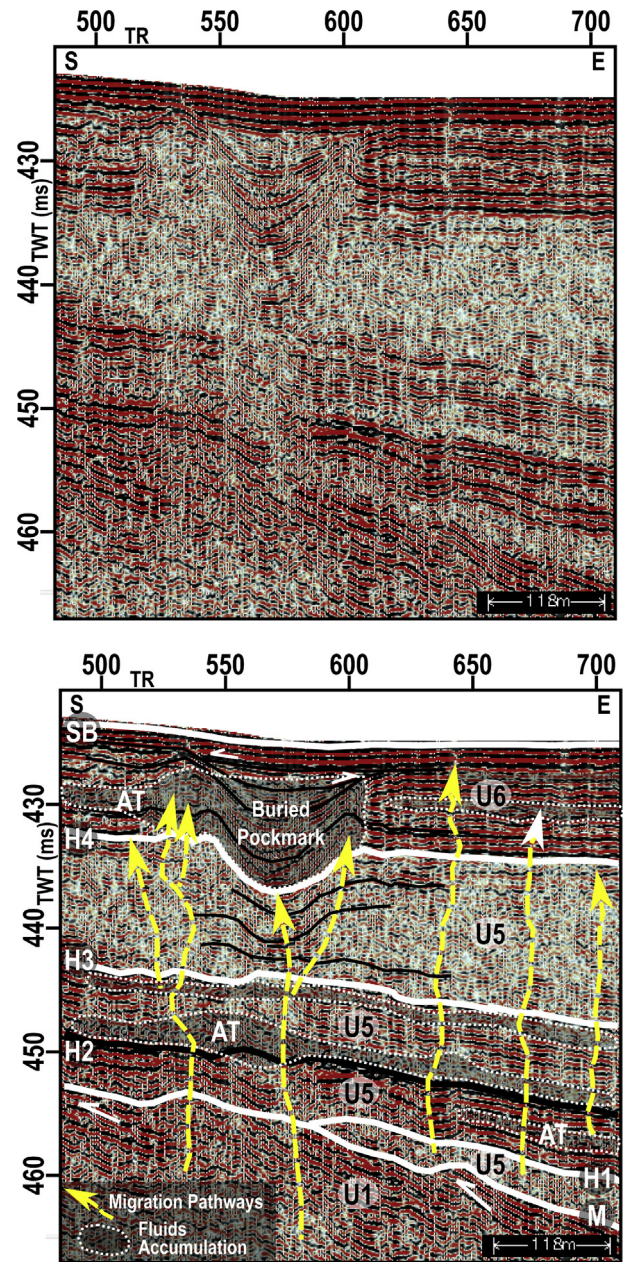


Fig. 7. Detail of seismic profile PM-C07 showing a buried pockmark and sub-seafloor evidences for fluid migration. Layers with AT are interpreted as fluids reservoirs (Fig. 2 for location).

variation in the Late Pliocene through Present exceeded 120 m causing significant variation of the hydraulic head in the study area that lies at a maximum of 400 m bsl. With respect to seismicity, the ES is the most important location of low to moderate seismicity in West Iberia, and the large magnitude earthquakes (M > 7) that are generated in the Africa-Eurasia plate boundary in South Iberia are also strongly felt in the ES (Custódio et al., 2016).

The seismic data and the direct observation of three pockmarks with ROV dives suggest that the pockmarks are not active at Present, i.e. fluid migration is at least partially quiescent in the study area. However, the existence of pockmarks at the sea floor and trapped fluids within U4 to U6 sediments can be taken as an indication of sporadic activity triggered by earthquake shaking.

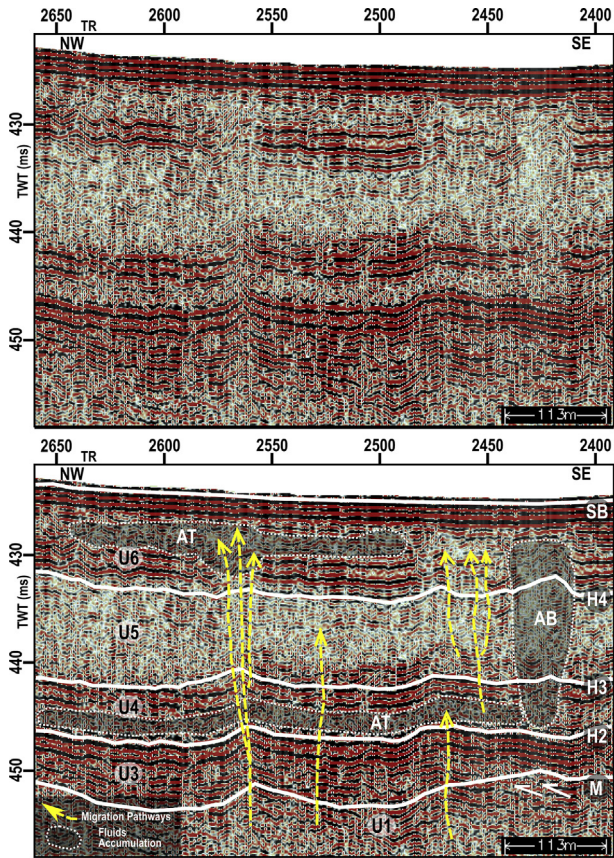Pockmarks are commonly associated with the presence of

**Fig. 8.** Detail of seismic profile PM-C06: seismic acoustic evidencs for fluid accumulation and migration. AT: acoustic turbidity; AB: acoustic blanking (Fig. 2 for location).
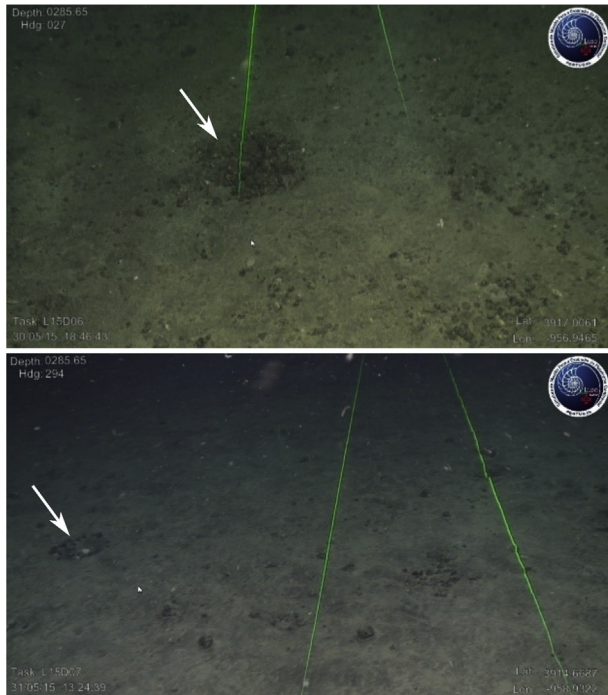


**Fig. 9.** Seafloor aspects observed during ROV/LUSO dives L15D06 and L15D07: fine to coarse sandy sediment with a rock clasts (breccia) cluster (indicated by white arrows). Distance between lasers is 60 cm.

authigenic carbonates that may cause higher values of acoustic reflectivity and roughness when compared to the surrounding seafloor (Klaucke et al., 2006; Orange et al., 2002), making possible the recognition of these features by their signature in the backscattered energy. The existence of high backscatter anomalies in several features in the Estremadura Spur can be observed, although the seafloor observations during the ROV dives, has provided no evidences for active seepage. Gay et al. (2007) argued that at seep sites, both active and recently active but currently inactive, authigenic carbonates buried under 10 m of sediments, may create anomalies on the backscatter signal which might be the case of the studied field. In this area of the Estremadura Spur there are no direct evidences for the thickness of the sedimentary package; however, a crude estimation using the seismic reflection profiles points to thicknesses of the surficial layer above the pockmarks of less than 5 m, supporting the applicability of Gay's model.

Further direct sampling and visual inspection of this pockmark field is needed to draw a conclusion as only 3 of the 76 pockmarks were inspected. The absence of buried pockmarks in the U1 seismic unit indicates that the system was active only during the Upper Pliocene and Quaternary, and clear evidence for three different episodes of fluid seepage are observed within this sequence. The time interval between the end of the seepage and the complete burial of the pockmarks depends on the sedimentation rate of the areas and it is expected to be a relatively fast process in a continental shelf environment close to the onshore source of sediments. However, the width of the Estremadura Spur continental shelf and the location of the pockmark field close to the shelf (here abnormally large) edge constrain the sediment supply to the area leading to a burial rate of the pockmarks slower than expected.

### 5.3.1. Seepage activity model

A four-phase cycle evolution model is proposed to explain the fluid migration system that originates and controls the Estremadura Spur pockmark field (illustrated in Fig. 10).

(i) Firstly, the occurrence of sub-surface pockets of fluids causes local deformation of the overlying sediments. Due to overpressuring the yield point of the sedimentary material is reached leading to fracturing and increase of the available percolation pathways facilitating the vertical fluid migration throughout the seismic sequence (Stage 1).

(ii) If fluid flow is rapid and sudden then a pockmark forms at the seafloor (Stage 2), due to the remobilization of seabed fine sediments (Hovland et al., 2010). Fluid flow becomes slower or even stops after the pressure release event.

(iii) In the phases of seepage quiescence, pockmarks are filled with sediments (Stage 3) until complete burial. Although the seepage is inactive, the sub-seafloor fluid migration can still be active, with fluids migrating vertically or laterally through and/or along the sedimentary layers and accumulating in more porous and permeable sediments beneath the seafloor.

(iv) If the pressure builds up again and overcomes the cohesion of the overlying cover, a new pockmark will form at the seafloor (Stage 4). This can be facilitated by the earthquake activity causing sediment fluidization.

### 5.4. Fluids source

The seismic interpretation allows for the identification of the fluid migration pathways and the location of shallow accumulations, to constrain a minimum depth of origin and infer the time frame of the seepage activity. Since the seismic image resolution deteriorates with depth, the source geometry and tectonic/structural control of migration pathways (pipes and chimneys; Fig. 8) is
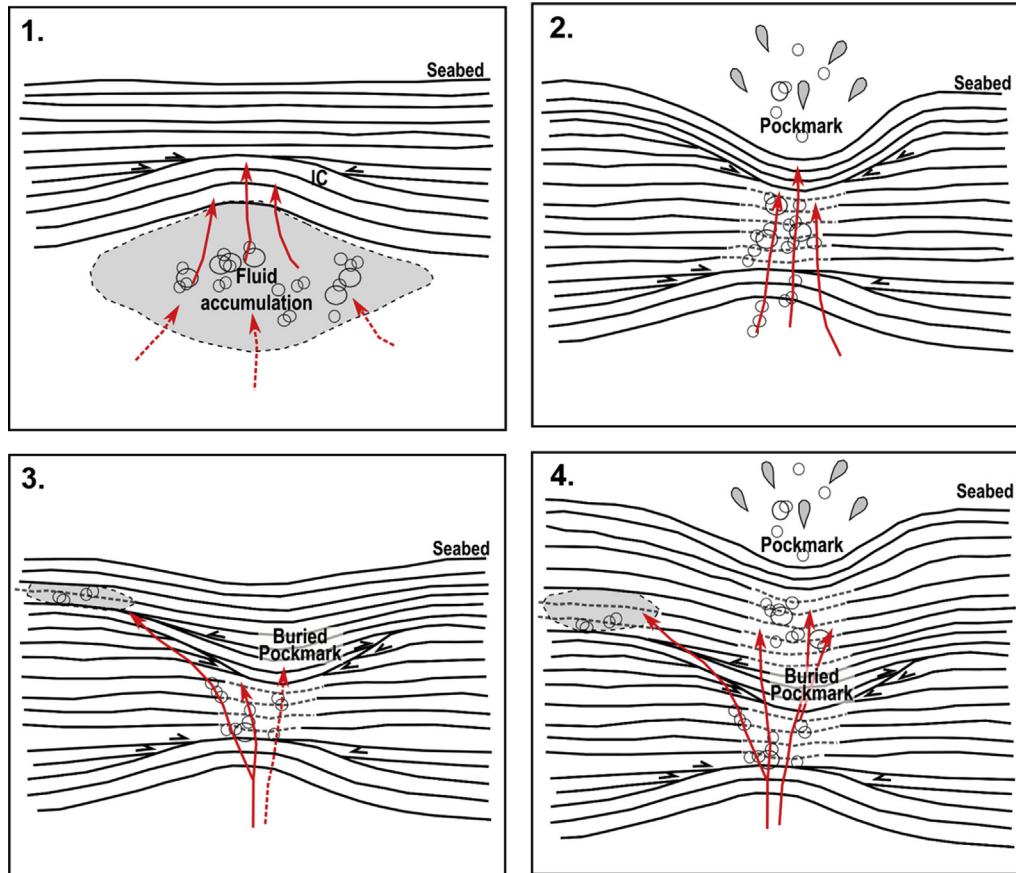
**Fig. 10.** Seepage evolution hypothesis (see text for discussion, 5.3.1). Red arrows: migration pathways; Red dashed arrows: possible migration pathways; Circles and drops: fluid; Dashed grey lines: acoustically disturbed reflection; Black arrows: onlap terminations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

limited.

However, the available seismic data show various locations where the fluid migration pathways seem to be rooted below the Pliocene-Quaternary sediments (Figs. 7 and 8) in the older seismic unit U1 or from below. This is an indication that the fluids in the sedimentary cover of the Lourinhã Monocline originate, at least partially, in the Miocene sediments or from deeper sources.

In the onshore part of the Lusitanian basin, adjacent to the Estremadura Spur, oil and gas seepage in the outcrops of the Upper Jurassic sediments were described (Pena dos Reis et al., 2010; Pena dos Reis and Pimentel, 2014). In the well 20B-1, located 40 km SE of the Lourinhã Monocline, a small gas occurrence in the Late Jurassic Coimbra Formation was reported (Shell Prospex Portuguesa, 1976a, 1976b). These two occurrences suggest that the Estremadura Spur pockmark associated fluids may have a deep origin, with a source, possibly related with the Jurassic hydrocarbon system.

However, with the available data, fluids formed at shallow depths within the Pliocene-Quaternary seismic sequence cannot be discarded.

## 6. Conclusions

The NW region of the Estremadura Spur outer shelf has been affected by several episodes of fluid migration and fluid escape that are expressed by a vast number of seabed and buried pockmarks. These pockmarks correspond to the first record of fluid seepage in the W Portuguese Margin. The analysis of high-resolution seismic lines covering this pockmark field allowed the identification of a sequence of six seismic units (of Miocene to Quaternary age)

disturbed by the migration and accumulation of fluids. The migration of fluids to the seabed occurred during the Pliocene-Quaternary, as indicated by the presence of buried pockmarks at different depths. At present the pockmarks are mainly inactive, as the seabed pockmarks are covered by recent sediments. The vertical stacking of various pockmarks suggests a cyclical fluid flow activity that can possibly be the result of the eustatic sea level variations and the subsequent changes of the hydrostatic pressure. An alternative hypothesis can be considered assuming the episodes of intense fluid flow as being associated with the local seismicity and neotectonics. The imaged fluids migration pathways that are rooted below the Pliocene-Quaternary sediments, in the seismic unit U1 or bellow it, suggest that the fluids originated in pre-Miocene sediments.

## References

Badagola, A., Rodrigues, A., Terrinha, P., Veiga, L., 2006. New insights on the plio-quaternary deposits of the Estremadura Spur shelf (West Iberian margin). In: Abstract Book of the 5th Symposium on the Iberian Atlantic Margin, pp. 21–22. Aveiro.

Badagola, A.P.L., 2008. Evolução morfo-tectónica da plataforma continental do Esporão da Estremadura. Master Thesis. Faculdade de Ciências da Universidade de Lisboa.

Barnes, P.M., Lamarche, G., Bialas, J., Henrys, S., Pecher, I., Netzeband, G.L., Greinert, J., Mountjoy, J.J., Pedley, K., Crutchley, G., 2010. Tectonic and Geological framework to gas hydrates and cold seeps on the Hikurangi subduction margin, New Zealand. Mar. Geol. 272, 26–48.

Benedetti, M.M., Haws, J.A., Funk, C.L., Daniels, J.M., Hesp, P.A., Bicho, N.F., Minckley, T.A., Ellwood, B.B., Forman, S.L., 2009. Late Pleistocene raised beaches of coastal Estremadura, central Portugal. Quat. Sci. Rev. 28 (27-28) http://dx.doi.org/10.1016/j.quascirev.2009.09.029.

Cathles, L.M., Su, Z., Chen, D., 2010. The physics of gas chimney and pockmark formation, with implications for assessment of seafloor hazards and gas sequestration. Mar. Pet. Geol. 27, 82–91.

Chand, S., Mienert, J., Andreassen, K., Knies, J., Plassen, L., Fotland, B., 2008. Gas hydrate stability zone modelling in areas of salt tectonics and pockmarks of the Barents Sea suggests an active hydrocarbon venting system. Mar. Pet. Geol. 25, 625–636.

Cunha, T.A., Matias, L.M., Terrinha, P., Negredo, A.M., Rosas, F., Fernandes, R.M.S., Pinheiro, L.M., 2012. Neotectonics of the SW Iberia margin, Gulf of Cadiz and Alboran Sea: a reassessment including recent structural, seismic and geodetic data. Geophys. J. Int. 188 (3) http://dx.doi.org/10.1111/j.1365-246X.2011.05328.x.

Custódio, S., Lima, V., Vales, D., Cesca, S., Carrilho, F., 2016. Imaging active faulting in a region of distributed deformation from the joint clustering of focal mechanisms and hypocentres: application to the Azores-western Mediterranean region. Tectonophysics 676. http://dx.doi.org/10.1016/j.tecto.2016.03.013.

Duarte, H., 2009. High-resolution Seismic Reflection Investigation of Gas Accumulation and Seepage in the Tidal Channels of the Ria of Aveiro Barrier Lagoon (Portugal). University of Aveiro.

Duarte, H., Pinheiro, L.M., Teixeira, F.C., Hipólito Monteiro, J., 2007. High-resolution seismic imaging of gas accumulations and seepage in the sediments of the Ria de Aveiro barrier lagoon (Portugal). Geo-Marine Lett. 27, 115–126.

García-García, A., García-Gil, S., Vilas, F., 2004. Echo characters and recent sedimentary processes as indicated by high-resolution sub-bottom profiling in Ria de Vigo (NW Spain). Geo-Marine Lett. 24 (1) http://dx.doi.org/10.1007/s00367-003-0156-8.

García-García, A., García-Gil, S., Vilas, F., 2003. Monitoring the Spanish gas fields in the Ría de Vigo (1991–2001). Geo-Marine Lett. 23, 200–206.

García-García, A., Vilas, F., García-Gil, S., 1999. A seeping sea-floor in a Ria environment: Ria de Vigo (NW Spain). Environ. Geol. 38, 296–300.

García-García, S., Cartelle, V., Blas, E., Carlos, A., Díez, R., Durán, R., Ferrín, A., García-Moreiras, I., García-García, A., Iglesias, J., Martínez-Carreño, N., Muñoz Sobrino, C., Ramíraz-Pérez, A.M., 2015. Gas somero en el margen continental Ibérico. Bol. Geol. Min 126, 575–608.

Gay, A., Lopez, M., Berndt, C., Séranne, M., 2007. Geological controls on focused fluid flow associated with seafloor seeps in the Lower Congo Basin. Mar. Geol. 244 (1-4) http://dx.doi.org/10.1016/j.margeo.2007.06.003.

Gay, A., Lopez, M., Cochonat, P., Séranne, M., Devaché, D., Sermondadaz, G., 2006. Isolated seafloor pockmarks linked to BSRs, fluid chimneys, polygonal faults and staked Oligocene-Miocene turbiditic paleochannels in the Lower Congo Basin. Mar. Geol. 226, 25–40.

Gutscher, M.-A., Dominguez, S., Westbrook, G.K., Le Roy, P., Rosas, F., Duarte, J.C., Terrinha, P., Miranda, J.M., Graindorge, D., Gailler, A., Sallares, V., Bartolome, R., 2012. The Gilbraltar subduction: a decade of new geophysical data. Tectonophysics 574–575, 72–91.

Gutscher, M.-A., Malod, J., Rehault, J.-P., Contrucci, I., Klingelhoefer, F., Mendes-Victor, L., Spakman, W., 2002. Evidence for active subduction beneath Gilbraltar. Geology 30, 1071–1074.

Haq, B.U., Hardenbol, J., Vail, P.R., 1987. Chronology of fluctuating sea levels since the triassic. Science 235 (80), 1156–1167.

Hensen, C., Scholz, F., Nuzzo, M., Valadares, V., Gràcia, E., Terrinha, P., Liebetrau, V., Kaul, N.E., Silva, S., Martinez-Loriente, S., Bartolome, R., Piñero, E., Magalhães, V.H., Schmidt, M., Weise, S.M., Cunha, M.R., Hilário, A., Perea, H., Rovelli, L., Lackschewitz, K.S., 2015. Strike-slip faults mediate the rise of crustal-derived fluids and mud volcanism in the deep sea. Geology 43 (4), 339–342.

Hovland, M., Heggland, R., De Vries, M.H., Tjelta, T.I., 2010. Unit-pockmarks and their potential significance for predicting fluid flow. Mar. Pet. Geol. 27 (6) http://dx.doi.org/10.1016/j.marpetgeo.2010.02.005.

Judd, A., Hovland, M., 2007. Seabed Fluid Flow, the Impact on Geology, Biology, and the Marine Environment. Cambridge University Press, Cambridge.

Kim, J.-H., Villanueva, L., Zell, C., Sinninghe Damste, J.S., 2016. Biological source and provenance of deep-water derived isoprenoid tetraether lipids along the Portuguese continental margin. Geochim. Cosmochim. Acta 172.

Klaucke, I., Sahling, H., Weinrebe, W., Blinova, V., Bürk, D., Lursmanashvili, N., Bohrmann, G., 2006. Acoustic investigation of cold seeps offshore Georgia, eastern Black Sea. Mar. Geol. 231, 51–67.

Kopf, A.J., 2002. Significance of mud volcanism. Rev. Geophys. 40, 2–1-2–52.

Kullberg, J.C., Rocha, R.B., Soares, A.F., Rey, J., Terrinha, P., Azerêdo, A.C., Callapez, P., Duarte, L.V., Kullberg, M.C., Martins, L., Miranda, J.R., Alves, C., Mata, J., Madeira, J., Mateus, O., Moreira, M., Nogueira, C.R., 2013. A Bacia Lusitaniana: Estratigrafia, Paleogeografia e Tectónica. In: Dias, R., Araújo, A., Terrinha, P., Kullberg, J.C. (Eds.), Geologia de Portugal. Volume II: Geologia Meso-cenozóica de Portugal. Escolar Editora, Lisboa, 798 pp.

León, R., Somoza, L., Medialdea, T., Hernández-Molina, F.J., Vázquez, J.T., Díaz-del-Rio, V., González, F.J., 2010. Pockmarks, collapses and blind valleys in the Gulf of Cádiz. Geo-Marine Lett. 30, 231–247.

Ligtenberg, J.H., 2005. Detection of fluid migration pathways in seismic data: implications for fault seal analysis. Basin Res. 17, 141–153.

LNEG, 2010. Carta Geológica de Portugal à escala 1:1 000 000. Edição 2010.

Magalhães, V.H., 2007. Authigenic Carbonates and Fluid Escape Structures in the Gulf of Cadiz. University of Aveiro.

Magalhães, V.H., Pinheiro, L.M., Ivanov, M.K., Kozlova, E., Blinova, V., Kolganova, J., Vasconcelos, C., McKenzie, J.A., Bernasconi, S.M., Kopf, A.J., Díaz-del-Río, V., González, F.J., Somoza, L., 2012. Formation processes of methane-derived authigenic carbonates from the Gulf of Cadiz. Sediment. Geol. 243–244, 155–168.

Martínez-Carreño, N., García-Gil, S., 2013. The Holocene gas system of the Ría de Vigo (NW Spain): factors controlling the location of gas accumulations, seeps and pockmarks. Mar. Geol. 344, 82–100.

Mata, J., Alves, C.F., Martins, L., Miranda, R., Madeira, J., Pimentel, N., Martins, S., Azevedo, M.R., Youbi, N., De Min, A., Almeida, I.M., Bensalah, M.K., Terrinha, P., 2015. 40Ar/39Ar ages and petrogenesis of the West Iberian Margin onshore magmatism at the Jurassic-Cretaceous transition: geodynamic implications and assessment of open-system processes involving saline materials. Lithos 236-237, 156–172.

Mitchum, R.M.J., Vail, P.R., Sangree, J.B., 1977a. Seismic stratigraphy and global changes of sea level, part 6: stratigraphic interpretation of seismic reflection patterns in depositional sequences. In: Payton, C.E. (Ed.), Seismic Stratigraphy-applications to Hydrocarbon Exploration, Am. Ass. Petrol. Geol., Mem. 26, pp. 117–133.

Mitchum, R.M.J., Vail, P.R., Thompson III, S., 1977b. Seismic stratigraphy and global changes of sea level, part 2: the depositional sequence as a basic unit for stratigraphic analysis. In: Payton, C.E. (Ed.), Seismic Stratigraphy-applications to Hydrocarbon Exploration, Am. Ass. Petrol. Geol., Mem. 26, pp. 53–62.

Mitchum, R.M.J., Vail, P.R., Thompson III, S., 1977c. Seismic stratigraphy and global changes of sea level, part 1: overview. In: Payton, C.E. (Ed.), Seismic Stratigraphy-applications to Hydrocarbon Exploration, Am. Ass. Petrol. Geol., Mem. 26, pp. 51–52.

Mougenot, D., 1989. Geologia da Margem Portuguesa. Doc. Técnico 32.

Noiva, J., Duarte, H., Terrinha, P., Brito, P., Magalhães, V., Alves, P., Rosa, M., Oliveira, M., Curado, F., 2014. Searching for landslides in the stratigraphic record of the Tagus river delta as evidences for tsunami and earthquakes, using 3D seismic reflection. Comun. Geol. LNEG 101, 697–700.

Orange, D.L., Yuna, J., Maherb, N., Barry, J., Greene, G., 2002. Tracking California seafloor seeps with bathymetry, backscatter and ROVs. Cont. Shelf Res. 22, 2273–2290.

Pais, J., 2002. The Neogene of the lower Tagus basin (Portugal). Rev. Española Paleontol. 19, 229–242.

Pais, J., Cunha, P.P., Pereira, D., Legoinha, P., Dias, R., Moura, D., Brum da Silveira, A., Kullberg, J.C., González-Delgado, J.A., 2012. The paleogene and Neogene of western Iberia (Portugal). A cenozoic record in the european atlantic domain. Springer.

Pena dos Reis, R., Pimentel, N., 2014. Analysis of the petroleum systems of the Lusitanian basin (Western Iberian Margin) - a tool for deep offshore exploration. In: Bob Perkins Conference "Sedimentary Basins: Origin, Depositional Histories and Petroleum Systems." GCSSEPM. Houston, Texas.

Pena dos Reis, R., Pimentel, N., Garcia, A., 2010. A evolução da Bacia Lusitânica (Portugal) e dos sistemas petrolíferos associados. Rev. Electrónica Ciências Terra 19, 1–4.

Pinheiro, L.M., Ivanov, M.K., Sautkin, A., Akhmanov, G., Magalhães, V.H., Volkonskaya, A., Monteiro, J.H., Somoza, L., Gardner, J., Hamouni, N., Cunha, M.R., 2003. Mud volcanism in the Gulf of Cadiz: results from the TTR-10 cruise. Mar. Geol. 195 (1-4) http://dx.doi.org/10.1016/S0025-3227(02)00685-0.

Rodrigues, A.C.C., 2001. Tectono-Estratigrafia da Plataforma Continental Setentrional Portuguesa. PhD Thesis. Faculdade de Ciências da Universidade de Lisboa.

Shell Prospex Portuguesa, S.A., 1976a. 17 C-1 Well Completion Report.

Shell Prospex Portuguesa, S.A., 1976b. 20 B-1 Well Completion Report.

Talukder, A.R., 2012. Review of submarine cold seep plumbing systems. Terra Nov. 24, 255–272.

Zitellini, N., Gràcia, E., Matias, L., Terrinha, P., Abreu, M.A., DeAlteriis, G., Henriet, 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 Gilbraltar. Earth Planet. Sci. Lett. 280, 13–50.